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# Driving the circular economy through public environmental and energy R&D: Evidence from SMEs in the European Union

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## ABSTRACT

Governments at the EU and the member state level are placing increased emphasis on public research and development (R&D) for energy and the environment to advance a circular economy (CE). To achieve CE goals, it is critical to engage SMEs as they represent the vast majority of enterprises in the EU. To date, there is a lack of evidence regarding the impact of these public R&D investments on SMEs' CE activities. We address this gap by analysing the impact of public environmental and energy R&D on CE implementation and investment by SMEs. The study draws from a multi-level database of 10,618 SMEs across 28 EU member states for the period 2013–2015 from the Flash Eurobarometer 441 survey and country-level data from other EU sources. Employing a mixed-level probit regression, we find that the knowledge generated by public environmental and energy R&D, defined as country-level investments in this activity from 2004 to 2015, positively affects SMEs' implementation of CE activities. Additionally, the study finds that public environmental and energy R&D affects the level of SMEs' investment in CE activities negatively, suggesting that more public R&D can substitute for the financial efforts that SMEs have to take when implementing CE activities.

## 1. Introduction

Curtailling the increasing environmental degradation caused by human activity requires significant changes in current production and consumption patterns (European Commission, 2015a; United Nations Development Programme, 2019). In particular, it is necessary to move from linear production-consumption models of 'take, make, use and waste' towards circular models that minimise, recover, recycle, and reuse materials, water, and energy (Geissdoerfer et al., 2017; Kirchherr et al., 2018). The concept of Circular Economy (CE) describes a circular production-consumption model that maximises the utility of products, components, and materials across their life cycle (Kirchherr et al., 2018; Kirchherr et al., 2017). It represents a means to reduce environmental impact while encouraging economic growth (Millar et al., 2019).

Transitioning to a CE requires the commitment of numerous actors, including governments and firms (Diercks et al., 2019). In particular, CE requires firms to develop and adopt innovative technologies and

business models (Bocken et al., 2016) as part of a more CE-oriented organisational culture (Ghisellini and Ulgiati, 2020). This may lead to new 'circular risks' as firms transition from tried-and-tested linear production methods to new circular ones (Ghisetti and Montresor, 2020; European Resource Efficiency Knowledge Centre (EREK), 2019). Firms—especially micro, small and medium enterprises (SMEs)—can face challenges related to a lack of financial resources, proper technology, and/or technical expertise, which can deter them from implementing and investing in CE activities (European Commission, 2019; European Resource Efficiency Knowledge Centre (EREK), 2019; Ormazabal et al., 2018; Rizos et al., 2016).<sup>1</sup> This represents a limitation for the transition to a CE as SMEs are the predominant type of firm in most economies, especially in the European Union (EU), and are an essential driver of economic and social development (OECD, 2019).

Governments at regional, national and EU levels have responded to this challenge by offering dedicated support to SMEs to stimulate engagement in CE activities including grant programmes, training, and

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<sup>1</sup> In this paper, SMEs are defined as firms with less than 250 employees following the EU recommendation 2003/361 (<http://data.europa.eu/eli/reco/2003/361/oj>). In the EU, micro firms employ fewer than 10 employees, Small between 10 and 49, and Medium 50 to 249.

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technology consulting (KPMG, 2019; European Commission, 2019; European Resource Efficiency Knowledge Centre (EREK), 2018). To be effective, these dedicated support measures need to be linked to a better understanding of how environmental and energy systems can be transformed towards a higher degree of sustainability (Domenech and Bahn-Walkowiak, 2019). In this context, the landmark 2015 *Paris Agreement*, part of the United Nations Framework Convention on Climate Change (UNFCCC), calls explicitly for Science, Technology, and Innovation (STI) policies to contribute to this goal (Diercks et al., 2019). Public environmental and energy R&D (PEERD) is a key STI policy instrument in this respect as it has the potential to provide firms with much-needed scientific knowledge to guide the development and adoption of new technologies, skills, resources, and awareness related to CE activities (de Jesus and Mendonça, 2018; Weber and Rohrer, 2012). In Europe, for example, the European Commission (EC) has budgeted €1 billion for R&D in activities focused on circular material flow, €3.3 billion for low-carbon and climate change resilience, and €2.2 billion for clean energy projects as part of the broader €30 billion public R&D strategy for the period 2017–2020 (European Commission, 2018).

However, our understanding of how PEERD helps firms, particularly SMEs, to overcome the challenges faced for transitioning to a CE remains limited. The existing literature on PEERD has, so far, mainly focussed on macro, regional, and sector perspectives (see Jaffe et al., 2005; Costa-Campi et al., 2017). Moreover, studies focusing on firms, including SMEs, only consider some aspects of CE, namely environmental innovations (see de Jesus et al., 2019; Demirel and Kesidou, 2019) and resource efficiency (Bodas-Freitas and Corrocher, 2019). Generating a deeper understanding of the factors underpinning SMEs' transition to a CE (European Resource Efficiency Knowledge Centre (EREK), 2019), and how PEERD contributes to these activities, is crucial for ensuring a successful transition towards a sustainable economy (de Jesus and Mendonça, 2018). Our analysis makes a significant contribution to understanding how PEERD acts as a catalyst for CE activity in SMEs. Specifically, it addresses the critical research question of whether public R&D investments in the areas of environment and energy increase SMEs' likelihood of implementing CE activities and investment in CE activities.

We define CE implementation as SMEs implementing at least one of the following five CE activities: (i) re-planning energy usage to minimise consumption; (ii) using renewable energy; (iii) minimising waste by recycling or reusing waste or selling it to another company; (iv) re-designing products and services to minimise the use of materials or usage of recycled materials, and (v) re-planning the way water is used to minimise usage and maximise re-usage. As explained in Section 3 (Data and variables), these CE activities are in line with widely accepted definitions of CE [see Korhonen et al. (2018) and Geissdoerfer et al. (2017), for examples]. Recent studies, such as García-Quevedo et al. (2020) and Bassi and Dias (2019), also focus on these CE activities when analysing the drivers and constraints affecting CE activities in SMEs.

A novel multi-level dataset is constructed by merging three datasets. Micro-data on firm implementation of CE activities, investment levels in CE, and firm-specific factors influencing the CE behaviour of 10,618 SMEs across 28 EU member states are obtained from the Flash Eurobarometer 441 dataset for the period 2013–2015. This dataset is merged with national-level data on government R&D investment in environment and energy over the period 2004–2015, which was obtained from Eurostat. Additionally, national-level data on R&D funding for environmental and energy issues from the EU Seventh Framework Programme (FP7) for the period 2007–2015 was obtained from the European Commission. The micro-level dataset permits a comprehensive understanding of the role of firms' internal resources in influencing their ability to implement and invest in CE activities. Combining

national R&D and FP7 data enables us to capture most of the spectrum of public investment in environmental and energy R&D.<sup>2</sup>

As the outcome and several of the control variables are at the level of the firm, but the key policy variable of interest is at the national level, we employ a multi-level modelling framework (Hox et al., 2017). This explicitly accounts for the different data present in our analysis and controls for additional unobserved country characteristics by means of mixed-effect models (Ng et al., 2006).

Our study makes two significant contributions. First, to the best of our knowledge, this is the first study to empirically assess the effect of PEERD on SMEs' CE activities. In this way, it extends studies that focus on environmental innovation or resources efficiency, as noted above, by focusing on other critical CE activities which have received less research attention. Second, the focus on SMEs is of particular importance as this cohort of firms is paramount for transitioning to a CE. The insights arising from our study, therefore, contribute to the design and implementation of STI policy instruments that further encourage SMEs to implement and invest in CE activities.

The paper is organised as follows. Section 2 sets out the theoretical context of the research and presents the hypotheses. Section 3 describes the data. Section 4 details the empirical approach. Section 5 presents the empirical results and discusses these vis-à-vis the pertinent literature on CE. Finally, Section 6 concludes.

## 2. Background and hypotheses

Two main sets of science, technology, and innovation (STI) policy instruments can influence the transition to a Circular Economy (CE) in SMEs. The first one is the provision of direct support for CE (e.g. grant programmes, training, and technology consulting). This includes public financial support to encourage firms' transition to a CE, which is a focal point for the European Commission as highlighted by the 'Support to Circular Economy Financing' Expert Group (European Commission, 2019). Furthermore, other support channels for CE activities are currently being developed at the local, regional and national levels in each EU member state with respect to the provision of technical assistance and consultancy services (European Resource Efficiency Knowledge Centre (EREK), 2019; KPMG, 2019; Bodas-Freitas and Corrocher, 2019). These financial supports and the establishment of technical assistance services are expected to accelerate SMEs' implementation of CE activities (European Resource Efficiency Knowledge Centre (EREK), 2019; European Commission, 2019).<sup>3</sup>Cecere et al. (2018), for example, find that public financial support and fiscal incentives improve SMEs' ability to introduce environmental innovations (i.e. innovations that decrease environmental impacts). This is in line with growing evidence on the impact of public subsidies for increasing R&D investment amongst SMEs (Becker, 2015).

The second type of instrument, which is the focus of our analysis, is public R&D on issues related to the environment and energy (PEERD). The OECD (2015) and the European Commission (2008) highlight environmental R&D activities such as the generation of scientific knowledge related to solid waste, the protection of the atmosphere, air, climate, water, and pollution control. Energy R&D includes the generation of scientific knowledge related to energy-efficient processes for energy production, distribution, and consumption. These two facets of R&D are the central R&D components relating to the main dimensions of the CE (Demirel and Kesidou, 2011; Mazzanti et al., 2016). Existing

<sup>2</sup> From 2004 to 2015, our data shows that €68.2 billion was invested in PEERD across the EU 28 member states by national governments (98%) and FP7 funding (2%).

<sup>3</sup> Despite the focus on financial support for CE at the EU level, as noted above, only 36% of the SMEs in the Flash Eurobarometer 441 survey declare being aware of financial support for CE activities, with only 4.6% of SMEs in the sample using this support (i.e. 467 firms out of a sample of 10,610 SMEs).

research focuses on these two types of public R&D when analysing the transition to CE at national, regional, and sectoral levels (Jaffe et al., 2005; Costa-Campi et al., 2017).

As opposed to direct financial and technical support, which specifically target the firm, PEERD can influence firms' CE activities indirectly. This is accomplished through the generation of scientific and technical knowledge and the promotion of a conducive environment for knowledge diffusion for CE at the macro-level (Kivimaa and Kern, 2016). Specifically, it is the effect that PEERD has on SMEs' implementation of CE activities and their investments in CE which is the focus of this study. The mechanisms through which this process may take place are discussed below.

### 2.1. Public environmental and energy R&D and the implementation of CE activities by SMEs

Firms generate and absorb knowledge, which in the context of this study relates to the knowledge required for CE activities, from intramural and external search activities (Roper and Hewitt-Dundas, 2015). The successful utilisation of knowledge for the development of new technologies and innovation depends on the appropriate combination of internal knowledge and capabilities, and accessible external knowledge that firms can absorb (Teece, 2007).

SMEs can find it challenging to accumulate scientific knowledge and the capabilities required for implementing CE activities and adopting new technologies internally (Ormazabal et al., 2018; Rizos et al., 2016). Relative to larger firms, SMEs have less access to external finance (Hall et al., 2016), possess lower tangible assets and human capital (Ipinnaiye et al., 2017), and have a smaller market presence (Schot and Steinmueller, 2018). These difficulties often result in SMEs failing to implement or avoid CE activities altogether (Garcés-Ayerbe et al., 2019).

Building on the innovation literature, public R&D facilitates the creation and dissemination of scientific knowledge and creates new opportunities for knowledge commercialisation (Edler and Fagerberg, 2017). It develops networks amongst firms, universities, and other key stakeholders for diffusion and standardisation of knowledge (Diercks et al., 2019). A proportion of the knowledge generated by public R&D transitions into freely accessible information, such as articles, reports, and manuals. Thus, public R&D is a crucial STI policy instrument for generating a stock of knowledge which firms, especially SMEs, can use in their R&D and innovation efforts (Mazzucato, 2018).

In particular, PEERD creates the necessary scientific and technological knowledge to facilitate the implementation of CE activities (de Jesus and Mendonça, 2018). It offsets some of the limitations impeding CE activities amongst SMEs by, for example, standardising knowledge, concepts, practices, and objectives that firms use for implementing CE approaches (Kivimaa and Kern, 2016). Also, it may outline national priorities such as the need for cleaner production practices, and signal potential new sources of revenue, such as the development of environmental innovations (Veugelers, 2012). In the long-run, PEERD may also enable the creation of new standards and regulations, which shape the overall institutional framework where firms operate (Sierzchula and Nemet, 2015). In summary, PEERD facilitates SMEs to formulate realistic CE strategies (Pacheco et al., 2018). This leads to our first hypothesis:

*H1: Public environmental and energy R&D investment increases CE implementation in SMEs.*

### 2.2. Effect of public environmental and energy R&D on SME investments in CE activities

Progressing on from SMEs' implementation of CE activities, we now consider the impact of PEERD on SMEs' CE investments levels. Investments in PEERD influence SMEs' CE investments by creating spillovers for knowledge generation and technology adoption (Jaffe et al., 2005). As noted above, public R&D provides cost-free exploitable

knowledge for firms (Edler and Fagerberg, 2017). Firms can build on this knowledge, generated by PEERD, and profit from CE activities (Tojeiro-Rivero and Moreno, 2019). The absorption and application of publicly generated knowledge may, however, require SMEs to carry out additional investments internally (Aghion et al., 2009). Some SMEs would be well-positioned (relative to other SMEs) to apply the knowledge generated by PEERD into commercial applications. Such firms, in turn, may decide to invest in CE activities early to develop new competitive advantages (Katsikeas et al., 2016). This leads us to our second hypothesis:

*H2: Public environmental and energy R&D investment increases the level of investment in CE by CE active SMEs.*

PEERD however, may also substitute private investment in CE. SMEs may require lower investments to implement CE activities in part due to the necessary knowledge having already been generated. PEERD may also negatively impact SMEs' perceived financial rewards of investing in CE (Weber and Rohrer, 2012). Public R&D in the areas of the environment and energy may increase the awareness of firms to CE activities in other firms. Further, it may also improve their ability to absorb and apply new knowledge more quickly. Therefore, SMEs considering investing in CE may be deterred from doing so because of potential unintended spillovers to others (Rodríguez-Pose and Crescenzi, 2008). In summary, because of PEERD, SMEs may be deterred from investing in CE. This leads to our third hypothesis:

*H3: Public environmental and energy R&D decreases the level of investment in CE by CE active SMEs.*

### 2.3. Conceptual framework

Fig. 1 summarises the mechanisms through which PEERD influences firm-level CE activities based on the discussions above. The process begins with public funding directed to the generation of scientific and technical knowledge to guide the transition to a CE. This flows from national government and EU (FP7) funding into universities, research centres and firms (A). Knowledge generation then takes place in this network of knowledge providers incorporating universities, research centres, and firms, which results in the generation of public knowledge (B).<sup>4</sup> This knowledge, which feeds into the national economy, leads to the accumulation of a stock of knowledge (C). As knowledge continues to disseminate, new networks (e.g. research groups and industrial clusters) and institutions (e.g. regulation) further support knowledge diffusion. Firms can access this knowledge and use it for developing new technologies, processes, and business models for transitioning to a CE (D). Thus, the impact of PEERD manifests as an indirect effect on SMEs' CE activities and investments, as denoted by H1, H2 and H3.

### 3. Data and variables

This paper draws on a multi-level database constructed for this study by merging firm-level and country-level data from several sources. The Flash Eurobarometer 441 served as the base dataset (European Commission, 2016a) as it contains information on firm Circular Economy (CE) activity and other firm characteristics. The data are from 2015, but

<sup>4</sup> We assume that publicly funded environment and energy R&D (PEERD) in firms also results in public knowledge. Public funders often require beneficiaries to publish the results of publicly funded R&D projects, e.g. by patenting the newly generated technologies (see Köhler and Peters, 2017). In addition, public funding of R&D in firms in the field of energy and environment frequently takes place in collaborative projects involving universities or research centres, and the results of these collaborative R&D efforts are published by the scientific partners (see Anciaux et al., 2016).

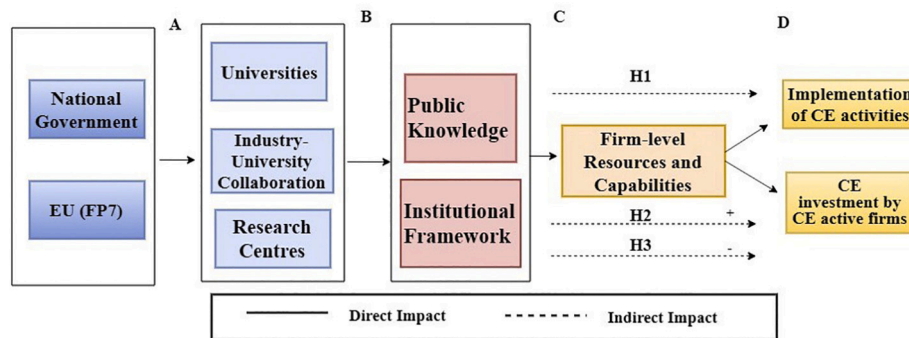


Fig. 1. The indirect effect of public environmental and energy R&D on SMEs' CE activities.

some variables refer to the period 2013–2015.<sup>5</sup>

Data on Public Environmental and Energy R&D (PEERD) is obtained from two sources. Environment and Energy Government Budget Appropriations on R&D from 2004 to 2015 were obtained from Eurostat. The second source of data is the European Commission's funds to environmental and energy projects under the umbrella of the EU FP7 by country from 2007 to 2015 (European Commission, 2015b).<sup>6</sup> These two sources represent a good proxy of public funding for PEERD in each EU member state. National-level data from these two sources are merged with the Flash Eurobarometer 441 at the country level.

The final dataset consisted of 10,618 SMEs, the vast majority of which were micro firms (62.97%), followed by small firms (23.30%), and medium-sized firms (13.71%). Representativeness was ensured through stratified random sampling by firm size and sector, and these quotas were adjusted according to each country's economic structure and to ensure the sample was large enough in every stratum (see European Commission, 2016b).<sup>7</sup>

### 3.1. Dependent variables

The Flash Eurobarometer 441 considers five CE activities. These are: (i) re-planning energy usage to minimise consumption, (ii) using renewable energy, (iii) minimising waste by recycling or reusing waste or selling it to another company, (iv) re-designing products and services to minimise the use of materials or use recycled materials, and (v) re-planning the way water is used to minimise usage and maximise re-use. For each CE activity, the Flash Eurobarometer 441 survey asked SMEs to select one of the following answers: 1 = "Yes, activities have been implemented"; 2 = "Yes, activities are underway"; 3 = "No, but we plan to do so"; and 4 = "No, and we do not plan to do so". We construct a new variable that is equal to 1 if the firm implemented at least one of the five CE activities considered from 2013 to 2015, or 0 otherwise (i.e. we define CE implementation as occurring if the firm answered 1 = "Yes, activities have been implemented" to any of the five CE activities considered). This variable is used as our dependent variable to measure SMEs' implementation of CE activities.

Our empirical definition of CE covers the main elements of CE as discussed in the literature. Geissdoerfer et al. (2017, p. 759) define CE as "a regenerative system in which resource input and waste, emission, and

energy leakage are minimised by slowing, closing, and narrowing material and energy loops". This includes the reuse of materials and products as well as designing long-lasting products. In a similar vein, Korhonen et al. (2018) stress the role of closing materials flows and using renewable energy sources for achieving CE goals. The first four CE activities included in the Flash Eurobarometer 441 Survey directly address these widely accepted definitions of CE (i.e. reducing energy consumption, using renewable energy, minimising or recycling waste, re-designing of products and minimising material or resource inputs) (Demirel and Danisman, 2019). The fifth item (on minimising water consumption) focuses on a particular resource which is part of 'resource input' or 'material' in CE definitions, but which may be overlooked by respondents if not mentioned explicitly.

Studies such as Sartal et al. (2020) and Ghisetti and Montresor (2020), specifically focus on the adoption of CE business models by firms, namely lean-manufacturing, ReSOLVE or Industrial Symbiosis (Kalmykova et al., 2018; Korhonen et al., 2018).<sup>8</sup> However, as Prime et al. (2020) and Sartal et al. (2020) highlight, uncertainty and complex business environments may deter SMEs from adopting CE business models that require radical changes to their core capabilities, especially if they conflict with existing investments. In turn, SMEs may gradually adapt their existing business models by implementing CE activities that can be accommodated as part of their existing operations (D'Amato et al., 2020; Ghisellini and Ulgiati, 2020). The five CE activities considered in this paper are valid measures of CE in the context of SMEs as they capture different elements of CE business models (Lewandowski, 2016; Geissdoerfer et al., 2017), such as product designs which avoid waste and enable reuse, products and services produced based on renewable energy use, or re-organising material flows along value chains (Demirel and Danisman, 2019).

The constructed variable is in line with standard practice in the innovation literature when innovation activity includes several sub-activities (e.g. Griffith et al., 2006). Our definition also applies the standard practice in innovation measurement, as outlined in the Oslo Manual (OECD/Eurostat, 2018), as we solely consider CE activities that were implemented, and exclude those that were only underway. This approach is also consistent with many studies on eco-innovations (Demirel and Kesidou, 2019; Triguero et al., 2013; Horbach et al., 2012). Focussing on CE activities implemented by SMEs ensures that we only examine activities that contributed to the CE. Activities that are still

<sup>5</sup> This is similar to the use of periods in the Community Innovation Survey which is recommended by the Oslo (2018) manual when capturing innovation activities.

<sup>6</sup> Data for FP7 funding is not available prior to 2007 as FP7 funding commenced in 2007. Data for FP7 projects funded beyond 2013 (i.e. end of FP7) correspond to projects approved prior to 2013 that continued receiving funding until December 31st, 2015.

<sup>7</sup> Given that all merges were carried out at the country level, the total sample corresponds to the total number of observations in the Flash Eurobarometer Survey number 441 (i.e. no observations were dropped in the merging process).

<sup>8</sup> The ReSOLVE framework comprises six action areas for businesses and countries wanting to move towards the circular economy, namely Regenerate, Share, Optimise, Loop, Virtualise and Exchange (Ellen McArthur Foundation, 2015). Industrial Symbiosis encompasses a variety of practices to link industrial processes with regional industrial systems through by-product exchange and utility sharing (Jiao and Boons, 2014).

underway may be stopped at a later point in time or may fail to contribute to the CE.<sup>9</sup> While our definition deviates from the one used in some other studies based on the same data, which also include CE activities that were underway (e.g. Bassi and Dias, 2019; Demirel and Danisman, 2019), our focused definition provides a more precise measure of SMEs' actual contribution to the CE (see also Katz-Gerro and López Sintas, 2019).

Fig. 2 illustrates the percentage of SMEs in the sample that implemented at least one of the five CE activities considered, with a detailed description of CE implementation for each activity and across countries presented in Table A1 in the Supplementary Material to this paper. The percentage of SMEs that have implemented at least one CE activity across the 28 EU countries in the period from 2013 to 2015 is 51.3%.<sup>10</sup> There are, however, large differences in the levels of implementation of CE activities by SMEs across the 28 EU countries; while around 86% of SMEs in Ireland implemented at least one CE activity, only around 15% of SMEs in Bulgaria did so.

From Table A1, minimising waste (35.81%), re-planning energy usage to minimise consumption (24.81%) and the re-designing of products and services to minimise material use (20.15%) were the most commonly implemented CE activities by SMEs across the 28 EU countries, followed by water re-usage (11.76%) and the use of renewable energy (11.23%). Approximately 22% of SMEs implemented only one CE activity, 37% of SMEs implemented at least two CE activities, approximately 4.6% of SMEs implemented at least four CE activities and only 1.5% of SMEs implemented all five CE activities.

Progressing on to SMEs' investments in CE, for those SMEs that implemented at least one CE activity, the Flash Eurobarometer 441 includes an ordered categorical variable that measures their collective investment in the five CE activities considered (as the percentage of total turnover). That is, the survey does not have data on the euro amount of investment in CE activities. Instead, it requests firms to select one of the following options: 0 if an SME did not carry out investments in CE activities in the period 2013–2015 (i.e. 0%); 1 if the SME invested between 1% and 5% of total turnover in CE activities; 2 if CE investments were between 6% and 10% of total turnover, and 3 if the SME invested 11% or more of total turnover in CE activities. Furthermore, the investment

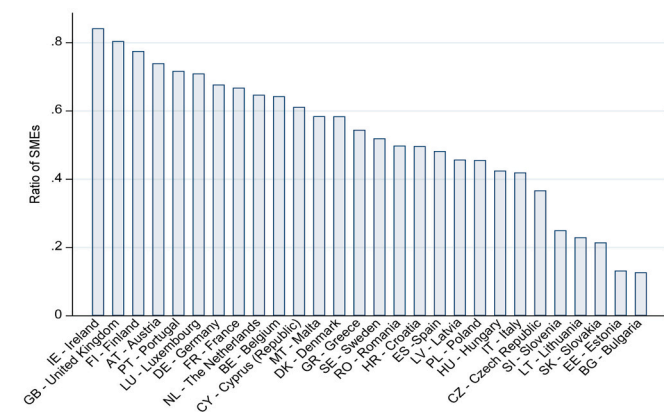


Fig. 2. SMEs' CE Implementation Across the 28 EU Countries. Source: Authors' own elaboration using data from Flash Eurobarometer 441.

<sup>9</sup> The Flash Eurobarometer 441 survey does not provide any additional information regarding how advanced the CE activities that are underway are (i.e. planning, resourcing and implementation).

<sup>10</sup> The European Commission (2016a) reports from the same dataset that around 73% of SMEs have undertaken at least one CE activity. This differs from our value of 51% as our study focuses on SMEs' implementation (instead of engagement) of CE activities (i.e. we exclude CE activities that are underway).

figures are not available in a form disaggregated by CE activity type, only the total combined investment in all five CE activities is requested in the survey.<sup>11</sup> We use this variable as our measure of the investment levels that SMEs direct to CE activities.

Table A2 in the Supplementary Material presents a detailed description of SMEs' investments (as a percentage of turnover) in CE activities across the 28 EU countries. At the EU level, around 60% of SMEs that implemented at least one CE activity from 2013 to 2015 invested in these CE activities, with 50.89% of SMEs investing between 1% and 5% of total turnover. From the SMEs that implemented at least one CE activity, only around 5% invested more than 11% of their turnover in these activities. Austria has the highest proportion of SMEs investing more than 11% of their turnover in CE activities (approximately 8% of firms), while Luxemburg has the smallest proportion of SMEs investing more than 11% of their turnover in CE activities (approximately 1.4%). Fig. 3 illustrates SMEs' investments in CE activity across the 28 EU countries in the sample. We observe a significant degree of variability of the percentage of turnover that SMEs invest in CE activity.

### 3.2. Explanatory variables

Our explanatory variable of primary interest measures the stock of PEERD from 2004 to 2015. The variable was constructed in three steps. The first step was summing the national-level data (deflated by the national GDP deflator) on government R&D investment in environment and energy over the period 2004–2015 with investments from the EU FP7 relating to environment and energy R&D for the period 2007–2015. Government R&D expenditure or EU FP7 investment are standard variables used in the innovation literature to measure STI policy activities (see Salter and Martin, 2001; Szücs, 2018). While we use the GDP deflator to adjust both funding sources for inflation, we assume that the knowledge generated by public funding has not depreciated in value. Essentially, we assume that all PEERD spent in 2004 or later remains fully economically relevant, which is in line with the length of patent protection for new technology. As presented in Fig. 4, PEERD investments have increased continuously since 2004 in the 28 EU coun-

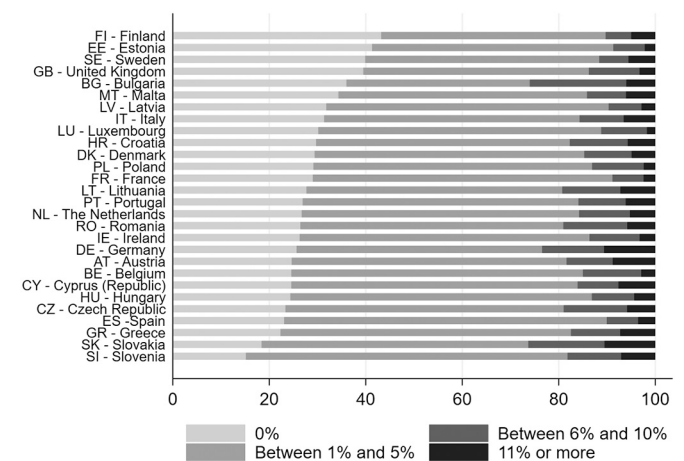
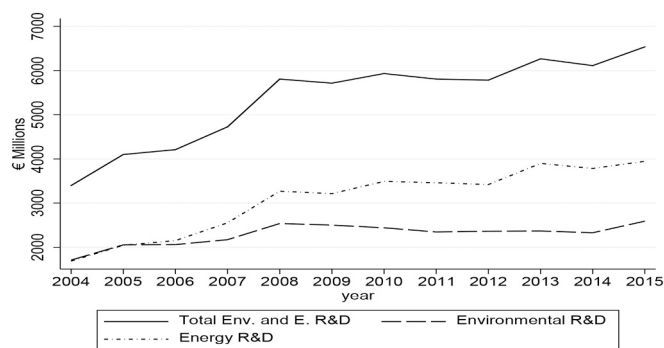


Fig. 3. SMEs' Investments (percentage of turnover) in CE Activity Across the 28 EU Countries. Source: Authors' own elaboration using data from Flash Eurobarometer 441.

<sup>11</sup> This corresponds to Question Q2a in the Flash Eurobarometer 441 survey: "Over the last 3 years, what percentage of your company's turnover have you invested on average per year to undertake these activities?"

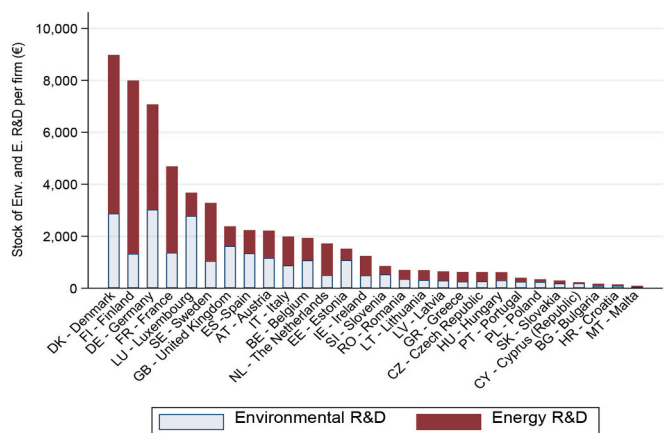


**Fig. 4.** Total PEERD for the period 2004 to 2015 in 28 EU countries. Source: Authors’ own elaboration using data from Eurostat and the European Commission.

tries despite a slight decrease during the 2008–09 global financial crisis. Table A3 in the Supplementary Material disaggregates these investments by country and for the 28 EU countries together, showing that on average, the 28 EU countries experienced a 5.6% year-on-year growth of PEERD investments from 2004 to 2015.

The second step to construct the variable was to normalise the knowledge stock from 2004 to 2015 by the number of firms in each country in 2015. We use the number of firms in 2015 as a country size proxy. Fig. 5 compares PEERD stocks across the 28 EU countries normalised by their number of firms. Figs. 4 and 5 combined show that some countries have both an above-average PEERD per firm and CE implementation rate (e.g. Finland and Denmark), while others have a high CE implementation rate despite low levels of PEERD per firm (e.g. Malta and Ireland).

Finally, in principle, one could assume that public knowledge, as a public good, is available to all firms without any restriction. However, not all knowledge is relevant to all firms, and firms are not able to absorb all of this knowledge. Therefore, we assume that the larger the level of investment in PEERD, the more heterogeneous the knowledge stock will be, as PEERD will be spread over a larger array of fields and targeting various sector-specific or regional needs. Thus, the third step in constructing the variable was to model this effect as non-linear in nature (i.e. the marginal increase in the usability of knowledge decreases as investments in PEERD in a country increase). This was carried out by using a logarithmic transformation of total PEERD investments divided by the number of firms in each country in 2015.



**Fig. 5.** Stock of public Environmental and Energy R&D per firm (including Environmental and Energy FP7 funds) for the period 2004 to 2015 in the EU countries. Source: Authors’ own elaboration using data from Eurostat and the European Commission.

At the firm level, we control for firm size and age. Firm size is represented by three categories: micro (less than 10 employees), small (10 to 49 employees), and medium-sized (50 to 249 employees). Firm age is measured as a binary variable taking a value equal to 1 if an SME is older than six years, or 0 otherwise. Also, four binary variables to capture SMEs’ R&D investment intensity are included, representing a firm’s innovative potential and its absorptive capacities (Cohen and Levinthal, 1989).

As discussed in Section 2, several direct support measures are being developed at the EU and national levels to support firms’ transition to a CE (e.g. grant programmes, training, and technology consulting). To control for the effect of these support measures, we also include the following variables: (i) a count variable measuring the number of sources of finance available for CE activities (from 0 to a maximum of 6); (ii) a dummy variable measuring SMEs’ awareness of other non-government financial incentives for CE activities; and (iii) a dummy variable measuring SMEs’ awareness of other financial incentives by government programmes supporting CE activities (e.g. tax incentives and loan guarantees). Together, these variables are used to proxy for the range of external financial resources and other support mechanisms available to firms at the local, regional, and national level (Ghisetti and Montresor, 2020; Demirel and Danisman, 2019).

On the supply side, the sector of the SME can determine its access to ‘green’ suppliers, industrial recirculation of materials or easier channels to retrieve products that customers no longer use (Prieto-Sandoval et al., 2018). Therefore, we include binary variables to control for one-digit NACE rev.2 sectors. On the demand side, consumer interest in, and awareness of, sustainable development encourages CE activities (Kirchherr et al., 2018). Thus, we include a binary variable that is equal to 1 if the SME sells directly to consumers so as to capture the direct demand for ‘green’ products and services, or 0 otherwise.

At the national level, we control for a variety of factors. The share of a firm’s sector in the country’s GDP is used to capture localisation effects (Carlino and Kerr, 2015). We also include the percentage of firms facing issues due to complex administrative or legal procedures as a proxy for governmental laws, regulation, and legal procedures obstructing the adoption of CE activities (Kirchherr et al., 2018; Rizos et al., 2016). Moreover, we include average annual price growth in electricity and intermediate goods in the period 2010–2013 by country to control for changes in the cost of material and resources.<sup>12</sup> Total renewable water is used as a proxy for water prices (due to the lack of information on the latter in all EU countries).<sup>13</sup> Table 1 reports descriptive statistics of the model variables. Table A4 in the Supplementary Material reports no correlation between the variables to be higher than 0.4.

Regarding the CE investment model, which is estimated only for CE active SMEs, we include further controls to account for government financial support and additional sources of external financing for implementing CE activities (as only firms which implemented CE activities answered these questions). As highlighted by the EU’s Expert Group on ‘Circular Economy Financing’ (European Commission, 2019), both, public and private financial channels need to be developed to support firms’ transition to the CE, and this is already ongoing in some EU member states. To capture the effect of direct public financial support, we include: (i) a dummy variable measuring the receipt of financial support for CE activity from the EU; and (ii) a dummy variable

<sup>12</sup> We mean-centred the country-level continuous variables to facilitate the interpretation of the coefficients (Yu et al., 2015). The variable is the average growth rate in the period 2010–2013. We selected the period prior to the period covered by the dependent variable (i.e. 2013–2015) to avoid issues of endogeneity.

<sup>13</sup> This is measured as the average annual value of cubic metre of clean water per inhabitant for the period 2013–2017. This variable is reported in periods of 5 years by Eurostat. We selected the period 2013–2017, as data for the period 2008–2013 were not available for all countries.

**Table 1**  
Descriptive statistics.

Variables	Eq. 1 on CE implementation				Eq. 2 on CE investment			
	Mean/Proportion	Std. Dev.	Min	Max	Mean/Proportion	Std. Dev.	Min	Max
CE implementation	0.52		0	1				
CE investment					0.91	0.77	0	3
Public env. & energy R&D (ln)	6.97	1.23	4.52	9.10	6.97	1.23	4.52	9.10
Admin. Barriers (%)	10.94	6.00	0.53	24.92	9.83	5.48	0.53	24.92
Intermediate prices growth (%)	6.54	4.76	-8.5	13.4	6.54	4.76	-8.5	13.4
Energy prices growth (%)	2.70	5.92	-7.46	20.99	2.70	5.92	-7.46	20.99
Fresh water (ln)	8.40	1.21	4.79	10.12	8.40	1.21	4.79	10.12
Economic structure (%)	15.55	7.36	1.59	34.27	15.36	7.10	1.59	34.27
Micro firms	0.63		0	1	0.60		0	1
Small firms	0.23		0	1	0.24		0	1
Medium firms	0.14		0	1	0.16		0	1
Firm age (6 years or less)	0.17		0	1	0.15		0	1
Sell directly to consumers	0.62		0	1	0.64		0	1
Info available to CE	0.23		0	1	0.28		0	1
Alternative financial sources	0.66	1.25	0	6				
Aware of gov. programmes to CE	0.36		0	1				
R&D [1, 5)	0.09		0	1				
R&D [5,10)	0.08		0	1				
R&D [10,20)	0.06		0	1				
R&D ≥ 20%	0.05		0	1				
R&D dummy					0.34		0	1
EU funds					0.02		0	1
Government grant					0.01		0	1
Bank loan					0.10		0	1
Green loan					0.01		0	1
Other external sources					0.01		0	1
Number of observations	10,618				4,985			

Country-level variables are calculated as the unweighted average based on 28 observations (countries).

measuring the receipt of national grants for CE activities. To capture the effect of private financial channels for CE (at the firm level) we include dummy variables measuring SMEs’ access to (a) standard bank loans; (b) green loans; and (c) other alternative sources of finance for CE activities (e.g. crowdfunding and capital markets).

**4. Empirical approach**

To analyse the impact of public environmental and energy R&D (PEERD) on SME implementation of Circular Economy (CE) activities, we use SMEs’ introduction of CE activities in the period 2013–2015 as the dependent variable. The likelihood of an SME implementing CE activities depends on national-level PEERD and firm and national level variables. When country and firm-level data are matched, this generates a nested structure. Two approaches can be adopted to address potential bias arising from intra-cluster correlation. The first one is using a normal probit model with the error terms clustered at the country level (Doran and Fingleton, 2016). The second is to use a multilevel mixed-effect probit model (Ng et al., 2006; Hox et al., 2017). We use the second approach as we can explicitly control for country level effects by including country-level controls.

Eq. (1) specifies the function used to estimate the probability of introducing CE activities amongst SMEs. It is estimated for  $i = 1 \dots n_i$  firm observations in  $j = 1 \dots 28$  countries (clusters) using a two-level mixed effect probit model specified as:

$$Pr(CE_{ij} = 1 | x_{ij}, c_{ij}, u_j) = \Phi(x_{ij}\beta + c_{ij}\gamma + z_{ij}u_j) \tag{1}$$

where  $Pr$  denotes probability,  $CE_{ij}$  is the binary dependent variable,  $x_{ij}$  is a vector with the public environmental and energy R&D variable, and  $c_{ij}$  is a matrix with the constant and control variables explained in Section 3.2. The term  $u_j$  is the random intercept (random effect) of each country. The term  $\Phi$  is the cumulative distribution function (CDF) of the standard normal distribution. Finally,  $\beta$  is the coefficient of our variable of interest,  $\gamma$  is the vector of parameters measuring the effect of the control variables, and  $z_{ij}$  contains the covariates related to the random effects. As we apply a two-level random intercept model,  $z_{ij}$  is the scalar 1.

In Eq. (2), we analyse the impact of PEERD on the level of CE investments (as a percentage of turnover) in CE active firms using four categories. Given the categorical nature of the dependent variable originally included in the Flash Eurobarometer 441 survey and the multi-level nature of the data, Eq. (2) is estimated using a mixed-effects ordered probit regression model. Eq. (2) specifies the function estimated for  $i = 1 \dots n_i$  firm observations in  $j = 1 \dots 28$  countries (clusters):

$$Pr(Exp_{ij} > k | x_{ij}, c_{ij}, k, u_j) = \Phi(x_{ij}\beta + c_{ij}\delta + z_{ij}u_j - k_k) \tag{2}$$

This equation is estimated only for firms that implemented CE activities. Therefore, we also include an inverse Mills ratio (IMR) derived from Eq. (1). This corrects for a possible sample selection bias which may occur when moving from the full sample to a sub-sample of firms that implemented CE activities (Heckman, 1979). This is standard in the innovation literature (see Crepon et al., 1998). All variables are defined as above with the addition that  $Exp_{ij}$  is a categorical ordered variable representing the level  $k$  of CE expenditure of firm  $i$  in the period 2013 to 2015.  $x_{ij}$  is the vector with the PEERD variable, and  $c_{ij}$  is the vector including the regression constant, control variables as explained in Section 3.2, and the IMR.

**5. Results and discussion**

**5.1. Public environmental and energy R&D (PEERD) and SMEs’ CE activities**

Table 2 presents the results of the multi-level model estimation of Eq. (1). Public environmental and energy R&D (PEERD) has a positive and significant effect on SMEs’ likelihood to implement Circular Economy (CE) activities. We interpret PEERD as the stock of public scientific and technological knowledge related to CE for firm  $i$  in country  $j$ . The marginal effects presented at the bottom of the table suggest that an increase of one log point in PEERD per firm (i.e. €11.22 per firm or €25.7 million total investment on average) leads to an increase of around 6% in SMEs’ probability of implementing at least one CE activity. Therefore, SMEs located in countries with a higher stock of knowledge are more likely to



**Table 2**  
Determinants of implementation of Circular Economy (CE) activities in SMEs: results of mixed probit regression.

Variables	Coefficient	SE
Public environmental and energy R&D (ln)	0.195***	(0.067)
Aware of government programmes to CE	0.264***	(0.029)
Info available to CE	0.235***	(0.034)
Alternative financial sources	0.026**	(0.012)
Administrative barriers	-0.041***	(0.015)
Small size	0.198***	(0.055)
Medium size	0.278**	(0.122)
Firm age (6 years or less)	-0.014	(0.034)
Sell directly to consumers	0.198***	(0.029)
R&D (1, 5)	0.295***	(0.052)
R&D (5,10)	0.183***	(0.051)
R&D (10, 20)	0.327***	(0.056)
R&D ≥ 20%	0.288***	(0.062)
Material prices	-0.003	(0.020)
Energy prices	0.020	(0.014)
Fresh water (ln)	0.016	(0.069)
Localisation effects	-0.011***	(0.004)
Var (_cons[country])	0.157***	(0.044)
Constant	-1.313**	(0.533)
Observations	10,618	
Number of groups	28	
Sector	Included	
Marginal effect of Public env. and energy R&D <sup>†</sup>	0.067***	(0.028)
Min Marginal effect of Public env. and energy R&D	0.061***	
Max Marginal effect of Public env. and energy R&D	0.069***	

Dependent variable: dummy variable with 1 (CE implementation), 0 otherwise. Standard errors (SE) in parentheses. <sup>†</sup>Predicted average marginal effect. Delta-method standard errors in parentheses for the marginal effect \*\*\**p* < 0.01, \*\**p* < 0.05, \**p* < 0.1.

implement CE activities. This result supports Hypothesis 1 which posited a positive relationship between the stock of PEERD and the likelihood of SMEs' implementing CE activities. It provides evidence that the provision of specialised knowledge for CE generates a conducive environment for the dissemination of CE approaches in SMEs (Korhonen et al., 2018; Demirel and Kesidou, 2019).

Amongst our control variables, SMEs' awareness of government programmes related to CE activities and the availability of information regarding CE positively contribute to the implementation of CE activities by SMEs. This provides evidence to support the argument that the existence of support channels at the EU, national and regional levels are effective at driving SMEs' implementation of CE activity (European Commission, 2019). The availability of external sources of finance for CE is also significant and positively related to SMEs' likelihood of implementing CE activities. This is expected, as SMEs typically experience financial resource constraints (Hall et al., 2016); this is especially true for micro-firms (Roper and Hewitt-Dundas, 2017) which represent the majority of our sample.

Larger firms are more likely to implement CE activity, which is in line with most of the literature on firm size and innovation (see Cohen, 2010). However, the additional analysis presented in Table A8 in the Supplementary Material reveals that PEERD has a similar effect on firm implementation of CE activities across micro, small, and medium-sized firms.

We also find that firms that engage in R&D are more likely to implement CE activities compared to non-R&D active firms. This result suggests that implementing CE is not only about adopting concepts and technologies developed by others, but also requires firms' own creative and innovative efforts. For example, firms may need to develop new production, distribution, commercialisation, and product design methods (Bocken et al., 2016; de Jesus and Mendonça, 2018). In this vein, implementing CE activities is closely related to product and process innovation activities (de Jesus et al., 2019). SMEs selling directly to consumers are more likely to implement CE activities than other SMEs (including SMEs in business-to-business markets). This points to the

importance of consumers as drivers for a transition towards CE (de Jesus and Mendonça, 2018; Rizos et al., 2016).

Regarding the national environment, we find that changes in the costs of energy, materials and other resources do not affect SMEs' implementation of CE activities. However, the results also demonstrate that complex administration, legal procedures, and regulation (administrative barriers) decrease SMEs' likelihood of implementing CE activities. Finally, we find a negative localisation effect. SMEs in industries with a high share in their country's GDP are less likely to implement CE activities. This may be linked to prospect theory (see Kahneman and Tversky, 1979; Kahneman, 2003) whereby dominant sectors can lose more when transforming their business models and ways of production than lagging sectors, thereby implying that the former may be less likely to take the risk.

### 5.2. Public environmental and energy R&D (PEERD) and SME investment in circular economy (CE)

This section focuses on the intensity of SMEs' CE efforts, measured as the proportion of their turnover invested in CE activities. The analysis is confined to SMEs which implemented CE activities –CE active SMEs. Furthermore, given the categorical nature of the dependent variable, results are interpreted as SMEs' probability to move up/down one category of CE investment as a proportion of turnover i.e. 0 = 0%; 1 = 1% to 5%; 2 = 6%–11%; and 4 = 11% or more) as per an additional log unit of PEERD. A log unit of PEERD is equal to €11.22 per firm or €25.7 million in total investment on average.

Table 3 shows that as PEERD levels increase, CE active SMEs are less likely to invest a higher share of their turnover in CE activities. The marginal effects presented at the bottom of the table suggest than as

**Table 3**  
Determinants of investment in CE activities in SMEs: results of mixed ordered probit regression.

Variables	Coefficient	SE
Public environmental and energy R&D (ln)	-0.110***	(0.041)
Info available to CE	0.200***	(0.048)
EU funds	0.319**	(0.138)
Government grant	0.282**	(0.142)
Bank loan	0.344***	(0.056)
Green loan	0.419*	(0.235)
Other external sources	0.198	(0.157)
Admin. barriers	0.017*	(0.009)
Small size	-0.014	(0.065)
Medium size	0.050	(0.132)
Firm age (6 years or less)	0.041	(0.042)
Sell directly to consumers	0.039	(0.043)
R&D (dummy)	0.428***	(0.045)
Intermediate prices	0.012	(0.011)
Energy prices	-0.005	(0.007)
Fresh water (ln)	-0.017	(0.037)
Localisation effects	-0.007	(0.005)
Inver Mills ratio	-0.557***	(0.153)
Cutpoint 1	-0.096	(1.123)
Cutpoint 2	1.522	(1.123)
Cutpoint 3	2.119*	(1.122)
Var (_cons[country])	0.038**	(0.015)
Observations	4985	
Number of groups	28	
Sector	Included	
ME Public environmental and energy R&D Pr(CE Inv.) = 0 <sup>†</sup>	0.036***	(0.014)
ME Public environmental and energy R&D Pr(CE Inv.) = 1	-0.012**	(0.005)
ME Public environmental and energy R&D Pr(CE Inv.) = 2	-0.012***	(0.005)
ME Public environmental and energy R&D Pr(CE Inv.) = 3	-0.012***	(0.005)

Dependent variable: Ordered categorical variable with 0 (no CE investment), 1 (1 to 5% CE investment in sales), 2 (5 to 10% CE investment in sales) and 3 (11% and more CE investment in sales).

Standard errors (SE) in parentheses. <sup>†</sup> Predicted average marginal effect. Delta-method standard errors in parentheses for the marginal effect. \*\*\**p* < 0.01, \*\**p* < 0.05, \**p* < 0.1.

PEERD per firm increases by one log point (i.e. €11.22 per firm or €25.7 million in total investment on average) CE active SMEs are 3.6% more likely to decrease their investments from 1% to 5% of their turnover in CE activities to 0% of their turnover in CE activities. Similar negative effects are observed for the other investment categories. This provides support for Hypothesis 3, which posited that the availability of publicly generated knowledge may ameliorate firms' need for higher investment intensity in CE. Consequently, no support is found for Hypothesis 2 which posited that the availability of publicly generated knowledge increases firms' investment in CE activities.

This result suggests that PEERD may be diverting, instead of incentivising private investments in CE. High investments in CE may not prove viable if returns to these investments are restricted due to a large public production of knowledge, which is available free to all firms (Weber and Rohrer, 2012).

Amongst the control variables, firms which have received government grants, bank loans, and green loans invest more in CE activities when compared to CE active firms which did not receive these resources. Again, this points to the importance of direct support for SMEs' transition to a CE and also points to financial barriers for SMEs when implementing CE activities. This is in line with the literature on external financing constraints in SMEs (Ormazabal et al., 2018). Findings also suggest that size, age, and selling products/services directly to consumers do not affect investment in CE.

Regarding factors external to the firm, complex administrative procedures and legal barriers are associated with higher CE investment levels in CE active firms. As Veugelers (2012) notes, regulation can be an important lever for private-sector research. However, our results rather suggest that 'red tape' is increasing the costs for SMEs to implement CE, resulting in a need for higher expenditure.

### 5.3. Robustness checks and additional analysis

This section presents additional analyses carried out to test the robustness of our results. First, we repeat our main analysis using a probit model with clustered country standard errors (Doran and Fingleton, 2016) to determine if our results are sensitive to the econometric technique used. The results of this alternative estimation technique are similar to those obtained by mixed-effect models (see Tables A5 and A6 in the Supplementary Material to this paper).

Second, to gain a better understanding of how PEERD affects the intensity of SMEs' implementation of CE activities, we analyse the impact of PEERD on the number of CE activities implemented by SMEs. This is operationalised by replacing the binary variable measuring SMEs' implementation of CE activities (Eq. 1) with a categorical variable measuring the number of CE activities that SMEs implemented from 2013 to 2015. The variable takes the value 0 if an SME did not implement any CE activity, 1 if it implemented any of the five CE activities, 2 if it implemented two CE activities and so on (i.e. the maximum is 5). Table A7 in the Supplementary Material presents the results of this analysis, showing that as PEERD increases, the probability of SMEs introducing an additional CE activity also increases. For firms that did not implement CE activities, an increase of one log point in PEERD per firm (i.e. €11.22 or €25.7 million in total investment on average) increases their probability of implementing at least one CE activity by 1.1%. For firms that have already implemented 1, 2 or 3 CE activities, an increase of one log unit of PEERD increases their probability of implementing an additional CE activity by between 1.2% to 1.8%. The lowest effect (i.e. 0.6%) is found in the case of SMEs that already implemented four CE activities.

Third, we explore potential heterogeneous effects between government R&D investment and FP7 funding on CE implementation and investment but find no significant differences (Tables A12 and A13). Fourth, we analyse the effect of PEERD across firm size. Results show that PEERD has a similar effect across micro, small and medium-sized firms (see Tables A8 and A9). Fifth, we analyse whether PEERD

influences firms in high-technology and low technology sectors differently, following the EU's classification.<sup>14</sup> Results in Tables A10 and A11 show that PEERD mainly drives CE implementation amongst SMEs in low technology sectors. Findings also show that PEERD impacts investment levels in CE for SMEs in both sectors negatively, which is consistent with our main findings.

Finally, a country's national innovation system may influence the effect of science, technology, and innovation policies (Edler and Fagerberg, 2017). Thus, we compare PEERD's impact on SMEs in countries categorised as innovation leaders and strong innovators, with SMEs in moderate and modest innovative countries as per the European Innovation Scoreboard (EIS). Tables A14 and A15 show that PEERD largely impacts the implementation of CE activities in SMEs located in the most innovative countries. However, the impact of PEERD on SMEs' CE investments is similar between firms in these two groups. In summary, the robustness checks and additional analyses largely support our main findings.

### 5.4. Discussion

In our conceptual framework summarised in Fig. 1, PEERD is hypothesised to impact SMEs' implementation of CE activities by enabling these firms to access key scientific knowledge and by creating an appropriate knowledge and institutional environment for CE. The results of this study support these propositions. We find that higher PEERD stocks increase SMEs' likelihood of implementing CE activities. The spillover from PEERD stocks to SMEs' implementation of CE activities can take various forms which we cannot identify based on our data. One spillover mechanism may be that high levels of PEERD produce a large number of specialised researchers and engineers from which SMEs can profit in their CE implementation efforts. Another channel could be based on more tailor-made and more affordable CE technologies for SMEs if a country engages more broadly in the development of new environmental and energy technologies. Veugelers (2012, p. 1) argues, in the context of clean innovations, that firms alone are "not up to this challenge" and require support. This study contributes to this discussion by providing novel evidence validating PEERD as a mechanism to encourage SMEs' transition to a CE. PEERD can enable SMEs to develop CE capabilities, especially in those firms who are not high-technology sectors (as identified in Table A9). This is particularly important as SMEs typically avail of fewer resources in comparison to large firms for implementing CE activities.

In addition, we find a negative relationship between the stock of PEERD and the investment intensity in CE of SMEs that have implemented CE activities. High expenditure in PEERD seems to lower the amount SMEs invest when implementing CE activities. This suggests that PEERD can substitute for SMEs' own financial efforts when implementing CE through positive knowledge spillovers. When viewed from this perspective, public R&D acts as an indirect subsidy and frees resources in CE active SMEs that can be used for other productive investment.

An alternative interpretation of our result is that SMEs may refrain from investing more in CE activities as they expect their private returns to deteriorate when public R&D levels are high (Rodríguez-Pose and Crescenzi, 2008). That is, SMEs may primarily resort to exploiting current publicly generated knowledge and adopt only those CE activities that require minimum investments. For example, SMEs may engage in incremental changes to current processes such as end-of-pipe activities, which may not be particularly costly to implement (De Marchi and Grandinetti, 2013).

<sup>14</sup> We used the sectoral approach aggregation described by Eurostat using NACE Rev.2 at the 2-digit level as described in: [https://ec.europa.eu/eurostat/cache/metadata/Annexes/htec\\_esms\\_an3.pdf](https://ec.europa.eu/eurostat/cache/metadata/Annexes/htec_esms_an3.pdf).

## 6. Conclusion

The Circular Economy (CE) has emerged as an economic model to curtail current environmental degradation levels while generating sustainable economic development and societal value (Korhonen et al., 2018). Transitioning to a CE will require the commitment of many actors, including governments and firms. We investigate whether public environmental and energy R&D (PEERD) provides SMEs with the scientific knowledge and capabilities to tackle CE implementation.

This study extends previous analyses by examining how domestic scientific knowledge related to the environment and energy (based on R&D investment by national government and EU FP7 funds) strengthen CE implementation and investment by SMEs. As SMEs are important in the European economy, and given that this group of firms typically disproportionately suffers from capability and resource constraints for CE relative to larger firms (Garcés-Ayerbe et al., 2019), this study is timely. To date (to the best of our knowledge), no study has analysed the effect of PEERD investment on the CE amongst SMEs (including micro-firms).

The study draws from a multi-level database with data on CE activities of 10,618 SMEs from 28 EU countries, data on public expenditure on energy and environmental R&D from 2004 to 2015 for each country, and national-level data on EU FP7 for environmental and energy R&D for the period 2007–2015.

The study finds that as PEERD stocks increase, the likelihood of SMEs' implementing CE activities also increases. We interpret these results as an indirect effect arising from a process through which publicly available knowledge on environmental and energy issues enables the development of capabilities for CE amongst SMEs. However, the study also finds a negative relationship between the stock of PEERD and SME investment intensity in CE activities. We suggest that this is the result of positive knowledge and technology spillovers from public R&D to SMEs which lowers firms' private investment needs.

These findings are highly relevant given the inclusion of 'Resource Efficiency' as a key pillar of the Europe 2020 strategy and in Horizon Europe (the next Framework Programme for Research and Innovation for 2021 to 2027). These are significant attempts to align environmental challenges and social necessities with STI policies. Policies to promote knowledge sharing, cooperation, networking, and know-how in environmental and energy increase SMEs' awareness and ability to implement CE activities. Subsequently, initiatives such as the 'Climate-neutral Europe by 2050' launched in 2018, the 'EU action plan for 'Circular Economy' (2015), and the 'Green Action Plan for SMEs' (2014) are suitable tools to be promoted and coordinated with national agendas. The European Resource Efficiency Knowledge Centre (EREK) is currently working on encouraging knowledge sharing, collaboration, and the provision of financial and non-financial resources for aiding SMEs' transition to a CE (European Resource Efficiency Knowledge Centre (EREK), 2019; KPMG, 2019). Together, these initiatives are expected to further accelerate SMEs' transition to a CE. A recent study by Domenech and Bahn-Walkowiak (2019) found that despite aspirational EU objectives, only a few member states have adopted resource efficiency or a CE strategy. Therefore, further monitoring and evaluation may be necessary to continue driving the EU's agenda for transitioning to a CE.

Some limitations of this study offer avenues for future research. The categorical nature of the dependent variables used for measuring the CE activities implemented by SMEs, along with their levels of investment is a limitation of the current analysis. Future studies may usefully undertake a similar analysis but using a continuous dependent variable. In addition, we assume that the cost of knowledge generated by PEERD is similar across EU member states. It would be interesting for future research to refine our approach by further controlling for potential differences across countries (e.g. by publications, projects, or patents). Future studies could also investigate whether other STI policy outputs—such as those generated by environment and energy publications, projects, or patents—affect the implementation and investment in CE

activities by SMEs. This, perhaps, can be done by employing policy mix analyses such as those proposed by Dumont (2017) and Mulligan et al. (2019). Furthermore, we overlook international knowledge spillovers from other countries' PEERD stock. It would be interesting if future research investigates cross-country effects of national STI policies in the implementation of CE in SMEs.

## Declaration of Competing Interest

The authors declare no competing interests.

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## Appendix A. Supplementary Material

Supplementary Material to this article can be found online at <https://doi.org/10.1016/j.ecolecon.2020.106884>.

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