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DISCUSSION PAPER

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Identifying Circular Public Procurement with Large Language Models: An Application to Firm-Level Circular Innovation

Identifying circular public procurement with large language models: An application to firm-level circular innovation

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Abstract

Policy makers increasingly recognize circular public procurement as a demand-pull instrument for stimulating the transition to a circular economy. However, empirical studies on circular public procurement have been hampered by a fundamental measurement challenge, as public procurement databases do not contain structured ways of identifying circular projects. This paper presents the first application of an LLM-based semantic similarity approach to identify circular procurement at scale. Adapting a bibliometric text-embedding approach from circular economy research, we show its application in comparing tender descriptions to a reference corpus of circular economy scientific abstracts, generating circularity scores for each award. We then apply the identified circular public procurement awards in an empirical study of firm-level adoption of circular economy innovation, matching the classified tenders to German data from the Community Innovation Survey. The results show that firms winning circular procurement are more likely to introduce circular economy innovation after three to five years, while no significant results are found at shorter or longer time horizons. Overall, this paper demonstrates the potential of using LLMs to identify circular public procurement and study its effectiveness in enabling the circular transition.

Keywords: Circular economy, Innovation, Circular public procurement
JEL-Classification: H57 – O38 – Q55 – Q58

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1 Introduction

The increasing pressure on natural resources and the growing awareness of environmental degradation have driven public institutions to design policies aimed at sustainable development. In Europe, the European Green Deal (European Commission, 2019) serves as the cornerstone policy framework to address these challenges, aiming to achieve net-zero greenhouse gas emissions by 2050, primarily through investments in renewable energy, the reduction of emissions, and green technologies.

Central to the European Green Deal is the promotion of the circular economy (European Commission, 2019). Unlike the current linear economic model, which follows a 'take-make-waste' approach, the goal of the circular economy is to create a closed-loop system of production and consumption. This is achieved primarily through investment in technologies that help in reducing, reusing, and recycling materials, energy, and water to extend product lifecycles while minimizing environmental impact (Geissdoerfer et al., 2017; Kirchherr et al., 2017).

The EU's commitment to the circular economy is reinforced through the Circular Economy Action Plan (European Commission, 2015; 2020), which outlines measures to enable the transition towards the circular economy, for instance by promoting sustainable resource management, enhancing product lifecycles, and encouraging waste reduction. It emphasizes areas like eco-design, waste prevention, and the development of a market for secondary raw materials, especially in high-impact industries for resource use and waste generation such as plastics, food, textiles, and construction.

One of the measures that is recognized within the Circular Economy Action Plan (European Commission, 2015; 2020) as an important driver of the circular economy transition is public procurement, which concerns the purchase of goods and services by the public sector (European Commission, 2017). Since it accounts for about fourteen percent of GDP in the EU (European Commission, 2022), public procurement has great potential to shape the circular economy by setting requirements for resource efficient product development and driving market demand for circular products and services (Alhola et al., 2019; European Commission, 2017; Rainville, 2021). This form of procurement, called circular public procurement (CPP), aims to minimize the environmental impact and prolong the lifespan of procured goods and services, with the goal of supporting the transition towards a closed-loop economy.

A fundamental obstacle to studying CPP empirically is the absence of structured circularity labels in public procurement data. Public procurement databases such as the Tenders Electronic Daily (TED) database, which covers EU-wide contract awards from 2006 onwards, record rich information on public tenders, such as exact award dates, awarding authorities, and winning firms. However, they do not contain structured labels on the potential circularity of a tender. While for more broad green public procurement (GPP), previous studies have used keyword-based approaches in award criteria (Krieger & Zipperer, 2022; Rosell, 2021; Yu et al., 2020), circularity is a more complex and context-dependent concept (Geissdoerfer et al., 2017). Unlike GPP, which benefits from codified EU-level criteria that create a standardized vocabulary in procurement documents (Magrini & Gama Caldas, 2026), no equivalent structured criteria exist for CPP specifically. As a result, no study has yet systematically identified CPP in a large-scale procurement dataset, and the empirical literature on the effectiveness of CPP remains essentially absent.

Recent advancements in large language models (LLMs) offer potential to address this gap. For instance, by mapping texts such as the topic description of tenders into semantic embedding spaces, LLMs could assess the conceptual proximity between documents without relying on keywords that may not specifically promote circularity or remain absent in award criteria either way. This capacity has been demonstrated in bibliometric contexts. In a report for the Flemish Government, ECOOM (2024) uses LLM-based semantic embeddings to map thematic structures across circular economy research. We directly adapt this approach to procurement data, comparing TED tender descriptions to a reference corpus of scientific abstracts of circular economy research to create circularity score for each award.

By doing so, this paper has two main contributions. First, it provides the first systematic identification of CPP in a large-scale procurement database, applying LLM-based semantic similarity to tender descriptions from TED. We further validate this approach through a manual reliability exercise, finding a relatively low false-negative and a relatively large false-positive rate, likely because the model was not tailored to a public procurement context. As a result, it provides a low-resource approach to analyze CPP compared to a manual classification in more finite databases, such as the Community Innovation Surveys, as well as a foundation for future empirical research on the systematic identification of CPP across the population of tenders within large-scale tender databases, such as the TED.

Second, to demonstrate the utility of the identified CPP variable, we apply the result in an empirical study of the relationship between winning CPP awards and firm-level adoption of circular economy innovation (CEI). By matching the classified procurement data to German firm-level data from the German Community Innovation Survey (CIS) of 2021 and 2023, our results indicate that winning a CPP award is associated to a higher likelihood of CEI adoption, but only after a delay of three to five years after winning the award, consistent with known medium-term lags in general procurement-induced innovation (Chiappinelli et al., 2025; Bastianin et al., 2022; de Rassenfosse et al., 2019). This suggests that CPP can function as an effective demand-pull policy instrument for fostering CEI, yet its materialization into innovation unfolds only in the medium run rather than immediately. While previous literature has looked increasingly at the relationship between green public procurement (GPP) and environmental innovation outcomes (e.g., Krieger and Rainville, 2026; Schäfer et al. 2024: Krieger & Zipperer, 2022; Stojčić, 2021; Caravella and Crespi, 2020; Orsatti et al., 2020), no study has examined CPP specifically. The application of this paper provides the first such evidence and illustrates possible avenues of research made feasible by LLM-based classifications of CPP.

The remainder of this paper is structured as follows. Section 2 provides the conceptual background of this study, Section 3 describes the LLM-based approach for identifying CPP in public procurement data and presents the validation results. Section 4 presents the empirical application, covering the methodology, econometric strategy, and results. Section 5 discusses the results and provides a conclusion.

2 Conceptual background

Public procurement refers to the process whereby public authorities (e.g., government departments or local institutions) purchases goods and services from firms. In the EU, it accounts for about 14 percent of GDP (European Commission, 2022). In addition to responding to public demand, public procurement is considered a strong tool within demand-oriented innovation policy (Dalpé et al., 1992; Edler & Georghiou, 2007; Edquist & Zabala-Iturriagagoitia, 2012). The ability of public innovation procurement to promote innovation activities among firms has been empirically confirmed repeatedly (e.g., Chiappinelli et al., 2025; Czarnitzki et al., 2020; Stojčić et al., 2020; Raiteri, 2018).

Besides its potential for innovation, public procurement has long been argued as a tool to achieve broader environmental (and social) objectives as well (Arrowsmith, 2010; McCrudden, 2004). This form of procurement, commonly referred to as "green public procurement" (GPP), leverages the purchasing power of public authorities for products and services with environmental benefits through the inclusion of green criteria in tenders and by broadening the markets for green products (Arrowsmith, 2010; Li & Geiser, 2005; Testa et al., 2016).

While GPP has gained considerable attention over the past two decades, CPP is a relatively new concept in academia and practice (Sönnichsen & Clement, 2020). Alhola et al. (2019) define CPP as "*a procurement of competitively priced products, services, or systems that lead to extended life spans, value retention, and/or remarkably improved and non-risky cycling of biological or technical materials, making use of and supporting the circular business models and related networks*" (p. 105). Although GPP and CPP can be overlapping concepts, CPP goes beyond the traditional scope of GPP by focusing on circular economy principles, such as reuse, recycling, and material recovery, directly into procurement strategies (Alhola et al., 2019; European Commission, 2017; Grimbert and Zabala-Iturriagagoitia, 2024). CPP thus not only seeks to reduce the environmental impact of purchased goods and services but specifically aims to extend their lifecycle and facilitate the transition to a closed-loop economy.

Alhola et al. (2019) and Grimbert and Zabala-Iturriagagoitia (2024) lay out a theoretical framework of how public entities can approach CPP. Firstly, they can procure currently existing products while using circular criteria (i.e., recyclability, improved life-cycle, use of recycled materials).[1] Secondly, these circular criteria can also be applied to the procurement and development of new products and services (Alhola et al., 2019; Rainville, 2021).[2] Thirdly, public institutions can procure new circular business models, such as transforming towards a product-service system (i.e., renting instead of selling products) or introducing leasing concepts (Grimbert & Zabala-Iturriagagoitia, 2024; Tukker, 2004; Tunn et al., 2019).[3] Lastly, public procurement can promote circular ecosystems, which involves procuring commitment and cooperation from different stakeholders to create closed loop networks (Alhola et al., 2019). For example, within these networks, waste from one stakeholder could be used as input for another stakeholder.[4] In summary, these CPP channels offer significant potential for promoting CEI among firms by setting requirements for resource efficient product development and driving market demand for circular products and services (Alhola et al., 2019; Rainville, 2019). The development of these innovations is considered crucial for allowing

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[1] An example is the Flemish government's procurement of refurbished office furniture, where they used circular criteria such as durability, recyclability, and the use of recycled materials to extend product life cycles (Circular Flanders, 2023a).

[2] For example, bpost, Belgium's national postal service, launched a tender for vending machines innovations in relation to their energy usage, reusable packaging, and reverse logistics (Circular Flanders, 2023b).

[3] For example, the 'Green Deal Circular Procurement' initiative in Flanders supports buyers in transitioning to circular business models (Flanders Circular, n.d.). One of these buyers is the Spadel group, a Belgian drinking water company that aims to have fully circular operations by the end of 2025 by gradually increasing the use of recycled materials in their bottles and packaging (Circular Flanders, 2020).

[4] An example from Alhola et al. (2019) where public procurement can promote circular ecosystems concerns the city of Vaasa, located in Finland, which procured two tenders to create a closed public transportation ecosystem: one for a public transport service provider and another for biogas-powered buses and maintenance. Through this approach, Vaasa partnered with a local biogas producer, converting local waste into biogas fuel and establishing a circular ecosystem.

the circular economy transition (de Jesus & Mendonça, 2018; Ellen MacArthur Foundation, 2019), while simultaneously stimulating economic growth (Millar et al., 2019).

Despite the potential of public procurement to stimulate CEI, some scholars argue that using public procurement as an environmental policy instrument may not be effective or can even be counterproductive. Lundberg et al. (2016) argue that market reactions can undermine the effectiveness of CPP. When public authorities prioritize green products, increased demand may drive up prices, making these products less accessible to private consumers. As a result, private consumers might shift their consumption towards more polluting alternatives, offsetting the intended environmental gains. In some cases, CPP may even lead to unintended increases in emissions or pollution if lower demand for non-green products in public procurement causes price reductions that encourage higher private consumption. Also, from an innovation economics perspective, firms may only focus on compliance with circular criteria rather than investing in actual innovation, leading to rent-seeking behavior and reduced competition in procurement processes (Lundberg et al., 2016). Moreover, it may only be firms that are already operating in environmentally friendly ways that choose to participate in CPP tenders (Krieger and Zipperer, 2022). Finally, public institutions may also lack knowledge about the specific technical or functional requirements necessary to stimulate CEI development (Aldenius & Khan, 2017; European Commission, 2017; Testa et al., 2016). Given these limitations, Lundberg et al. (2016) argue that CPP alone is likely not a sufficiently effective environmental policy instrument for green or more specifically CEI.

Given the discussion in the literature about the effectiveness of public procurement to stimulate CEI, providing empirical evidence on the relationship between public procurement and CEI is essential for the development of effective policies to stimulate CEI adoption, especially given the double externality problem that these innovations face (De Marchi, 2012; Jaffe et al., 2005; Rennings, 2000).

Next to knowledge spillovers that are formed by all forms of R&D and innovation and that create a positive externality for other firms, CEI also produces an additional positive externality in the form of environmental benefits captured by society. This results in systematic underinvestment in CEI, as firms may lack sufficient incentives to adopt CEI, strengthening a stronger need for policy and external frameworks such as public procurement to support CEI compared to general innovation (De Marchi, 2012; Jaffe et al., 2005; Rennings, 2000).

However, as data on public procurement do not contain structured circularity labels, large-scale empirical evidence in this area remains scarce (Cheng et al., 2018; Ntsondé & Aggeri, 2021; Sönnichsen & Clement, 2020), and, to the best of our knowledge, no study has examined CPP specifically in this context. Existing work suggests that public procurement may support circular or environmental activities primarily among firms that are already engaged in such practices (Meili & Stucki, 2023), and that procurement participation is associated with a higher likelihood of introducing environmental innovations more generally (Yu et al., 2023). Meanwhile, Krieger and Zipperer (2022) show that winning GPP increases firms' probability to introduce environmental product innovations, but do not find statistically significant effects for process innovations.

This study addresses the identification gap of CPP by exploiting a LLM that compares tender descriptions from the TED database to a reference corpus of abstracts from circular economy research to generate contract level circularity scores. This allows us to systematically capture the circular content of procurement contracts and providing the first identification of CPP at scale. Furthermore, to demonstrate the utility of the resulting CPP classification, we add to the emerging body of literature on the role of public procurement in enabling the circular economy by being the first to empirically investigate the relationship between CPP and CEI. Our analysis also accounts for the temporal dimension of procurement-induced CEI, as prior work suggests that the innovation effects of public procurement typically materialize only over a medium- to long-term horizon of several years (Bastianin et al., 2022; de Rassenfosse et al., 2019). Similarly, Chiappinelli et al. (2025) show that emission intensity improvements in firms emerge only starting from the second year after winning GPP. These time lags may be particularly relevant for CEI, as such innovations are often complex and systemic in nature (de Jesus & Mendonça, 2018; Geissdoerfer et al., 2017) and may require firms to develop capabilities outside their core technological capabilities (De Marchi, 2012; Horbach et al., 2013).

Therefore, our analysis distinguishes between short-, medium-, and longer-term exposure to CPP to capture potential delays in the translation from winning CPP to introducing CEI.

3 LLM-based identification of circular public procurement

3.1 Identification challenge and semantic similarity approach

Public procurement databases do not classify contracts by circular content or criteria. In the TED database, each contract award is accompanied by a textual description of the subject matter, as well as on what criteria the contract is awarded, such as price or quality. While keyword-based approaches have proven effective in identifying GPP by searching for environmental criteria (Krieger & Zipperer, 2022), circular criteria are more difficult to identify and do barley directly appear in the award criteria of tenders (Krieger & Zipperer, 2022),[5] as circularity is a more complex and context-specific concept (Geissdoerfer et al., 2017). Identifying CPP therefore requires reading and interpreting the free-text descriptions that describe the content of the procurement, which quickly becomes an infeasible task at scale across hundreds of thousands of contracts published annually.

This paper addresses this challenge by applying LLM-based semantic similarity, adapting the bibliometric approach from ECOOM (2024) to procurement data, who use LLM-based semantic embeddings of scientific abstracts to assess contextual similarity and map thematic patterns in circular economy research.[6] We use TED data of all awards won by German firms between 2010 and 2022 above the publishable financial threshold. Specifically, each contract description is compared to a corpus of scientific abstracts related to the circular economy. These abstracts are retrieved from the Web of Science bibliographic databases between 2011 and 2022. The LLM maps both contract descriptions and abstracts into a shared semantic

[5] Krieger and Zipperer (2022, p.6) demonstrate green criteria to be i) generally rare, and ii) mostly broadly formulated as „environment,“ sustainability,“ or ecology.“

[6] See https://huggingface.co/sentence-transformers/all-MiniLM-L6-v2 for more info on the LLM.

embedding space, in which textual similarity reflects contextual relatedness. This means that although a tender's description may not share many common words with a certain abstract, a high similarity score can still be achieved if the context of the description is similar. Likewise, identical words appearing in different contexts will not contribute to a high similarity score. For each contract, a similarity score between 0 and 1 is computed by the LLM with respect to the circular economy abstracts, and the maximum similarity value is retained as the tender's circularity score for this study. The results of the LLM reveal an average circularity score of 0.66 (std. dev. = 0.04), with scores ranging from 0.35 to 0.85.

3.2 Validation exercise

To test the reliability of the LLM, we manually perform a number of validity tests on the LLM results. We restrict the validation analysis to awards won by firms that can be matched to the CIS data used in the empirical application of the CPP classification (Section 4 of this paper), yielding a total sample of 27,052 tenders. To start, as an initial cut-off value, all descriptions with a similarity score of 0.70 or higher are identified as circular, representing 18.24% of the total sample of tenders. Then, we generate a random sample of 800 contract descriptions from the total sample, half of which exceed the set threshold of 0.70, and manually check of these descriptions against the CPP definition of Alhola et al. (2019). This exercise is done blindly, not knowing the similarity score calculated by the LLM.

We then compare the manual circular labeling against the LLM similarity scores, calculating the amount of true/false positives and negatives. The results of this manual test show that out of 400 descriptions that are identified as non-circular at a similarity cut-off of 0.70, only 24 (6%) of them are false negatives. This implies that the LLM is relatively efficient in identifying circular tender descriptions. However, 176 out of 400 (44%) descriptions are false positives according to the manual testing, meaning that while the LLM does not easily miss a tender description related to the circular economy, many of the descriptions with a similarity score of 0.70 or above are falsely identified as circular descriptions. Many of these false positives include words that may be related to certain circular economy principles (i.e., energy, heating, efficiency), but where the topic of the tender in itself is not circular.[7]

Given the high rate of false positive CPP descriptions, every contract description that exceeds the similarity threshold of 0.70 is then manually checked whether it meets the CPP definition. From the 4,935 descriptions that got a similarity score of at least 0.70, 1742 (35.29%) of these are eventually identified as circular after manual checking, representing 6.44% of the total sample of tenders.

The high amount of false positives reflects a fundamental limitation of the current approach. As the LLM is originally used to map thematic structures within circular economy scientific literature rather than procurement texts, it is not fine-tuned to the specific language conventions found in contract descriptions. As a result, it lacks the specificity in our specific context needed to reliably distinguish circular from other procurement texts. More targeted models that are fine-tuned to procurement data – for example by taking the product category of a tender into account – would most likely substantially improve classification precision and could eventually enable fully automated CPP identification without manual correction steps. Nevertheless, this approach constitutes the first systematic, large-scale identification of CPP in a public procurement database. Crucially, the combination of automated scoring and targeted manual correction ensures a high degree of accuracy in the final classification. Thus, the presented approach represents a low-resource approach to analyze CPP compared to an entirely manual classification in more finite databases, such as the Community Innovation Surveys, as well as a foundation for future empirical research on the systematic identification of CPP across all tenders within large-scale tender databases, such as the TED.

[7] One example of such tender descriptions is "*As part of the project (…), the geological card must be created 1:25,000 (…) with profile cuts, explanations and documentation.*" Another example is "*Delivery of district heating combined with the sale of the district heating infrastructure and its edition.*"

As a first application of its usefulness, the remainder of this paper presents an empirical analysis of the acquired CPP data and its relation with firm-level adoption of CEI.

4 Empirical application

4.1 Data and methods

4.1.1 Data sources

The analysis uses a combination of survey data from the German contribution to the Community Innovation Survey (CIS) from 2021 and 2023 and public procurement contract data from OECD's Tender Electronics Daily database. The CIS is a biennial representative large-scale survey, coordinated by Eurostat, that collects official innovation statistics for the EU. The survey is based on the guidelines laid down in the Oslo Manual.[8] The 2021 and 2023 survey waves include a question that measures firm-level adoption of innovations with specific environmental benefits over a reference period of the previous three years, which forms the source for the main outcome variable. In addition, the survey data also includes information on firm characteristics that are relevant as firm-level controls.

The Tenders Electronic Daily database (TED) is managed by the European Commission and provides data on public procurement contracts from 2006 onwards that exceed the Commission's financial thresholds for ensuring a transparent and competitive procurement process across borders (Krieger and Zipperer, 2022). We specifically employ awards won by German firms between 2010 and 2023.

The merge of the two data sources is based on the firm identifier from the Mannheim Enterprise Panel – the sampling frame of the German CIS. We start our matching by extracting all German and international tenders won by German firms from the TED. In total, we find

[8] For more details on the German CIS, which is conducted as a panel survey ('Mannheim Innovation Panel'), see Peters and Rammer (2013).

812,236 German tenders won by 325,987 German firms.[9] Next, we use a fuzzy string-matching algorithm for firm names and addresses (Doherr, 2023) to identify the winners of German tenders in the Mannheimer Enterprise Panel. We match 720,261 (88.68%) of these tenders and 286,196 (87.79%) of these German firms with the firm population of the Mannheim Enterprise Panel.[10] Similarly, out of 21,380 international tenders won by 13,918 German firms, we link 19,160 (89.62%) tenders and 12,362 (88.82%) firms. Finally, we identify the tenders won by firms within our investigated survey waves of the German Community Innovation Survey by directly linking them to the Tenders Electronic Daily database via the generated joined firm identifier of the Mannheim Enterprise Panel.

The final sample considers firm-year observations that have full information on all model variables, containing 8,422 unique firms across 10,425 firm-year observations.

4.1.2 Construction of variables

4.1.2.1 Circular economy innovation

The primary outcome variable captures whether or not the firm introduced a CEI in the last three years. This measure is derived from a question in the German CIS on environmental innovations, in which firms could report whether they have implemented innovations with significant or insignificant environmental effects across 13 possible impact categories. Table 1 presents the list of environmental impacts available for selection.

We measure CEI using survey items from the CIS that capture environmental innovation outcomes. Following the 4R-framework (reduce, reuse, recycle, recover; Kirchherr et al., 2017; 2023) and prior empirical work employing CIS data for CEI identification (Cainelli et al., 2020;

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[9] After normalizing firm names and addresses according to Doherr (2023), 325,987 unique German supplier name-address combinations are identified in the Tenders Electronic Daily database.

[10] It is important to note that we disambiguate multiple suppliers per award. This allows us to correctly identify different suppliers within one award.

Horbach & Rammer, 2020), we include all environmental impact items that are related to the circular economy. Consequently, three items are excluded: the reduction of other air emissions (SOx, NOx) and the reduction of noise pollution (items 4 and 6), both of which likely reflect end-of-pipe pollution control rather than circular practices, and a composite item covering reductions in emissions to air, water, soil, and noise, which overlaps with these two non-circular measures (item 11).

Table 1: Types of environmental impact

Positive environmental effects in your firm
1. Reduction of energy consumption per unit/process
2. Reduction of material consumption/ water consumption per unit/process
3. Reduction of CO_2 emissions per unit/process
4. Reduction of other air emissions (e.g. SO_x, NO_x)
5. Reduction of water or soil pollution
6. Reduction of noise pollution
7. Replacement of fossil energy sources with renewable energy
8. Replacement of hazardous materials/ substances
9. Recycling of waste, waste water, or materials for own use or sale
Positive environmental effects when using your products/services
10. Reduction in energy consumption/ overall CO_2 balance
11. Reduction in emissions in the areas of air, water, soil noise
12. Improvement in the recyclability after use of products
13. Increase in the lifespan of products/ longer-lasting products

Furthermore, we restrict our measure to significant circular economy innovations. Krieger and Rainville (2026) argue that public procurement is particularly effective in stimulating innovations with large environmental performance improvements, as such innovations are typically more early-stage innovations and therefore do not yet face stable market demand and often require substantial upfront investments in development and production (Edler & Georghiou, 2007).

Furthermore, they argue that innovations with more incremental environmental improvements are typically located at later stages of the innovation lifecycle. These innovations likely face lower demand uncertainty and require smaller additional investments, as they build on existing technologies and production processes. Therefore, they face fewer problems that public procurement policies are likely particularly effective to resolve, such as demand uncertainty and financing constraints.

Empirically, both Krieger and Zipperer (2022) and Krieger and Rainville (2026) support this argument, showing that (green) public procurement requirements positively influence the introduction of environmentally significant innovations, while the effects for their insignificant counterparts are statistically insignificant.

With these considerations in mind, CEI equals one if a firm reports having introduced an innovation with at least one significant circular impact, and zero otherwise.

4.1.2.2 Circular public procurement

We define firms' involvement in CPP tenders by aggregating the amount of won circular and non-circular tenders to the firm-year level, indicating for each year between 2010 and 2023 the amount of awards a firm has won within that respective year, including both the total number of awards and the number of CPP won. Based on this yearly classification, we create several variables that indicate three-year time blocks of winning CPP awards relative to the timing of CEI adoption to capture the potential lag-structure that is required for CPP awards to translate into realized CEI. First, we create a dummy variable that is equal to one if the firm has won at least one CPP award in the same reference period as CEI (*CPP0-2*), and zero otherwise (i.e., 2018-2020 for firms from the 2021 wave of the MIP and 2020-2022 for firms from the 2023 wave). The second three-year time block continues on the previous one and indicates whether the firm has won at least one CPP award in the last three to five years relative to the final year of the CEI reference period (*CPP3-5*). This translates to the years 2015 to 2017 for firms from the 2021 wave and 2017 to 2019 for firms from the 2023 wave. The third block (*CPP6-8*) covers six to eight years before the last year of the reference period of CEI, meaning 2012 to 2014 and 2014 to 2016 for the two respective survey waves.

Finally, following Krieger and Zipperer (2022), we create a dummy variable that is equal to one if the firm has ever won at least one CPP award across the whole available TED data coverage of 2010 to 2023 (*CPPE*), to account for unobservable time-constant differences between the group of firms winning CPP, and the group of firms not winning CPP.

In addition to CPP, we also account for winning general public procurement awards, of which CPP constitutes a subset. This strategy is also in line with Krieger and Zipperer (2022) and enables us to isolate the circular component of procurement-induced CEI. Analogous to the construction of the CPP variables, we construct the same three-year time blocks indicating whether the firm has won at least one public procurement award relative to the timing of CEI adoption in the contemporaneous period (*PP0-2*), in the medium term (*PP3-5*), and in the longer term (*PP6-8*). Furthermore, we define a dummy variable indicating whether the firm has ever won at least one public procurement contract over the full 2010 to 2023 period (*PPE*).

4.1.2.3 Control variables

The analysis employs several other firm-level control variables that can potentially explain CEI outcomes besides the awarding of (circular) public procurement tenders (e.g.; Czarnitzki et al., 2020; Krieger and Zipperer, 2022). First, we consider the size of the firm, using the logarithm of the number of full-time equivalent employees (*lnEMP*), since the amount of resources available to invest in innovation activities is generally higher for larger firms. Similarly, we include a variable indicating innovation intensity (*INNOVINT*), measured as innovation expenditures divided by revenues and two dummy variables indicating whether the firm performs R&D continuously (*RDCON*) or occasionally (*RDOCC*). Then, we include a dummy variable (*GROUP*) to indicate whether a firm is part of a corporate group, capturing potential benefits stemming from group synergies. Next, we include the logarithm of export revenues to capture firms' engagement in foreign markets (*lnEXPORT_REV*), which may affect CEI through regulatory pressure, knowledge spillovers, and demand for circular or sustainable products (e.g., Aguilera-Caracuel et al., 2012; Torrecillas & Fernández, 2022). We also consider a dummy variable indicating whether the firm received public R&D investment support (*PUBSUPPORT*) firms' access to public funding. While this variable focuses on all types of innovation and is therefore not specific to CEI, it still captures the extent to which firms' access to public funding influences their capacity to introduce CEI.

Finally, we employ industry-year fixed effects following the NACE Rev. 2 classification of economic activities on two-digit level to absorb sector-specific trends and changes over time.[11]

4.2 Empirical strategy

The empirical strategy further builds upon the work of Krieger and Zipperer (2022), who examine whether GPP increases firms' likelihood of introducing environmental product and process innovations. Specifically, we estimate linear probability models with industry-year fixed effects and perform entropy balancing as additional robustness check to account for potential bias arising from observable differences between winners and non-winners of CPP. The estimated equation can be written as follows:

$$CEI_{it} = \beta_0 + \beta_1 CPP_{i,t} + \beta_2 CPP_{i,t-1} + \beta_3 CPP_{i,t-2} + \beta_4 CPPE_i + \beta_5 X_{it} + \tau + \varepsilon_{it} \tag{1}$$

Where CEI_{it} indicates whether the firm has introduced a CEI in the three years of reference period t, $CPP_{i,t}$ is a dichotomous variable that is equal to one if a firm has won at least one CPP award in the same reference period t (i.e., zero to two years before the final year of period t), and zero otherwise, $CPP_{i,t-1}$ represents the same variable with a lag of one time period (i.e., three to five years before the final year of period t), and $CPP_{i,t-2}$ indicates a delay of two time blocks (i.e., six to eight years before the final year of period t). The combination of these three time blocks dummies allow for examining the time required for firms to materialize CPP awards into realized CEI. Next, $CPPE_i$ is defined as a dummy variable equal to one if a firm

[11] See Eurostat (2008) for more information on the two-digit industry codes.

has ever won a CPP award between 2010-2022, and zero otherwise. X_{it} represents a vector of the firm-level control variables. τ indicates the industry-year fixed effects, and ε_{it} is the error term.

4.3 Descriptive statistics

Table 2 provides a descriptive overview of the main variables from our model specification. 329 firms have been awarded at least one CPP award between 2010 and 2022, containing 3.15% of the total sample. Among these CPP-winning firms, 45.9% has won at least one CPP award in contemporary period *t*, while this percentage for the lagged time blocks of three to five years and six to eight years are 39.5% and 31.6% respectively; indicating an increasing occurrence of CPP within the German economy.

Regarding the adoption of CEI, 25.1% of firms that have never won a CPP award indicate they introduced CEI, while this number is significantly larger for CPP-winners at 34.7%. CPP-winning firms are also substantially larger compared to non-winners, have a higher likelihood of being part of a group, have higher export revenues, have a lower level of innovation intensity, perform more occasional R&D, and are more likely to receive public support for R&D investment.

Table 2: Descriptive statistics of main variables

	Non-CPP winning firms (*CPPE* = 0)				CPP-winning firms (*CPPE* = 1)				Diff.
	Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	Max	
CEI	0.251	0.434	0	1	0.347	0.477	0	1	***
CPP0-2	0	0	0	0	0.459	0.499	0	1	-
CPP3-5	0	0	0	0	0.395	0.490	0	1	-
CPP6-8	0	0	0	0	0.316	0.466	0	1	-
PP0-2	0.076	0.266	0	1	0.760	0.428	0	1	-
PP3-5	0.0612	0.240	0	1	0.771	0.454	0	1	-
PP6-8	0.051	0.220	0	1	0.632	0.483	0	1	-
PPE	0.133	0.340	0	1	1	0	1	1	-
EMP	171.181	2000.494	1	103598	510.134	3317.958	4	54100	***
GROUP	0.325	0.468	0	1	0.477	0.500	0	1	***
EXPORT_REV	13.132	314.591	0	25900	55.808	512.725	0	8246	***
INNOVINT	0.088	0.518	0	10	0.036	0.145	0	2.353	**
RDCON	0.242	0.428	0	1	0.264	0.442	0	1	
RDOCC	0.050	0.219	0	1	0.076	0.265	0	1	**
PUBSUPPORT	0.255	0.436	0	1	0.325	0.469	0	1	***
N		10097				329			

Note: Export revenues are reported in thousands of Euros. *Diff.* displays the significance levels for t-tests of equal means between firms that have won at least one CPP award between 2010 and 2022 (*CPPE* = 1) and firms that have never won such an award (*CPPE* = 0). * p<0.10, ** p<0.05, *** p<0.01

4.4 Empirical results

4.4.1 Main results

The main results of the linear probability models with industry-year fixed effects are displayed in Table 3. Columns 1 and 2 show the baseline regression models, without and with control variables respectively. The first model finds a positive and significant relationship between winning CPP and CEI adoption after three to five years (*CPP3-5*). After including *CPPE* and the forementioned set of control variables, the positive and significant coefficient of *CPPE3-5* remains. Specifically, winning at least one CPP award relates to a 10.3 percentage points higher likelihood of adopting CEI three to five years later, while winning at least one CPP award within the reference period of CEI adoption does no longer relate to an increase in CEI. Compared to the base probability of adopting CEI among firms that have never won CPP, this translates into a relative increase in probability of 38.2%. Winning CPP does neither increase the likelihood of CEI adoption the same contemporary period (CPP0-2) or six to eight years later (*CPP6-8*) in both specifications. Overall, this suggests that while CPP might be an effective demand-pull policy instrument to stimulate firm-level CEI, there exists a substantial time-lag of three to five years after winning the respective award to translate into actual introduction of CEI.

Among the controls, firm size, engagement in internal R&D activities, and public R&D support display a positive and significant relationship with CEI adoption. There is no significant relationship between winning CPP regardless of time (*CPPE*) and firms' likelihood of introducing CEI.

Columns 3 and 4 include the equivalent three-year time blocks of winning at least one general public procurement award to further isolate the circular aspect of winning CPP and do not reflect a relationship to public procurement more generally. Column 3 is similar to Column 1, while now also including the general public procurement time blocks. Column 4 adds the same set of control variables as Column 2, as well as the dummy variable indicating whether the firm has ever won a public procurement award (*PPE*). In the specification without control variables, the positive and significant coefficient of *CPP3-5* remains, while as before, the other two time blocks do not show a relationship with CEI. When control variables are included in Column 4, the results are also similar to the specification excluding the general procurement dummies, with *CPP3-5* showing a positive and significant relationship with CEI that is similar in terms of magnitude compared to Column 2. This further supports the finding that CPP is effective in driving firm-level CEI adoption, yet the translation into tangible innovation occurs predominantly with a three to five year delay.

Table 3: Main results

	(1) CEI	(2) CEI	(3) CEI	(4) CEI
CPP0-2	0.020	-0.018	-0.013	-0.023
	(0.042)	(0.048)	(0.044)	(0.049)
CPP3-5	0.113**	0.103**	0.084*	0.103**
	(0.048)	(0.049)	(0.050)	(0.050)
CPP6-8	0.054	0.047	0.047	0.061
	(0.056)	(0.056)	(0.058)	(0.057)
CPPE	-	-0.033	-	-0.029
	-	(0.040)	-	(0.041)
PP0-2	-	-	0.036*	0.009
	-	-	(0.020)	(0.023)
PP3-5	-	-	0.031	0.003
	-	-	(0.022)	(0.023)
PP6-8	-	-	-0.008	-0.027
	-	-	(0.023)	(0.023)
PPE	-	-	-	0.001
	-	-	-	(0.022)
ln(EMP)	-	0.027***	-	0.027***
	-	(0.003)	-	(0.004)
GROUP	-	0.014	-	0.014
	-	(0.010)	-	(0.010)
ln(EXPORTREV + 1)	-	0.001	-	0.001
	-	(0.002)	-	(0.002)
INNOVINT	-	0.003	-	0.003
	-	(0.010)	-	0.000
RDCON	-	0.186***	-	0.185***
	-	(0.15)	-	(0.015)
RDOCC	-	0.162***	-	0.162***
	-	(0.022)	-	(0.022)
PUBSUPPORT	-	0.076***	-	0.076***
	-	(0.011)	-	(0.011)
Constant	0.252***	0.087***	0.247***	0.086***
	(0.004)	(0.010)	(0.005)	(0.010)
Industry-year fixed effects	yes	yes	yes	yes
Observations	10425	10425	10425	10425
R^2	0.069	0.129	0.070	0.129

Note: Firm-clustered standard errors in parentheses; * p<0.10, ** p<0.05, *** p<0.01.

Regarding general public procurement, a positive and significant coefficient is found for winning an award within the same three year time period as CEI. However, its significance disappears once control variables are included. The other two time blocks and the dummy variable indicating whether the firm has ever won an award are also insignificant. We interpret this as no indication for a relationship between public procurement in general and CEI.

4.4.2 Entropy balancing

To further assess the robustness of the baseline results and mitigate potential bias arising from observable differences between CPP winners and non-winners, we employ entropy balancing as a reweighting procedure. This approach constructs a set of weights such that the distribution of selected covariates of firms-year observations not winning CPP at any point in time (CPPE = 0) matches that of the group of CPP winners (*CPPE* = 1), thereby eliminating imbalances on observed characteristics. Specifically, we balance on the means and variances of the full set of control variables used in the main specification. After obtaining the entropy weights, we repeat the estimation of the linear probability models using the weighted sample. As in the main analysis, this exercise is conducted in two variants. Model 1 excludes the general public procurement time blocks and *PPE* from the balancing, while Model 2 includes these variables to further isolate circular aspect of the award. The results of the entropy balancing procedure, reporting pre- and post-weighted means and variances of the control variables for non-CPP winners as well as their differences relative to CPP winners are presented in Appendix A1. The balancing procedure achieves nearly exact alignment of all covariates between the groups of CPP and non-CPP winners, suggesting that the balance is successful.

The regression results based on the balanced samples are reported in Table 4. Model 1 employs the entropy balanced sample excluding the general public procurement time blocks and *PPE*, while in Model 2 these variables are included. The findings are consistent with the main results. In both specifications, the coefficient of *CPP3-5* remains positive and significant, indicating that winning at least one CPP award is associated with a higher likelihood of CEI adoption three to five years later. The estimated coefficients are also similar in magnitude compared to the main results, with winning a CPP award being associated with a 10.1 percentage point increase in the probability of CEI adoption after three to five years when excluding the general public procurement variables, while adding the general public procurement time blocks and *PPE* to the balancing procedure leads to an estimated coefficient of 9 percentage points for *CPP3-5*. Once again, the coefficients for *CPP0-2* and *CPP6-8* are insignificant across both models, providing no evidence of either an immediate or longer-term relationship between CPP awards and the introduction of CEI beyond the three to five year window.

Table 4: Entropy balancing

	(1) CEI	(2) CEI
CPP0-2	-0.005	-0.001
	0.045	(0.046)
CPP3-5	0.101**	0.090*
	(0.051)	(0.053)
CPP6-8	0.042	0.038
	(0.056)	(0.057)
Constant	0.296***	0.298***
	(0.016)	(0.019)
Industry-year fixed effects	yes	yes
Additional controls	no	no
Observations	10424	10424
R^2	0.113	0.155

Note: Firm-clustered standard errors in parentheses; * p<0.10, ** p<0.05, *** p<0.01.

5 Conclusion

The transition towards a circular economy stands central in European environmental and industrial policy. One of the main accelerators of this transition are innovations that enable the reduction, reuse, and recycling of materials and the extension of product lifecycles (de Jesus & Mendonça, 2018; Ellen MacArthur Foundation, 2019; Geissdoerfer et al., 2017). However, these innovations are subject to a double externality problem, combining knowledge spillovers with environmental benefits that are not fully appropriated by firms, leading to systematic underinvestment in CEI (Rennings, 2000). Therefore, recent literature suggests CPP as a demand-side policy instrument that can stimulate CEI by leveraging the purchasing power of public authorities and by creating markets for circular products and services (Alhola et al., 2019; Rainville, 2021).

Despite its growing policy relevance, empirical evidence on whether and how CPP can effectively trigger CEI adoption remains absent (Cheng et al., 2018; Ntsondé & Aggeri, 2021; Sönnichsen & Clement, 2020). The main reason for this absence is that in contrast to GPP (Magrini & Gama Caldas, 2026), public procurement databases such as TED do not contain structured circularity labels in contract descriptions or award criteria, making it difficult to identify CPP at scale without a dedicated classification approach. To address this gap, this paper provides the first systematic identification of CPP in a large-scale procurement database. By adapting the bibliometric embedding approach of ECOOM (2024) to the context of public procurement, we compare tender descriptions from the TED database to a reference corpus of circular economy scientific abstracts to generate contract-level circularity scores. While we show that the approach requires a manual correction step to address a significant false positive rate, suggesting that the underlying model is not fine-tuned to procurement environment, the resulting CPP data represents the first classification of CPP at scale. More precisely, it a low-resource approach to analyze CPP compared to a manual classification in more finite databases, such as the Community Innovation Surveys, as well as a foundation for future empirical research on the systematic identification of CPP across the population of tenders within large-scale tender databases, such as the TED.

Second, as an initial application of the acquired CPP identification, this paper provides the first empirical evidence on the relationship between CPP and firm-level adoption of CEI. By linking the procurement data to firm-level data from the 2021 and 2023 wave of the German CIS, we show that CPP is associated with a higher likelihood of CEI adoption, but only after three to five years after winning the CPP award. This finding aligns with previous research who find that public procurement (Meili & Stucki, 2023; Yu et al., 2023) and GPP (e.g., Krieger and Rainville, 2026; Schäfer et al. 2024: Krieger & Zipperer, 2022; Stojčić, 2021; Caravella and Crespi, 2020) positively affects firms' environmental innovation outcomes.

The lagged pattern is consistent with earlier findings on procurement-induced innovation more generally, which emphasize medium term time lags between the contract award and innovation outcomes (Bastianin et al., 2022; de Rassenfosse et al., 2019). It also aligns with Chiappinelli et al. (2025), who show that environmental performance improvements in firms only emerge after two years.

The significant delay of CPP to materialize into the introduction of CEI can be explained by the nature of these innovations. CEI are typically complex as they require systemic changes in product design, production processes, and organizational routines (de Jesus & Mendonça, 2018; Geissdoerfer et al., 2017), often requiring firms to develop additional capabilities outside their existing technological core (De Marchi, 2012; Horbach et al., 2013). These complexities imply that firms need time to translate procurement requirements into actual CEI outcomes.

Several limitations should be acknowledged. First, while the LLM-based identification strategy allows for a systematic classification of CPP tenders, it is subject to a significant false positive rate. While the model misses relatively few genuinely circular contracts, a substantial share of contracts it flags as circular were not identified as circular upon manual testing. This reflects the model's origins in scientific literature analysis and its lack of fine-tuning to a public procurement environment. A manual correction step was therefore required to arrive at an accurate final classification. Consequently, future work developing procurement-specific embedding models could substantially improve classification precision and eventually enable fully automated CPP identification without requiring manual oversight.

Second, the analysis focuses on public procurement won by German firms and may not directly generalize to other contexts, where CPP may be more or less prevalent and can be different in nature or design. However, based on the detailed description of the German procurement context within the European Union by Krieger et al. (2026) and previous studies finding similar procurement results for different countries (e.g.,Czarnitzki et al., 2020; Stojčić , 2020), we consider the risk as marginal. However, future research could still extend this approach to other countries and examine how specific differences of interest in CPP designs and strategies, such as the mandatory vs. the voluntary inclusion of circular requirements, affect the effectiveness in stimulating firm-level CEI and other circular practices.

Finally, future work could explore potential heterogeneity across sectors and firm characteristics, as well as complementarities between CPP and other policy instruments such as carbon pricing or direct subsidies for CEI, as suggested by Lundberg et al. (2016) and previous research on GPP (Caravella and Crespi, 2020; Stojčić, 2021).

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7 Appendix

Table A 1: Mean differences of controls before and after entropy balancing

	(1) CPPE = 1	(2) CPPE = 0 Unbalanced	(3) CPPE = 0 Balanced	(4) (1) - (2)	(5) (1) - (3)
PP won in last 0-2y	0.762	0.075	0.761	0.687***	0.001
PP won in last 3-5y	0.708	0.060	0.707	0.648***	0.001
PP won in last 6-8y	0.633	0.050	0.632	0.583***	0.001
PPE	1.000	0.130	0.999	0.870***	0.001***
ln(EMP)	4.392	3.218	4.390	1.174***	0.002
GROUP	0.479	0.325	0.479	0.154***	0.000
ln(EXPORTREV + 1)	2.702	2.606	2.701	0.096	0.001
INNOVINT	0.036	0.088	0.036	-0.052**	0.000
RDCON	0.262	0.239	0.262	0.023	0.000
RDOCC	0.075	0.050	0.075	0.025**	0.000
PUBSUPPORT	0.322	0.252	0.322	0.071***	0.000

Note: * p<0.10, ** p<0.05, *** p<0.01.

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