Master's Thesis – Master Sustainable Business and Innovation

The contribution of patenting to a circular economy

How patents on waste management influence resource efficiency and waste reduction

Author:	Robin de Zwart
Student number:	5873029
Email address:	r.dezwart@students.uu.nl

Date: 21-07-2021

Word Count: 17.537

Supervisor: Dr. Anne Rainville
Second reader: Dr. Frank van Rijnsoever

Abstract

The concept of circular economy is one of the main solutions to achieve a sustainable future. However, while most countries have taken steps towards a circular economy, more progress needs to be made. Patenting activities on waste management technologies show promise to contribute to the transition towards a circular economy since patents indicate innovating and sharing knowledge. Therefore the contribution of patenting to circular economy progress needed to be analysed. To achieve this, this research has answered the research question: *How does patenting in waste management contribute towards circular economy progress?* This question is answered by comparing patent data to circular economy indicators resource efficiency and waste reduction. Within the patent data, a distinguishing between patent count, radicalness and technical relevance of patents on waste management is made. Correlation and regression analyses are used to find a relation between the patent data and circular economy indicators. Results indicate, however, that on a global scale patents currently do not lead to circular economy progress. However, evidence has been found that under the right circumstances patents can contribute. In this case, patents protecting radically new technologies conduce more than patents protecting incremental innovation. Based on the findings useful policy recommendations, such as a focus on collaboration and patenting strategies, are provided to governments to reach the circumstances in which the current patenting activities will contribute in transitioning to a circular economy.

Table of Contents

1. Introduction

An increase in consumption has led to a growing demand for resources over the last years (Schandl et al., 2016), gaining international concern. A circular economy can counter the growing resource demand by retaining the value of resources used, by narrowing or closing material loops (Geissdoerfer et al., 2017). The United Nations recognize this value and have implemented a circular economy in their Sustainable Development Goals (United Nations, 2020). This positive reception has led to countries following suit (Ganzevles et al., 2017) and setting their own goals towards a circular economy (Potting et al., 2017). A leading country in circular economy progress is the Netherlands (Iles, 2018), which focuses on increasing resource efficiency and decreasing the amount of waste produced, also known as waste reduction (Potting et al., 2017).

In order to achieve resource efficiency and waste reduction, innovation in waste management technologies is needed (Cramer, 2014; Ghisellini et al., 2016; Lang-Koetz et al., 2010). Firms play a crucial role in the development of such innovations, however current business models are often not supportive of this, due to uncertainties relating to the economic viability of circular economy practices (Cramer, 2014). This perceived barrier of uncertainty prevents firms from participating in circular economy activities, including R&D practices that are needed for innovation (Rizos et al., 2015). Currently, there is an uncertainty on how the innovation activities of firms exactly influence the progress towards a circular economy. While there is consensus that sustainable innovation is needed for a circular economy (Boons et al., 2013), a rethinking of the innovation process is required (Aarikka-Stenroos et al., 2021). In a circular economy, technological innovations are relevant, requiring innovating firms to introduce novelties in their businesses (Aarikka-Stenroos et al., 2021). These technological innovations should allow for more recyclability, thereby resulting in less waste compared to the current linear model of take, make and dispose (Ness, 2008). Therefore the innovation process in a linear economy is not directly applicable to a circular economy, resulting in a lack of transferability in knowledge on the contribution of innovation towards an economic system. Here a knowledge gap can be found since it is not yet clear how innovations enable a circular economy (Boons et al., 2013). Linder & Williander (2017) show that circular business models require a reduction in this uncertainty for firms, since they need to predict results further into the future than business models not operating towards a circular economy.

Protecting inventions by patenting circular economy solutions may provide economic incentives for firms to commercialize their inventions (Habib et al., 2019). Their objective is to reduce the aforementioned uncertainty, encouraging more firms to innovate towards a circular economy. Examining patenting activities can provide insight into the extent to which firms have included R&D activities in their business models (Dziallas & Blind, 2019). By looking at patenting activities in the area of circular economy, it can be determined if there is a focus on circular economy in business models. However, while patenting activities show innovativeness, which is needed in the transition to a circular economy, how and if patents contribute to a circular economy is not yet clear. This research aims to lessen this knowledge gap. By comparing patenting outputs to indicators of circular economy progress, such as resource efficiency and waste reduction, an understanding of the extent to which these innovation activities are indeed contributing to circular economy progress can be provided.

This thesis aims to provide insight into this problem by answering the following research question:

RQ: *How does patenting in waste management contribute towards circular economy progress?*

This research answers this question by analysing patents on waste management on a national level in OECD countries. By performing a cross country analysis this paper tests the relationship between patenting towards waste management and circular economy progress. A cross country comparison is relevant when research seeks to identify factors that appear relevant for a particular outcome (Cacace et al., 2013), in this case circular economy progress. In order to achieve this goal, data from the OECD database is used.

Further research as recommended by Garrido-Prada et al. (2021) to expand the existing scientific knowledge on how a policy output such as patents affects the implementation of circular economy activities is conducted in this study. The results of this research carried out on the effect of patenting on circular economy progress will improve the understanding of how innovation activities contribute to a circular economy. This can enable policymakers to set more relevant targets on policies towards a circular economy.

This thesis is presented as follows. In Section 2 both dependent and independent variables will be defined and discussed, and a hypothesis with two sub-hypotheses will be presented. Section 3 describes the methodology this research used, including the research design, data collection measurements and analysis done. An overview of the data used is then presented in Section 4. In Section 5 the results of the analysis done are presented and discussed. These results will be compared to academic literature and the hypotheses will be discussed in Section 6. This proposal closes with Section 7, a chapter containing the conclusion where the research question is answered and a recommendation and take-home message are presented.

2. Theory

2.1 Background

In recent years there has been a focus on the transition to a circular economy in Europe. Next to Europe-wide policy goals, every country has its own roadmap (Construcia, 2020). This has led to a disparity between Western European countries, which are leading in circular economy progress, and Eastern European countries, which are lacking in circular economy progress due to a lack of a clear roadmap (Construcia, 2020). Outside of Europe, the most progress towards a circular economy can be found in China and Japan, where policies on circular economy progress put a focus on innovation (Iles, 2018). In the United States, a circular economy has also gained attention, however, at a federal level, political priorities lead to a lack of circular economy progress (Iles, 2018). The lacking of the Eastern European countries and the United States can be explained by the lack of a clear roadmap, which is a critical success factor in progress towards a circular economy (Lopes de Sousa Jabbour et al., 2018). The countries leading in circular economy progress all have presented a national roadmap (Iles, 2018). It is suspected that the leading position of the Western European countries, as well as China and Japan, will be reflected in the patents on waste management. The countries described above as leading and lacking are all included in the databases used from the OECD.

2.2 Dependent variables

Since the late 1970s, the topic of circular economy has gained increasing attention (MacArthur, 2020). A leading actor in the field of circular economy, the Ellen MacArthur Foundation, defines a circular economy as: "an industrial economy that is restorative or regenerative by intention and design" (MacArthur, 2020, p. 14). One essential aspect of this definition is that a circular economy is an economy with a regenerative design. This regenerative design is achieved by ensuring a *closed loop of material flow* (Geng & Doberstein, 2008; Yuan et al., 2006) and by *maximizing the value gained* out of materials and *minimizing the waste* of materials (Ellen MacArthur Foundation & McKinsey & Company, 2014; Webster, 2017). All three measures can on a national level coherently be achieved by implementing waste management (Huysman et al., 2015) and will affect any given country's resource efficiency and waste reduction. Therefore, the indicators of a circular economy this research uses as dependent variables are *resource efficiency* and *waste reduction*.

2.2.1 Resource efficiency

Material resources are at the heart of all production-based economies (DEFRA, 2018a). A solution to use fewer resources without directly lowering production is increasing the efficiency of the resources used. Therefore *resource efficiency* can be used as an indicator towards circular economy progress. The concept of resource efficiency is maintaining the same output or value while lowering the input of resources (Bleischwitz et al., 2018). This can, for example, be done by recovering already used resources and using them again, this way the input of a system can be lowered and the output can remain constant (MacArthur, 2020). Another way to increase the resource efficiency is by finding new compounds which use fewer resources but have the needed characteristics of current compounds used (MacArthur, 2020). Both processes, the recovery of materials and developing new compounds out of these recovered resources, are covered within the topic of waste management (Haščič & Migotto, 2015). Resource efficiency is used by the United Nations to monitor progress towards SDGs 8, achieving sustainable economic growth, and 12, ensuring sustainable consumption and production patterns (Flachenecker & Rentschlehler, 2019; United Nations, 2020). Leaders of the G7 (an inter-governmental forum consisting of the richest industry-based countries in the world) have also requested extensive policy guidance specifically on resource efficiency to develop a circular economy (OECD, 2016).

A most common policy to increase resource efficiency through innovation is the 3R approach (Ghisellini et al., 2016), which consists of reducing, reusing and recycling. This is supported by the policy guidance the Organisation for Economic Co-operation and Development (OECD) provides towards resource efficiency, dedicating an action plan to implement the 3R approach (OECD, 2016). This approach emphasizes the need for technological innovation in the management of waste (Ghisellini et al., 2016). Ergo, technological innovation output regarding waste management is needed to increase resource efficiency.

2.2.2 Waste Reduction

Another indicator of a circular economy is *waste reduction*. Within the concept of the circular economy, recycling is promoted to extend the life of materials (Tisserant et al., 2017). Degli Antoni & Vittucci Marzetti (2019) show that an increase in recycling directly connects with a decrease in waste. This has led to recycling being the most widespread strategy so far in achieving a circular economy (Haas et al., 2015). Accordingly, waste reduction indicates progress towards a circular economy, making it a suitable indicator. Innovation is needed to design new products and materials to achieve effective waste recycling (Cramer, 2014). Moreover, technological innovation focussing on recycling supports waste management, resulting in the need for technological innovation towards waste reduction (Ghisellini et al., 2016).

International policy goals show the relevance of waste reduction. The European Commission (2011) prioritizes policies towards waste reduction in their waste management strategies, stating that a focus on recycling technologies is needed to reach long-term objectives. Furthermore, the OECD emphasizes the importance of waste reduction in their circular economy policies, stating the main challenge is to foster innovation to prevent waste (OECD, 2020a).

2.3 Independent variables

As mentioned before, both enhancing resource efficiency and waste reduction require technological innovation regarding waste management (Ghisellini et al., 2016). By innovating in technologies to recover resources to use again and innovating in new compounds which use less resources, the resource efficiency can be increased (MacArthur, 2020). By innovating in technologies that allow for the recycling of waste, the waste reduction can improve (Cramer, 2014). Firms are expected to perform a key role in the development of these technological innovations (Cramer, 2014). This is done by investing in R&D activities, resulting in inventions, which become technological innovations when they are successfully commercialised (Albers et al., 2018). This can lead to a lot of uncertainty for the firms investing in R&D since the economic viability of R&D activities towards circular economy innovations remains unclear leading to barriers for innovation

(Chenarani et al., 2017). Patenting can reduce these barriers by protecting the inventive outputs of R&D, thus reducing the uncertainty (Spulber, 2014). Patents document inventions and are a way of providing legal protection for intellectual property for a limited time (Kim & Bae, 2017). To effectively achieve this, patents include in-depth characteristics of the invention it is protecting (Kim & Bae, 2017; Park et al., 2015). Patents have certain advantages over alternative measures of innovation; where R&D investments are commonly used to measure innovation input, patents can be used to measure innovation outputs (Dang & Motohashi, 2015). Furthermore, patents provide quantitative data that is widely available, this data can be separated into specific technological fields allowing the selection of data based on relevant inventions (Haščič & Migotto, 2015). This leads to patents being a customary performance indicator for innovation (Hu, 2008). Therefore, innovations in waste management can be suitably analysed using patents.

2.3.1 Patent counts

The most common way to analyse patents is by patent count. Patents are a measure of inventions and assuming these inventions are aimed to be commercialized, they can be used as an indicator of innovative activity in countries (Oltra et al., 2010). Where R&D data is often unavailable to the public, patent data is available allowing for a more complete account of the amount of innovation in countries (Oltra et al., 2010). Therefore, this paper will use **patent counts** as an independent variable to analyse how patenting in waste management contribute towards the circular economy indicators resource efficiency and waste reduction. Since patents in waste management are an indicator for innovations on waste management, which are needed for a circular economy, it is expected that higher patent counts will contribute positively towards a circular economy. This leads to the following hypothesis:

H1: *Patent counts on waste management have a positive impact on progress towards a circular economy, as evidenced by increases in resource efficiency and waste reduction at the national level.*

However, only using patent counts could lead to a distorted picture of a country's innovative activities (Pohlmann et al., 2016). When only the number of patents is used as an indicator, more in-depth information on the patents is neglected. Therefore this research uses two more patent indicators: radicalness and technological relevance.

2.3.2 Radicalness

A circular economy requires radical rather than incremental changes (Boons et al., 2013). Moreover, Aarikka-Stenroos et al. (2021) state that similar reasoning can be applied to *resource efficiency* which also requires radical, rather than incremental, technological innovation. Furthermore, radical innovation is necessary to convert the *value creation of waste* (Antikainen et al., 2015). If there is a high-value creation of waste more materials can be reused or recycled, leading to less waste, this will result in higher *resource efficiency* and *waste reduction*. This requires a radical innovation capability of the firms innovating (Aminoff & Pihlajamaa, 2020). By examining the radicalness of patents, the radicalness of the innovation it is protecting can be measured. Therefore, the second independent variable this research uses is **radicalness**. It is expected that patents with a relatively large inventive step are embodied in innovations in circular economy. Therefore, countries leading in circular economy progress, are expected to have a higher radicalness of patents on waste management filed compared to countries that are further behind. Potting et al.

(2017) argue that while radical innovation is important, both radical innovation and incremental innovation are vital to a circular economy. However, currently innovation policies mostly focus on incremental innovation (Rizos et al., 2016). If radical innovations are also important for a circular economy, there should be policies in place to support radical as well as incremental innovations. This makes it important to investigate the radicalness of patents, which leads to sub hypothesis 1:

SH1: *The radicalness of patents on waste management has a positive impact on progress towards a circular economy, as evidenced by increases in resource efficiency and waste reduction at the national level.*

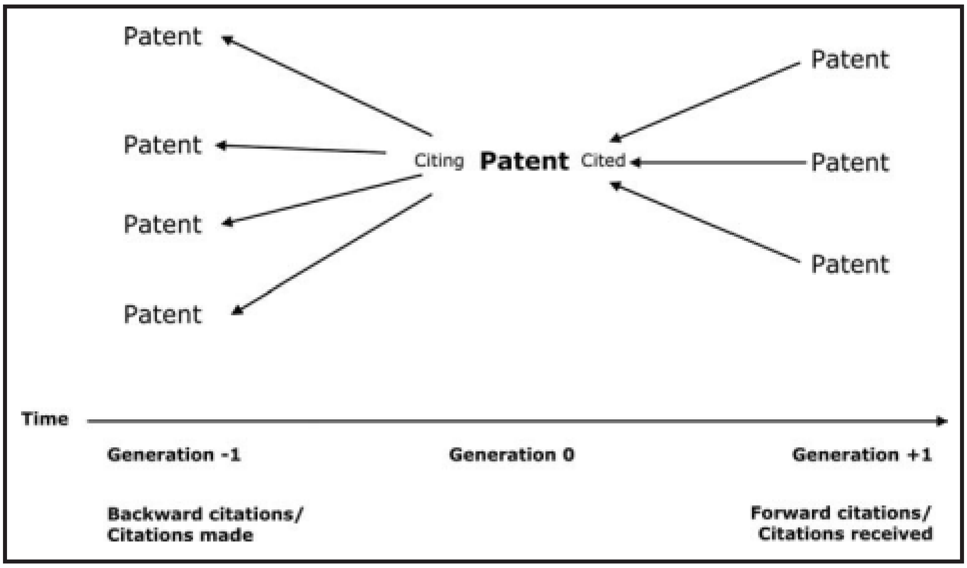
2.3.3 Technical relevance

Novel inventions with a potentially high impact necessary for a circular economy cause a larger spillover, meaning they entice other firms to innovate in similar technologies (Abrams et al., 2013). These new inventions are obligated to cite all prior art patents on which they are based (Abrams et al., 2013), therefore patents that cause more innovation will receive more citations by subsequent patents (forward citations). A high technical relevance indicates the invention affects the content of future inventions by different firms who invest in similar waste management technologies. Furthermore, when a patent has a high technical relevance, the invention it is protecting has a higher chance of success (Alfaro et al., 2019). Therefore, patents with higher technical relevance can be expected to have a high impact on circular economy progress. Patents differ in the technological value they provide, if a patent is cited a lot it provides a lot of technical value for subsequent inventions. Only counting patents will ignore the impact a patent has on subsequent inventions. By taking the technical relevance of patents into account this can be corrected (Pohlmann et al., 2016). This makes it important to investigate the **technical relevance** of patents and use it as an independent variable, which leads to sub hypothesis 2:

SH2: *The technical relevance of patents on waste management has a positive impact on progress towards a circular economy, as evidenced by increases in resource efficiency and waste reduction at the national level.*

The radicalness indicates the position of a patent in respect to previous patents, while the technical relevance indicates the position of a patent in respect to future patents (Karvonen & Kässi, 2011). This is shown in Figure 1, where the radicalness is represented by generation -1 and the technical relevance is indicated by generation +1. When moving forward in time from past to future generations, technological innovations keep building up. In these technological innovations, the patents towards waste management become embodied. By finding to which generations the patents filed in a country belong, it can become clear how far a country has progressed towards a circular economy. If the patents belong in an early generation this indicates progress towards circular economy has just started; if the patents, on the other hand, build upon a lot of generations this indicates a focus on circular economy progress.

Figure 1
Patent placement in time-based on citations (Karvonen & Kässi, 2011, p. 38)



3. Methodology

3.1 Research design

The goal of this research was to gain insights into the contribution of patenting in waste management towards circular economy progress. To achieve this, quantitative research towards the effect on circular economy indicators resource efficiency and waste reduction was done, by analysing implemented technological innovations for waste management under circular economy business models. A quantitative research design was most suitable to test the deductive hypotheses and subject them to empirical scrutiny (Bryman, 2016). A quasi-experimental research design was used to test the relationship between patents and a circular economy. To achieve this, the method as described below was used. In this research patent data and statistical information from the OECD were used.

This research aims to answer the research question by a cross-country analysis. This approach is suitable since both chosen indicators on circular economy progress can be measured on a national level, and patents are filed on a country level as well (Krauss & Kuttenkeuler, 2018). A cross-country analysis is appropriate in this research to find a relationship between patents on waste management and circular economy progress (Cacace et al., 2013). By studying and comparing different countries, trends can become clear (Gimenez-Nadal & Sevilla, 2012).

3.2 Sample and data collection

To measure circular economy progress, this research used statistical data from the OECD on resource efficiency and waste reduction. The OECD is an intergovernmental organisation that focuses on stimulating worldwide trade and economic progress, consisting of 37 member countries (OECD, 2020b). To achieve this, the OECD provides a knowledge hub including data, analysis and policy guidance (OECD, n.d.). This includes data for all member countries on the circular economy indicators resources efficiency and waste reduction. Furthermore, the OECD has relations with non-member countries which allow for statistical data collection (OECD, 2020c). This allows the availability of data on resource efficiency and waste reduction for the 37 OECD countries as well as Brazil, China, Costa Rica, India, Indonesia and Russia.

A sample of these 43 countries was constructed for the 1990-2019 period, based on the availability of data. The data collected by the OECD is self-reported information by countries and may therefore have a less objective nature. However, due to the availability of data and the scope of this research, this database was chosen since the countries described in the theory as leading and lacking towards circular economy progress are all included. This was then related to national circular economy progress reports, allowing for a comparison between countries. By relating to policy reports, the progress within a country could be seen without a bias caused by the size of the country.

In order to find the contribution of only patents on waste management towards a circular economy, it was important to first identify the relevant patents. There are three possible ways to search for patents: using manual selection, using keywords, and via patent qualifications (Haščič & Migotto, 2015). Both searching by manual selection and keywords have the distinguished disadvantage of a "linguistic bias", meaning the outcome of the search is sensitive to the language used (Haščič & Migotto, 2015). This makes both approaches less suitable for a cross-country analysis (Haščič & Migotto, 2015). Patent classifications mitigate this disadvantage by classifying all patents with a code. The World Intellectual Property Organisation (WIPO) developed the International Patent Classification (IPC) system by classifying inventions into technological groups (World Intellectual Property Organization, 2020). This made using the IPC system a suitable approach when selecting patents based on certain technologies, in this case technological inventions in waste management. The IPC system is used by almost all countries with a patent law system (Kang, 2012), making it suitable to use when doing a cross-country analysis.

Waste management is one of the technological groups of the IPC system. Within this group, multiple industry sectors are present. By breaking the waste management technological group down into industry sectors, the inventions contributing to circular economy progress could be more specifically categorized. The classification of industry sectors this paper used is based on a study published by the WIPO (Schmoch, 2008). The industry sectors are built around the IPC classification system so all inventions classified can be placed into these sectors. The five overarching sectors are Electrical engineering, Instruments, Chemistry, Mechanical engineering and Other fields (Schmoch, 2008). Lastly, a sixth section, New technologies, was added to include codes that tag new technology developments which may span across several of the other sectors (EPO & USPTO, 2021). It is expected that most inventions related to circularity in waste management are done in the chemistry sector since this sector contains subcategories related to materials, material processing and environmental technology (Schmoch, 2008). It is also expected that next to chemistry most inventions are done in mechanical engineering, which entails subcategories related to the handling of waste (Schmoch, 2008).

In this study, patents on waste management were collected using the IPC system. Patents on waste management represent only a small part of the overall patenting activity. Therefore, it is important to use an appropriate search strategy. Haščič & Migotto (2015) have developed a search strategy on all environment-related patenting, one category in this strategy is focussed specifically on waste management. Table 1 provides an overview of all IPC codes related to waste management. The topics found in Table 1 can be further subcategorized allowing for differentiation in sectors (Appendix 1), which allowed for a more in-depth analysis.

Table 1

IPC code used per topic of waste management based on Haščič & Migotto (2015)

Topic (1)	IPC code
Solid waste collection (waste reduction)	E01H15, B65F
Material recovery, recycling and re-use (resource efficiency and waste reduction)	A23K1/06-10, A43B1/12,, A43B21/14, B03B9/06, B22F8, B29B7/66, B29B17, B30B9/32, B62D67, B65H73, B65D65/46, C03B1/02, C03C6/02, C03C6/08, C04B7/24-30, C04B11/26, C04B18/04-10, C04B33/132, C08J11, C09K11/01, C10M175, C22B7, C22B19/28-30, C22B25/06, D01G11, D21B1/08-10, D21B1/32, D21C5/02, D21H17/01, H01B 15/00, H01J 9/52, H01M 6/52, H01M 10/54
Fertilisers from waste (waste reduction)	C05F1, C05F5, C05F7, C05F9, C05F17
Incineration and energy recovery (resource efficiency)	C10L5/46-48, F23G5, F23G7
Waste management – Not elsewhere classified (waste reduction)	B09B, C10G1/10, A61L11

(1) dependent variable which is targeted by topic

While the outcome of R&D activities is uncertain, they are aimed at achieving certain objectives. Table 1 shows for each topic which dependent variable is aimed to be influenced with the R&D activities (OECD, 2015). The topic of solid waste collection focuses on all patents related to collecting waste (Schmoch, 2008). This in turn allows for the separating of waste streams for recycling and reusing (Magrini et al., 2020). Recycling is the most widespread strategy to reduce waste (Haas et al., 2015) and together with reuse the most effective method to achieve waste reduction (Magrini et al., 2020).

Investing in material recovery focuses on increasing resource efficiency, when materials are recovered this results in a lower consumption of natural resources (Schmoch, 2008). Encouraging innovation in material recovery is the primary policy to increase the resource efficiency in countries leading in circular economy progress such as the Netherlands (Capital, 2015) and Japan (Bangert, 2020). The topic of fertilisers from waste focuses on the chemical processes of using organic waste and turning it into fertilisers (Haščič & Migotto, 2015). By using organic waste to create fertilisers, fewer artificial fertilisers based on compounds harming the environment need to be used. Therefore this is the main strategy to reduce organic waste in the Netherlands (Capital, 2015), Germany (BVSE et al., 2020) and Japan (Bangert, 2020).

R&D on incineration and energy recovery is focused on increasing the resource efficiency. This topic consists mainly of patents protecting technologies that minimise the input of energy into a system (Jin, 2016). The European Commission (2020) puts a focus on resource efficiency and implemented policies to stimulate R&D in energy recovery. In Korea, energy recovery is the main policy to increase resource efficiency (Jin, 2016). The last topic of waste management consists of technologies that are not classified under any of the other topics. This consists mostly of technologies focusing on the disposal and treatment of solid waste (Haščič & Migotto, 2015), allowing for waste reduction.

The patent data was found using the IPlytics platform, a tool that provides access to multiple databases of patents, standards and scientific publications (IPlytics GmbH, n.d.-b). The IPlytics platform sources patent documents from individual patent offices and allows for access to 99% of worldwide patent filings (IPlytics GmbH, n.d.-a), making it sufficiently comprehensive for this study. The tool allows for the analysis of patents in different technology sectors, following the sector classification as presented in the theory (IPlytics GmbH, n.d.-b). The IPlytics platform allows for the differentiation of patents based on characteristics like forward and backward citations.

Patents from 1980 until 2021 were searched for, since the IPlytics platform has a patent coverage in this timeframe (IPlytics GmbH, n.d.-d). While the first time the IPC codes for waste management used in patents may be later than 1980, setting 1980 as the starting year ensured the first patents are not missed. The scope used for the patent data was that of the 43 countries included in the statistical data of the OECD. The IPlytics platform provides access to all patent offices included in this scope (IPlytics GmbH, n.d.-a). A preliminary search indicated a sample size of 100,000 patents.

3.3 Measurements

When using a regression analysis to test the hypotheses, it is important to have dependent variables which reflect the progress of goals towards the circular economy. Given the worldwide scope of the patent data, the dependent variable must be measured with statistical data with the same scope. The dependent variables, intended to capture circular economy progress, are *resource efficiency* (the amount of goods produced divided by the consumption of materials) and *waste reduction* (the reduction in the amount of waste generated). These variables were adopted since they are closely connected to the goals countries set for progress towards a circular economy (Potting et al., 2017). Both these variables should have a strong correlation with innovation towards recycling technologies (Murray et al., 2017). When measuring resource efficiency on a national level, the value of all goods produced (GDP) was divided by the domestic material consumption (Flachenecker et al., 2018). The waste reduction was measured by the difference in the amount of waste in tonnes between a year and the previous year. A description of the dependent variables can be found in Table 2. Both variables were based on statistical data from the OECD.

Independent variables need to identify the effect of a measure, in this case patents, towards a circular economy. In order to test the hypotheses, three different independent variables were chosen, which are: **patent count**, **radicalness** and **technical relevance**. To test the hypothesis (H1), the **patent count** of patents on recycling technologies was used as an independent variable. This was measured by counting the number of patents on waste management filed in a country in a year. To give more in-depth insights into how patents on waste management contribute towards circular economy progress, the independent variables radicalness (SH1) and technical relevance (SH2) were used.

The independent variable **radicalness** aims to measure the radicalness of patents and can be indicated by the number of backward citations, which are the citations a patent made (Alfaro et al., 2019). The less backward citations, the more radical the invention the patent is protecting. To make the radicalness measurable and comparable, the number of backward citations a patent made was normalised based on the average citations of patents filed in the same country in the same year (IPlytics GmbH, n.d.-c). Since this normalization was done within a country, it was possible to compare countries to each other, thus allowing for a cross-country analysis. The average radicalness of all patents on waste management within a country in a year was used to facilitate this.

The independent variable **technical relevance** aims to measure the technological relevance patents provide. The technical relevance of a patent can be measured by the number of forward citations (Aristodemou & Tietze, 2018). The forward citations of a patent are an indicator of the relevance of the patent for further technological applications (Baron et al., 2016), patents with a high amount of citations have a high technical relevance (Fisch et al., 2016). To make the technical relevance measurable and comparable, the number of forward citations a patent receives was normalized based on the average citations of patents filed in the same country in the same year (IPlytics GmbH, n.d.-c). The average technical relevance of all patents on waste management within a country in a year was used in the cross-country analysis.

An example; searching for patents for recovery or working-up of waste materials (using IPC: C08J 11/22) in the United States results in the patent "Re-processed rubber and a method for producing same" with patent number US9902831B2 from 2018 (Rakhman et al., 2018). This patent has received 4 forward citations and cites 2 patents as prior art (Rakhman et al., 2018). In 2018 patents on average in the United States received 0.36 citations and cited 0.20 patents as prior art. The technical relevance of this patent is 4/0.36=11 and the radicalness is 2/0.20=9.84. This indicates that this patent has a relatively high technical relevance and protects an invention that could be used in radical innovation.

Table 2

Descriptive statistics of variables

Variable	Name	Definition	Unit
Dependent	Resource efficiency	Gross domestic product divided by domestic material consumption	USD/kg
Dependent	Waste reduction	The decrease in waste generated per year	Tonnes/year
Independent	Patent count	Number of patents on recycling in a year	Patents/year
Independent	Radicalness	Number of forward citations normalized with the average of similar patents[1]	No unit
Independent	Technical relevance	Number of backward citations normalized with the average of similar patents[1]	No unit

3.4 Analysis

This research performed a regression analysis, taking methodological guidance from Cainelli et al. (2020), who applied a regression in a similar approach. A regression analysis allowed identifying a relationship between independent and dependent variables. When a regression modelled a statistically significant relationship, the influence of the independent variables on a dependent variable could be predicted.

[1] Similar patents are patents filed in the same country in the same year

This method first saw for which countries a correlation between each independent and dependent variable could be found. If there was a correlation between the variables, a regression may have been found. Therefore, the correlation analysis was used to indicate for which countries there was a possible relationship between independent and dependent variables. Then, for these variables, a regression analysis could be performed. For these countries, a simple linear regression analysis was done between the variables that show correlation. This resulted in a regression equation, which was identified using the independent variables. Outcome equations were then provided for the dependent variables if they showed correlation and regression. When the simple regression analyses showed that in a country more than one variable may have explained a dependent variable, a multiple regression was done. This resulted in an outcome equation showing how each independent variable may explain a dependent variable when there was an interaction between the independent variables.

3.5 Validity and reliability

The validity of research refers to whether the indicators used actually measure the concepts intended to measure (Bryman, 2016). To guarantee the internal validity of this research the indicators used were derived from both literature where the concepts came from and from research with a similar methodology. This should ensure the concepts are measured correctly. To guarantee external validity, this research looked to generalize its findings of the contribution of patents on resource efficiency and waste reduction to the broader concept of circular economy progress.

For a study to be reliable it is important to have reliable measurements (Hancké, 2009). This was done by being as consistent in the data collection as possible. For each measurement, the same methodological steps are taken. To guarantee high reliability, a study needs to be repeatable as well (Leung, 2015). The replicability of this research was assured by consistently documenting in such a way it is insightful for a third party how the data is gathered. An example is that a database is created of all the patents used in the analysis. Every manipulation of the raw data to achieve that database is provided. This makes it insightful where the analysis comes from and enhances the replicability. Furthermore, the methodology used was documented to support the replicability.

Since this study only uses public patents and public data from the OECD as data sources, there are no ethical issues suspected to have occurred in the obtaining of data.

4. Data

4.1 Data manipulations

To analyse the data, the data needed to be manipulated so that all data is consistent. Since the data used by the OECD comes from different sources, as each country supplies their own data (OECD, 2021a, 2021b), the data is not unified. Systemic collection of environmental data has not been done for long and the data sources are mostly divided across different levels of government in different countries (OECD, 2021a, 2021b). To create a unified dataset from the OECD data, this research looked at years in which the data is available for all countries, whilst still maintaining a sufficient time period. After collecting all patent data, only the countries with patent data on waste management were used to fall within the scope of this research.

The data on resource efficiency in gross domestic product per domestic material consumption was directly downloaded from the OECD database. When looking at the data on resource efficiency, all countries within the scope provided data between 2000 and 2017. The only exception here was Norway, providing data from 2010 until 2017. To maintain a sufficient time period, data from 2000 until 2017 was used and Norway was excluded from the dataset.

The data on waste reduction was calculated by using data on waste generation from OECD in tonnes, then the difference with the previous year was calculated as the reduction in waste in tonnes per year. Most countries that provided data on waste to the OECD provided data in the same time span, however, there were some exceptions. Australia lacked data of multiple years within the scope, leading to gaps in the dataset. In order to ensure no skewness, Australia was deleted from the dataset. Brazil, India, Mexico and Russia provided data until 2012. It was chosen to delete these countries from the dataset as well. As more than 40% of the patents were filed after 2012 due to an increase in the total number of patents filed each year. Lastly, Canada did not provide any data on waste at all and was therefore removed from the dataset.

After a coherent dataset was created from the OECD data, the patent data was manipulated to accommodate the scope and timeline. After excluding the countries mentioned above and patents outside of the timespan this resulted in 60636 patents in 22 countries.

4.2 Resource efficiency and waste reduction

Tables 3 and 4 give an overview of the variables per country. For some countries, a value for radicalness or technical relevance could not be computed due to the impossibility to calculate them. Since both are normalized on year, country and IPC average, if there are no other patents that cover the same year, country and IPC code, no value will be present. The countries for which this is the case are excluded from the analyses on those variables. For some countries, there is an average value present but no correlation between radicalness or technical relevance and a dependent variable was computed. In this case, a value for radicalness or technical relevance for at least one year in the sample was missing. To prevent skewed results, no value is present for the correlation, in Table 4 this is visualised by ".[a]" instead of a value.

In this assessment, a difference is made between Western and Eastern European countries. The division of the United Nations is used to classify Western and Eastern European countries. This is a widely accepted geographical division that does not assume any political affiliations (United Nations, 2017). Western European countries in this sample are: Germany, France and the Netherlands, while Eastern European countries in this sample are: Czech Republic, Hungary and Poland (United Nations, 2017).

Table 3

Average resource efficiency (Gross domestic product divided by domestic material consumption) and waste reduction (decrease in waste compared to the previous year) per country based on OECD data (OECD, 2021a, 2021b).

Country	Resource efficiency (USD/kg)	Waste reduction (tonnes/year)
China	0,49	-5614,27
Czech Republic[e]	1,98	-100,63
Denmark	2,03	-77,72
Estonia	1,05	3,07
Finland	1,28	-17,31
France[w]	3,36	-289,18
Germany[w]	2,82	32,38
Greece	2,11	-63,94
Hungary[e]	2,16	65,27
Ireland	2,57	-33,33
Italy	3,92	-67,11
Japan	3,96	600,27
Korea	2,72	-159,69
Latvia	1,94	-10,28
Lithuania	1,77	-2,80
Netherlands[w]	4,63	22,94
Poland[e]	1,38	19,34
Portugal	1,81	-32,20
Spain	3,35	136,22
Sweden	2,08	-43,16
United Kingdom	4,44	137,77
United States	2,54	-1702,44

[w] Western European country and [e] Eastern European country.

Table 3 shows the average resource efficiency per country. Next to the Netherlands, which has the highest resource efficiency (4,63 USD/kg), all Western European countries show a high resource efficiency. For the non-European countries, Japan scores highest with the third-highest resource efficiency (3,96 USD/kg). This is in line with section 2.2.1 which states that Western European countries and Japan are leading in circular economy progress. Iles (2018) states that Western European countries tend to focus on the 3R approach since there are low amounts of resources to be extracted relative to other countries. This is reflected in the progress reported by the countries themselves. In the Netherlands there was a focus on resource efficiency even before 2000, allowing them to have a relatively high resource efficiency already which grew over the years (Ministry of Infrastructure and Environment & Ministry of Economic Affairs, 2016). In Germany, resource efficiency is taken as a prime indicator for circular economy progress (BVSE et al., 2020). Traditionally the economy of Germany is dependent on the country's heavy industry (Iles, 2018), however since there is a focus on a circular economy Germany reports an increase in resource efficiency and less reliability on heavy industry (BVSE et al., 2020). Like Western European countries, Japan is resource-constrained as well (Iles, 2018). According to Japan's progress report, this has led to attention on resource efficiency in the early 2000s (Bangert, 2020).

Furthermore, Eastern European countries perform lower on resource efficiency, this is also in line with section 2.2.1. While the same focus on resource efficiency can be found in Eastern Europe as in Western Europe (European Commission, 2020), Eastern European countries have a lower resource efficiency. However, where Western European governments have the capital to invest in resource efficiency, Eastern European countries lack this capital and therefore lack investments (Iles, 2018).

Notable is that Korea scores high on resource efficiency (2,72 USD/kg) relative to other non-European countries and China has the lowest resource efficiency. This circular economy progress is not in line with the literature in section 2.2.1. Korea is considered neither leading nor lacking in CE progress, however, the data suggest high resource efficiency, which is in accordance with Korea's own progress report (Jin, 2016). Korea has one of the highest GDPs in the world, through their production of mostly technological components (Jin, 2016). Since this requires a high amount of resources, Korea adopted a focus on resource efficiency to allow an increase in production without increasing the resources needed (Jin, 2016).

The economy of China in the early 2000s was based on cheap production, which has caused a low efficiency of resources (0,49 USD/kg) (Iles, 2018). According to China's progress report, there is no focus on increasing the resource efficiency (MOFA PRC, 2019). However, over time China has moved away from this economy and started focussing more on innovation (Iles, 2018). Since resource efficiency requires innovation, this may be a reason the data shows an increase in resource efficiency without a specific policy.

Table 3 shows the average waste reduction per country, where a negative waste reduction means an increase in the amount of waste generated compared to the year before. The highest waste reduction is achieved by Japan (600,27 tonnes/year). Japan started mapping its material flows before 2000 in order to achieve less waste (Iles, 2018). This is reflected in the progress report of Japan, where a similar reduction in waste can be found as the data of this research shows (Bangert, 2020). The Western European countries Germany (32,38 tonnes/year) and the Netherlands (22,94 tonnes/year) both show a positive waste reduction. According to their respectively progress reports, this can be explained by specific policies aimed to reduce waste (BVSE et al., 2020; Ministry of Infrastructure and Environment & Ministry of Economic Affairs, 2016). France however has a negative waste reduction (-289,18 tonnes/year), which means an increase in waste in respect to the previous year. According to its progress report, there has not been a focus on reducing waste until 2018, which is after the researched timespan (Ministry for an Ecological and Solidary Transition & Ministry for the Economy and Finance, 2018). This may explain why there is previously no reduction in waste.

The United States (-1702,44 tonnes/year) and China (-5614,28) both have the highest amount of waste and the most negative waste reduction. In the United States, this can be explained by a lack of federal policy (Iles, 2018), the government relies on the private sector to develop its own waste policies (U.S. Chamber of Commerce Foundation, 2015). The government of China does have a policy in place to reduce the amount of waste, however, this fully relies on not importing waste from other countries (MOFA PRC, 2019). No policy is in place to reduce the waste generated in China itself.

The data on waste reduction shows high circular economy progress for Japan, Germany and the Netherlands. A lack in progress for the United States can be found, which is expected from section 2.2.1. However, the waste increase of France and China does not comply.

4.3 Patent count, radicalness and technical relevance

This section gives an overview of the patent data used in the analyses of this research. Most patents are filed in Japan, China, Korea, the United States and Germany, as can be seen by the patent counts in Table 4. Notable is that most patents are filed in the Asian countries on the sample.

Table 4

Overview of the patent count, average radicalness and average technical relevance of patents on waste management per country.

Country	Patent count (total)	Radicalness (mean)	Technical relevance (mean)
China	13929	0,98	0,07
Czech Republic[e]	322	0,78	2,12
Denmark	724	0,04	0,20
Estonia	37	.[a]	.[a]
Finland	87	.[a]	.[a]
France[w]	1071	1,18	0,05
Germany[w]	5543	0,60	0,54
Greece	75	.[a]	.[a]
Hungary[e]	133	.[a]	2,50
Ireland	15	.[a]	.[a]
Italy	157	1,29	0,00
Japan	18173	1,32	0,16
Korea	9179	1,04	0,81
Latvia	30	.[a]	.[a]
Lithuania	27	.[a]	.[a]
Netherlands[w]	164	1,06	0,63
Poland[e]	771	.[a]	0,48
Portugal	19	.[a]	1,32
Spain	2840	0,92	1,26
Sweden	142	.[a]	0,38
United Kingdom	536	1,20	0,04
United States	6662	2,57	1,33

a. Was not computed because the variable has a missing value. [w] Western European country and [e] Eastern European country.

Table 4 shows that the highest average radicalness of patents is found in the United States, followed by Japan. China, Spain, Czech Republic, Germany and Denmark show a radicalness below one. However, most countries have a radicalness above 1, indicating patents protect technologies on waste management that are new and not build upon pre-existing technologies.

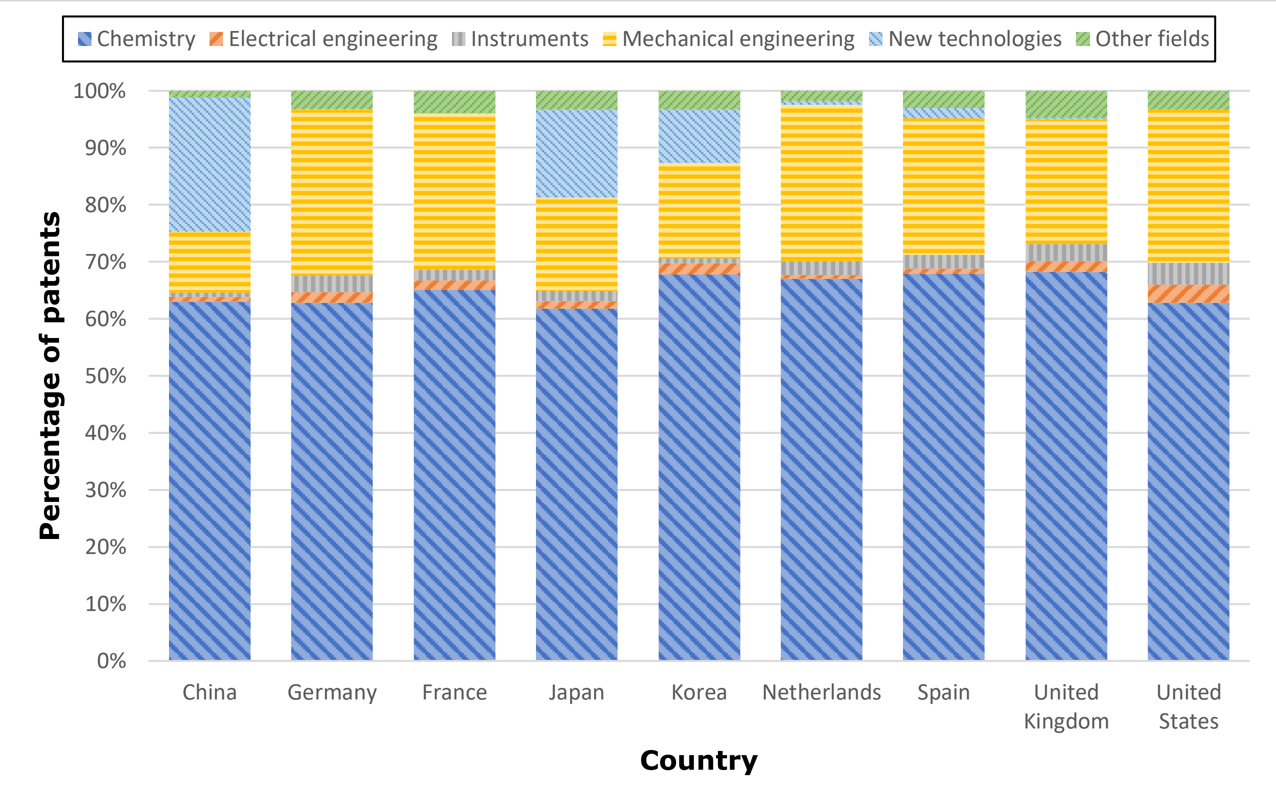
The highest average technical relevance of patents is found in Hungary, Czech Republic, Russia, the United States and Sweden. These are the only countries where an average above one can be found. This shows an overall low technical relevance in patents on waste management, indicating a low overall spillover of knowledge between firms.

4.4 Sectors

This section will focus further on the sectors in which patents on waste management were filed for countries that showed a correlation. Figure 2 shows how the patents are distributed within the different sectors for these countries. A full overview of all data on the number of patents per sector for each country in the assessment can be found in Appendix 2.

Figure 2

Distribution of patens in sectors of selected countries



Overall only little significant differences in distribution over different sectors can be found between these countries. According to Figure 2, most patents are filed within the chemistry sector. These are patents on inventions that allow for the chemical process of recovering resources, altering the materials of which products are made of and chemical processes that allow for the recovery of materials (Schmoch, 2008; WIPO, 2020). This sector focuses on material use and environmental technologies, therefore it is to be expected that most patents on waste management fall into this sector. Currently most countries in this assessment use recycling in order to reduce waste, which is a chemical process (Magrini et al., 2020). After chemistry, most patents are filed in the mechanical engineering sector (as shown in Figure 2). Most patents filed in this sector are of technologies on mechanical machines and tools which allow for the recovery of hard materials. Furthermore, the sector includes all technologies related to handling waste, such as sorting waste streams to be further broken down. A major part of this is the sorting of plastics to be recycled or reused. The sector of new technologies is an overarching sector that includes patents that are filed in multiple sectors (EPO & USPTO, 2021). In this assessment, the biggest difference between countries can be found in the latter two sectors.

5. Results

Tables 5 and 8 report the correlation between an independent variable and the dependent variables, resource efficiency and waste reduction, for each country. This is done by comparing data on variables per country per year. In order to be able to accept the hypotheses, there should be a positive correlation between each dependent variable and the resource efficiency and waste reduction.

5.1 Resource efficiency

This section discusses the correlation between the independent variables and the resource efficiency (shown in Table 5). For countries that show a correlation a simple linear regression analysis is carried out to find out which independent variable can explain the resource efficiency in a country. For countries that show multiple explanatory variables, a multiple regression is done to find the interaction between the independent variables and their combined explanatory value on the resource efficiency.

Table 5

The correlation between the independent variables and resource efficiency.

Country	Patent count	Radicalness	Technical relevance
China	0,971**	0,759*	-0,701*
Czech Republic[e]	-0,405	.[a]	-0,758
Denmark	-0,547	0,372	0,112
Estonia	-0,248	.[a]	.[a]
Finland	0,587	.[a]	.[a]
France[w]	0,479	0,305	-0,088
Germany[w]	-0,874**	0,668*	0,052
Greece	0,275	.[a]	.[a]
Hungary[e]	0,003	.[a]	0,712
Ireland	0,245	.[a]	.
Italy	-0,374	.[a]	.[a]
Japan	-0,240	0,271	0,698*
Korea	0,769**	0,642	-0,516
Latvia	-0,206	.[a]	.[a]
Lithuania	-0,364	.[a]	.[a]
Netherlands[w]	0,698*	-0,568	-0,437
Poland[e]	0,577	.[a]	-0,322
Portugal	-0,140	.[a]	.[a]
Spain	-0,440	0,374	-0,694*
Sweden	-0,424	.[a]	-0,614
United Kingdom	-0,307	-0,064	-0,407
United States	0,330	0,754*	-,642*

**. Correlation is significant at the 0.01 level (2-tailed); *. Correlation is significant at the 0.05 level (2-tailed). a. Was not computed because at least one of the variables has a missing value. [w] Western European country and [e] Eastern European country.

It emerges that, overall, resource efficiency displays an insignificant correlation with the patent count, radicalness and technical relevance for most countries in this assessment. This means that an overall relationship between the independent variables and resource efficiency is not likely to be found. Some countries, however, do show a correlation between variables.

China shows the highest significant positive correlation between patent count and resource efficiency (0,971). Korea (0,769) and the Netherlands (0,698) show a strong significant positive correlation as well. This indicates that patent count may influence resource efficiency positively. In Germany a strong significant negative correlation (-0,874) can be found, indicating that the patent count can have a possible negative effect on resource efficiency. Overall only four out of 22 countries show a correlation, indicating that in most cases the patent count has no relationship with resource efficiency.

A significant positive correlation between radicalness and resource efficiency can be found in China (0,759), Germany (0,668) and the United States (0,754). This indicates that in these countries patenting radically new technologies has a possible positive influence on the resource efficiency. However, only three of the ten cases show a correlation, indicating the radicalness of patents on waste management does not correlate with the resource efficiency.

Only Japan exhibits a significant positive correlation between technical relevance and resource efficiency (0,698), where China (-0,701), Spain (-0.694) and the United States (-0,642) show a significant negative correlation. Since overall only four of the 14 cases show correlation, no relationship between the technical relevance of patents and resource efficiency is likely to be found. Furthermore, the correlations which do emerge show a negative relation between the variables. This indicates that further R&D into already patented technologies is negatively contributing to the resource efficiency.

The results of the regression analyses for all countries showing correlation are shown in Table 6. In this table, the explanatory factor (β1), the standard error and the variance are shown for each regression model. A more in-depth description including a regression equation is given for each prediction model.

Table 6
Summary of regression analyses between independent variables and resource efficiency within countries which have show correlation between the variables.

Country	Patent count [1.] (a.)	Radicalness [1.] (a.)	Technical relevance [1.] (a.)
China	9.47E-5** [0.000] (0.942)	0.44* [0.141] (0.576)	-1.72* [616] (0.492)
Germany[w]	-1.30E-3** [0.000] (0.763)	0.40* [0.159] (0.446)	
Japan			2.56* [0.927] (0.487)
Korea	2.28E-3** [0.001] (0.591)		
Netherlands[w]	0.04* [0.015] (0.763)		
Spain			-3.09* [1.131] (0.482)
United States		0.97* [0.299] (0.569)	-0.74* [0.313] (0.412)

**. significant at the 1% level (2-tailed); *. significant at the 5% level (2-tailed). [1] Standard error and (a) variance of each model. [w] Western European country.

5.1.1 Patent count

According to the simple linear regression, the patent count of China can significantly predict its resource efficiency. The results of the regression indicate that the model explained 94.2% of the variance and that the model was significant, $F(1, 8) = 130.77$, $p<.001$. It is found that the patent count significantly predicts the resource efficiency in China ($\beta1 = 9.47E-5$, $p<.001$). The final predictive model in China is: *resource efficiency = 0.39 + (9.47E-5*patent count)*. The high variance indicates that the patent count can explain much of the resource efficiency in China. There is a positive relation, however, the β1 is very low, which indicates that the resource efficiency does change little when there is a change in patent count. China has a high patent count, which may be explained by a change from a cheap production economy to an innovation-based economy since 2000 (Dang & Motohashi, 2015). This includes innovating in waste management (Minghua et al., 2009), which supports the high patent count of patents on waste management. This resulted in a very low resource efficiency, yet there is still no focus on improving the resource efficiency (MOFA PRC, 2019). However progress reports from China report an increase in resource efficiency nonetheless (West et al., 2013). The regression supports why the resource efficiency in China still increased marginally over the years.

Next to China, in Korea the patent count can significantly predict its resource efficiency. The results of the regression indicate that the model explained 59.1% of the variance and that the model was significant, $F(1, 8) = 11.54$, $p<.01$. It is found that the patent count significantly predicts the resource efficiency in Korea ($\beta1 = 2.28E-3$, $p<.01$). The final predictive model in Korea is: *resource efficiency = 1.24 + (2.28E-3*patent count)*. The positive regression may be explained by the fact that Korea does have a focus on increasing the resource efficiency (Jin, 2016). As within China, however, the low β1 indicates a small influence from patent count on resource efficiency in Korea. While Korea focuses on the use of innovation of products to increase the resource efficiency, there is also a focus on increasing their production (Jin, 2016). This could explain this small influence, as the domestic material consumption is kept high by an increasing production. Therefore the resource efficiency remains high.

Germany and the Netherlands are the Western European countries that show a significant correlation here. For Germany the results of the regression indicate that the model explained 76.3% of the variance and that the model was significant, $F(1, 8) = 25.80$, $p<.005$. It is found that the patent count significantly predicts the resource efficiency in Germany ($\beta 1 = -1.30E-3$, $p<.005$). The final predictive model in Germany is: *resource efficiency = 3.05 + (-1.30E-3*patent count)*. In this model, the patent count does not explain much of the variance in resource efficiency. Furthermore, the model indicates a negative influence of patent count on resource efficiency, the patent count in Germany decreased while the resource efficiency increased. Germany was in early 2000 leading in waste management technology already (Iles, 2018). Recognising their leading position in waste management technologies, the German government decided to stop stimulating patenting activities (BVSE et al., 2020). This would allow other countries to use German technologies on waste management to further progress their own circular economy progress (BVSE et al., 2020).

For the Netherlands the results of the regression indicate that the model explained 76.3% of the variance and that the model was significant, $F(1, 8) = 7.58$, $p<.05$. It is found that the patent count significantly predicts the resource efficiency in the Netherlands ($\beta 1 = 0.04$, $p<.05$). The final predictive model in the Netherlands is: *resource efficiency = 3.05 + (0.04*patent count)*. The models explain a high percentage of the variance of the resource efficiency and the β1 is compared to the other models presented above high, suggesting a relatively large influence of patent count on resource efficiency in the Netherlands. This may be explained by the focus the Dutch government has on increasing the resource efficiency in their strategy towards a circular economy (Ministry of Infrastructure and Environment & Ministry of Economic Affairs, 2016). The Dutch government actively stimulates businesses to innovate in waste management to achieve this (Ministry of Infrastructure and Environment & Ministry of Economic Affairs, 2016). The regression confirms the influence of patent count on the increase in resource efficiency.

For the countries which show a correlation between patent count and resource efficiency, the Netherlands shows the highest influence of patent count on resource efficiency. Furthermore, the model in the Netherlands explains a lot of the variance. The model in China explains a lot of the variance as well, however shows less influence of the patent count. A point of difference between the Netherlands and the other countries which show correlation is that the Netherlands is the only country with a service-based economy rather than an industry-based economy (Iles, 2018). This could be a reason for the higher β1 and therefore a bigger influence of patent count on the resource efficiency.

5.1.2 Radicalness

In China the radicalness of patents can significantly predict its resource efficiency. The results of the regression indicate that the model explained 57.6% of the variance and that the model was significant, $F(1, 7) = 9.52$, $p<.05$. It is found that the radicalness significantly predicts the resource efficiency in China ($\beta1 = 0.44$, $p<.05$). The final predictive model in China is: *resource efficiency = 0.03 + (0.44*radicalness)*. The model indicates that the radicalness can explain much of the variance in resource efficiency in China. There is a positive relation, which indicates that the resource efficiency does change when there is a change in radicalness. China has an average radicalness lower than one, indicating low radicalness overall. However, over the years the radicalness of patents in China is increasing. Since China started to focus on an innovation-based economy a large inventive step was required (Dang & Motohashi, 2015). This could explain an increasing radicalness. The progress report of China mentions the large innovative steps which were taken, which resulted in an increase in resource efficiency (West et al., 2013). According to the regression, the radicalness may explain the increase in the resource efficiency in China over the years.

In Germany, the regression model of radicalness explained 44.6% of the variance and that the model was significant, $F(1, 8) = 6.44$, $p<.05$. It is found that the radicalness significantly predicts the resource efficiency in Germany ($\beta1 = 0.40$, $p<.05$). The final predictive model in Germany is: *resource efficiency = 2.46 + (0.40*radicalness)*. The data show that since 2008, when the German government stopped simulating patents and the patent count per year decreased, the radicalness of the patents increased. This indicates that only radically new technologies were patented. This is in line with the progress report towards a circular economy from Germany, where this focus on radically new technologies is emphasized (BVSE et al., 2020). Since an increase in resource efficiency requires radically new technologies (Aarikka-Stenroos et al., 2021) and Germany shows progress in an increase in resource efficiency (BVSE et al., 2020), it is valid that the regression indicates this increase in radicalness may explain the increase in resource efficiency.

The results of the regression in the United States on radicalness indicate that the model explained 56.9% of the variance and that the model was significant, $F(1, 8) = 10.54$, $p<.05$. It is found that the radicalness significantly predicts the resource efficiency in the United States ($\beta1 = 0.97$, $p<.05$). The final predictive model in the United States is: *resource efficiency = -0.14 + (0.97*radicalness)*. In the progress towards circular economy in the United States, there are no federal policies in place to increase the resource efficiency (U.S. Chamber of Commerce Foundation, 2015). The data shows an increase in resource efficiency nonetheless, which is confirmed by the US government (US EPA, 2016). The strategy towards a circular economy in the United States does have a focus on innovation, the reason for this is to allow businesses to get a competitive advantage (U.S. Chamber of Commerce Foundation, 2015). According to the data of this assessment the patents filed in the United States have a high and increasing radicalness, which reflects the strategy of innovation. The regression shows that the radicalness of patents can explain the increase in resource efficiency in the United States. This suggests that even though no active federal policies to increase resource efficiency are in place, the radicalness of patenting activity influences the resource efficiency in the United States.

5.1.3 Technical relevance

In China the technical relevance of the patents can significantly predict its resource efficiency. The results of the regression indicate that the model explained 49.2% of the variance and that the model was significant, $F(1, 8) = 7.75$, $p<.05$. It is found that the technical relevance significantly predicts the resource efficiency in China ($\beta 1 = -1.72$, $p<.05$). The final predictive model in China is: *resource efficiency = 0.59 + (-1.72* technical relevance)*. The model indicates that the technical relevance can explain much of the variance in resource efficiency in China. There is, however, a negative relation, which indicates that the resource efficiency does change negatively when there is a change in technical relevance. China has a very low average technical relevance compared to other countries in this assessment, which decreases over the years. China recognised a large inventive step needed to be taken in waste management technologies (West et al., 2013). Since China was lacking in a lot of areas related to waste management technologies, this resulted in a broad focus on different innovations (Dang & Motohashi, 2015). This could explain the low technical relevance of patents, different firms could focus on different technologies allowing many different technologies to contribute to the increase in resource efficiency. According to the regression, the technical relevance negatively explains the increase in the resource efficiency in China over the years.

The results of the regression of the technical relevance in Japan indicate that the model explained 48.7% of the variance and that the model was significant, $F(1, 8) = 7.61$, $p<.05$. It is found that the technical relevance significantly predicts the resource efficiency in Japan ($\beta 1 = 2.56$, $p<.05$). The final predictive model in Japan is: *resource efficiency = 3.36 + (2.56* technical relevance)*. As mentioned before, a circular economy is important in Japan (Iles, 2018). Both according to the data and monitored circular economy progress, the resource efficiency in Japan is high in comparison with the other countries in this research (Bangert, 2020). The technical relevance is according to the data however low compared to the rest of the sample. The data does show a vast increase of the technical relevance over the assessed period. This is likely due to a renewed focus on improving existing processes of waste management (Bangert, 2020). Since 2009 Japan has invested more to improve current waste management technologies (Bangert, 2020). The regression supports that the increase in resource efficiency can be explained by the increase in technical relevance in Japan.

In Spain the regression model of technical relevance indicates that the model explained 48.2% of the variance and that the model was significant, $F(1, 8) = 7.45$, $p<.05$. It is found that the technical relevance significantly predicts the resource efficiency in Spain ($\beta 1 = -3.09$, $p<.05$). The final predictive model in Spain is: *resource efficiency = 4.09 + (-3,09* technical relevance)*. Spain shows a high resource efficiency compared to other assessed countries, a reason for this can be that Spain has a focus on increasing the resource efficiency in their strategy towards a circular economy (Ministerio de Economía Industria y Competitividad, 2018). The data also show that Spain has a low technical relevance compared to other countries in this assessment. Over the investigated period a decrease in technical relevance can be found in Spain, which means a low spillover from innovating activities (Abrams et al., 2013). This may be explained by the fact that, while there is a countrywide policy, Spain has laid the responsibility to stimulate innovation on waste management more and more by municipalities (Ministerio de Economía Industria y Competitividad, 2018). Currently, only a small portion of municipalities in Spain actively do this (Magrini et al., 2020). The regression shows that the increase in resource efficiency can be explained by a decrease in technical relevance.

Lastly for the United States, the results of the regression of technical relevance indicate that the model explained 41.2% of the variance and that the model was significant, $F(1, 8) = 5.61$, $p<.05$. It is found that the technical relevance significantly predicts the resource efficiency in the United States ($\beta1 = -0.74$, $p<.05$). The final predictive model in the United States is: *resource efficiency = 3.35 + (-0.74* technical relevance)*. The resource efficiency is increasing over the years according to the data and monitored circular economy progress in the United States (US EPA, 2016). The United States show a relatively high technical relevance, which is however decreasing over the years. This indicates no further innovations on a technology by different companies or spillover effects (Abrams et al., 2013). This may be due to a lack of active stimulation (Iles, 2018) or targets set on circular economy progress on a federal level (U.S. Chamber of Commerce Foundation, 2015). The regression shows that the decreasing technical relevance can explain the increasing resource efficiency.

Notable is that three of the four regression models show a negative impact from technical relevance on resource efficiency.

5.1.4 Interaction between variables

For China, Germany and the United States, multiple independent variables suggest a change in resource efficiency. In order to compare the influence of these variables, a multiple regression analysis was carried out for each country. The results are shown in Table 7, including the explanatory factor (β1), the standard error and the variance of each model.

Table 7

Summary of regression analyses between independent variables and resource efficiency within countries that have shown explanatory values for multiple variables.

	China [1.] (0.952)	Germany[w] [1.] (0.812)	United States [1.] (0.717)
Patent count	1.03E4** [0.000]	1.92E3** [0.001]	
Radicalness	-0.122 [0.106]	-0.283 [0.211]	0.769* [0.280]
Technical relevance	-0.394 [0.334]		-0.481 [0.251]

**. significant at the 1% level (2-tailed); *. significant at the 5% level (2-tailed). [1.] Standard error and (*variance*) variance of each model. [w] Western European country.

In China patent count, radicalness and technical relevance all have an explaining factor towards resource efficiency. According to a multiple regression, these variables statistically significantly predict the resource efficiency, $F(3, 5) = 33.05$, $p <.005$, and variance of 95.2%. Of the three variables, only the patent count added statistically significantly to the prediction, $p <.005$. This indicates that while all three variables jointly explain the resource efficiency, the statistical power to adequately disentangle the effects of radicalness and technical relevance is missing. The final predictive model in China is: *resource efficiency = 0.53 + (1.03E4* patent count)*. This indicates that the resource efficiency in China can be explained by looking at the patent count. However, the patent count has a low influence on the resource efficiency. The patents in China have increased in radicalness over the years, together with a high patent count this can explain the increase in resource efficiency. This suggests that China is searching for new technologies not based on previous work. However, the patents in China show a very low technical relevance, indicating little innovation on top of patented technologies and a low spillover of knowledge. This may be explained by the difference in circular economy goals of China compared to other countries in the assessment. China focuses more on living conditions, ending poverty and reducing CO_2 emissions by closing loops (MOFA PRC, 2019). Little focus is put on resource efficiency or waste reduction (MOFA PRC, 2019).

A multiple regression was run to predict the resource efficiency in Germany from patent count and radicalness. These variables statistically significantly predict the resource efficiency, $F(2, 7) = 15.10$, $p < .005$, and variance of 81.2%. Of the two variables, only the patent count added statistically significantly to the prediction, $p < .01$. The final predictive model in Germany is: *resource efficiency = 3.42 + (1.92E3* patent count)*. The patent count in Germany follows a decreasing trend, while the radicalness increases. This suggests that the policy of Germany to patent less works for patents that do not protect a radical new technology. These technologies keep being patented, most likely because firms require protection for radically new technologies.

In the United States, the radicalness and technical relevance of patents have a possible explanatory value. According to the regression model these variables statistically significantly predict the resource efficiency, $F(2, 7) = 8.85$, $p < .05$, and variance of 71.7%. Of the three variables only the radicalness added statistically significantly to the prediction, $p < .05$. The final predictive model in the United States is: *resource efficiency = 0.95 + (0.77* radicalness)*. This shows that the increasing radicalness has a higher influence on the resource efficiency than the decreasing technical relevance. Furthermore, the high radicalness shows that radically new inventions have a high likeliness to be protected by patents in the United States.

In different countries patent count, radicalness and technical relevance all have an explaining factor towards resource efficiency. To see if the independent variables can explain the resource efficiency globally, a multiple regression analysis is carried out over all countries in the sample. According to the multiple regression, these variables statistically significantly predict the resource efficiency, $F(3, 6) = 32.55$, $p < .001$, and variance of 94.2%. Of the three variables, only the patent count added statistically significantly to the prediction, $p < .001$. This indicates that while all three variables jointly explain the resource efficiency, the statistical power to adequately disentangle the effects of radicalness and technical relevance is missing. The final overall predictive model is: *resource efficiency = 0.49 + (4.73E4* patent count)*. This shows that overall the patent count can explain a change in resource efficiency across countries. For some countries both radicalness and technical relevance showed to influence the resource efficiency, this is however not significant globally. This indicates that the radicalness and technical relevance do not cross borders.

5.2 Waste reduction

This section discusses the correlation between the independent variables and the waste reduction (as shown in Table 8). For countries that show a correlation, a simple linear regression analysis is carried out to find out which variable can explain the waste reduction in a country. For countries that show multiple explanatory variables, a multiple regression is done to find the interaction between the independent variables.

Table 8

The correlation between the independent variables and waste reduction.

Country	Patent count	Radicalness	Technical relevance
China	0,341	-0,048	-0,119
Czech Republic[e]	0,184	.[a]	-0,116
Denmark	-0,094	-0,545	0,415
Estonia	0,345	.[a]	.[a]
Finland	0,063	.[a]	.[a]
France[w]	-0,025	0,497*	0,347
Germany[w]	0,433	-0,299	0,346
Greece	-0,233	.[a]	.[a]
Hungary[e]	0,371	.[a]	-0,471
Ireland	0,023	.[a]	.[a]
Italy	-0,224	.[a]	.[a]
Japan	0,421	0,540*	-0,016
Korea	0,100	0,162	0,060
Latvia	0,316	.[a]	.[a]
Lithuania	-0,126	.[a]	.[a]
Netherlands[w]	0,580*	0,642	0,045
Poland[e]	-0,130	.[a]	0,026
Portugal	-0,287	.[a]	0,138
Spain	-0,164	0,591**	-0,003
Sweden	-0,033	.[a]	-0,426
United Kingdom	0,489*	0,155	-0,015
United States	-0,405	0,137	0,183

**. Correlation is significant at the 0.01 level (2-tailed); *. Correlation is significant at the 0.05 level (2-tailed).a. Was not computed because at least one of the variables has a missing value. [w] Western European country and [e] Eastern European country.

Table 8 shows the findings of the correlation between the independent variables and waste reduction within each country. It emerges that, overall, waste reduction displays an insignificant correlation with patent count for most countries in this assessment. This means that an overall relationship between the independent variables and waste reduction is not likely present. In some countries, however, a correlation between variables can be found.

A significant moderate positive correlation between patent count and waste reduction can only be found in the United Kingdom (0,489) and the Netherlands (0,580). This indicates that the patent count may explain the waste reduction in some cases. However, since only two of the 22 countries show a correlation, an overall relationship between patent count and waste reduction is unlikely.

France (0,497), Japan (0,540) and Spain (0,591) show a significant moderate positive correlation between radicalness and waste reduction. This indicates that it is possible that patenting radically new innovations contribute to the waste reduction in a country. However, since only three out of ten countries in the sample show a correlation this is unlikely.

No impactful significant correlation can be found between technical relevance and waste reduction. This indicates the technical relevance has no impact on waste reduction. This indicates that further R&D into already patented technologies does not influence the waste reduction in a country.

The results of the regression analyses for all countries showing correlation are shown in Table 9. In this table, the explanatory factor (β1), the standard error and the variance are shown for each regression model. A more in-depth description including a regression equation is given for each prediction model.

Table 9

Summary of regression analyses between independent variables and waste reduction within countries which have show correlation between the variables.

Country	Patent count [1.] (a.)	Radicalness [1.] (a.)
France[w]		2961.63* [1291.482] (0.247)
Japan		4626.38* [1804.113] (0.291)
Netherlands[w]	9.23* [3.209] (0.336)	
Spain		1770.08** [604.599] (0.349)
United Kingdom	46.51* [20.719] (0.239)	

**. significant at the 1% level (2-tailed); *. significant at the 5% level (2-tailed). [1.] Standard error and (a.) variance of each model. [w] Western European country.

5.2.1 Patent count

For the Netherlands the results of the regression indicate that the model on patent count explained 33.6% of the variance and that the model was significant, $F(1, 16) = 8.10$, $p<.05$. It is found that the patent count significantly predicts the waste reduction in the Netherlands ($\beta1 = 9.23$, $p<.05$). The final predictive model in the Netherlands is: *waste reduction = -60.28+ (9.13*patent count)*. This model explains little of the variance of waste management. This may be explained by the fact that in the early 2000s the Dutch government focussed on resource efficiency rather than waste management (Ministry of Infrastructure and Environment & Ministry of Economic Affairs, 2016). The β1 shows a positive influence of the patent count on waste reduction. This may be explained by the fact that the Dutch government started focussing on waste reduction around 2008 in their strategy towards a circular economy (Ministry of Infrastructure and Environment & Ministry of Economic Affairs, 2016).

The regression model of patent count in the United Kingdom explained 23.9% of the variance and that the model was significant, $F(1, 16) = 5.04$, $p<.05$. It is found that the patent count significantly predicts the waste reduction in the United Kingdom ($\beta 1 = 46,51$, $p<.05$). The final predictive model in the United Kingdom is: *waste reduction = -1247.12+ (46.51*patent count)*. In the United Kingdom, the influence of patent count is much larger than in the Netherlands, as can be seen by the higher β1. This may be explained by the policies in the United Kingdom towards a circular economy. Starting in 2000 with a focus on recycling waste (DEFRA, 2018a), the United Kingdom has one of the highest waste reductions in this sample. A vital part is of their strategy is the Waste and Resources Action Programme, which is intended to incentivise innovation in waste management (DEFRA, 2018a). This has resulted in an increase in the recycling rate of 45% (DEFRA, 2018b). The strategy of enabling innovation to increase the recycling rate may be a reason for the high influence from patent count on waste reduction.

The correlation between patent count and waste reduction for both the Netherlands and the United Kingdom is moderate. This may be the reason for the models explaining a small amount of the variance.

5.2.2 Radicalness

For France the results of the regression indicate that the model of the radicalness of patents explained 24.7% of the variance and that the model was significant, $F(1, 16) = 5.26$, $p<.05$. It is found that the patent count significantly predicts the waste reduction in France ($\beta 1 = 2961.63$, $p<.05$). The final predictive model in France is: *waste reduction = -3778.84 + (2961.63* radicalness)*. The data shows a poor radicalness compared to other countries in the sample, which does increase nor decrease over the years. Of the Western European countries, France focuses most on waste reduction rather than resource efficiency (Iles, 2018). Frances strategy depends on instating laws that oblige businesses to reduce waste, rather than stimulating them (Ministry for an Ecological and Solidary Transition & Ministry for the Economy and Finance, 2018). The data, however, show a lack in waste reduction without improvement in the investigated period. This may be explained since the laws on waste reduction from the French government are mainly focused on food waste (Ministry for an Ecological and Solidary Transition & Ministry for the Economy and Finance, 2018). This means that all industrial waste will be hardly affected by the French policy. According to the regression, the radicalness does explain the waste reduction in France, suggesting the lack of radicalness explains the lack of waste reduction.

The regression model of radicalness in Japan explained 29.1% of the variance and that the model was significant, $F(1, 16) = 6.58$, $p<.05$. It is found that the radicalness significantly predicts the waste reduction in Japan ($\beta 1 = 4626.38$, $p<.05$). The final predictive model in Japan is: *waste reduction = -5508.76 + (4626.38* radicalness)*. Japan scores high on radicalness, with only patents in the United States showing a higher radicalness. Circular economy is an important topic in Japan, with a heavy focus on material flows (Iles, 2018). In Japan stimulating new technologies to close loops is central to achieve a circular economy (Bangert, 2020). Japan scores very high on waste reduction compared to other countries in the assessment according to the data as well as according to their own progress reports (Bangert, 2020). In their strategy towards a circular economy, Japan has a heavy focus on reducing its waste (Bangert, 2020). Firstly this is done for environmental benefits, less waste causes less CO_2 emissions (Bangert, 2020). Secondly, Japan is very space-constrained and waste needs to go somewhere, giving an incentive to innovate in waste management technologies (Iles, 2018). The regression shows that the waste reduction in Japan can be explained by the radicalness of patents.

For Spain the results of the regression indicate that the model explained 34.9% of the variance of radicalness and that the model was significant, $F(1, 16) = 8.57$, $p<.01$. It is found that the radicalness significantly predicts the waste reduction in Spain ($\beta 1 = 1770.08$, $p<.01$). The final predictive model in Spain is: *waste reduction = -1483.65+ (1770.08* radicalness)*. Spain shows a high waste reduction in comparison to other countries in this assessment. In their strategy towards a circular economy, Spain has a clear goal of reducing 15% of waste generated in 2030 compared to 2010 on achieving waste reduction (Ministerio de Economía Industria y Competitividad, 2018). Progress shows that Spain is on track to reach their target (Gracia & Gómez, 2020). To reach its goals Spain actively stimulates and invests in innovation towards waste management technologies (Ministerio de Economía Industria y Competitividad, 2018). The data do not show a particular high radicalness compared to other countries assessed, however, an increase in radicalness over the years can be found. This may be a result of the focus on innovation Spain has in their circular economy strategy, since the regression shows that the waste reduction in Spain can be explained by the increase in radicalness. All three models explain a low amount of the variance in waste reduction, this is likely due to the moderate correlation all countries display.

5.2.3 Technical relevance

As shown in Table 8, no correlation between technical relevance and waste reduction can be found. Therefore, no regression analysis has been carried out between these two variables.

5.2.4 Interaction between variables

In different countries patent count and radicalness have an explaining factor on the waste reduction. To see if the independent variables can explain the resource efficiency globally, a multiple regression analysis is carried out over all countries in the sample. A multiple regression was performed, however, no variables significantly explain the waste reduction, $p>0.05$. This is most likely due to the big differences in the waste reduction between the countries in the sample. This leads to a scattered image and does not allow for a significant regression.

5.3 Explanatory values

Overall there are some noteworthy findings in the data, such as an overall lack in waste reduction within the sample countries. Furthermore, there are no countries to show a significant positive correlation between almost all variables tested. The data reflects Japan is leading in circular economy progress on both indicators, which does however not correlate with all patent data. According to Iles (2018), China is leading in circular economy progress as well, this does however not show in the data. It should be noted that the resource efficiency in China improves over the years, although not so that it can be considered leading in progress. China is however the only country in which all three independent variables can explain the resource efficiency. Furthermore, there is a large increase in waste instead of waste reduction. This does not correlate with the patent data. Western European countries display a lot of circular economy progress in resource efficiency and waste reduction. An exception here is France which shows lacking progress on waste reduction. The data on patents in Western European countries is quite diverse, which may explain an overall lack of correlation between the variables. In Germany both patent count and radicalness explain the resource efficiency, in the Netherlands the patent count explains both dependent variables and in France only the radicalness explains the waste reduction. The United States and Eastern European countries show the most lack in circular economy progress (Iles, 2018), which the data confirms. The United States is, however, improving on both radicalness in patents and resource efficiency over the years, which explain the correlation between these variables. Altogether there is a low significant correlation between variables in the data used. A regression over all countries in the sample does however show that the patent count has an explanatory value for the resource efficiency. No independent variable can be found to have a global explanatory value on waste reduction.

5.4 Conclusion of results

The results of the regression analyses between patent count on waste management and resource efficiency show global evidence that the resource efficiency can be explained by the patent count. However, when looking at a national level this is supported in only four of the 22 countries. The patent count does not give an explanatory factor for the waste reduction on a global level, whereas on a national level this can only be found in two of the 22 countries.

The results of regression analyses between radicalness and either resource efficiency or waste reduction show no significant explanatory value. The regression analyses on a country level support this, wherein only three out of ten countries the radicalness of patents on waste management can explain the resource efficiency. Furthermore, also in only three out of ten countries, the waste reduction can be explained by the radicalness.

The results of regression analyses between the technical relevance and either resource efficiency or waste reduction show no significant explanatory value. The regression analyses on a country level support this since in only four out of 14 countries the technical relevance of patents on waste management can explain the resource efficiency. However, only in one of these countries, a positive influence can be found where the other cases show a negative influence. Furthermore, there are no countries in which the waste reduction can be explained by the technical relevance.

6. Discussion

This section discusses the hypotheses based on the empirical findings in the results. The results are interpreted based on the theory and compared to previous work and policy reports of the countries within the sample and compared to academic literature. Furthermore, the limitations of this research are discussed and avenues for further research are recommended.

6.1 Discussion of hypotheses

In this research the following hypothesis was tested:
H1: *Patent counts on waste management have a positive impact on progress towards a circular economy, as evidenced by increases in resource efficiency and waste reduction at the national level.*

Overall very little significant correlation has been found between the **patent count** of patents on waste management and the resource efficiency or waste reduction. In order to accept the hypothesis, there must be evidence on a global scale. Since the correlation does not prove a positive impact from patent count on both *resource efficiency* and *waste reduction*, hypothesis 1 is rejected.

The following sub hypotheses were tested:
SH1: *The radicalness of patents on waste management has a positive impact on progress towards a circular economy, as evidenced by increases in resource efficiency and waste reduction at the national level.*

SH2: *The technical relevance of patents on waste management has a positive impact on progress towards a circular economy, as evidenced by increases in resource efficiency and waste reduction at the national level.*

Again very little correlation was found between the **radicalness** and **technical relevance** of patents on waste management and the resource efficiency or waste reduction. Therefore there is not sufficient proof that either of these independent variables has a positive impact on both the *resource efficiency* and *waste reduction*. Both sub-hypotheses are rejected.

Overall, insufficient valid proof was found to accept any of the three hypotheses. However, in the regression analyses in different cases evidence was found that patents can contribute towards circular economy progress. The contribution of this thesis is to describe this evidence and compare it to academic literature.

6.2 Contribution of patents on a circular economy

While insufficient evidence was found to accept any of the hypotheses, some evidence suggests that under the right circumstances patents do have an influence on circular economy progress. Both the patenting strategies and the policies to achieve a circular economy differ between countries. In this section, the differences in results between countries are discussed based on their strategies and policies. Furthermore, the literature on which the hypotheses were based will be compared to this evidence. This will help understand why in certain countries patenting contributes more to circular economy progress than in other countries.

The countries with the highest percentage of patents filed in the new technologies sector are China, Japan and Korea. These countries have instead a lower percentage of patents filed in the mechanical engineering sector. This can be due to the different approaches these countries take in comparison to the other countries within this sample. Firstly China does not focus on either resource efficiency or waste reduction nor has it set clear targets on them (MOFA PRC, 2019). This may explain the lack of circular economy progress in China as well. Lopes de Sousa Jabbour et al. (2018) argues that it is critical to have a clear roadmap to achieve a circular economy, the lack of progress in China supports this. Instead, in the development of new technologies, a focus lies on increasing the current quality of life of its residents (MOFA PRC, 2019). A cleaner production is highly implemented in China's strategy to ensure better living conditions (Yuan et al., 2006). To achieve cleaner production, development of technologies that fall in both the chemistry and mechanical engineering sector is central. An example of this is the recycling of lithium batteries, which is responsible for most patents filed in the new technology sector in China. China is responsible for over half of the global lithium consumption, the lithium is used in the production of lithium batteries (Hao et al., 2017). Waste of these batteries contains toxic chemicals which have a negative impact on human health (Kang et al., 2013). Therefore, to reduce the health risks of its population, China aims to recover the waste of lithium batteries (Hao et al., 2017). This requires technologies that can both collect and handle the batteries as well as deal with the chemical components, leading to patents that cover technologies in both the mechanical engineering and chemistry sectors. This may explain the increase in resource efficiency which the data show in China as well. Academic literature states that recovering materials and cleaner production to maximise the value creation of waste is the basis for increasing resource efficiency (MacArthur, 2020). The example that China's focus on lithium batteries may lead to an increased resource efficiency without clear policies supports this.

Secondly, Japan does not focus on resource efficiency or waste reduction either. Instead, Japan has a more coherent approach, using the same policies to improve both (Bangert, 2020). These policies focus mainly on closing loops and monitoring material flow (Bangert, 2020), which according to the literature is vital to both resource efficiency and waste reduction (Geng & Doberstein, 2008). The coherent approach of Japan could have resulted in more patents in the new technology sectors since a cross-sectoral approach enables the transition towards a circular economy (Milios, 2021). Therefore, patents overarching sectors are more likely to impact both the resource efficiency and waste reduction at the same time. This coherent approach together with investing heavily in waste management technologies has lead Japan to be leading in circular economy progress (Bangert, 2020). This can be seen in Japan's own progress reporting, as well as in the data of this assessment. This is in line with Huysman et al. (2015) who suggests a coherent approach is needed to achieve a circular economy on a national level.

Thirdly, Korea shows patenting in the new technology sector. The economy in Korea is largely based on the production of consumer electronics, being the number one producer of electronics in the world (Holroyd, 2019). This causes a lot of waste, which Korea actively tries to recycle (Jang, 2016). Therefore a large patent count in the electrical engineering sector can be expected. However, Figure 2 show no significantly larger share in this sector than other countries in the sample. This is most likely since the recycling of electronics to gain value out of electronic waste also requires specified mechanical tools and processes (Cui & Forssberg, 2003). This could be an explanation for the patents filed in the new technology sector in Korea, which in turn may have led to the high resource efficiency in

Korea. This is in line with current literature, which put a focus on the importance of recycling to extend the lifespan of materials and, thereby, achieve circular economy progress (Degli Antoni & Vittucci Marzetti, 2019; Tisserant et al., 2017). On the other hand, the example of Korea also contradicts academic literature. Bleischwitz et al. (2018) state that resource efficiency consists of a decrease in resource inputs and that should be obtained by recycling products. However, Korea also has a focus on innovating on production processes, allowing them to increase the resource efficiency without lowering resource inputs.

China, Japan and Korea notably also have the highest patent count in the sample. This may be because technologies that span over different sectors have more uncertainty, which leads to more protection and therefore are more often patented. This can be explained since technologies overarching sectors lead to a larger knowledge spillover than technologies within a sector (Koutroumpis et al., 2021). This knowledge spillover can be visualised by patents since patents display the exploitation of new knowledge in a sector (Lööf & Nabavi, 2015). The sectors electrical engineering, instruments and other fields make up the lowest percentage of patents and differ only slightly between countries.

The European countries follow a similar distribution of patents between sectors. This is explicable by the fact that the European Union has a central strategy towards circular economy progress (European Commission, 2020). This focuses on increasing resource efficiency, reducing waste through innovation and collaborating (European Commission, 2020). Most European countries are restricted in natural resources, which gives motivation to increase the resource efficiency (Ellen MacArthur Foundation & McKinsey & Company, 2014). With a higher resource efficiency, more products can be made with fewer resources than with a lower resource efficiency. Therefore when a country has low resources available, it incentivises to increase the resource efficiency and thereby allow for higher production. Furthermore, Europe is space-constrained, which gives motive to achieve waste reduction (Iles, 2018). Since most waste is landfilled, a large amount of waste requires a large amount of space (Deer, 2021). This internal motivation could be a reason why the European countries in this sample lead in circular economy progress according to the data. By putting a focus on both innovation and collaboration, it can be explained why no significant correlation can be found for many variables within European countries. As explicitly stated in the German policy towards a circular economy, it is believed that instead of protecting technologies with patents, it is important to share information on technologies that contribute towards a circular economy and share those technologies with other European countries (BVSE et al., 2020). This can also be an explanation for why European countries have generally lower patent counts than other countries in the sample.

This is an interesting finding, current literature on patents states that investing in R&D leads to technical innovation (Albers et al., 2018). However to reduce the uncertainties of R&D investments, patenting activities are done (Spulber, 2014). This leads to patents being a suitable measure for innovation output (Dang & Motohashi, 2015; Hu, 2008). The example in Europe however indicates that this does not have to be the case. The circular economy policy in Europe does put a focus on investing in R&D (European Commission, 2020). However since collaboration stands central and knowledge is shared willingly, patenting is discouraged by governments (BVSE et al., 2020). Hereby there is still innovative output in Europe which has allowed for circular economy progress, it can however not be measured by looking at patenting activities. To find whether collaboration between countries leads to better knowledge sharing than knowledge spillover of patents, further research is recommended.

The United States follow the same distribution of patents in sectors as the countries in Europe. This can be explained by the fact that the United States takes great inspiration in circular economy policies from Europe (Iles, 2018). Still, the United States show overall less circular economy progress according to progress reports (Wiedmann et al., 2015) and the data of this assessment. This can be explained because the United States is a country with important geographical differences from Europe. Where European countries are very space-constrained, the United States do not have this constrain (Iles, 2018). Where this constrain is a problem in Europe, leading to a motivation to find a solution towards circular economy progress, this internal motivation is lacking in the United States. Furthermore, The United States is one of the most resource-rich countries in the world (Garside, 2019). This does not trigger the same motivation to increase the resource efficiency as in Europe. Combined this has lead to a lack of urgency for the federal government to actively stimulate innovation towards a circular economy (U.S. Chamber of Commerce Foundation, 2015), which can explain the lack of circular economy progress. This indicates that motivation is vital for circular economy progress. The United States scored relative to the other countries in this research high on all independent variables, however circular economy progress is still lacking. A reason for this may be that motivation to reach a circular economy is more important than patenting activities. Further research is advised to analyse the effect of motivation on circular economy progress.

The topics in which is innovated and patented are important for circular economy progress. There is evidence that patents can contribute in certain situations. However some other important factors have come forward as well, for example, a clear roadmap, collaboration between countries and motivation seem even more important for circular economy progress. This would explain why in general European countries score high on the circular economy indicators and why the hypotheses were rejected. Patents in the new technology sector seem to have an impact on circular economy progress. Therefore it is important to have policies that stimulate patenting in the topics which fall under this sector. Furthermore, there are vast differences between what the circular economy policies in different countries cover and which goals are set. Overall the patent count seems to have the most impact on circular economy progress. However only looking at patent count does lead to a distorted picture that conforms to academic literature (Pohlmann et al., 2016). Next to patent count, the radicalness of patents have the most impact, there is however no unambiguous evidence that and how the technical relevance contributes. This indicates that patents that do influence circular economy progress are protecting radically new innovations. This is in line with the literature, which states that radicalness is important in the value creation of waste (Aarikka-Stenroos et al., 2021; Antikainen et al., 2015). There was no evidence found that patents protecting incremental improvements of already existing technologies contribute to a circular economy. This is not in line with current literature, which states that both the radicalness and technical relevance of patents are important to measure the quality of patents (Pohlmann et al., 2016). Abrams et al. (2013) state that patents with a high technical relevance indicate a knowledge spillover. Since towards a circular economy knowledge sharing is already achieved by collaboration, the technical relevance of patents may be less important as a measure in this case. Currently technical relevance or the forward citations of patents are widely used to determine the quality of patents (Dang & Motohashi, 2015), further research is advised to find whether this is appropriate when investigating circular economy.

This research sought to find out whether patents contribute to circular economy progress. The results indicate that patenting can contribute to circular economy progress, however only under specific circumstances. More in-depth and specific research on the circumstances under which patents can contribute to a circular economy is recommended. Different countries all have different patenting strategies and circular economy policies. Therefore, future research should include a design that allows for a detailed study per country to gain a holistic understanding, such as a case study.

6.3 Limitations

There are some limitations to the outcome of this research. No in-depth case study could be done into all patenting strategies and circular economy policies due to the scope and time constraint of this research. Furthermore, not every country has the same standards in their circular economy progress reports. In some countries, the progress and policy reports are very coherent and in-depth, in other countries, this is not the case. China has, for example, recent policy reports with their goals on how to achieve a circular economy (MOFA PRC, 2019). Since China does not have a strong focus on resource efficiency, their last progress report monitoring this to see if policy changes may be beneficial is from 2013 (West et al., 2013). In comparison to countries that have more recent progress reports and use them to adapt their policies on resource efficiency, this can lead to a certain skewness of results. It can not be discerned if in this example China used patenting strategies after 2013 specifically to increase their resource efficiency.

The OECD data used in this study is mostly self-provided by each country. There is no guarantee that the measurement methods used to gain this data are the same in each country. Furthermore, counties may only provide favourable data, which shows more circular economy progress than is the actual case and may lead to rival explanations. These rival explanations are mitigated by choosing to use data that is measured mostly the same in each country due to international standards. For example, when looking at resource efficiency, the *System of National Accounts* dictates how the GDP in a country should be measured (UN & DESA, 2010). This should eliminate threats to the internal validity of this research and therefore reduce rival explanations.

The last limitation is a methodological one and is based on the difficulty to prove causation in scientific research. While a correlation can be used to see whether a relationship is present between variables, it does not indicate the direction of the relationship. Therefore next to a correlation, regression was used to determine a predictive value and to be able to find how independent variables predict the dependent variables. While this still does not prove causation, a directional relationship can be estimated using regression. Therefore the research question can be answered sufficiently using this methodology.

7. Conclusion

This research has aimed to answer the research question '*How does patenting in waste management contribute towards circular economy progress?*' by analysing patent data and comparing it to circular economy progress data.

7.1 Summary of the results

Firstly, correlation analyses were done between on the one hand patent count, radicalness and technical relevance of patents on waste management and on the other hand resource efficiency and waste reduction within each country to find whether a relationship is possible. The results of the correlation analyses showed little significant correlation in most countries of the sample. Notably, there was more correlation found between patent data and resource efficiency than between patent data and waste reduction.

Secondly, regression analyses were done within countries which did show correlation, to find how an independent variable can explain a dependent variable. Overall, the regression analyses between patent data and *resource efficiency* show a higher variance and significance than between patent data and *waste reduction*. Furthermore, of the patent data, the **patent count** showed the most explanatory value, having the most significance in every regression model and being the only variable to contribute to circular economy progress worldwide. However, the patent count can on a global scale only explain the resource efficiency and not the waste reduction. The **radicalness** of patents on waste management showed the second most explanatory value. Within different countries the radicalness can explain circular economy progress, this is however not the case on a global scale. The **technical relevance** showed mixed results in the regression analyses with *resource efficiency*, and no correlation was found with *waste reduction*, which offers little explanatory value with circular economy progress. From this can be concluded that radically new technologies contribute more to a circular economy than (incremental) improvements of already existing technologies.

Overall the results don't provide a one-sided answer to the research question. The analyses showed too little significant correlation to find a worldwide contribution of patents on itself to circular economy progress. There is, however, evidence that shows cases in which patents on waste management do contribute. This is most likely due to the different policies in different countries on circular economy progress. In Europe, there is a focus on collaboration and knowledge sharing without patenting (European Commission, 2020). In Asian countries, on the other hand, there is much more focus on competition between countries, which may lead to more patenting. This has lead to circular progress on the resource efficiency in a country like China, where there is no policy to achieve a higher resource efficiency. Notably, the patents filed in these Asian countries are more focused on technologies overarching in sectors. Therefore it seems that patents protecting these technologies contribute more to circular economy progress than patents filed in a single sector.

7.2 Recommendations

Based on the results of this research, policy recommendations can be made. The results have shown that it is possible to be leading in circular economy progress without active patenting strategies. The best example can be found in Europe, where collaboration and knowledge sharing without patents is the strategy towards a circular economy. Therefore when making policies for a circular economy it is recommended that collaboration with other countries is a central theme.

It is also possible to lead in circular economy progress by implementing correct patenting strategies, an example in this research can be found in the case of Japan. In that case, it seems vital to have a cross-sectoral approach when stimulating patenting, since patents covering technologies overarching sectors contribute more to a circular economy.

Lastly, when stimulating patents, the radicalness of patents on waste management has evidence to contribute to a circular economy in multiple countries. The higher the radicalness of a patent, the more it assists in reaching a circular economy. This is not the case with the technical relevance of patents. Little evidence was found that the technical relevance of patents contributes and the little evidence that was found show that technical relevance could even impact a circular economy negatively. Current policies on innovation towards a circular economy have a focus on incremental innovation, which is measured by the technical relevance of patents (Rizos et al., 2016). Since this research does not indicate impact from incremental innovation, policies should stimulate the patenting of radically new technologies and deter incremental improvements of already existing technologies.

7.3 Take-home message

This research suggests that patents can contribute to the goal of achieving a circular economy. When the right technologies are patented evidence shows that patents can lead to progress in circular economy. On the other hand, this research has also shown that patents will only assist in reaching a circular economy under the right circumstances. Currently, on a global scale, there is no evidence that patents contribute to a circular economy. This shows the complexity of implementing a circular economy. If the right circumstances, however, could be guaranteed, patents show promise in facilitating transitioning towards a circular economy.

8. References

Aarikka-Stenroos, L., Ritala, P., & Thomas, L. D. W. (2021). Circular economy ecosystems: A typology, definitions and implications. *Handbook of Sustainability Agency*, *September 2020*, 32.

Abrams, D., Akcigit, U., & Popadak, J. (2013). Understanding the Link between Patent Value and Citations: Creative Destruction or Defensive Disruption. *NBER Working Paper*, *19647*. http://www.nber.org/papers/w19647

Albers, A., Heimicke, J., Walter, B., Basedow, G. N., Reiß, N., Heitger, N., Ott, S., & Bursac, N. (2018). Product Profiles: Modelling customer benefits as a foundation to bring inventions to innovations. *Procedia CIRP*, *70*, 253–258. https://doi.org/10.1016/j.procir.2018.02.044

Alfaro, E., Yu, F., Rehman, N. U., Hysa, E., & Kabeya, P. . (2019). Strategic management of innovation. In *Routledge Companion to Innovation Management* (pp. 107–168). Routledge.

Aminoff, A., & Pihlajamaa, M. (2020). Business experimentation for a circular economy - Learning in the front end of innovation. *Journal of Cleaner Production*, *275*, 124051. https://doi.org/10.1016/j.jclepro.2020.124051

Antikainen, M., Lammi, M., Paloheimo, H., Ruppel, T., & Valkokari, K. (2015). Towards Circular Economy Business Models : Consumer Acceptance of Novel Services Maria Antikainen * Minna Lammi Harri Paloheimo , Timo Rüppel. *The Proceedings of the ISPIM Innovation Summit: Changing the Innovation Landscape*, *December*, 16. https://helda.helsinki.fi/bitstream/handle/10138/160018/Towards_Circular_Economy_Business_Models_Paper.pdf?sequence=1

Aristodemou, L., & Tietze, F. (2018). Citations as a measure of technological impact: A review of forward citation-based measures. *World Patent Information*, *53*(May), 39–44. https://doi.org/10.1016/j.wpi.2018.05.001

Bangert, H. (2020). *Japan ' S Circularity: A Panorama of Japanese Policy, Innovation, Technology and Industry Contributions Towards Achieving the Paris Agreement*. 0–75.

Baron, J., Pohlmann, T., & Blind, K. (2016). Essential patents and standard dynamics. *Research Policy*, *45*(9), 1762–1773. https://doi.org/10.1016/j.respol.2016.05.004

Bleischwitz, R., Spataru, C., VanDeveer, S. D., Obersteiner, M., van der Voet, E., Johnson, C., Andrews-Speed, P., Boersma, T., Hoff, H., & van Vuuren, D. P. (2018). Resource nexus perspectives towards the United Nations Sustainable Development Goals. *Nature Sustainability*, *1*(12), 737–743. https://doi.org/10.1038/s41893-018-0173-2

Boons, F., Montalvo, C., Quist, J., & Wagner, M. (2013). Sustainable innovation, business models and economic performance: An overview. *Journal of Cleaner Production*, *45*, 1–8. https://doi.org/10.1016/j.jclepro.2012.08.013

Bryman, A. (2016). *Social research methods* (5th ed.). Oxford University Press.

BVSE, BDSV, BDE, VCDMA, & VDM. (2020). *Statusbericht der deutschen Kreislaufwirtschaft*. 228. https://www.bdsv.org/fileadmin/news/Master_Statusbericht_final_26.04.18_V4.pdf

Cacace, M., Ettelt, S., Mays, N., & Nolte, E. (2013). Assessing quality in cross-country comparisons of health systems and policies: Towards a set of generic quality criteria. *Health Policy*, *112*(1–2), 156–162. https://doi.org/10.1016/j.healthpol.2013.03.020

Cainelli, G., D'Amato, A., & Mazzanti, M. (2020). Resource efficient eco-innovations for a circular economy: Evidence from EU firms. *Research Policy*, *49*(1), 103827. https://doi.org/10.1016/j.respol.2019.103827

Capital, N. (2015). *From Waste to Resource Annex 1 : Progress of the actions per operational objective*. *6*.

Chenarani, A., Druzhinin, E. A., & Kritskiy, D. N. (2017). Simulating the impact of activity uncertainties and risk combinations in R & D projects. *Journal of Engineering Science and Technology Review*, *10*(4), 1–9. https://doi.org/10.25103/jestr.104.01

Construcia. (2020). *Which countries are leading the change in circular economy?* https://www.construcia.com/en/noticias/which-countries-are-leading-the-change-in-circular-economy/

Cramer, J. (2014). *Moving Towards a Circular Economy in the Netheralnds: Challenges and Directions*. 1–9.

Cui, J., & Forssberg, E. (2003). Mechanical recycling of waste electric and electronic equipment: A review. *Journal of Hazardous Materials*, *99*(3), 243–263. https://doi.org/10.1016/S0304-3894(03)00061-X

Dang, J., & Motohashi, K. (2015). Patent statistics: A good indicator for innovation in China? Patent subsidy program impacts on patent quality. *China Economic Review*, *35*, 137–155. https://doi.org/10.1016/j.chieco.2015.03.012

Deer, R. (2021). LANDFILLS: WE'RE RUNNING OUT OF SPACE. *Roadrunner WM*. https://www.roadrunnerwm.com/blog/landfills-were-running-out-of-space

DEFRA. (2018a). Our waste, our resources: a strategy for England. *HM Goverment*, 1–146. www.nationalarchives.gov.uk/doc/open-government-licence/version/3/oremailPSI@nationalarchives.gsi.gov.uk

DEFRA. (2018b). Resources and waste strategy: at a glance. *Policy Paper*. https://www.gov.uk/government/publications/resources-and-waste-strategy-for-england/resources-and-waste-strategy-at-a-glance

Degli Antoni, G., & Vittucci Marzetti, G. (2019). Recycling and Waste Generation: An Estimate of the Source Reduction Effect of Recycling Programs. *Ecological Economics*, *161*(September 2018), 321–329. https://doi.org/10.1016/j.ecolecon.2019.04.002

Ellen MacArthur Foundation, & McKinsey & Company. (2014). Towards the Circular Economy : Accelerating the scale-up across global supply chains. *World Economic Forum*, *January*, 1–64.

EPO, & USPTO. (2021). *Cooperative Patent Classification Y*. 1–3.

European Commission. (2011). REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS on the Thematic Strategy on the Prevention and Recycling of Waste. *European Commission*, 1–10.

European Commission. (2020). *A new Circular Economy Action Plan For a cleaner and more competitive Europe*. 1–20.

Fisch, C. O., Block, J. H., & Sandner, P. G. (2016). Chinese university patents: quantity, quality, and the role of subsidy programs. *Journal of Technology Transfer*, *41*(1), 60–84. https://doi.org/10.1007/s10961-014-9383-6

Flachenecker, F., & Rentschlehler, J. (2019). From barriers to opportunities: Enabling investments in resource efficiency for sustainable development. *Public Sector Economics*, *43*(4), 345–373. https://doi.org/10.3326/pse.43.4.2

Flachenecker, F., Rentschler, J., & De Kleuver, W. (2018). Monitoring Resource Efficiency Developments: Indicators, Data, and Trends. In *Investing in Resource Efficiency* (pp. 31–50). Springer.

Ganzevles, J., Potting, J., & Hanemaaijer, A. (2017). Evaluation of the Green Deals for a Circular Economy. *PBL Netherlands Environmental Assessment Agency*, *July*.

Garrido-Prada, P., Lenihan, H., Doran, J., Rammer, C., & Perez-Alaniz, M. (2021). Driving the circular economy through public environmental and energy R&D: Evidence from SMEs in the European Union. *Ecological Economics*, *182*(October 2020), 106884. https://doi.org/10.1016/j.ecolecon.2020.106884

Garside, M. (2019). *Leading countries worldwide based on natural resource value as of 2019*. https://www.statista.com/statistics/748223/leading-countries-based-on-natural-resource-value/

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., & Hultink, E. J. (2017). The Circular Economy – A new sustainability paradigm? *Journal of Cleaner Production*, *143*, 757–768. https://doi.org/10.1016/j.jclepro.2016.12.048

Geng, Y., & Doberstein, B. (2008). Developing the circular economy in China: Challenges and opportunities for achieving "leapfrog development." *International Journal of Sustainable Development and World Ecology*, *15*(3), 231–239. https://doi.org/10.3843/SusDev.15.3:6

Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. *Journal of Cleaner Production*, *114*, 11–32. https://doi.org/10.1016/j.jclepro.2015.09.007

Gimenez-Nadal, J. I., & Sevilla, A. (2012). Trends in time allocation: A cross-country analysis. In *European Economic Review* (Vol. 56, Issue 6). https://doi.org/10.1016/j.euroecorev.2012.02.011

Gracia, A., & Gómez, M. I. (2020). Food sustainability and waste reduction in Spain: Consumer preferences for local, suboptimal, and/or unwashed fresh food products. *Sustainability (Switzerland)*, *12*(10). https://doi.org/10.3390/su12104148

Haas, W., Krausmann, F., Wiedenhofer, D., & Heinz, M. (2015). How circular is the global economy?: An assessment of material flows, waste production, and recycling in the European union and the world in 2005. *Journal of Industrial Ecology*, *19*(5), 765–777. https://doi.org/10.1111/jiec.12244

Habib, M., Abbas, J., & Noman, R. (2019). Are human capital, intellectual property rights, and research and development expenditures really important for total factor productivity? An empirical analysis. *International Journal of Social Economics*, *46*(6), 756–774. https://doi.org/10.1108/IJSE-09-2018-0472

Hancké, B. (2009). *Intelligent research design : A guide for beginning researchers in the social sciences.* Oxford University Press.

Hao, H., Liu, Z., Zhao, F., Geng, Y., & Sarkis, J. (2017). Material flow analysis of lithium in China. *Resources Policy*, *51*(December 2016), 100–106. https://doi.org/10.1016/j.resourpol.2016.12.005

Haščič, I., & Migotto, M. (2015). Measuring Innovation Using Patent Data. *OECD Environment Working Papers*, *89*. https://doi.org/10.1787/5js009kf48xw-en

Holroyd, C. (2019). Digital content promotion in Japan and South Korea: Government strategies for an emerging economic sector. *Asia and the Pacific Policy Studies*, *6*(3), 290–307. https://doi.org/10.1002/app5.277

Hu, M. C. (2008). Knowledge flows and innovation capability: The patenting trajectory of Taiwan's thin film transistor-liquid crystal display industry. *Technological Forecasting and Social Change*, *75*(9), 1423–1438. https://doi.org/10.1016/j.techfore.2008.04.005

Huysman, S., Debaveye, S., Schaubroeck, T., Meester, S. De, Ardente, F., Mathieux, F., & Dewulf, J. (2015). Resources , Conservation and Recycling The recyclability benefit rate of closed-loop and open-loop systems : A case study on plastic recycling in Flanders. *"Resources, Conservation & Recycling," 101*, 53–60. https://doi.org/10.1016/j.resconrec.2015.05.014

Iles, J. (2018). Which country is leading the circular economy shift? *Medium*. https://medium.com/circulatenews/which-country-is-leading-the-circular-economy-shift-3670467db4bb

IPlytics GmbH. (n.d.-a). *Data Sources*. Retrieved February 23, 2020, from https://intelligence.iplytics.com/data_sources

IPlytics GmbH. (n.d.-b). *IPlytics, The Company*.

IPlytics GmbH. (n.d.-c). *IPlytics Patent Valuation Indicators*.

IPlytics GmbH. (n.d.-d). *IPlytics Platform Data Sources*.

Jang, Y. (2016). Recycling and Management of Electronic Waste in Korea : recent trends and suggestions for sustainable management. *Https://Ewit.Site/Kb/Recycling-Management-Electronic-Waste-Korea/*, 120–128.

Jin, I. (2016). Circular Economy Policy in Korea. *ERIA Research Project Report*, *September*, 163–184. http://www.eria.org/RPR_FY2014_No.44_Chapter_10.pdf

Kang, D. H. P., Chen, M., & Ogunseitan, O. A. (2013). Potential environmental and human health impacts of rechargeable lithium batteries in electronic waste. *Environmental Science and Technology*, *47*(10), 5495–5503. https://doi.org/10.1021/es400614y

Kang, H. Y. (2012). Science inside law: The making of a new patent class in the international patent classification. *Science in Context*, *25*(4), 551–594. https://doi.org/10.1017/S0269889712000233

Karvonen, M., & Kässi, T. (2011). Patent analysis for analysing technological convergence. *Foresight*, *13*(5), 34–50. https://doi.org/10.1108/14636681111170202

Kim, G., & Bae, J. (2017). A novel approach to forecast promising technology through patent analysis. *Technological Forecasting and Social Change*, *117*, 228–237. https://doi.org/10.1016/j.techfore.2016.11.023

Koutroumpis, P., Leiponen, A., & Thomas, L. D. W. (2021). Digital instruments as invention machines. *Communications of the ACM*, *64*(1), 70–78. https://doi.org/10.1145/3377476

Krauss, J. B., & Kuttenkeuler, D. (2018). Intellectual property rights derived from academic research and their role in the modern bioeconomy—A guide for scientists. *New Biotechnology*, *40*, 133–139. https://doi.org/10.1016/j.nbt.2017.06.013

Lang-Koetz, C., Pastewski, N., Schimpf, S., & Heubach, D. (2010). Resource efficiency as a key-driver for technology and innovation management: Dealing with an emerging trend in technology intelligence. *International Journal of Technology Intelligence and Planning*, *6*(2), 164–184. https://doi.org/10.1504/IJTIP.2010.035155

Leung, L. (2015). Validity, reliability, and generalizability in qualitative research. *Journal of Family Medicine and Primary Care*, *4*(3), 324. https://doi.org/10.4103/2249-

4863.161306

Linder, M., & Williander, M. (2017). Circular Business Model Innovation: Inherent Uncertainties. *Business Strategy and the Environment*, *26*(2), 182–196. https://doi.org/10.1002/bse.1906

Lööf, H., & Nabavi, P. (2015). Knowledge spillovers, productivity and patent. *Annals of Regional Science*, *55*(1), 249–263. https://doi.org/10.1007/s00168-015-0681-1

Lopes de Sousa Jabbour, A. B., Jabbour, C. J. C., Godinho Filho, M., & Roubaud, D. (2018). Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations. *Annals of Operations Research*, *270*(1–2), 273–286. https://doi.org/10.1007/s10479-018-2772-8

MacArthur, E. (2020). Towards the circular economy - Economic and Business Rationale for an Accelerated transition. *Ellen Macarthur Foundation Rethink the Future*, 100.

Magrini, C., D'Addato, F., & Bonoli, A. (2020). Municipal solid waste prevention: A review of market-based instruments in six European Union countries. *Waste Management and Research*, *38*(1_suppl), 3–22. https://doi.org/10.1177/0734242X19894622

Milios, L. (2021). Overarching policy framework for product life extension in a circular economy—A bottom-up business perspective. *Environmental Policy and Governance*, *January*, 1–17. https://doi.org/10.1002/eet.1927

Minghua, Z., Xiumin, F., Rovetta, A., Qichang, H., Vicentini, F., Bingkai, L., Giusti, A., & Yi, L. (2009). Municipal solid waste management in Pudong New Area, China. *Waste Management*, *29*(3), 1227–1233. https://doi.org/10.1016/j.wasman.2008.07.016

Ministerio de Economía Industria y Competitividad. (2018). Circular Economy Spanish Strategy "España Circular 2030." *Exacutive Summary*, 20. https://www.miteco.gob.es/es/calidad-y-evaluacion-ambiental/temas/economia-circular/espanacircular_2030_executivesummary_en_tcm30-510578.pdf

Ministry for an Ecological and Solidary Transition, & Ministry for the Economy and Finance. (2018). *Roadmap for the circular economy*. http://ci.nii.ac.jp/naid/40005517287/en/

Ministry of Infrastructure and Environment, & Ministry of Economic Affairs. (2016). *A circular economy in the Netherlands by 2050*. 72. https://www.government.nl/binaries/government/documents/policy-notes/2016/09/14/a-circular-economy-in-the-netherlands-by-2050/17037+Circulaire+Economie_EN.PDF

MOFA PRC. (2019). *China's Progress Report on Implementation of the 2030 Agenda for Sustainable Development (2019)*. *September*, 126. https://www.fmprc.gov.cn/mfa_eng/topics_665678/2030kcxfzyc/P020190924780823323749.pdf

Murray, A., Skene, K., & Haynes, K. (2017). The Circular Economy: An Interdisciplinary Exploration of the Concept and Application in a Global Context. *Journal of Business Ethics*, *140*(3), 369–380. https://doi.org/10.1007/s10551-015-2693-2

Ness, D. (2008). Sustainable urban infrastructure in China: Towards a Factor 10 improvement in resource productivity through integrated infrastructure systems. *International Journal of Sustainable Development and World Ecology*, *15*(4), 288–301. https://doi.org/10.3843/SusDev.15.4:2a

OECD. (n.d.). *About the OECD*. Retrieved March 2, 2021, from https://www.oecd.org/about/

OECD. (2015). Frascati Manual 2015: Guidelines for Collecting and Reporting Data on

Research and Experimental Development. *The Measurement of Scientific, Technological and Innovation Activities*, 43–80. https://doi.org/https://doi.org/10.1787/9789264239012-en

OECD. (2016). Policy Guidance on Resource Efficiency. In *Policy Guidance on Resource Efficiency*. https://doi.org/10.1787/9789264257344-en

OECD. (2020a). Evironment at a Glance: Circular economy, waste and materials. *Environment at a Glance*, *May 2020*, 1–12. https://www.oecd.org/environment/environment-at-a-glance/Circular-Economy-Waste-Materials-Archive-February-2020.pdf

OECD. (2020b). *Our global reach*. https://www.oecd.org/about/members-and-partners/

OECD. (2020c). *Relations with non-member countries*. https://www.oecd.org/sti/ieconomy/relationswithnon-membercountries.htm

OECD. (2021a). *Material resources*. OECD. https://stats.oecd.org/

OECD. (2021b). *Waste Generation and Treatment*. OECD. https://stats.oecd.org/

Oltra, V., Kemp, R., & De Vries, F. P. (2010). Patents as a measure for eco-innovation. *International Journal of Environmental Technology and Management*, *13*(2), 130–148. https://doi.org/10.1504/IJETM.2010.034303

Park, I., Jeong, Y., Yoon, B., & Mortara, L. (2015). Exploring potential R&D collaboration partners through patent analysis based on bibliographic coupling and latent semantic analysis. *Technology Analysis and Strategic Management*, *27*(7), 759–781. https://doi.org/10.1080/09537325.2014.971004

Pohlmann, T., Neuhäusler, P., & Blind, K. (2016). Standard essential patents to boost financial returns. *R and D Management*, *46*(2011), 612–630. https://doi.org/10.1111/radm.12137

Potting, J., Hekkert, M., Worrell, E., & Hanemaaijer, A. (2017). Circular Economy: Measuring innovation in the product chain - Policy report. *PBL Netherlands Environmental Assessment Agency*, *2544*, 42.

Rakhman, M., Feiglin, T., & Golobrodsky, O. (2018). *Re-processed rubber and a method for producing same* (Patent No. US9902831B2).

Rizos, V., Behrens, A., Kafyeke, T., Hirschnitz-Garbera, M., & Ioannou, A. (2015). *The Circular Economy: Barriers and Opportunities for SMEs. CEPS Working Documents No. 412/September 2015*. *September*.

Rizos, V., Behrens, A., van der Gaast, W., Hofman, E., Ioannou, A., Kafyeke, T., Flamos, A., Rinaldi, R., Papadelis, S., Hirschnitz-Garbers, M., & Topi, C. (2016). Implementation of circular economy business models by small and medium-sized enterprises (SMEs): Barriers and enablers. *Sustainability (Switzerland)*, *8*(11). https://doi.org/10.3390/su8111212

Schandl, H., Fischer-kowalski, M., West, J., Giljum, S., Dittrich, M., Eisenmenger, N., Geschke, A., Lieber, M., Wieland, H., Schaffartzik, A., Lenzen, M., Tanikawa, H., & Miatto, A. (2016). *Global Material Flows Resource and Productivity*.

Schmoch, U. (2008). Concept of a Technology Classification for Coun- World Intellectual Property Organisation (WIPO). *Innovation*, *June*, 1–15.

Spulber, D. F. (2014). How Patents Provide the Foundation of the Market for Inventions. *SSRN Electronic Journal*, *June*. https://doi.org/10.2139/ssrn.2487564

Tisserant, A., Pauliuk, S., Merciai, S., Schmidt, J., Fry, J., Wood, R., & Tukker, A. (2017). Solid Waste and the Circular Economy: A Global Analysis of Waste Treatment and

Waste Footprints. *Journal of Industrial Ecology*, *21*(3), 628–640. https://doi.org/10.1111/jiec.12562

U.S. Chamber of Commerce Foundation. (2015). *ACHIEVING A CIRCULAR ECONOMY: How the Private Sector Is Reimagining the Future of Business*. 76. https://www.uschamberfoundation.org/sites/default/files/Circular Economy Best Practices.pdf

UN, & DESA. (2010). *System of National Accounts 2008* (1st ed.).

United Nations. (2017). *Standard country or area codes for statistical use*. https://unstats.un.org/unsd/methodology/m49/

United Nations. (2020). Global indicator framework for the Sustainable Development Goals and targets of the 2030 Agenda for Sustainable Development. *Work of the Statistical Commission Pertaining to the 2030 Agenda for Sustainable Development*, 1–21. https://unstats.un.org/sdgs/indicators/Global Indicator Framework after 2019 refinement_Eng.pdf%0Ahttps://unstats.un.org/sdgs/indicators/Global Indicator Framework_A.RES.71.313 Annex.pdf

US EPA. (2016). *Advancing Resource Efficiency in the Supply Chain – Observations and Opportunities for Action*. *September*.

Webster, K. (2017). *The circular economy: A wealth of flows*. Ellen MacArthur Foundation Publishing.

West, J., Schandl, H., & Heyenga, S. (2013). *Resource efficiency: economics and outlook for China*.

Wiedmann, T. O., Schandl, H., Lenzen, M., Moran, D., Suh, S., West, J., & Kanemoto, K. (2015). The material footprint of nations. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(20), 6271–6276. https://doi.org/10.1073/pnas.1220362110

WIPO. (2020). Guide to the International Patent Classification. *Guide to the International Patent Classification*, 51. https://www.wipo.int/export/sites/www/classifications/ipc/en/guide/guide_ipc.pdf.

World Intellectual Property Organization. (2020). World Intellectual Property Indicators 2020. In *World Intellectual Property Organization* (Vol. 1). http://www.wipo.int/export/sites/www/freepublications/en/intproperty/941/wipo_pub_941_2013.pdf

Yuan, Z., Bi, J., & Moriguichi, Y. (2006). The circular economy: A new development strategy in China. *Journal of Industrial Ecology*, *10*(1–2), 4–8. https://doi.org/10.36661/2596-142x.2019v1i1.10902

9. Appendix

9.1 Appendix 1: Patent search strategy

Table A1
Overview of sectors and IPC codes in topics on waste management patents, based on Haščič & Migotto (2015) and Schmoch (2008).

Waste management topic	Sector	IPC code
Solid waste collection		
Street cleaning; Removing undesirable matter, e.g. rubbish, from the land, not otherwise provided for	Other fields	E01H15
Transporting; Gathering or removal of domestic or like refuse	Electrical engineering	B65F
Material recovery, recycling and re-use		
Animal feeding-stuffs from distillers' or brewers' waste; waste products of dairy plant; meat, fish, or bones; from kitchen waste	Chemistry	A23K1/06-10
Footwear made of rubber waste	Other fields	A43B1/12
Heels or top-pieces made of rubber waste	Other fields	A43B21/14
Separating solid materials; General arrangement of separating plant specially adapted for refuse	Electrical engineering	B03B9/06
Manufacture of articles from scrap or waste metal particles	Chemistry	B22F8
Preparing material; Recycling the material	Mechanical engineering	B29B7/66
Recovery of plastics or other constituents of waste material containing plastics	Mechanical engineering	B29B17
Presses specially adapted for consolidating scrap metal or for compacting used cars	Mechanical engineering	B30B9/32
Systematic disassembly of vehicles for recovery of salvageable components, e.g. for recycling	Mechanical engineering	B62D67
Stripping waste material from cores or formers, e.g. to permit their re-use	Mechanical engineering	B65H73
Applications of disintegrable, dissolvable or edible materials	Mechanical engineering	B65D65/46
Compacting the glass batches, e.g. pelletizing	Mechanical engineering	C03B1/02
Glass batch composition - containing silicates, e.g. cullet	Chemistry	C03C6/02
Glass batch composition - containing pellets or agglomerates	Chemistry	C03C6/08
Hydraulic cements from oil shales, residues or waste other than slag	Chemistry	C04B7/24-30
Calcium sulfate cements starting from phosphogypsum or from waste, e.g. purification products of smoke	Chemistry	C04B11/26
Use of agglomerated or waste materials or refuse as fillers for	Chemistry	C04B18/04-10

mortars, concrete or artificial stone; Waste materials or Refuse		
Clay-wares; Waste materials or Refuse	Chemistry	C04B33/132
Recovery or working-up of waste materials (plastics)	Mechanical engineering	C08J11
Luminescent, e.g. electroluminescent, chemiluminescent, materials; Recovery of luminescent materials	Chemistry	C09K11/01
Working-up used lubricants to recover useful products	Chemistry	C10M175
Working-up raw materials other than ores, e.g. scrap, to produce non-ferrous metals or compounds thereof	Chemistry	C22B7
Obtaining zinc or zinc oxide; From muffle furnace residues; From metallic residues or scraps	Chemistry	C22B19/28-30
Obtaining tin; From scrap, especially tin scrap	Chemistry	C22B25/06
Textiles; Disintegrating fibre-containing articles to obtain fibres for re-use	Mechanical engineering	D01G11
Paper-making; Fibrous raw materials or their mechanical treatment - using waste paper	Mechanical engineering	D21B1/08-10
Paper-making; Fibrous raw materials or their mechanical treatment; Defibrating by other means - of waste paper	Mechanical engineering	D21B1/32
Paper-making; Other processes for obtaining cellulose; Working-up waste paper	Mechanical engineering	D21C5/02
Paper-making; Pulping; Non-fibrous material added to the pulp; Waste products	Mechanical engineering	D21H17/01
Apparatus or processes for salvaging material from electric cables	Electrical engineering	H01B 15/00
Recovery of material from discharge tubes or lamps	Electrical engineering	H01J 9/52
Reclaiming serviceable parts of waste cells or batteries	Electrical engineering	H01M 6/52
Reclaiming serviceable parts of waste accumulators	Electrical engineering	H01M 10/54
Fertilisers from waste		
Fertilisers made from animal corpses, or parts thereof	Chemistry	C05F1
Fertilisers from distillery wastes, molasses, vinasses, sugar plant, or similar wastes or residues	Chemistry	C05F5
Fertilisers from waste water, sewage sludge, sea slime, ooze or similar masses	Chemistry	C05F7
Fertilisers from household or town refuse	Chemistry	C05F9
Preparation of fertilisers characterized by the composting step	Chemistry	C05F17
Incineration and energy recovery		

Solid fuels essentially based on materials of non-mineral origin; on sewage, house, or town refuse; on industrial residues or waste materials	Chemistry	C10L5/46-48
Cremation furnaces; Incineration of waste; Incinerator constructions; Details, accessories or control therefor	Electrical engineering	F23G5
Cremation furnaces; Incinerators or other apparatus specially adapted for consuming specific waste or low grade fuels	Electrical engineering	F23G7
Waste management – Not elsewhere classified		
Disposal of solid waste	Electrical engineering	B09B
Production of liquid hydrocarbon mixtures from rubber or rubber waste	Chemistry	C10G1/10
Medical or veterinary science; Disinfection or sterilising methods specially adapted for refuse	Instruments	A61L11

9.2 Appendix 2: patents divided in sectors

Table A2a

Overview of the distribution of patents in different industry sectors per country

		Industry Sector					
		Chemistry		Electrical engineering		Instruments	
		n	%	n	%	n	%
Country	China	8774	63,0%	126	0,9%	95	0,7%
	Czech Republic	204	63,4%	2	0,6%	2	0,6%
	Denmark	444	61,3%	7	1,0%	17	2,3%
	Estonia	20	54,1%	1	2,7%	0	0,0%
	Finland	63	72,4%	0	0,0%	2	2,3%
	France	697	65,1%	18	1,7%	20	1,9%
	Germany	3483	62,8%	101	1,8%	164	3,0%
	Greece	47	62,7%	0	0,0%	2	2,7%
	Hungary	72	54,1%	2	1,5%	2	1,5%
	Ireland	12	80,0%	1	6,7%	0	0,0%
	Italy	137	87,3%	2	1,3%	0	0,0%
	Japan	11235	61,8%	226	1,2%	333	1,8%
	Korea	6225	67,8%	179	2,0%	79	0,9%
	Latvia	23	76,7%	0	0,0%	0	0,0%
	Lithuania	14	51,9%	0	0,0%	2	7,4%
	Netherlands	110	67,1%	1	0,6%	4	2,4%
	Poland	478	62,0%	4	0,5%	7	0,9%
	Portugal	17	89,5%	0	0,0%	0	0,0%
	Spain	1927	67,9%	28	1,0%	67	2,4%
	Sweden	86	60,6%	3	2,1%	3	2,1%
	United Kingdom	366	68,3%	10	1,9%	16	3,0%
	United States	4185	62,8%	211	3,2%	256	3,8%
Total		38619	63,7%	922	1,5%	1071	1,8%

Table A2b
Overview of the distribution of patents in different industry sectors per country (continued)

		Industry Sector					
		Mechanical engineering		New technologies		Other fields	
		n	%	n	%	n	%
Country	China	1487	10,7%	3284	23,6%	163	1,2%
	Czech Republic	76	23,6%	31	9,6%	7	2,2%
	Denmark	232	32,0%	6	0,8%	18	2,5%
	Estonia	14	37,8%	2	5,4%	0	0,0%
	Finland	20	23,0%	1	1,1%	1	1,1%
	France	294	27,5%	0	0,0%	42	3,9%
	Germany	1611	29,1%	3	0,1%	181	3,3%
	Greece	16	21,3%	9	12,0%	1	1,3%
	Hungary	47	35,3%	6	4,5%	4	3,0%
	Ireland	2	13,3%	0	0,0%	0	0,0%
	Italy	18	11,5%	0	0,0%	0	0,0%
	Japan	2979	16,4%	2798	15,4%	602	3,3%
	Korea	1529	16,7%	861	9,4%	306	3,3%
	Latvia	5	16,7%	2	6,7%	0	0,0%
	Lithuania	9	33,3%	2	7,4%	0	0,0%
	Netherlands	45	27,4%	1	0,6%	3	1,8%
	Poland	158	20,5%	106	13,7%	18	2,3%
	Portugal	2	10,5%	0	0,0%	0	0,0%
	Spain	682	24,0%	51	1,8%	85	3,0%
	Sweden	36	25,4%	8	5,6%	6	4,2%
	United Kingdom	117	21,8%	1	0,2%	26	4,9%
	United States	1788	26,8%	0	0,0%	222	3,3%
Total		11167	18,4%	7172	11,8%	1685	2,8%

Table A2c
Overview of the distribution of patents in different industry sectors per country (continued)

		Total	
		n	%
Country	China	13929	100,0%
	Czech Republic	322	100,0%
	Denmark	724	100,0%
	Estonia	37	100,0%
	Finland	87	100,0%
	France	1071	100,0%
	Germany	5543	100,0%
	Greece	75	100,0%
	Hungary	133	100,0%
	Ireland	15	100,0%
	Italy	157	100,0%
	Japan	18173	100,0%
	Korea	9179	100,0%
	Latvia	30	100,0%
	Lithuania	27	100,0%
	Netherlands	164	100,0%
	Poland	771	100,0%
	Portugal	19	100,0%
	Spain	2840	100,0%
	Sweden	142	100,0%
	United Kingdom	536	100,0%
	United States	6662	100,0%
Total		60636	100,0%