Technological Forecasting & Social Change 152 (2020) 119887

Contents lists available at ScienceDirect

Technological Forecasting & Social Change

journal homepage: www.elsevier.com/locate/techfore

# Recycling of end-of-life vehicles: Assessing trends and performances in Europe

Idiano D'Adamo[a,b,*], Massimo Gastaldi[b], Paolo Rosa[c]

[a] Department of Law and Economics, Unitelma Sapienza – University of Rome, Viale Regina Elena 295, 00161, Roma, Italy
[b] Department of Industrial Engineering, Information and Economics, University of L'Aquila, Via G. Gronchi 18, 67100 L'Aquila, Italy
[c] Department of Management, Economics and Industrial Engineering – Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133, Milano, Italy

ARTICLE INFO

*Keywords:*
Circular economy
End-of-life vehicles
Gross domestic product
Sustainable recycling technologies
Waste management performance
Europe

ABSTRACT

End of Life Vehicles (ELVs) represent one of the most important waste streams in terms of volumes and material contents. During the last decades, they received attention from both researchers and industrial actors. However, there are still many knowledge gaps in terms of variables to predict future ELV volumes and trends. To this aim, the paper focuses on evaluating the potential correlation among European ELV flows (in terms of generated and recycled volumes) and two key variables (Gross Domestic Product (GDP) and population) through a linear regression model. Results show that an increase of 1000 GDP means +350 g of recycled ELVs and +10.7 kg of recycled ELVs per capita. Future values of both generated and recycled ELVs have been estimated in 2030, equal to 9.3 and 8.3 million tons, respectively. Here, a Likert scale provided by managers shows a priority of the economic side and the relation between the technological progress of the recycling plants and the adoption Circular Economy models. In addition, a comparison of European ELV flows clustered Member States' performances into three groups, with Bulgaria, Ireland and United Kingdom excelling among all European countries. Finally, some policy implications are presented at the end of the paper in terms of both the economic importance of the Likert scale and the relevance of a synergy between Circular Economy (CE) and technology.

## 1. Introduction

Technology and sustainability represent a central concern within both scientific and industrial contexts (Ogawa et al., 2017; Phillips, 2019). The integration of recycling technologies within the industrial context through the adoption of circular economy (CE) models represents an epochal challenge (Song et al., 2019). Therefore, the efficiency of waste management must be measured and inserted within a life cycle analysis (De Almeida and Borsato, 2019), in which the use of renewable resources is favoured (Sadik-Zada et al., 2018). The technological progress (e.g. under the form of the Industry 4.0 paradigm) has been demonstrated be positively related with the development of CE models (Despeisse et al., 2017; Rosa et al., 2019). Recycling is not considered the first solution in terms of waste hierarchy, but it is a technology able to perform the sustainable goals in several contexts (Banacu et al., 2019; Kirchherr et al., 2017).

Managing waste streams represents a global challenge towards sustainability (Gupta et al., 2019). Among them, ELVs are one of the most interesting topics (Zhou et al., 2019), both in terms of yearly generated volumes (Rosa and Terzi, 2018; Sakai et al., 2014), growth rates (Nykvist et al., 2019; Reuter et al., 2013), embedded valuable materials (D'Adamo et al., 2019; Rosa and Terzi, 2018), environmental issues (Chen et al., 2019; Onat et al., 2019) and illegal waste flows among European Union (EU) and extra-EU countries (Wang and Chen, 2013; Xiao et al., 2019). This way, during the last decades environmental regulations on ELV recycling & processing have become even more restrictive (Shankar et al., 2018), by influencing the technological development of both cars and waste processing technologies, with a final aim to push the adoption of the CE paradigm (Soo et al., 2019). The philosophy of CE suggests reuse, recycling and recovery operations for ELVs industry in order to improve energy-saving and resource exhaustion (Zhou et al., 2019).

Several authors proposed in literature new concepts in this sense, both in terms of more energy-efficient vehicles (Sato et al., 2019), innovative End of Life (EOL) strategies and business models (Andersson et al., 2019b) and sustainable waste management technologies (Amato et al., 2019; Oliveira et al., 2019). Indirectly, both the technological development and more restrictive environmental regulations fuelled a rapid increase in substitution rates of old cars (Chai et al., 2016; Despeisse et al., 2015). About this point, the experts

* Corresponding author at: Department of Law and Economics, Unitelma Sapienza – University of Rome, Viale Regina Elena 295, 00161, Roma, Italy.
*E-mail addresses:* idiano.dadamo@unitelmasapienza.it (I. D'Adamo), massimo.gastaldi@univaq.it (M. Gastaldi), paolo1.rosa@polimi.it (P. Rosa).

https://doi.org/10.1016/j.techfore.2019.119887
Received 2 November 2019; Received in revised form 11 December 2019; Accepted 17 December 2019

**Nomenclature**

| | |
|---|---|
| 3R | Reduce, Reuse, Recycle |
| AAGR | Average Annual Growth Rate |
| CE | Circular Economy |
| ELV | End of Life Vehicle |
| EoL | End of Life |
| EU | European Union |
| GDP | Gross Domestic Product |
| IT | Information Technology |
| MS | Member State |
| MSW | Municipal Solid Waste |
| OEM | Original Equipment Manufacturer |
| PPS | Purchasing Power Standard |
| WEEE | Waste from Electrical and Electronic Equipment |

focused their attention in developing refined models able to predict with an increasing level of precision ELV volumes to be managed. However, very few efforts have been done in improving estimation methods of future ELV flows, either by studying their correlation with other (quantitative) variables or comparing national ELV management performance through common indexes (Andersen et al., 2008; Ene and Öztürk, 2017; Hao et al., 2018; Hu and Kurasaka, 2013; Krapp et al., 2013; Lee et al., 2012; Tian et al., 2013). Existing literature has well addressed some topics, as recycling techniques, life cycle environmental impacts and life cycle costs, but in a separate manner. Hence, it is relevant to define the impact of costs, revenues, levels of greenhouse gas emissions for each recycling stage (Qiao et al., 2019).

Following these issues, this work wants to investigate the following aspects:

- RQ1: What type of correlation links ELV volumes (generated and recycled) with nation-related variables (e.g. GDP PPS - Purchasing Power Standard - and population)?
- RQ2: How to get alternative projections of ELV volumes in 2030?
- RQ3: How European countries' ELV management performance can be compared and ranked?
- RQ4: What is the role of ELVs within CE contexts?

Results obtained by a linear correlation will be compared to those calculated using both a standard mathematical parameter – the Average Annual Growth Rate (AAGR) – and a dynamic model proposed by (Rosa and Terzi, 2018). Historical data have been adopted to classify EU 28 Member States (MSs) proposing a comparison based on three indexes referred to the current amount of recycled ELV flows. The European average is considered as reference value and three groups of countries have been identified: i) high performer, ii) in-between and iii) low performer. Finally, considering that future growth of reused/recycled/recovered ELV streams can be encouraged through CE models, this work tries to investigate factors able to increase the circularity of ELV flows through a survey.

The paper is organized as follows: Section 2 presents the adopted methods (linear regression model and Likert scale). Section 3 shows trends and circularity of ELV flows, by proposing a discussion of the main findings. Section 4 presents some concluding remarks.

## 2. Materials and methods

This work tests the presence (or not) of a linear regression between ELV waste streams and economic (e.g. GDP PPS) and social variables (e.g. population). Considering recycling (i.e. the process of converting wasted products into new materials (Amankwah-Amoah, 2016) as reference method, the analysis has been conducted on two different perspectives:

- Generated ELVs
- Recycled ELVs

This section is structured as follows. Section 2.1 describes the linear regression model, useful to provide a response to RQ1. In addition, other parameters are proposed with the final goal of defining a valid estimate of future ELV flows in 2030 (see RQ2). Section 2.2 proposes input data referred to several EU countries and Section 2.3 defines a unique value where three indicators are grouped (see RQ3). A survey (based on the Likert scale) conducted among managers is presented in Section 2.4, with the aim to illustrate some practical implications to adopt in the automotive sector towards the development of CE models (see RQ4).

### 2.1. Mathematical models for future trends estimation

Linear regression is a basic type of regression useful for conducting a predictive analysis. The most common form of linear regression is the least squares fitting and the coefficient of determination ($R^2$) – defining the goodness of fit of the model (Umrao et al., 2018). In addition, the statistical significance of the data is verified. To this aim, the *F*-Test Two-Sample for Variances tool tests the null hypothesis that two samples come from two populations having the equal variances. It is verified when *F* value ($F$) is greater than *F* critical value ($F_{crit}$). The probability that $F$ is lower than $F_{crit}$ under the null hypothesis is quantified by a *p*-value ($P$) (Mudd et al., 2014; Soava et al., 2018). The model is well developed in literature (Awasthi et al., 2018; Jamin et al., 2019). GDP PPS and population represent the dependent variables, while generated ELV and recycled ELV are independent variables. Historical data do not capture possible trends determined by greater awareness towards environmental challenges. This way, a correction coefficient is introduced comparing the growth of both generated and recycled ELV flows. To this aim, the use of AAGR can be suitable (Gu et al., 2018). In addition, this mathematical variable can be used to estimate directly the future streams of ELV flows. Finally, by applying dynamic simulation models (e.g. System Dynamics (SD)-based ones) a real-time comparison of several configurations (scenarios) of the ELV recovery chain can be implemented.

### 2.2. Input data

The set of data points is defined by statistical values proposed by Eurostat. The use of this database is widely justified in literature (Busu, 2019; Mehedintu et al., 2018). Typically, input data have a grade of uncertainty and their non-homogeneity can determine values not reliable. For this motive, we use a unique source of reference (Eurostat, 2019):

- GDP PPS [*Economy and finance → National accounts → Annual* *national accounts → Main GDP aggregates*] – Tables A1-A2.

- Population [*Population and social conditions → Demography and migration → Population change – Demographic balance and crude rates at national level*] – Tables A3-A4.
- Generated ELV *[Environment and energy → Environment → Waste → Waste streams → End-of-life vehicles - reuse, recycling and recovery, totals]* – Tables A5-A6.
- *Recycled ELV [Environment and energy → Environment → Waste → Waste streams → End-of-life vehicles - reuse, recycling and recovery, totals]* – Tables A7-A8.

The EU is composed by 28 MSs. Consequently, 28 is the number of alternatives compared in this work. Regarding the period of reference, we have considered all years currently available in Eurostat from 2006 to 2016. Each data set is composed by 308 potential values. However, there are 17 missing data concerning Croatia, Malta, Netherlands, Romania and Slovenia. Consequently, the effective number of data points analyzed in this work is equal to 291 (regarding generated ELV, while it is equal to 290 for recycled ELV because there is also a missing data for Sweden).

Directive 2000/53/EC on ELVs aims to favor their reuse, recycling and other forms of recovery (practices environmentally friendly) to reduce the final disposal of waste. No later than 1 January 2015, it fixes the following targets - reusable and/or recyclable to a minimum of 85% by weight per vehicle and reusable and/or recoverable to a minimum of 95% by weight per vehicle – Table 1.

### 2.3. Recycled ELV flows-based indexes

The use of historical data allows to define future trends of ELV flows. The solidity of results is confirmed by the homogeneity of sources (Eurostat) for all input data. This work focused on four variables: i) generated ELV flows; ii) recycled ELV flows; iii) GDP PPS and iv) population. By analyzing Eurostat, three indexes are proposed according to the existing literature (Andersson et al., 2019a; D'Adamo and Rosa, 2019):

- Percentage of recycled ELV flows out of generated ones.
- Percentage of recycled ELV flows on GDP PPS.
- Percentage of recycled ELV flows on population.

Input data proposed in Section 2.2 refer to these indexes, but absolute values change significantly from country to country. This way, it is necessary to normalize them. The ratio between absolute values and population represents a solution to this issue (Antonopoulos et al., 2014). This is performed initially by identifying a maximum and minimum value for each index and, subsequently, the remaining 26 values are defined as intermediate varying from 0 (minimum) to 1 (maximum). The aggregation of three indexes in a single value can be done by hypothesizing a weight for each of them. This work hypothesizes that three indexes have the same relevance. However, further analyses could assess this limit (Cucchiella et al., 2017).

### 2.4. A Likert scale-based survey

The previous sub-sections are based on historical data useful to estimate future trends and propose a comparison among 28 MSs. This work focuses on ELVs. The attention is given to recycling, a good solution for the experts to improve the environmental challenge favouring the circularity of materials employed in vehicles. At the same time, the perception of managers can provide new aspects to assess. Here, a survey is conducted in order to define strategic aspects of ELV management.

The survey method was selected in order to collect information in an efficient, general and versatile way (Schutt, 2018). The final aim is analysing barriers and opportunities faced by companies when adopting CE models (Ormazabal et al., 2018). A common method exploited in literature for making surveys is the Likert scale, or a five-point agreement scale (where 1 = totally disagree, 2 = disagree, 3 = neither agree or disagree, 4 = agree and 5 = completely agree) (Fonseca et al., 2018).

The questionnaire is structured in 15 items where all questions require a response on a 5-point Likert scale. . The choice of interviewees was based on experts involved in research projects funded by public funds (e.g. European Horizon 2020 projects), with long-term expertise in ELVs management and employed in the automotive sector. In fact, the number of years of expertise was been used as a constraint, in which almost a period of 10 years was required (Falcone and Imbert, 2018). Subsequently, it was sent an e-mail of invitation and ten positive responses have been received. Experts have been interviewed through individual Skype video calls (from March to April 2019) and each interview lasted one hour on average. The years of experience of respondents are reported in Table 2 and the list of questions is reported in Table 3. A similar approach used in the automotive sector was defined according to the literature (Förster, 2015; Gopal and Thakkar, 2016).

## 3. Results

This section provides main findings. Section 3.1 defines the linear correlation between ELV flows, GDP PPS and population. Section 3.2 shows future projections of ELV flows in Europe towards 2030. Section 3.3 examines the current situation in Europe, by proposing a ranking of countries. Finally, Section 3.4 provides the role of ELV flows within CE models, by defining some practical solutions.

### 3.1. Correlating ELV flows with GDP PPS and population

Starting from assumptions defined in Section 2.1 and input data proposed in Section 2.2, results of a regression model are proposed as follows:

**Table 1**
ELV streams in Europe (tons) – year 2016.

| Countries | Generated ELV | Reused and recycled ELV | Recycled ELV |
|---|---|---|---|
| Austria | 45,338 | 39,536 | 34,017 |
| Belgium | 119,188 | 109,713 | 93,971 |
| Bulgaria | 92,111 | 87,101 | 84,823 |
| Croatia | 18,912 | 17,755 | 17,668 |
| Cyprus | 5094 | 4601 | 2965 |
| Czechia | 139,881 | 126,354 | 120,177 |
| Denmark | 100,957 | 89,616 | 77,020 |
| Estonia | 14,113 | 12,112 | 9807 |
| Finland | 123,273 | 102,061 | 95,151 |
| France | 1103,927 | 959,361 | 845,917 |
| Germany | 420,113 | 375,234 | 358,320 |
| Greece | 45,570 | 45,984 | 33,174 |
| Hungary | 12,527 | 11,953 | 8569 |
| Ireland | 104,105 | 89,565 | 88,851 |
| Italy | 1086,425 | 896,097 | 775,067 |
| Latvia | 8253 | 7781 | 7000 |
| Lithuania | 27,752 | 26,334 | 18,563 |
| Luxembourg | 2063 | 1781 | 1752 |
| Malta* | 4803 | 3730 | 3277 |
| Netherlands* | 196,215 | 168,919 | 121,603 |
| Poland | 395,216 | 372,639 | 317,366 |
| Portugal | 84,473 | 70,494 | 67,257 |
| Romania* | 38,851 | 33,077 | 31,794 |
| Slovakia | 34,822 | 33,478 | 32,395 |
| Slovenia* | 5960 | 5411 | 4928 |
| Spain | 642,514 | 548,824 | 436,748 |
| Sweden | 240,697 | 208,770 | 173,694 |
| United Kingdom | 1246,447 | 1076,843 | 1049,018 |
| EU 28 | 6359,600 | 5525,124 | 4910,892 |

* Data in 2016 are not available. We have used the value referred to the previous year.

**Table 2**
Summarized list of participants from selected countries.

| N° | Role | Country | No. years |
|---|---|---|---|
| 1 | Environmental manager | Germany | 23 |
| 2 | Operations manager | Italy | 16 |
| 3 | R&D manager | China | 11 |
| 4 | Plant manager | France | 18 |
| 5 | Marketing manager | Japan | 16 |
| 6 | Chief Executive Officer | Germany | 12 |
| 7 | Operations manager | Italy | 18 |
| 8 | Plant manager | China | 19 |
| 9 | Account manager | France | 11 |
| 10 | Environmental manager | Japan | 19 |

- ELV flows (both generated and recycled ones) and GDP PPS - Fig. 1.
- ELV flows (both generated and recycled ones) and population – Fig. 2.
- ELV flows (both generated and recycled ones) per capita and GDP PPS per capita – Fig. 3.

Results show a linear correlation between ELV volumes (variable $y$) and GDP PPS (variable $x$). They define that an increase of 1 GDP PPS means an additional 0.46 g of generated ELV ($y = 0.4615 \times x$) and 0.35 g of recycled ELV ($y = 0.3547 \times x$). Constant rates are not considered because their value is not significant evaluating the dimensional scale of both dependent and independent variables. Regarding generated ELV and GDP PPS, $R^2$ is equal to 0.714 (that is 71.4% of values fits the regression model). Concerning recycled ELV and GDP PPS, 73.5% of the dependent variable ($y$-value) is explained by the independent variable ($x$-value).

The study of relations between ELV volumes (variable $y$) and population (variable $x$) provides values of $R^2$ greater than the previous ones (0.751 and 0.766, respectively). Here, an increase of 14.0 kg of generated ELV ($y = 0.014 \times x$) and 10.7 kg of recycled ELV ($y = 0.0107 \times x$) can be gathered from each additional citizen.

Finally, it is verified also a linear correlation between ELV volumes per capita (variable $y$) and GDP PPS per capita (variable $x$). Here, $R^2$ values are equal to 0.715 and 0.739, respectively. Results show that an increase of 0.46 g of generated ELV per capita for 1 GDP PPS per capita ($y = 0.461 \times x$) and 0.71 g of recycled ELV per capita for 1 GDP PPS per capita ($y = 0.715 \times x$).

In order to give solidity to results, $F$-test analysis has been conducted for all the combinations of variables - Table A9. The statistical significance of the model is verified because $F$ value is always greater than $F_{crit}$ value. Here, we assumed a level of significance equal to 0.05 and $p$-values are significantly low.

Certainly, the linear regression is useful for estimating future trends

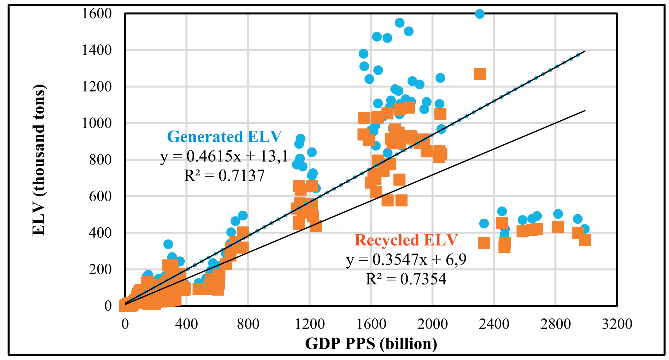


**Fig. 1.** Correlation between generated ELV (or recycled ELV) and GDP PPS.

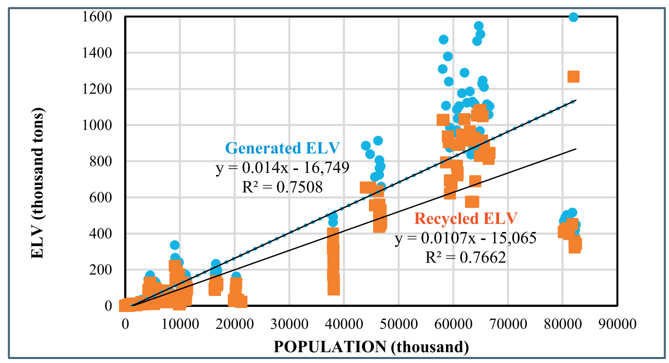


**Fig. 2.** Correlation between generated ELV (or recycled ELV) and population.

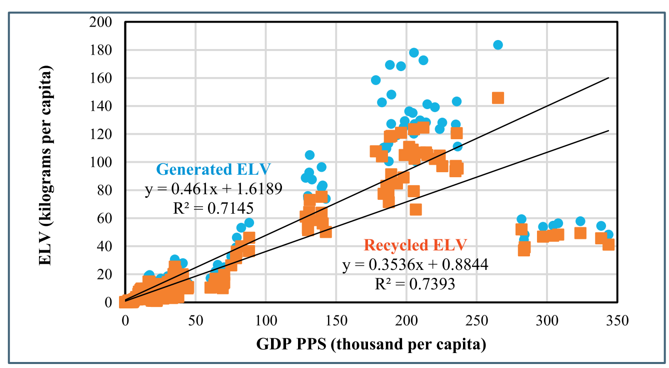


**Fig. 3.** Correlation between generated ELV per capita (or recycled ELV per capita) and GDP PPS per capita.

**Table 3**
The list of questions used during the survey.

| ID | Question | Likert scale 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| Q1 | How much is important avoiding landfill costs? | | | | | |
| Q2 | How much are important economic aspects? | | | | | |
| Q3 | How much are important environmental aspects? | | | | | |
| Q4 | How much are important social aspects? | | | | | |
| Q5 | How much are important EOL strategies during vehicle's design? | | | | | |
| Q6 | How much are important ELV recycling processes? | | | | | |
| Q7 | How much is relevant the EU ELV directive? | | | | | |
| Q8 | How much should be relevant to have a global ELV regulation? | | | | | |
| Q9 | Do you think that directives can support CE practices? | | | | | |
| Q10 | How much is important to have standard methods for quantifying illegal ELV volumes? | | | | | |
| Q11 | Do you think that investments in innovative ELV recycling process could offer better opportunities than current plants? | | | | | |
| Q12 | How much is important a collaboration between companies and universities within the ELV management sector? | | | | | |
| Q13 | How much is important the technological progress? | | | | | |
| Q14 | How much is important the technological progress towards environmental practices? | | | | | |
| Q15 | How much is relevant the estimation of ELV streams? | | | | | |

of wastes (Awasthi et al., 2018; Beigl et al., 2008; Kusch and Hills, 2017; Vujić et al., 2015), but several studies focused on other flows. To this aim, the work is useful not only to confirm the role of ELVs within environmental challenges, but also to support the definition of future trends. Some authors underlined as the linear regression is not a complex model, but a suitable value of $R^2$ indicates that a consistent percentage of values fits the regression analysis (Abdulredha et al., 2018; Qian et al., 2018).

A direct comparison with existing literature is not possible because in some cases the Chinese context is analyzed (Hao et al., 2018; Hu and Kurasaka, 2013; Tian et al., 2013), while in other cases European countries are referred to old data (Andersen et al., 2008) or only a single country is evaluated (Ene and Öztürk, 2017). Other works investigate the management of vehicles within the entire manufacturing process (Krapp et al., 2013; Lee et al., 2012). However, ELV volumes are significantly increased in the last years. This trend determined a significant change in statistical terms. From one side, governmental initiatives pushed EU countries to move towards environmental friendly solutions (Andersson et al., 2019a). At the same time, this way of doing determined the evolution of the concept of waste as a resource (Xu et al., 2019). Similar results have been proposed in other works, but referring to either Waste from Electrical and Electronic Equipment (WEEE) (Awasthi et al., 2018; Kusch and Hills, 2017) or Municipal Solid Waste (MSW) (Beigl et al., 2008; Vujić et al., 2015).

### 3.2. Future projections of European ELV flows

The definition of a linear correlation between some variables is useful to estimate future projections. Alternative approaches are used in this work to estimate future values in 2030 – Table 4. The first one is based on AAGR, which is equal to 1.7% and 2.8% for generated and recycled ELVs, respectively. For example, if the initial value of generated ELV is equal to 6359,600 tons in 2016, the hypothesized value in 2030 is 8052,359 tons (obtained as product between 6467,713 and $1.017^{14}$). Other three approaches are based on relationships previously defined in Figs. 1-3. The first step quantifies the future estimates of both GDP PPS and population in 2030 and starting by these inputs it is possible to obtain the values of ELV streams. For this aim, the initial value of analysis is 512,379,225 habitants in 2018 and 15,389,256 million GDP PPS in 2017. Their future estimates are referred to AAGR, which is equal to 0.3% and 2.1% for population and GDP PPS, respectively. The following values are obtained in 2030: GDP PPS is equal to 20,162,866 million and population is equal to 531,132,295. For example, $y = 0.4615 \times x$ shows the relationship between generated ELV (variable $y$) and GDP PPS (variable $x$). The hypothesized value in 2030 is equal to 9305,163 tons (obtained as product between 20,162,866 and 0.4615). A previous research (Awasthi et al., 2018) has underlined the limit of this static approach, in fact it is not able to intercept the growing attention towards environmental practices maintaining constant the percentage of recycled ELVs. In this way, this work proposes a corrective coefficient able to provide a dynamic aspect and this coefficient is calculated as difference between AAGR of recycled ELVs and one of generated ELVs (equal to 1.1%). For example, the estimate of recycled ELVs is equal to 7151,769 tons in 2030 (obtained as product between 20,162,866 million and 0.3547) in absence of corrective coefficient. In its presence, it will become equal to 8335,461 tons (obtained as product between 7151,769 and $1.011^{14}$). Finally, the input used in this work are inserted in the dynamic model proposed by (Rosa and Terzi, 2018). It can provide a simulation on future ELVs streams based on both old and new vehicles. The number of generated ELVs is equal to 9252,100 tons and the percentage of recycled ELVs corresponds to about 89%.

The analysis of results shows as the final value is strictly associated to the parameter of reference. Values vary significantly, but it is possible to define a range more restrict. In fact, future estimates, calculated in function of linear correlation with both GDP PPS and per capita, have identified a value of about 9.3 million tons of generated ELVs. This data is confirmed by the dynamic model where GDP directly influences both the production of new cars and their selling rate. It is greater than value associated to the AAGR of generated ELVs because the AAGR of GDP PPS presents an increase more consistent (2.1% vs 1.7%). At the same time, the low AAGR of population (0.3%) does not determine a significant increase of ELVs streams. The percentage of recycled ELVs in comparison to generated ones is equal to 77% in 2016 and a hypothetical 89% is estimated in 2030. A value of about 8.3 million tons of recycled ELVs is defined in three scenarios and this data is justified from a mathematical perspective because a corrective coefficient is used, and the dynamic model supports this finding. In addition, the sustainable goals push towards a minimization of ELV streams conferred in landfill avoiding dangerous environmental issues.

### 3.3. A comparison of European countries' ELV performance

European Directive regards the percentage of reused and recycled materials by weight per vehicle, but the system requires the analysis of multiple perspectives (Halkos and Petrou, 2019). This work proposes three indicators to evaluate the European countries considering all dimensions (environmental, economic and social) of sustainability – Table 5. The last year available in Eurostat (2016) is used as period of reference and three indicators are considered according to results obtained in Section 3.1.

These indicators have the same numerator (the amount of recycled ELV flows), but the performance of the single MSs changes significantly. An increase of GDP PPS or population determines a reduction of the indicators recycled ELVs for GDP PPS or for capita, respectively. However, the analysis defined in Section 3.1 identifies a relationship between these variables. Consequently, when the increase of recycled ELVs is more significant than one associated to GDP PPS (or population), it follows also an increase of the above-cited indicators.

Regarding recycled ELVs, Croatia occupies the first position with 93.4% followed by Slovakia and Bulgaria that have a percentage greater than 92%. The number of MSs with a percentage greater than the European average (77.2%) is equal to 14. Concerning recycled ELVs/GDP PPS, Bulgaria has the best performance with 839 kg/million and this value is significantly greater than European average equal to 328 kg/million. Finland and United Kingdom exceed 500 kg/million and 12 MSs have a value greater than EU 28. Finally, Ireland occupies the first position with 18.8 kg/capita followed by Sweden and Finland that have a value greater than 17 kg/capita. For this indicator, the number of MSs with a value greater than European average (9.6 kg/capita) is 9.

The value of single indicators must be normalized. It is necessary to de-couple the performance of MSs from the size of their population (Antonopoulos et al., 2014). For example, Croatia (93.4%) assumes the first position when the percentage recycled ELVs is considered and a value of 1 is associated to this country. Instead, the last position is occupied by Cyprus with 58.2% and this determines a value of 0. Finally, other 26 MSs have a value that ranges from 0 to 1. An example can be represented by Austria (75.0%), which has a value of 0.48 (obtained as ratio between two differences (0.750–0.582 and 0.934–0.582)).

The following step is represented by the definition of relevance

**Table 4**
European future projections of ELV streams in 2030 (tons).

| Parameter | Generated ELVs | Recycled ELVs |
|---|---|---|
| Average annual growth rate | 8052,359 | 7228,763 |
| Linear correlation GDP PPS | 9305,163 | 8335,461 |
| Linear correlation population | 7435,852 | 6623,731 |
| Linear correlation per capita | 9295,081 | 8309,611 |
| Dynamic model | 9252,100 | 8262,565 |

**Table 5**
Performance of recycled ELV streams in 2016.

| Countries | Percentage recycled ELVs (%) | Recycled ELVs/ GDP PPS (kg/ million) | Recycled ELVs/ Capita (kg/capita) |
|---|---|---|---|
| Austria | 75.0 | 104 | 3.9 |
| Belgium | 78.8 | 241 | 8.3 |
| Bulgaria | 92.1 | 839 | 11.9 |
| Croatia | 93.4 | 237 | 4.2 |
| Cyprus | 58.2 | 142 | 3.5 |
| Czechia | 85.9 | 444 | 11.4 |
| Denmark | 76.3 | 365 | 13.5 |
| Estonia | 69.5 | 332 | 7.5 |
| Finland | 77.2 | 544 | 17.3 |
| France | 76.6 | 414 | 12.7 |
| Germany | 85.3 | 120 | 4.4 |
| Greece | 72.8 | 155 | 3.1 |
| Hungary | 68.4 | 45 | 0.9 |
| Ireland | 85.3 | 362 | 18.8 |
| Italy | 71.3 | 450 | 12.8 |
| Latvia | 84.8 | 190 | 3.6 |
| Lithuania | 66.9 | 294 | 6.4 |
| Luxembourg | 84.9 | 39 | 3.0 |
| Malta | 68.2 | 258 | 7.3 |
| Netherlands | 62.0 | 191 | 7.2 |
| Poland | 80.3 | 414 | 8.4 |
| Portugal | 79.6 | 288 | 6.5 |
| Romania | 81.8 | 93 | 1.6 |
| Slovakia | 93.0 | 265 | 6.0 |
| Slovenia | 82.7 | 99 | 2.4 |
| Spain | 68.0 | 352 | 9.4 |
| Sweden | 72.2 | 490 | 17.6 |
| United Kingdom | 84.2 | 511 | 16.0 |
| EU 28 | 77.2 | 328 | 9.6 |

**Table 6**
The European map of ELV flows in 2016.

| Groups | Countries | Value |
|---|---|---|
| High performer | Bulgaria | 0.858 |
| | Ireland | 0.725 |
| | United Kingdom | 0.725 |
| | Finland | 0.696 |
| | Sweden | 0.632 |
| | Czechia | 0.626 |
| In-between | France | 0.550 |
| | Denmark | 0.541 |
| | Slovakia | 0.519 |
| | Italy | 0.517 |
| | Poland | 0.505 |
| | Croatia | 0.478 |
| | EU 28 | 0.463 |
| | Belgium | 0.418 |
| | Portugal | 0.411 |
| | Spain | 0.381 |
| | Latvia | 0.365 |
| | Germany | 0.355 |
| | Estonia | 0.351 |
| Low performer | Malta | 0.305 |
| | Luxembourg | 0.293 |
| | Lithuania | 0.291 |
| | Slovenia | 0.285 |
| | Romania | 0.260 |
| | Austria | 0.243 |
| | Greece | 0.227 |
| | Netherlands | 0.216 |
| | Hungary | 0.099 |
| | Cyprus | 0.092 |

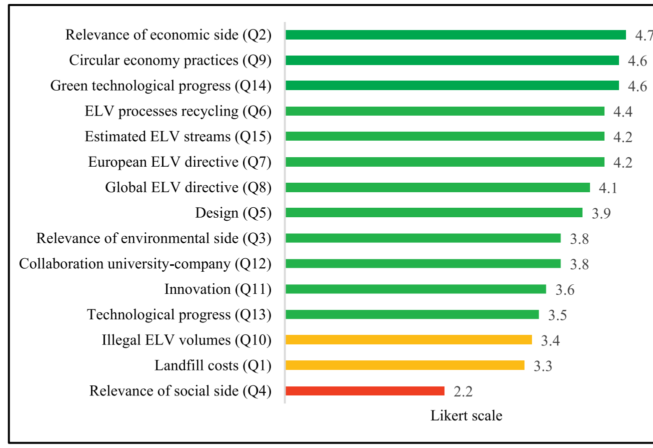


**Fig. 4.** Outlining the findings based on ``The Likert scale'' method.

associated to each indicator. In fact, it is necessary to assign a weight to them in order to have a unique value of analysis. This work has estimated an equal weight. Finally, it is appropriate to define a range as a reference to provide consistency to the analysis. A hypothetical interval surrounding the EU average (i.e. from - 0.10 to 0.10) is considered for this specific work. Countries are subdivided into three groups (Table 6) in function of the EU 28 equal to 0.463:

- ``High performer'', composed by six MSs that have almost a value equal to 0.563.
- ``In-between'', composed by twelve MSs that have a value that varies from 0.363 to 0.563.
- ``Low performer'', composed by ten MSs that have a value lower than 0.363.

The analysis of results shows as the six virtuous countries have a different situation considering the percentage of recycled ELV flows. From one side, Bulgaria, Ireland, United Kingdom and Czechia have a value greater than EU 28, while Finland and Sweden have an opposite situation. This result has a well-known motivation. Typically, western EU MSs export ELV streams to eastern EU MSs (and to countries outside the Europe), and the recycling process is developed in these territories. This drives up recycling rates per capita (and per unit of GDP) in these import states, whereas it tends to lower these rates in the export states. This explains that countries such as Czechia, Croatia, Slovakia and Bulgaria have high values of recycled ELV flows in comparison to generated ones. Currently, there are no studies able to estimate these streams and this study underlines as this aspect is extremely relevant and the European policy makers are responsible to provide a valuable solution.

### *3.4. The role of circular economy in ELV management and policy implications*

The literature has already demonstrated as the adoption of CE models within the ELV sector allows an increase in terms of sustainability performances (Sato et al., 2019; Zhou et al., 2019). Given the great amount of ELVs generated yearly in Europe, the adoption of circular practices within the automotive reverse logistic chain could help in improving its sustainability level in several ways. Responses of the Likert scale of the interviewees are collected and reported in Table A10 (for privacy reasons, numbers linked to each respondent in this Table are not specular to one reported in Table 2). All interviewees have the same relevance and consequently, an average value for each question is obtained – Fig. 4.

Results shows clearly as the economic perspective is considered strategic to favor the development of recycling process of ELVs streams. It is one of three criteria classified as ``strongly agree'' basing on the Likert scale. In fact, seven of ten experts have assigned a value of 5 to the Q2. Generally, all interviewees have provided almost one ``completely agree'' and in the overall analysis there are thirty-six cases in which the value of 5 is been attributed (about 24%). In addition to the Q2, there are some ``completely agree'' for the following questions: Q14 (6 cases), Q9 (6 cases), Q7 (4 cases), Q6 (4 cases), Q15 (4 cases), Q5 (3 cases) and Q8 (2 cases). Instead, the judgement ``totally disagree'' is absent in the responses.

The weight of the reduction of landfill costs is considered not decisive to implement recycling activities. For the category of managers, the implementation of these projects are interesting when not only a cost is avoided, but there is the opportunity to create a value-added (through the recovery of precious materials, and in particular gold, palladium and rare earths). For this motive, the role of Directives towards the success of the realization of CE models is defined strategic based on the assessment of ``agree'' provided by the Likert scale. The experts have preferred to use mainly this judgement (about 51%). Interviewees consider that the current ELV directive does not push towards the CE practices and a gear shift is necessary. In their opinion, the Directives have a primary role towards the minimization of waste conferred in landfill favoring techniques of reuse and recycling. At the same time, the European ELV Directive has a weight greater than global one and this depends probably because this work is based on the European context. However, this aspect must be monitored because it is possible to create market distortions. This issue is widely discussed by experts due to the absence of the transparency in some ELV flows. Currently, the number of illegal streams cannot be estimated. At the same time, the definition of ELV streams is the key-variable to define recycling plant size and managers are extremely interested to know its estimation. The technological side is considered ``completely relevant'' if oriented to implement green practices. In absence of this characteristic, its assessment is lower (3.5 vs 4.6). Consequently, the technological progress oriented to favor the development of CE models can play a vital role. In fact, the circularity is considered ``completely relevant''. In addition, recycling processes have a relevance slightly lower because the experts consider also other potential green EoL options (e.g. reuse) suitable to minimize the environmental impact. The relevance of CE models has underlined the relevance to study the whole life cycle of vehicles. For this aim, the design can be suitable to perform the consumers' demand, but also oriented to simplify its EoL management. In this way, the presence of harmful and toxic substances can be reduced. The relevance of the environmental side is lower than economic one, because the experts involved in this work consider as the preservation of the environment is strictly linked to the opportunities to use/recovery natural resources. It is the basis of the concept of CE model. Towards this direction, the innovation in recycling processes and their flexibility to manage more typologies of waste permits to exploit the advantages of economies of scale and to reduce the environmental impact associated to the transport of these streams. The opportunities provided by public funds is an occasion to create synergies providing an exchange of skills and ideas. Finally, the last pillar of sustainability represented by social side is associated to the assessment of ``disagree'' based on the Likert scale. This probably depends by the nature of experts (all have a technical profile) and this could be a limit of the current work. The social side must be incorporated within analysis of life cycle of products (Wang et al., 2018).

At the same time, the survey is not been limited to provide a value. In fact, all experts are been invited to provide solutions to implement CE practices within the automotive sector and the main solutions are reported as follows:

- The significant amount of valuable resources that are still landfilled (or lost) each year during the recovery process with huge economic and environmental losses for the worldwide society could be recovered and re-introduced in the value chain. The EoL responsibility is considered necessary towards this goal.
- Original equipment manufacturers (OEMs) designing components and selecting materials embedded into new cars could proceed in a more sustainable way, by directly easing also the reverse manufacturing process. This action could be stimulated in order to increase the number of green cars.
- Worldwide regulations dedicated to ELVs could better push reverse logistics actors in investing in dedicated recovery plants for valuable materials. It is necessary to check that regulations are not applied only to some countries.
- Current material recovery technologies could finally reach higher performance levels required by even more stringent ELV management directives. It is opportune to intensify the monitoring and control phases, by penalizing incorrect behaviors.
- Connections and collaboration among the actors involved in the ELV reverse logistics chain could be improved, by reducing illegal exports of ELVs in developing countries. The development of IT codes, if products presents harmful or toxic substances, can attenuate this phenomenon.
- Materials recovery plants could become more flexible and able to better exploit economies of scale. For this scope, the bureaucratic phases need to be streamlined.
- The use of renewable energies in all manufacturing and recycling process. The growth of renewables has been supported by subsidies and it is necessary to increase the cost of carbon dioxide in order to penalize the use of fossil fuels.

## 4. Conclusions

ELVs are one of the most important sources of waste globally. Several attempts have been done for predicting their volumes, controlling their generation and managing recycling efficiently. However, very limited works define the correlation among ELV amounts and GDP of nations. Therefore, the intent of this paper was assessing this relation through a linear regression method. Current analysis opens the way for considering both other (more sophisticated) methods and other sets of variables for assessing this type of relations and comparing performances. On the basis of three indicators (percentage recycled ELVs, the ratio between recycled ELVs and GDP PPS and the ratio between recycled ELVs and population) and considering only historical data in 2016, there are six countries that can be classified as ``high performer'': Bulgaria, Ireland, United Kingdom, Finland, Sweden and Czechia. Results suggest a good relation of both generated and recycled ELVs with two variables: i) GDP PPS and ii) population. In this way, it is possible to estimate future trends towards 2030 in Europe. Several approaches provide the same result: about 8.3 million tons of recycled ELVs with a percentage rate equal to 89% (+12% than 2016). This study confirms as Europe can move towards practices of environmental protection. A great limit is represented by the economic opportunities that are not verified for all components of automotive sector according to the opinion of experts involved in our analysis. At the same time, findings obtained by the Likert scale underline four relevant aspects: i) exploring economic opportunities providing models useful to intercept alternative business models; ii) favoring the development of CE practices through a reduction of both energy and materials used in the manufacturing process and with a valid EoL strategy (as the recycling), iii) the technological progress is able to provide solutions to climate change if oriented to implement green practices and iv) the key-role of Directives able to push producers to give attention to all phases of life cycle of products. In this way, a sustainable supply-chain can be developed on the basis to improve environment, to adopt 3R (reduce/reuse/recycle) strategy and to minimize energy consumption. These green initiatives can create economic opportunities. This could determine a greater interest to collect this typology of waste. In this way, a reduction of illegal flows could be obtained, but the Likert Scale identifies the relevance of Directives that must be uniformed. Finally, the dialogue between industry and research within projects funded by the European Commission is pushing towards real and applicable solutions to this problem, by providing a good support not only in terms of environmental and economic aspects, but also social ones. Citizens have great attention towards the technological progress and recycling plants require a social challenge. Not only the concept of waste is assumed as a resource, but the same citizens can ask to policy actors to favour actions in which the implementation of recycling infrastructures is actuated. In this way, social phenomena as Not in My Back Yard and Not in My Term of Office could be significantly reduced. Future directions of research can analyse the global context, because there are some new markets in which the selling of vehicles present a significant growth and the presentation of specific case studies in which the three pillars of sustainability applied to the recycling process are presented.

## Acknowledgements

The authors want to thank Dr. Abhishek Kumar Awasthi and Prof. Jinhui Li (Tsinghua University) who actively contributed in developing this work.

## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.techfore.2019.119887.

## Appendix

.

**Table A1**
GDP PPS in the European countries from 2006 to 2011 (million) - Source (Eurostat, 2019).

| Countries | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| Austria | 257,526 | 269,357 | 271,707 | 259,717 | 268,855 | 281,429 |
| Belgium | 308,982 | 322,949 | 322,755 | 312,120 | 333,962 | 343,801 |
| Bulgaria | 71,187 | 79,614 | 84,844 | 80,099 | 84,523 | 86,906 |
| Croatia | 62,147 | 68,695 | 70,968 | 65,604 | 65,023 | 67,039 |
| Cyprus | 18,640 | 20,772 | 21,649 | 20,827 | 21,094 | 21,307 |
| Czechia | 201,548 | 221,791 | 228,507 | 219,218 | 221,779 | 228,036 |
| Denmark | 167,887 | 175,437 | 179,203 | 169,446 | 182,557 | 186,612 |
| Estonia | 21,471 | 24,273 | 23,948 | 20,811 | 21,991 | 24,579 |
| Finland | 149,820 | 164,372 | 167,829 | 153,603 | 158,997 | 165,383 |
| France | 1708,230 | 1798,738 | 1785,431 | 1707,061 | 1786,549 | 1845,707 |
| Germany | 2335,015 | 2471,730 | 2467,672 | 2307,544 | 2452,459 | 2585,555 |
| Greece | 260,177 | 266,762 | 270,130 | 256,526 | 239,571 | 219,010 |
| Hungary | 152,554 | 157,736 | 164,042 | 157,433 | 164,803 | 171,836 |
| Ireland | 156,402 | 169,559 | 157,112 | 143,564 | 151,081 | 155,277 |
| Italy | 1556,208 | 1637,590 | 1645,854 | 1551,330 | 1588,109 | 1628,296 |
| Latvia | 28,931 | 32,883 | 33,436 | 27,481 | 28,186 | 30,726 |
| Lithuania | 44,621 | 50,861 | 52,430 | 43,654 | 47,621 | 52,211 |
| Luxembourg | 30,502 | 33,229 | 33,477 | 31,149 | 33,215 | 35,980 |
| Malta | 7792 | 8346 | 8474 | 8201 | 8822 | 8977 |
| Netherlands | 554,461 | 592,780 | 603,285 | 560,276 | 572,707 | 586,861 |
| Poland | 478,095 | 527,510 | 551,691 | 558,494 | 612,791 | 656,187 |
| Portugal | 214,783 | 223,407 | 222,203 | 212,744 | 220,962 | 213,305 |
| Romania | 202,545 | 235,597 | 272,384 | 257,705 | 262,888 | 272,197 |
| Slovakia | 83,908 | 93,765 | 100,715 | 94,471 | 102,994 | 105,219 |
| Slovenia | 42,801 | 45,922 | 47,322 | 42,625 | 43,488 | 44,611 |
| Spain | 1132,659 | 1215,277 | 1215,239 | 1142,116 | 1137,885 | 1130,868 |
| Sweden | 281,612 | 306,359 | 305,315 | 280,740 | 298,794 | 312,304 |
| United Kingdom | 1740,677 | 1789,848 | 1779,176 | 1646,776 | 1729,835 | 1757,243 |

**Table A2**
GDP PPS in the European countries from 2012 to 2016 (million) - Source (Eurostat, 2019).

| Countries | 2012 | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|---|
| Austria | 295,984 | 298,529 | 307,427 | 323,901 | 328,330 |
| Belgium | 356,214 | 357,521 | 368,546 | 386,219 | 389,228 |
| Bulgaria | 89,494 | 88,441 | 93,370 | 98,086 | 101,122 |
| Croatia | 68,236 | 68,176 | 68,974 | 72,671 | 74,479 |
| Cyprus | 20,838 | 19,389 | 19,098 | 20,113 | 20,867 |
| Czechia | 230,741 | 235,472 | 250,316 | 266,973 | 270,824 |
| Denmark | 189,337 | 192,740 | 199,268 | 209,502 | 211,255 |
| Estonia | 26,013 | 26,622 | 28,066 | 28,873 | 29,577 |
| Finland | 166,205 | 164,991 | 166,952 | 173,832 | 174,829 |
| France | 1869,761 | 1916,268 | 1962,252 | 2043,152 | 2045,250 |
| Germany | 2647,947 | 2679,739 | 2817,035 | 2944,848 | 2990,800 |
| Greece | 211,059 | 210,225 | 215,489 | 218,732 | 213,821 |
| Hungary | 173,149 | 177,797 | 185,590 | 194,927 | 191,718 |
| Ireland | 160,888 | 162,932 | 175,761 | 243,631 | 245,374 |
| Italy | 1630,590 | 1598,764 | 1616,316 | 1680,899 | 1722,194 |
| Latvia | 32,675 | 33,528 | 34,990 | 36,736 | 36,837 |
| Lithuania | 55,679 | 57,928 | 60,900 | 63,102 | 63,227 |
| Luxembourg | 36,765 | 38,156 | 41,540 | 43,989 | 44,495 |
| Malta | 9344 | 9725 | 10,694 | 12,102 | 12,698 |
| Netherlands | 598,596 | 607,881 | 612,050 | 640,260 | 636,079 |
| Poland | 685,603 | 690,782 | 717,644 | 766,527 | 766,161 |
| Portugal | 210,223 | 214,328 | 220,398 | 231,031 | 233,186 |
| Romania | 286,985 | 290,633 | 302,657 | 322,072 | 342,122 |
| Slovakia | 108,904 | 110,943 | 115,544 | 121,002 | 122,071 |
| Slovenia | 44,933 | 45,091 | 46,882 | 49,066 | 49,854 |
| Spain | 1130,761 | 1116,619 | 1154,972 | 1222,404 | 1241,645 |
| Sweden | 322,124 | 322,460 | 332,865 | 356,634 | 354,349 |
| United Kingdom | 1825,131 | 1861,094 | 1946,442 | 2057,427 | 2050,957 |

**Table A3**
Population in the European countries from 2006 to 2011 (million) - Source (Eurostat, 2019).

| Countries | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| Austria | 8254,298 | 8282,984 | 8307,989 | 8335,003 | 8351,643 | 8375,164 |
| Belgium | 10,511,382 | 10,584,534 | 10,666,866 | 10,753,080 | 10,839,905 | 11,000,638 |
| Bulgaria | 7629,371 | 7572,673 | 7518,002 | 7467,119 | 7421,766 | 7369,431 |
| Croatia | 4312,487 | 4313,530 | 4311,967 | 4309,796 | 4302,847 | 4289,857 |
| Cyprus | 744,013 | 757,916 | 776,333 | 796,930 | 819,140 | 839,751 |
| Czechia | 10,223,577 | 10,254,233 | 10,343,422 | 10,425,783 | 10,462,088 | 10,486,731 |
| Denmark | 5427,459 | 5447,084 | 5475,791 | 5511,451 | 5534,738 | 5560,628 |
| Estonia | 1350,700 | 1342,920 | 1338,440 | 1335,740 | 1333,290 | 1329,660 |
| Finland | 5255,580 | 5276,955 | 5300,484 | 5326,314 | 5351,427 | 5375,276 |
| France | 63,229,635 | 63,645,065 | 64,007,193 | 64,350,226 | 64,658,856 | 64,978,721 |
| Germany | 82,437,995 | 82,314,906 | 82,217,837 | 82,002,356 | 81,802,257 | 80,222,065 |
| Greece | 11,004,716 | 11,036,008 | 11,060,937 | 11,094,745 | 11,119,289 | 11,123,392 |
| Hungary | 10,076,581 | 10,066,158 | 10,045,401 | 10,030,975 | 10,014,324 | 9985,722 |
| Ireland | 4208,156 | 4340,118 | 4457,765 | 4521,322 | 4549,428 | 4570,881 |
| Italy | 58,064,214 | 58,223,744 | 58,652,875 | 59,000,586 | 59,190,143 | 59,364,690 |
| Latvia | 2227,874 | 2208,840 | 2191,810 | 2162,834 | 2120,504 | 2074,605 |
| Lithuania | 3289,835 | 3249,983 | 3212,605 | 3183,856 | 3141,976 | 3052,588 |
| Luxembourg | 469,086 | 476,187 | 483,799 | 493,500 | 502,066 | 511,840 |
| Malta | 404,999 | 405,616 | 407,832 | 410,926 | 414,027 | 414,989 |
| Netherlands | 16,334,210 | 16,357,992 | 16,405,399 | 16,485,787 | 16,574,989 | 16,655,799 |
| Poland | 38,157,055 | 38,125,479 | 38,115,641 | 38,135,876 | 38,022,869 | 38,062,718 |
| Portugal | 10,511,988 | 10,532,588 | 10,553,339 | 10,563,014 | 10,573,479 | 10,572,721 |
| Romania | 21,257,016 | 21,130,503 | 20,635,460 | 20,440,290 | 20,294,683 | 20,199,059 |
| Slovakia | 5372,928 | 5373,180 | 5376,064 | 5382,401 | 5390,410 | 5392,446 |
| Slovenia | 2003,358 | 2010,377 | 2010,269 | 2032,362 | 2046,976 | 2050,189 |
| Spain | 44,009,971 | 44,784,666 | 45,668,939 | 46,239,273 | 46,486,619 | 46,667,174 |
| Sweden | 9047,752 | 9113,257 | 9182,927 | 9256,347 | 9340,682 | 9415,570 |
| United Kingdom | 60,620,361 | 61,073,279 | 61,571,647 | 62,042,343 | 62,510,197 | 63,022,532 |

**Table A4**
Population in the European countries from 2012 to 2016 - Source (Eurostat, 2019).

| Countries | 2012 | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|---|
| Austria | 8408,121 | 8451,860 | 8507,786 | 8584,926 | 8700,471 |
| Belgium | 11,075,889 | 11,137,974 | 11,180,840 | 11,237,274 | 11,311,117 |
| Bulgaria | 7327,224 | 7284,552 | 7245,677 | 7202,198 | 7153,784 |
| Croatia | 4275,984 | 4262,140 | 4246,809 | 4225,316 | 4190,669 |
| Cyprus | 862,011 | 865,878 | 858,000 | 847,008 | 848,319 |
| Czechia | 10,505,445 | 10,516,125 | 10,512,419 | 10,538,275 | 10,553,843 |
| Denmark | 5580,516 | 5602,628 | 5627,235 | 5659,715 | 5707,251 |
| Estonia | 1325,217 | 1320,174 | 1315,819 | 1314,870 | 1315,944 |
| Finland | 5401,267 | 5426,674 | 5451,270 | 5471,753 | 5487,308 |
| France | 65,276,983 | 65,600,350 | 66,165,980 | 66,458,153 | 66,638,391 |
| Germany | 80,327,900 | 80,523,746 | 80,767,463 | 81,197,537 | 82,175,684 |
| Greece | 11,086,406 | 11,003,615 | 10,926,807 | 10,858,018 | 10,783,748 |
| Hungary | 9931,925 | 9908,798 | 9877,365 | 9855,571 | 9830,485 |
| Ireland | 4589,287 | 4609,779 | 4637,852 | 4677,627 | 4726,286 |
| Italy | 59,394,207 | 59,685,227 | 60,782,668 | 60,795,612 | 60,665,551 |
| Latvia | 2044,813 | 2023,825 | 2001,468 | 1986,096 | 1968,957 |
| Lithuania | 3003,641 | 2971,905 | 2943,472 | 2921,262 | 2888,558 |
| Luxembourg | 524,853 | 537,039 | 549,680 | 562,958 | 576,249 |
| Malta | 417,546 | 422,509 | 429,424 | 439,691 | 450,415 |
| Netherlands | 16,730,348 | 16,779,575 | 16,829,289 | 16,900,726 | 16,979,120 |
| Poland | 38,063,792 | 38,062,535 | 38,017,856 | 38,005,614 | 37,967,209 |
| Portugal | 10,542,398 | 10,487,289 | 10,427,301 | 10,374,822 | 10,341,330 |
| Romania | 20,095,996 | 20,020,074 | 19,947,311 | 19,870,647 | 19,760,585 |
| Slovakia | 5404,322 | 5410,836 | 5415,949 | 5421,349 | 5426,252 |
| Slovenia | 2055,496 | 2058,821 | 2061,085 | 2062,874 | 2064,188 |
| Spain | 46,818,219 | 46,727,890 | 46,512,199 | 46,449,565 | 46,440,099 |
| Sweden | 9482,855 | 9555,893 | 9644,864 | 9747,355 | 9851,017 |
| United Kingdom | 63,495,088 | 63,905,342 | 64,351,203 | 64,853,393 | 65,379,044 |

**Table A5**
Generated ELV in the European countries from 2006 to 2011 (tons) - Source (Eurostat, 2019).

| Countries | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| Austria | 69,329 | 50,805 | 52,202 | 74,211 | 67,997 | 67,384 |
| Belgium | 131,030 | 128,615 | 144,121 | 144,726 | 176,446 | 171,747 |
| Bulgaria | 45,127 | 23,433 | 38,600 | 63,027 | 74,422 | 65,428 |
| Croatia | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. |
| Cyprus | 918 | 1901 | 12,703 | 15,400 | 11,764 | 15,259 |
| Czechia | 48,094 | 62,000 | 132,533 | 147,217 | 135,479 | 118,147 |
| Denmark | 99,354 | 98,249 | 101,173 | 99,515 | 104,866 | 100,816 |
| Estonia | 10,637 | 12,334 | 13,716 | 7712 | 7679 | 12,123 |
| Finland | 14,183 | 14,734 | 96,130 | 89,849 | 118,976 | 135,973 |
| France | 837,000 | 875,144 | 1046,624 | 1464,843 | 1548,451 | 1501,850 |
| Germany | 449,280 | 420,424 | 387,693 | 1596,831 | 516,128 | 468,459 |
| Greece | 23,952 | 41,733 | 51,828 | 115,849 | 92,158 | 104,590 |
| Hungary | 16,380 | 30,207 | 28,287 | 27,419 | 15,589 | 14,959 |
| Ireland | 146,613 | 109,032 | 136,624 | 163,070 | 169,155 | 139,279 |
| Italy | 1310,050 | 1472,446 | 1106,929 | 1379,027 | 1240,204 | 986,391 |
| Latvia | 5659 | 10,979 | 10,578 | 8946 | 9650 | 10,115 |
| Lithuania | 14,057 | 17,207 | 19,426 | 19,014 | 22,885 | 27,823 |
| Luxembourg | 4557 | 3025 | 2537 | 6517 | 6115 | 2154 |
| Malta | n.d. | n.d. | n.d. | n.d. | 288 | 2225 |
| Netherlands | 179,883 | 156,758 | 146,316 | 187,296 | 232,239 | 198,173 |
| Poland | 124,173 | 150,063 | 170,100 | 192,281 | 217,636 | 284,307 |
| Portugal | 21,692 | 78,860 | 95,691 | 95,703 | 96,242 | 71,664 |
| Romania | 17,624 | 32,007 | 44,031 | 48,424 | 162,276 | 110,035 |
| Slovakia | 11,907 | 23,414 | 29,885 | 54,051 | 27,396 | 30,341 |
| Slovenia | 7810 | 6041 | 4790 | 5428 | 5305 | 5703 |
| Spain | 885,689 | 839,194 | 712,440 | 913,787 | 805,623 | 644,707 |
| Sweden | 335,605 | 266,144 | 178,524 | 162,391 | 207,554 | 226,504 |
| United Kingdom | 970,582 | 1105,480 | 1175,195 | 1289,019 | 1123,872 | 1185,468 |

**Table A6**
Generated ELVs in the European countries from 2012 to 2016 (tons) - Source (Eurostat, 2019).

| Countries | 2012 | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|---|
| Austria | 56,180 | 65,475 | 53,310 | 43,934 | 45,338 |
| Belgium | 171,466 | 145,652 | 138,703 | 119,054 | 119,188 |
| Bulgaria | 59,191 | 62,723 | 82,258 | 88,066 | 92,111 |
| Croatia | 33,221 | 29,017 | 22,584 | 19,617 | 18,912 |
| Cyprus | 15,617 | 11,759 | 10,468 | 8152 | 5094 |
| Czechia | 114,800 | 114,833 | 122,450 | 131,392 | 139,881 |
| Denmark | 114,392 | 128,869 | 118,597 | 109,762 | 100,957 |
| Estonia | 14,056 | 16,391 | 16,617 | 14,857 | 14,113 |
| Finland | 118,976 | 99,280 | 101,822 | 107,302 | 123,273 |
| France | 1229,096 | 1210,605 | 1115,190 | 1057,580 | 1103,927 |
| Germany | 475,719 | 490,771 | 502,656 | 474,379 | 420,113 |
| Greece | 78,433 | 81,619 | 79,668 | 84,046 | 45,570 |
| Hungary | 14,388 | 14,865 | 13,887 | 13,380 | 12,527 |
| Ireland | 105,339 | 98,015 | 92,208 | 79,405 | 104,105 |
| Italy | 874,887 | 959,542 | 953,690 | 1036,562 | 1086,425 |
| Latvia | 10,435 | 9037 | 8983 | 8989 | 8253 |
| Lithuania | 26,187 | 31,037 | 33,265 | 31,037 | 27,752 |
| Luxembourg | 2750 | 2501 | 2258 | 1746 | 2063 |
| Malta | 2177 | 1050 | 2835 | 4803 | n.d. |
| Netherlands | 191,260 | 189,138 | 196,215 | n.d. | n.d. |
| Poland | 340,212 | 401,639 | 462,202 | 493,468 | 395,216 |
| Portugal | 87,020 | 85,960 | 81,193 | 80,494 | 84,473 |
| Romania | 50,732 | 34,566 | 38,137 | 38,851 | n.d. |
| Slovakia | 26,373 | 29,678 | 24,710 | 23,199 | 34,822 |
| Slovenia | 4528 | n.d. | 5960 | n.d. | n.d. |
| Spain | 659,960 | 772,110 | 761,648 | 724,807 | 642,514 |
| Sweden | 231,218 | 240,626 | 237,605 | 242,411 | 240,697 |
| United Kingdom | 1129,392 | 1116,125 | 1074,747 | 966,657 | 1246,447 |

**Table A7**
Recycled ELV in the European countries from 2006 to 2011 (tons) - Source (Eurostat, 2019).

| Countries | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 |
|---|---|---|---|---|---|---|
| Austria | 52.628 | 37.932 | 41.255 | 58.350 | 54.195 | 52.192 |
| Belgium | 89.932 | 87.721 | 98.814 | 102.903 | 126.001 | 128.017 |
| Bulgaria | 35.422 | 20.237 | 30.094 | 51.497 | 65.644 | 58.381 |
| Croatia | n.d. | n.d. | n.d. | n.d. | n.d. | n.d. |
| Cyprus | 730 | 1.393 | 8.408 | 8.331 | 7.564 | 10.343 |
| Czechia | 36.744 | 47.368 | 102.316 | 114.241 | 105.132 | 91.682 |
| Denmark | 68.182 | 69.185 | 70.470 | 70.754 | 79.535 | 77.878 |
| Estonia | 8.779 | 10.140 | 11.852 | 6.498 | 5.563 | 8.246 |
| Finland | 10.411 | 10.245 | 66.818 | 62.452 | 85.801 | 98.060 |
| France | 549.166 | 575.942 | 689.415 | 1.052.306 | 1.074.053 | 1.083.691 |
| Germany | 361.576 | 342.325 | 322.217 | 1.267.582 | 452.644 | 407.315 |
| Greece | 19.091 | 34.076 | 39.872 | 82.792 | 60.370 | 68.466 |
| Hungary | 12.089 | 20.618 | 19.280 | 17.999 | 10.569 | 10.892 |
| Ireland | 110.260 | 87.455 | 102.634 | 127.320 | 128.859 | 110.947 |
| Italy | 793.669 | 1.028.185 | 793.758 | 937.037 | 905.739 | 694.295 |
| Latvia | 4.198 | 9.270 | 8.666 | 6.831 | 7.046 | 7.815 |
| Lithuania | 6.392 | 9.407 | 10.663 | 10.293 | 14.137 | 16.118 |
| Luxembourg | 3.879 | 2.159 | 1.962 | 4.911 | 4.881 | 1.668 |
| Malta | n.d. | n.d. | n.d. | n.d. | 176 | 1.838 |
| Netherlands | 108.773 | 94.772 | 87.717 | 113.214 | 136.744 | 118.162 |
| Poland | 91.223 | 90.832 | 111.831 | 146.257 | 170.168 | 228.900 |
| Portugal | 17.715 | 63.232 | 76.228 | 75.726 | 75.980 | 56.755 |
| Romania | 13.357 | 22.956 | 33.113 | 35.892 | 125.224 | 85.995 |
| Slovakia | 9.392 | 19.610 | 25.090 | 46.737 | 23.501 | 27.641 |
| Slovenia | 5.799 | 4.957 | 4.043 | 4.427 | 4.592 | 4.560 |
| Spain | 595.807 | 654.834 | 555.675 | 635.209 | 560.019 | 448.160 |
| Sweden | n.d. | 220.987 | 148.424 | 139.319 | 175.085 | 191.197 |
| United Kingdom | 773.122 | 890.610 | 947.061 | 1.032.120 | 913.456 | 964.701 |

**Table A8**
Recycled ELV in the European countries from 2012 to 2016 (million) - Source (Eurostat, 2019).

| Countries | 2012 | 2013 | 2014 | 2015 | 2016 |
|---|---|---|---|---|---|
| Austria | 43,913 | 51,677 | 42,916 | 33,159 | 34,017 |
| Belgium | 129,923 | 106,717 | 103,806 | 86,967 | 93,971 |
| Bulgaria | 52,392 | 57,362 | 75,621 | 80,900 | 84,823 |
| Croatia | 32,293 | 29,012 | 20,112 | 18,123 | 17,668 |
| Cyprus | 10,449 | 7861 | 5906 | 4707 | 2965 |
| Czechia | 89,085 | 89,110 | 95,020 | 113,896 | 120,177 |
| Denmark | 91,573 | 92,479 | 83,955 | 72,683 | 77,020 |
| Estonia | 10,306 | 11,538 | 11,668 | 10,472 | 9807 |
| Finland | 85,801 | 71,597 | 78,591 | 82,852 | 95,151 |
| France | 914,237 | 889,522 | 844,414 | 813,511 | 845,917 |
| Germany | 412,663 | 419,890 | 429,562 | 397,073 | 358,320 |
| Greece | 48,343 | 54,577 | 46,698 | 35,692 | 33,174 |
| Hungary | 10,477 | 11,012 | 8801 | 10,064 | 8569 |
| Ireland | 85,325 | 78,070 | 75,062 | 65,517 | 88,851 |
| Italy | 621,964 | 673,674 | 722,205 | 737,474 | 775,067 |
| Latvia | 9727 | 7841 | 7794 | 7093 | 7000 |
| Lithuania | 15,728 | 19,200 | 19,908 | 20,571 | 18,563 |
| Luxembourg | 2224 | 2052 | 1923 | 1493 | 1752 |
| Malta | 1847 | 928 | 1211 | 3277 | n.d. |
| Netherlands | 114,013 | 117,652 | 121,603 | n.d. | n.d. |
| Poland | 273,756 | 313,841 | 347,187 | 400,743 | 317,366 |
| Portugal | 68,913 | 68,263 | 64,637 | 64,349 | 67,257 |
| Romania | 39,204 | 26,979 | 30,728 | 31,794 | n.d. |
| Slovakia | 23,390 | 27,051 | 22,917 | 19,693 | 32,395 |
| Slovenia | 4074 | n.d. | 4928 | n.d. | n.d. |
| Spain | 459,718 | 531,484 | 509,415 | 489,271 | 436,748 |
| Sweden | 149,758 | 169,432 | 165,195 | 168,371 | 173,694 |
| United Kingdom | 928,144 | 929,894 | 910,052 | 829,431 | 1049,018 |

**Table A9**
*F*-test analysis.

| Parameter | *F*-test no. 1<br>GDP PPS | Generated ELV | *F*-test no. 2<br>GDP PPS | Recycled ELV |
|---|---|---|---|---|
| Mean | 473 | 175 | 473 | 232 |
| Variance | $462\times10^3$ | $79\times10^3$ | $462\times10^3$ | $138\times10^3$ |
| *N* | 289 | 289 | 288 | 288 |
| Dof | 288 | 288 | 287 | 287 |
| *F* | 3.35 | | 5.85 | |
| $P$ ($F\leq F_{crit}$) | $4.6e^{-25}$ | | $1.9e^{-48}$ | |
| $F_{crit}$ | 1.21 | | 1.21 | |

| Parameter | *F*-test no. 3<br>Generated ELV | Population | *F*-test no. 4<br>Recycled ELV | Population |
|---|---|---|---|---|
| Mean | 232 | 18 | 175 | 18 |
| Variance | $138\times10^3$ | 528 | $79\times10^3$ | 528 |
| *N* | 289 | 289 | 288 | 288 |
| Dof | 288 | 288 | 287 | 287 |
| *F* | 262 | | 149 | |
| $P$ ($F\leq F_{crit}$) | $1.5e^{-280}$ | | $6.0e^{-244}$ | |
| $F_{crit}$ | 1.21 | | 1.21 | |

| Parameter | *F*-test no. 5<br>Generated ELV per capita | GDP PPS per capita | *F*-test no. 6<br>Recycled ELV per capita | GDP PPS per capita |
|---|---|---|---|---|
| Mean | 54 | 27 | 54 | 20 |
| Variance | $6.1\times10^3$ | $1.8\times10^3$ | $6.1\times10^3$ | $1.0\times10^3$ |
| *N* | 289 | 289 | 288 | 288 |
| Dof | 288 | 288 | 287 | 287 |
| *F* | 3.36 | | 5.85 | |
| $P$ ($F\leq F_{crit}$) | $4.6e^{-25}$ | | $1.9e^{-48}$ | |
| $F_{crit}$ | 1.21 | | 1.21 | |

**Table A10**
Likert scale - responses.

| ID/N° | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Q1 | 4 | 3 | 3 | 3 | 4 | 3 | 3 | 3 | 4 | 3 |
| Q2 | 4 | 4 | 5 | 5 | 4 | 5 | 5 | 5 | 5 | 5 |
| Q3 | 4 | 4 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 3 |
| Q4 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 2 | 2 | 2 |
| Q5 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 |
| Q6 | 5 | 5 | 5 | 4 | 4 | 5 | 4 | 4 | 4 | 4 |
| Q7 | 5 | 5 | 4 | 4 | 5 | 5 | 4 | 4 | 4 | 4 |
| Q8 | 4 | 5 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Q9 | 5 | 5 | 5 | 4 | 4 | 5 | 5 | 4 | 5 | 4 |
| Q10 | 4 | 4 | 3 | 3 | 4 | 3 | 3 | 4 | 3 | 3 |
| Q11 | 4 | 3 | 4 | 3 | 4 | 3 | 3 | 4 | 4 | 4 |
| Q12 | 4 | 4 | 3 | 4 | 4 | 4 | 4 | 4 | 4 | 3 |
| Q13 | 3 | 4 | 3 | 4 | 3 | 4 | 3 | 4 | 4 | 3 |
| Q14 | 4 | 5 | 5 | 4 | 5 | 5 | 4 | 5 | 4 | 5 |
| Q15 | 4 | 5 | 5 | 4 | 5 | 5 | 4 | 4 | 4 | 4 |

## References


Abdulredha, M., Al Khaddar, R., Jordan, D., Kot, P., Abdulridha, A., Hashim, K., 2018. Estimating solid waste generation by hospitality industry during major festivals: a quantification model based on multiple regression. Waste Manage. 77, 388–400. https://doi.org/10.1016/J.WASMAN.2018.04.025.

Amankwah-Amoah, J., 2016. Global business and emerging economies: towards a new perspective on the effects of e-waste. Technol. Forecast. Soc. Change 105, 20–26. https://doi.org/10.1016/J.TECHFORE.2016.01.026.

Amato, A., Becci, A., Birloaga, I., De Michelis, I., Ferella, F., Innocenzi, V., Ippolito, N.M., Pillar Jimenez Gomez, C., Vegliò, F., Beolchini, F., 2019. Sustainability analysis of innovative technologies for the rare earth elements recovery. Renew. Sustain. Energy Rev. 106, 41–53. https://doi.org/10.1016/j.rser.2019.02.029.

Andersen, F.M., Larsen, H.V., Skovgaard, M., Isoard, S., 2008. Projection of end-of-life vehicles - Development of a projection model and estimates of ELVs for 2005-2030. Copenhagen Eur. Top. Cent. Resour. Waste Manag ETC/RWM Work. Pap. No. 2008/2 28.

Andersson, M., Ljunggren Söderman, M., Sandén, B.A., 2019a. Challenges of recycling multiple scarce metals: the case of Swedish ELV and WEEE recycling. Resour. Policy 63, 101403. https://doi.org/10.1016/J.RESOURPOL.2019.101403.

Andersson, M., Söderman, M.L., Sandén, B.A., 2019b. Adoption of systemic and socio-technical perspectives in waste management, WEEE and ELV research. Sustainability 11, 1–26. https://doi.org/10.3390/su11061677.

Antonopoulos, I.S., Perkoulidis, G., Logothetis, D., Karkanias, C., 2014. Ranking municipal solid waste treatment alternatives considering sustainability criteria using the analytical hierarchical process tool. Resour. Conserv. Recycl. 86, 149–159. https://doi.org/10.1016/j.resconrec.2014.03.002.

Awasthi, A.K., Cucchiella, F., D'Adamo, I., Li, J., Rosa, P., Terzi, S., Wei, G., Zeng, X., 2018. Modelling the correlations of e-waste quantity with economic increase. Sci. Total Environ. 613–614, 46–53. https://doi.org/10.1016/j.scitotenv.2017.08.288.

Banacu, C.S., Busu, M., Ignat, R., Trica, C.L., 2019. Entrepreneurial innovation impact on recycling municipal waste. a panel data analysis at the EU level. Sustainability 11, 5125. https://doi.org/10.3390/su11185125.

Beigl, P., Lebersorger, S., Salhofer, S., 2008. Modelling municipal solid waste generation: a review. Waste Manage. 28, 200–214. https://doi.org/10.1016/J.WASMAN.2006.12.011.

Busu, M., 2019. Adopting circular economy at the European Union level and its impact on economic growth. Soc. Sci. 8, 159. https://doi.org/10.3390/socsci8050159.

Chai, J., Yang, Y., Wang, S., Lai, K.K., 2016. Fuel efficiency and emission in China's road transport sector: induced effect and rebound effect. Technol. Forecast. Soc. Change 112, 188–197. https://doi.org/10.1016/J.TECHFORE.2016.07.005.

Chen, Y., Ding, Z., Liu, J., Ma, J., 2019. Life cycle assessment of end-of-life vehicle recycling in China: a comparative study of environmental burden and benefit. Int. J. Environ. Stud. 76, 1019–1040. https://doi.org/10.1080/00207233.2019.1618670.

Cucchiella, F., D'Adamo, I., Gastaldi, M., Koh, S.C.L., Rosa, P., 2017. A comparison of environmental and energetic performance of European countries: a sustainability index. Renew. Sustain. Energy Rev. 78, 401–413. https://doi.org/10.1016/j.rser.2017.04.077.

D'Adamo, I., Ferella, F., Gastaldi, M., Maggiore, F., Rosa, P., Terzi, S., 2019. Towards sustainable recycling processes: wasted printed circuit boards as a source of economic opportunities. Resour. Conserv. Recycl. 149, 455–467. https://doi.org/10.1016/J.RESCONREC.2019.06.012.

D'Adamo, I., Rosa, P., 2019. A structured literature review on obsolete electric vehicles management practices. Sustainability 11, 6876. https://doi.org/10.3390/su11236876.

De Almeida, S.T., Borsato, M., 2019. Assessing the efficiency of end of life technology in waste treatment—A bibliometric literature review. Resour. Conserv. Recycl. 140, 189–208. https://doi.org/10.1016/j.resconrec.2018.09.020.

Despeisse, M., Baumers, M., Brown, P., Charnley, F., Ford, S.J., Garmulewicz, A., Knowles, S., Minshall, T.H.W., Mortara, L., Reed-Tsochas, F.P., Rowley, J., 2017. Unlocking value for a circular economy through 3D printing: a research agenda. Technol. Forecast. Soc. Change 115, 75–84. https://doi.org/10.1016/J.TECHFORE.2016.09.021.

Despeisse, M., Kishita, Y., Nakano, M., Barwood, M., 2015. Towards a circular economy for end-of-life vehicles: a comparative study UK - Japan. Procedia CIRP 29, 668–673. https://doi.org/10.1016/j.procir.2015.02.122.

Ene, S., Öztürk, N., 2017. Grey modelling based forecasting system for return flow of end-of-life vehicles. Technol. Forecast. Soc. Change 115, 155–166. https://doi.org/10.1016/J.TECHFORE.2016.09.030.

Eurostat, 2019. Database [WWW Document]. URLhttps://ec.europa.eu/eurostat/data/database(accessed 7.5.19).

Falcone, P.M., Imbert, E., 2018. Social life cycle approach as a tool for promoting the market uptake of bio-based products from a consumer perspective. Sustainability 10, 1031. https://doi.org/10.3390/su10041031.

Fonseca, L.M., Domingues, J.P., Pereira, M.T., Figueiredo Martins, F., Zimon, D., 2018. Assessment of circular economy within Portuguese organizations. Sustainability 10, 2521. https://doi.org/10.3390/su10072521.

Förster, B., 2015. Technology foresight for sustainable production in the German automotive supplier industry. Technol. Forecast. Soc. Change 92, 237–248. https://doi.org/10.1016/J.TECHFORE.2014.09.010.

Gopal, P.R.C., Thakkar, J., 2016. Sustainable supply chain practices: an empirical investigation on Indian automobile industry. Prod. Plan. Control 27, 49–64. https://doi.org/10.1080/09537287.2015.1060368.

Gu, B., Li, Y., Jin, D., Yi, S., Gu, A., Bu, X., Zhou, H., He, S., Cheng, R., Jia, R., 2018. Quantizing, recognizing, and characterizing the recycling potential of recyclable waste in China: a field tracking study of Suzhou. J. Clean. Prod. 201, 948–957. https://doi.org/10.1016/J.JCLEPRO.2018.08.085.

Gupta, S., Chen, H., Hazen, B.T., Kaur, S., Santibañez Gonzalez, E.D.R., 2019. Circular economy and big data analytics: a stakeholder perspective. Technol. Forecast. Soc. Change 144, 466–474. https://doi.org/10.1016/J.TECHFORE.2018.06.030.

Halkos, G., Petrou, K.N., 2019. Assessing 28 EU member states' environmental efficiency in national waste generation with DEA. J. Clean. Prod. 208, 509–521. https://doi.org/10.1016/J.JCLEPRO.2018.10.145.

Hao, H., Zhang, Q., Wang, Z., Zhang, J., 2018. Forecasting the number of end-of-life vehicles using a hybrid model based on grey model and artificial neural network. J. Clean. Prod. 202, 684–696. https://doi.org/10.1016/J.JCLEPRO.2018.08.176.

Hu, S., Kurasaka, H., 2013. Projection of end-of-life vehicle (ELV) population at provincial level of China and analysis on the gap between the future requirements and the current situation of ELV treatment in China. J. Mater. Cycles Waste Manage. 15, 154–170. https://doi.org/10.1007/s10163-012-0102-9.

Jamin, N.A., Saleh, S., Abdul Samad, N.A.F., 2019. Properties prediction of torrefied municipal solid waste using linear correlation model. Energy Procedia 158, 836–841. https://doi.org/10.1016/J.EGYPRO.2019.01.217.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/j.resconrec.2017.09.005.

Krapp, M., Nebel, J., Sahamie, R., 2013. Forecasting product returns in closed-loop supply chains. Int. J. Phys. Distrib. Logist. Manage. 43, 614–637. https://doi.org/10.1108/IJPDLM-03-2012-0078.

Kusch, S., Hills, C.D., 2017. The link between e-Waste and GDP—New insights from data from the pan-european region. Resources. https://doi.org/10.3390/resources6020015.

Lee, E.-A., Choi, H.-R., Lee, H.-C., 2012. A study on the forecasting of the number of end of life vehicles in Korea using Markov Chain. J. Korean Inst. Ind. Eng. 38, 208–219. https://doi.org/10.7232/JKIIE.2012.38.3.208.

Mehedintu, A., Sterpu, M., Soava, G., 2018. Estimation and forecasts for the share of renewable energy consumption in final energy consumption by 2020 in the European Union. Sustainability 10, 1515. https://doi.org/10.3390/su10051515.

Mudd, G., Yellishetty, M., Reck, B., Graedel, T.E., 2014. Quantifying the recoverable resources of companion metals: a preliminary study of Australian mineral resources. Resources 3, 657–671. https://doi.org/10.3390/resources3040657.

Nykvist, B., Sprei, F., Nilsson, M., 2019. Assessing the progress toward lower priced long range battery electric vehicles. Energy Policy 124, 144–155. https://doi.org/10.

1016/j.enpol.2018.09.035.
Ogawa, T., Iyoki, K., Fukushima, T., Kajikawa, Y., 2017. Landscape of research areas for zeolites and metal-organic frameworks using computational classification based on citation networks. Materials (Basel) 10, 1428. https://doi.org/10.3390/ma10121428.
Oliveira, G.D., Roth, R., Dias, L.C., 2019. Diffusion of alternative fuel vehicles considering dynamic preferences. Technol. Forecast. Soc. Change 147, 83–99. https://doi.org/10.1016/J.TECHFORE.2019.06.002.
Onat, N.C., Kucukvar, M., Afshar, S., 2019. Eco-efficiency of electric vehicles in the United States: a life cycle assessment based principal component analysis. J. Clean. Prod. 212, 515–526. https://doi.org/10.1016/J.JCLEPRO.2018.12.058.
Ormazabal, M., Prieto-Sandoval, V., Puga-Leal, R., Jaca, C., 2018. Circular economy in Spanish SMEs: challenges and opportunities. J. Clean. Prod. 185, 157–167. https://doi.org/10.1016/J.JCLEPRO.2018.03.031.
Phillips, F., 2019. 50 years of TF&SC. Technol. Forecast. Soc. Change 143, 125–131. https://doi.org/10.1016/J.TECHFORE.2019.03.004.
Qian, X., Lee, S., Soto, A., Chen, G., Qian, X., Lee, S., Soto, A., Chen, G., 2018. Regression model to predict the higher heating value of poultry waste from proximate analysis. Resources 7, 39. https://doi.org/10.3390/resources7030039.
Qiao, Q., Zhao, F., Liu, Z., Hao, H., 2019. Electric vehicle recycling in China: economic and environmental benefits. Resour. Conserv. Recycl. 140, 45–53. https://doi.org/10.1016/J.RESCONREC.2018.09.003.
Reuter, M.A., Hudson, C., van Schaik, A., Heiskanen, K., Meskers, C., Hagelüken, C., 2013. Metal recycling: opportunities, limits, infrastructure, a report of the working group on the global metal flows to the international resource panel. UNEP.
Rosa, P., Sassanelli, C., Urbinati, A., Chiaroni, D., Terzi, S., 2019. Assessing relations between circular economy and industry 4.0: a systematic literature review. Int. J. Prod. Res. https://doi.org/10.1080/00207543.2019.1680896. in press.
Rosa, P., Terzi, S., 2018. Improving end of life vehicle's management practices: an economic assessment through system dynamics. J. Clean. Prod. 184, 520–536. https://doi.org/10.1016/j.jclepro.2018.02.264.
Sadik-Zada, E.R., Löwenstein, W., Ferrari, M., 2018. Privatization and the role of subnational governments in the Latin American power sector. Int. J. Energy Econ. Policy 8, 95–103.
Sakai, S., Yoshida, H., Hiratsuka, J., Vandecasteele, C., Kohlmeyer, R., Rotter, V.S., Passarini, F., Santini, A., Peeler, M., Li, J., Oh, G.-J., Chi, N.K., Bastian, L., Moore, S., Kajiwara, N., Takigami, H., Itai, T., Takahashi, S., Tanabe, S., Tomoda, K., Hirakawa, T., Hirai, Y., Asari, M., Yano, J., 2014. An international comparative study of end-of-life vehicle (ELV) recycling systems. J. Mater. Cycles Waste Manage. 16, 1–20. https://doi.org/10.1007/s10163-013-0173-2.
Sato, F.E.K., Furubayashi, T., Nakata, T., 2019. Application of energy and CO2 reduction assessments for end-of-life vehicles recycling in Japan. Appl. Energy 237, 779–794. https://doi.org/10.1016/J.APENERGY.2019.01.002.
Schutt, R.K., 2018. Investigating the Social world: The process and Practice of Research. Sage Publications.
Shankar, R., Bhattacharyya, S., Choudhary, A., 2018. A decision model for a strategic closed-loop supply chain to reclaim end-of-life vehicles. Int. J. Prod. Econ. 195, 273–286. https://doi.org/10.1016/J.IJPE.2017.10.005.
Soava, G., Mehedintu, A., Sterpu, M., Raduteanu, M., 2018. Impact of renewable energy consumption on economic growth: evidence from European Union countries. Technol. Econ. Dev. Econ. 24, 914–932. https://doi.org/10.3846/tede.2018.1426.
Song, M., Fisher, R., Kwoh, Y., 2019. Technological challenges of green innovation and sustainable resource management with large scale data. Technol. Forecast. Soc. Change 144, 361–368. https://doi.org/10.1016/J.TECHFORE.2018.07.055.
Soo, V.K., Compston, P., Doolan, M., 2019. Life cycle modelling of end-of-life products: challenges and opportunities towards a circular economy. Procedia CIRP 80, 607–612. https://doi.org/10.1016/J.PROCIR.2019.01.092.
Tian, G., Zhou, M., Chu, J., Wang, B., 2013. Prediction models of the number of end-of-life vehicles in China. In: 2013 International Conference on Advanced Mechatronic Systems. IEEE Explore. Luoyang, China. pp. 357–362.
Umrao, R.K., Sharma, L.K., Singh, R., Singh, T.N., 2018. Determination of strength and modulus of elasticity of heterogenous sedimentary rocks: an ANFIS predictive technique. Meas. J. Int. Meas. Confed. 126, 194–201. https://doi.org/10.1016/j.measurement.2018.05.064.
Vujić, G., Gonzalez-Roof, A., Stanisavljević, N., Ragossnig, A.M., 2015. Municipal solid waste development phases: evidence from EU27. Waste Manag. Res. 33, 1112–1120. https://doi.org/10.1177/0734242X15611738.
Wang, L., Chen, M., 2013. Policies and perspective on end-of-life vehicles in China. J. Clean. Prod. 44, 168–176. https://doi.org/10.1016/J.JCLEPRO.2012.11.036.
Wang, N., Tang, L., Pan, H., 2018. Analysis of public acceptance of electric vehicles: an empirical study in Shanghai. Technol. Forecast. Soc. Change 126, 284–291. https://doi.org/10.1016/J.TECHFORE.2017.09.011.
Xiao, Z., Sun, J., Shu, W., Wang, T., 2019. Location-allocation problem of reverse logistics for end-of-life vehicles based on the measurement of carbon emissions. Comput. Ind. Eng. 127, 169–181. https://doi.org/10.1016/J.CIE.2018.12.012.
Xu, G., Yano, J., Sakai, S., 2019. Recycling potentials of precious metals from end-of-life vehicle parts by selective dismantling. Environ. Sci. Technol. 53, 733–742. https://doi.org/10.1021/acs.est.8b04273.
Zhou, F., Lim, M.K., He, Y., Lin, Y., Chen, S., 2019. End-of-life vehicle (ELV) recycling management: improving performance using an ISM approach. J. Clean. Prod. 228, 231–243. https://doi.org/10.1016/J.JCLEPRO.2019.04.182.

**Idiano D'Adamo** is a Post Doctoral Research Fellow at Unitelma Sapienza - University of Rome. He worked in the University of Sheffield, the National Research Council of Italy, Politecnico di Milano and University of L'Aquila. In August 2015, he obtained the Elsevier Atlas Price with a work published in Renewable and Sustainable Energy Reviews. He received two Excellence Review Awards: Waste Management in 2017 and Resources Conservation and Recycling in 2018. During its academic career, Idiano D'Adamo published 57 papers in the Scopus database, receiving 1357 citations and reaching an h-index of 22. His current research interests are bioeconomy, circular economy, renewable energy, sustainability and waste management.

**Massimo Gastaldi** is now Full Professor in Managerial Engineering at University of L'Aquila, Department of Industrial and Information Engineering and Economics where he teaches Industrial Economics and Analysis of Financial Systems. Since 1993 he has contributed with several publications and edited books working for National Research Council (C.N.R.) and at University of Rome ``Tor Vergata". In 1995 he was visiting professor at the California State University, San Marcos, USA and in 1997 at Colorado University, Builder, USA. Current research issues: regulation and public utilities, green supply chain management, finance, renewable energy and real options. He is the responsible manager of private and public research projects. He was editor in chief of the International Journal of Management and Network Economics published by Inderscience. He is author of more than 180 papers published on refereed books, journals and conference proceedings.

**Paolo Rosa** received his MSc in Management Engineering from Politecnico di Milano in 2009 and received his PhD in Economics and Management of Technology in 2018. After having worked for several years as a research assistant at Politecnico di Milano and ITIA-CNR, he currently works as research coordinator at Politecnico di Milano for H2020 projects focused on product lifecycle management and circular economy topics.