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Assessing the relation between waste management policies and circular economy goals

Idiano D'Adamo [a], Massimiliano Mazzanti [b], Piergiuseppe Morone [c,*], Paolo Rosa [d]

[a] Department of Computer, Control and Management Engineering, Sapienza University of Rome, Via Ariosto 25, 00185 Roma, Italy
[b] University of Ferrara & SEEDS, Via Voltapaletto 11, 44100 Ferrara, Italy
[c] Department of Law and Economics, UnitelmaSapienza – University of Rome, Piazza Sassari 4, 00161 Roma, Italy
[d] Department of Management, Economics and Industrial Engineering, Politecnico di Milano, Piazza L. Da Vinci 32, 20133 Milano, Italy

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ABSTRACT

The European Union has recently prioritized waste policies by embedding them in the new Horizon Europe work programme. Here, circular economy (CE) and digitalization are matching together in order to support all the industrial sectors in increasing their sustainability level. One of the main impacts expected from the EU is a better exploitation of wasted resources. However, waste streams are very different in terms of volumes, embedded materials and management policies. Considering only those waste streams with highest volumes, this study focuses on End-of-Life Vehicle (ELV), Municipal Solid Waste (MSW) and Waste from Electrical and Electronic Equipment (WEEE). Starting from some policy recommendations and analyses identified through a literature review and the support of the experts, a survey has been conducted to identify the most critical items for each waste stream. Results of the survey show that, on the one hand, end of waste strategies has the highest importance for WEEE and ELV categories. On the other hand, social change has the highest importance for MSW. Consequently, end of waste strategies and social change should be considered as enablers of reuse and recycling practices in their reference contexts. In order to counteract the significant socio-economic issues already caused by delays in taking clear decisions about climate change mitigation strategies, policymakers should focus on these policy implications urgently if even more imminent environmental catastrophes are to be avoided.

1. Introduction

The European Commission adopted the new circular economy (CE) action plan in March 2020 (COM/2020/98). This plan pays attention to the entire life cycle of the product, from the phase in which the products are designed until the phase in which the waste is prevented trying to keep the resources used for as long as possible in the economic cycle.

The main objective of waste management policies is trying to limit climate changes through a better exploitation of critical resources embedded into obsolete products (Cainelli et al., 2020). During the last decades, experts developed several guidelines to improve the design and implementation of waste management (Domenech and Bahn-Walkowiak, 2017) and water management (Turrini et al., 2021) policies, aimed at protecting the environment and saving natural resources through recycling (Ko et al., 2020). However, they were more focused in supporting environmental protection and resource efficiency than considering the economic sustainability of involved actors.

(Andersson et al., 2019; Callao et al., 2019). This led to only a partial adoption of such guidelines by waste management actors. Instead, the role of environmental policies should be to drive actors towards more sustainable behaviours, by guaranteeing their economic survival. Together with environmental policies, also a set of reference waste streams to monitor should be identified, in order to define adequate corrective measures.

The issue is felt as much in developed countries as in emerging economies (Acerbi et al., 2022; Karuppiah et al., 2021). European countries show varying waste trends and countries that have implemented landfill and incineration directives show encouraging performance, but widen the gap with countries that have postponed such implementation (Mazzanti and Zoboli, 2008). In all cases, the implementation of strict waste policies must be accompanied by severe control measures to avoid the risk of increasing illegal waste (D'Amato

* Corresponding author.
E-mail addresses: idiano.dadamo@uniroma1.it (I. D'Adamo), mzzmsm@unife.it (M. Mazzanti), piergiuseppe.morone@unitelmasapienza.it (P. Morone), paolo1.rosa@polimi.it (P. Rosa).

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et al., 2018). The issue of supply chain management became even more crucial during the Covid-19 pandemic period (Shahed et al., 2021).

The adoption of CE principles aims to counter inefficient waste management practices by highlighting to managers the benefits that new business models can bring about (Rosa et al., 2019). For instance, CE is capable of bringing benefits because valuable materials are among the recycled materials (Favot and Massarutto, 2019), but its effective implementation requires the integration in the waste management value chain of an array of tools, including digitalisation and intelligent robotics (Sarc et al., 2019). This would allow overcoming economic, institutional, and socio-cultural hurdles (Salmenperä et al., 2021) addressing the growing concerns of Generation-Z and Millennials about protecting ecosystems, identifying circular economy models as a virtuous behaviour to tackle climate change by enabling supply chain resilience (Appolloni et al., 2021). Thus, change to happen requires an interdisciplinary approach and the involvement of all layers of the society. The role of indicators in assessing circularity performance within waste management is able to give useful information for decision-making processes (Colasante et al., 2022; Pires and Martinho, 2019) in order to reach sustainable goals (D'Adamo et al., 2021).

Some authors have focused on three categories of waste, as End-of-Life Vehicle (ELV), Municipal Solid Waste (MSW) and Waste from Electrical and Electronic Equipment (WEEE), for achieving a sustainable transition in a European context (Cucchiella et al., 2017). To the best of our knowledge, at present the literature has not investigated policy measures applied to these three categories of waste in a comparative way. Bearing this in mind, the present work aims at assessing the relation between waste management practices and policy implications in three of the most important waste streams in Europe (e.g. MSWs, WEEEs and ELVs), trying to identify which policy interventions are more suitable to support the achievement of CE goals in these contexts. The paper is structured as follows. Section 2 presents a literature review about current waste management practices and section 3 presents the research method. Section 4 reports results and Section 5 discusses key findings and proposes policy implications. Section 6 concludes the paper and presents some future research trends.

2. Literature review

CE is crucial to achieve waste management and prevention targets through innovation strategies and new business models (Ko et al., 2020). The waste recycling rate is growing in the EU27, but the rate of progress has shown a slowing down and little progress over the past 5 years. The CE strategy, elaborated by Europe, is the main driver of a new phase of enhanced waste management and prevention performance across sectors and regions (Pires and Martinho, 2019). Within this framework, a further point of reflection is that relating to the interactions that can be identified between CE and climate energy (Moktadir et al., 2020; Zoboli et al., 2020).

Waste management is a complex topic involving several categories of waste, stakeholders and directives. Within this macro area, the conservation of resources and the adoption of end-of-life strategies, such as reuse and recycling, may determine a positive impact on sustainability (Coelho et al., 2020). With respect to stakeholders, the concepts of consumer responsibility (Johansson and Corvellec, 2018) and producer responsibility (Domenech and Bahn-Walkowiak, 2017) are highly relevant. First, it may be useful to increase consumers' attitudes and behaviours towards recycling habits, as well as their willingness to participate in recycling educational programmes to support the development of waste management technologies. In addition to attempting to influence actors in the here and now, policy actors should identify long-term strategies to influence future generations (Giaccherini et al., 2021). Similarly, it is crucial to improve waste collection methods, encouraging the use of innovative models (Gallardo et al., 2021).

Second, the 'legal' and 'illegal' exchange of waste between countries determines the need for better traceability and, at the same time, application of the proximity principle (Kellenberg, 2015; Mazzanti and Zoboli, 2013; Weber et al., 2019). In applying these principles, policy actors should seek to minimise both the environmental impact and the cost of waste transport. A related priority is the prevention of damage to human health and the environment. The 'polluter pays' principle holds that the costs of waste disposal should be paid for by the current waste holders, previous waste holders or original producers (Appolloni et al., 2021). Virtuous European Member States (MSs), characterised by adequate performance in waste recycling and reuse, could be rewarded – for example, through international cooperation in information exchange, worker training incentives, and knowledge and technology sharing around recycling (De Almeida and Borsato, 2019). Through this scheme, stakeholders across Europe might improve their ability to share information and innovate technology in line with material evolution (Sakai et al., 2014). Consequently, an industrial symbiosis optimisation model based on the reuse and recycling of waste materials is considered propaedeutic to achieving sustainable manufacturing (Huang et al., 2020).

Independently from each country's political perspective, waste management performance should be clearly defined. The definition of standard models and indexes for measuring waste management at different geographical scales (i.e. national, regional and local) could support decision-makers by highlighting the strengths and weaknesses of various waste management practices (Wang et al., 2017). Furthermore, as environmental education has already been identified as a key factor in improving waste management (Pérez-Belis et al., 2015), best practices for recycling might be taught and applied in schools (Rada et al., 2016). Social change is considered strategic in the implementation of CE models, and information campaigns directed at citizens and civil society may be crucial in increasing the social acceptability of sustainable technologies (Morone and Imbert, 2020). In this context, aspects such as behavioral factors (Kumar et al., 2020) and public perception are important to evaluate (Adekola et al., 2021).

Better performance in waste management might also be achieved through the implementation of coordination programmes aimed at providing information and support for firms to define the economic opportunities associated with their waste management (Fuldauer et al., 2019). Firms can also provide valid support for the development of eco-designed products that are more easily reusable/recyclable (Soo et al., 2017). Technological improvement is required in several respects, including smart cities and eco-industrial parks (Wang et al., 2019), as well as Industry 4.0 (Mattos Nascimento et al., 2018; Urbinati et al., 2020).

In addition, as bureaucracy can determine a temporal delay in the realisation of infrastructures, communication between public and private actors should be facilitated, in order to simplify administrative procedures (Zhao et al., 2019). Coordination among various levels of government in the environmental sector, as well as among political groups, may be a particularly complex challenge. However, such coordination is necessary in the context of climate change (Antonioli et al., 2014).

End of waste is considered crucial to the development of the CE and includes only waste that is already in circulation. Its implementation is difficult in Europe. In fact, the issue has been decentralized but local authorities are not able to determine when waste is no longer considered as waste (Mazzanti and Montini, 2014). The space between waste and products should be explored (Johansson and Forsgren, 2020). Other authors also focus their attention on Europe and confirm that there is a need to identify clear and unquestionable criteria that define when a waste obtains product (or secondary raw material) status (Ragossnig and Schneider, 2019).

Finally, economic subsidies are always seen as an attractive element for developing new markets, alternative to those based on processes that cause significant emissions. However, their use should be directed towards initiatives that are truly circular (D'Adamo and Sassanelli, 2022). These aspects influence economic analyses, outline business models and

attract new players interested in the availability of these additional economic resources (Rosa and Terzi, 2018). The joint tax-subsidy mechanism is able to promote eco-innovations of the manufacturer (Colasante et al., 2022) and to stimulate the recycler to reduce the environmental harm and to increase the recycling rate (Chang et al., 2019).

All of the abovementioned interventions represent a bundle of policy directions that should be considered for the optimisation of waste management (i.e. reuse and recycling). However, the intent of this work is to start from these policy directions in order to comprehend the perspective of some experts in the field. The point of view of these experts will allow to prioritize the main aspects to be considered in order to adequately update the current European directives related with the different waste sources.

3. Methods

This paper uses a quantitative approach based on a structured survey addressed to a panel of experts belonging to different categories in order to capture a transdisciplinary aspect according to the taxonomy proposed by Sovacool et al. (2018). This method is particularly valid when it is applied to identify suitable policies to encourage a correct waste management (Morone et al., 2021).

The choice of experts has fallen on three different categories (academics, politicians, managers) characterized by a significant experience in waste management (Ghisetti et al., 2017). The reference territory for the choice is the European one. Among academics, guest editors who over the last two years have edited a special issue on waste management issues were invited. As for policymakers, they were sleeved during a workshop held in Brussels in 2019 by the Association of Cities and Regions for Sustainable Resource Management (ACR +). Finally, managers were identified by consulting members of the European Federation for Waste Management and Environmental Services (FEAD). An invitation email was sent to them to participate in this survey and twenty experts were identified (Table 1) using the approach used by (D'Adamo and Sassanelli, 2022). A few observations should be made: (i) the e-mail specified that not all applications would be accepted in order to maintain the percentage distribution decided at the beginning of the survey; (ii) all experts had to have at least 10 years of experience in waste management; and (iii) all purposes (scientific publication) and the way the survey would be carried out were indicated. In addition, the survey did not only cover the topic analysed in this work but was part of a larger research project. The panel of experts consisted of 8 women and 12 men. These experts were involved in a larger project, in which the incidence of the type of waste considered and its social, economic and environmental dimensions were assessed in the first phase (Colasante et al., 2022). The choice of European experts was made solely for the territory of analysis considered and thus for a more specific background to assess the territorial context.

The following step of this method involved the identification of policies and actions oriented to support the development of CE strategies according to literature and validated by experts – Table 2. All experts were sent the content of section 2, which was improved following several suggestions to put more attention to some aspects that were not initially highlighted. In particular, the main changes concerned four items (economic subsidies, end of waste, industrial symbiosis and prizes for virtuous countries). Everything was scheduled indicating deadlines within which it was necessary to receive the relative contributions.

Having identified fifteen potential policies and actions through this mix based on the literature and respondents' experience, the next step was to place a value on these items. In all cases this work has a limitation of considering the complementarity among different policies (Borghesi et al., 2015; Howlett et al., 2017). Experts had pointed out that it was basic to have a description of these items. This last step was divided in two phases: the first phase of the survey had seen the experts choose the tool of a Skype video call providing a first ranking of the policy recommendations and actions for each waste stream; subsequently, these rankings were validated in the second phase acting through e-mails. In fact, all experts were familiar with the proposed methodology.

They were sent an Excel sheet that also contained an explanation of the different alternatives to be evaluated (i.e. a revised version of the initially prepared document). The analysis was conducted specifically for the three waste categories (ELV, WEEE and MSW). Experts could use a 10-point Likert Scale, ranging from not at all relevant (1) to extremely relevant (10) for each policy and action (D'Adamo and Sassanelli, 2022).

4. Results

The Likert Scale, applicable to different categories of stakeholders, can support policymakers as it assigns relevance (or not) to policy actions and recommendations. Several studies highlighted the relevance of this methodology applied to waste management (Ananno et al., 2021; Imbert et al., 2019; Matsumoto, 2020). Our approach is new as it considers this set but applied differently to the three distinct categories and for each one identifies a priority to follow. It should be emphasized that the strength of this analysis is that the experts are identified among different categories of stakeholders.

Starting from the 15 policy recommendations and actions identified in section 3 (Table 2), forty-five values were collected from each of the 20 experts for a total of nine hundred. On a scale of 1 to 10, the lowest value was never assigned, while the highest value was assigned in sixty cases (Tables A1-3). Figs. 1-3 show the average values (where the same relevance was assigned to all experts) of each item obtained by the second round of survey. In the WEEE category, all experts assigned the highest value to End of Waste, in eight cases together with the Proximity

Table 1
Survey participants.

N°	Role	Country	No. of years of experience	N°	Role	Country	No. of years of experience
1	Full Professor	Denmark	24	*11*	Manager	France	18
2	Full Professor	Croatia	20	*12*	Manager	Spain	16
3	Full Professor	Czechia	21	*13*	Manager	Austria	21
4	Full Professor	Romania	18	*14*	Manager	Sweden	15
5	Full Professor	United Kingdom	25	*15*	Manager	Belgium	19
6	Associate Professor	Finland	18	*16*	Politician	Germany	18
7	Associate Professor	Greece	16	*17*	Politician	The Netherlands	16
8	Associate Professor	Ireland	18	*18*	Politician	Poland	10
9	Associate Professor	Italy	16	*19*	Politician	Portugal	14
10	Associate Professor	Slovakia	14	*20*	Politician	Hungary	10

Table 2
List of policy recommendations and actions.

N°	Item	Definition	Reference
1	Bureaucracy	A system of government in which most of the important decisions are taken by state officials rather than by elected representatives	Oxford Languages
2	Consumer social responsibility	Socially conscious or morally motivated individual consumers who buy ethical products that match their ethical concerns	Caruana and Chatzidakis, 2014
3	Digital divide	Gap between demographics and regions that have access to modern information and communications technology and those that don't. Though the term now encompasses the technical and financial ability to utilize available technology—along with access (or a lack of access) to the internet—the gap it refers to is constantly shifting with the development of technology.	Investopedia
4	Eco-design	The integration of environmental aspects into the product development process, by balancing ecological and economic requirements	European Environment Agency
5	Economic subsidies	A benefit given to an individual, business, or institution, usually by the government. It can be direct (such as cash payments) or indirect (such as tax breaks). The subsidy is typically given to remove some type of burden, and it is often considered to be in the overall interest of the public, given to promote a social good or an economic policy.	Investopedia
6	End of Waste	A criterion specifying when certain waste ceases to be waste and becomes a product, or a secondary raw material.	European Commission – Waste Framework Directive
7	Extended producer responsibility	A policy approach under which producers are given a significant responsibility – financial and/or physical – for the treatment or disposal of post-consumer products.	OECD
8	Industrial symbiosis	The process by which wastes or by-products of an industry or industrial process become the raw materials for another.	European Commission
9	Policy responsibility	The state or fact of having a duty to deal with policy or of having control over it	Oxford Languages
10	Polluters pay principle	The principle according to which the polluter should bear the cost of measures to reduce pollution according to the extent of either the damage done to society or the exceeding of an acceptable level (standard) of pollution.	OECD
11	Prizes for virtuous countries	Rewards given to countries presenting higher moral standards than an average level	Oxford Languages
12	Proximity principle	The principle implying that waste should generally be managed as near as possible to its place of production, mainly because transporting waste has a significant environmental impact.	European Environment Agency
13	Social change	A paradigmatic change in the socio-economic structure, driven through cultural, religious, economic, scientific or technological forces.	Wikipedia
14	Technological improvement	The process of invention, innovation and diffusion of technology or processes	Wikipedia
15	Waste management measurability	The action of measuring performances related to processes and actions required to manage waste from its inception to its final disposal.	Wikipedia

principle, in five cases with Social change, and in three cases to all three of the above-mentioned items. In the ELV category, End of Waste was again the item to which the experts assigned the highest value, in two cases with Social change, in one case with the Proximity principle and in one case with Waste management measurability. In the MSW category, the experts assigned the highest value to Social change, in twelve cases with Consumer social responsibility and the Polluters pays principle, and in four cases only with Consumer social responsibility. In Figs. 1-3 the item that is considered most prominent is characterized by a brighter green.

WEEE circular strategy sees a relevance of End of Waste among other dimensions. The big issue of deciding when a wasted material (or materials recovered from them) ends to be considered a waste and starts to be considered a secondary raw material still represents a legislative problem in several MSs (Johansson and Forsgren, 2020; Mazzanti and Montini, 2014; Ragossnig and Schneider, 2019). Without a clear definition of when a waste can leave its hazardous nature in order to become a valuable source for the same/other value chains, is a critical issue to be solved as soon as possible. Only in a way both advanced recycling technologies developed during the years and recovered materials available in the market could be really exploited towards the creation of a circular economy. A second important element is represented by the Proximity principle (Kellenberg, 2015; Mazzanti and Zoboli, 2013; Weber et al., 2019). This is one of the main issues in WEEE management, where printed circuit boards (PCBs) - the most valuable element of WEEEs - usually are sold to multinational companies. The chance to manage PCBs at national level (maybe, through a network of dedicated medium-scaled plants) could allow maintaining resources internally and avoiding environmental impacts caused by complex logistic chains. Thirdly, social aspects are seen as an important element in order to make a circular economy practicable (Adekola et al., 2021; Kumar et al., 2020; Morone and Imbert, 2020). Only through the direct involvement of citizens, WEEE can be correctly collected, treated and recovered. To this aim, MSs should push on correct behaviours in terms of WEEE collection and separation from other types of wastes and clarify what is the destination of their products after disposal. Linked to the previous point, the extended producer responsibility is another element that could support the correct collection and treatment of WEEEs (Domenech and Bahn-Walkowiak, 2017). The direct involvement of producers in reverse logistic chains can increase recovered volumes, investments in new recycling technologies and circularity performances. This last point is linked to waste management measurability (Wang et al., 2017). Only through the optimization of current practices there could be the chance to clarify (and quantify) the amount of waste managed and treated within Europe. In this way, Key-performance indexes (KPIs) developed in a growing number of studies (see, for instance, (Colasante et al., 2022; Miola and Schiltz, 2019) could be easily calculated and performances of different nations could be easily compared.

ELV circular strategy is focusing (like discussed for WEEE) on End of

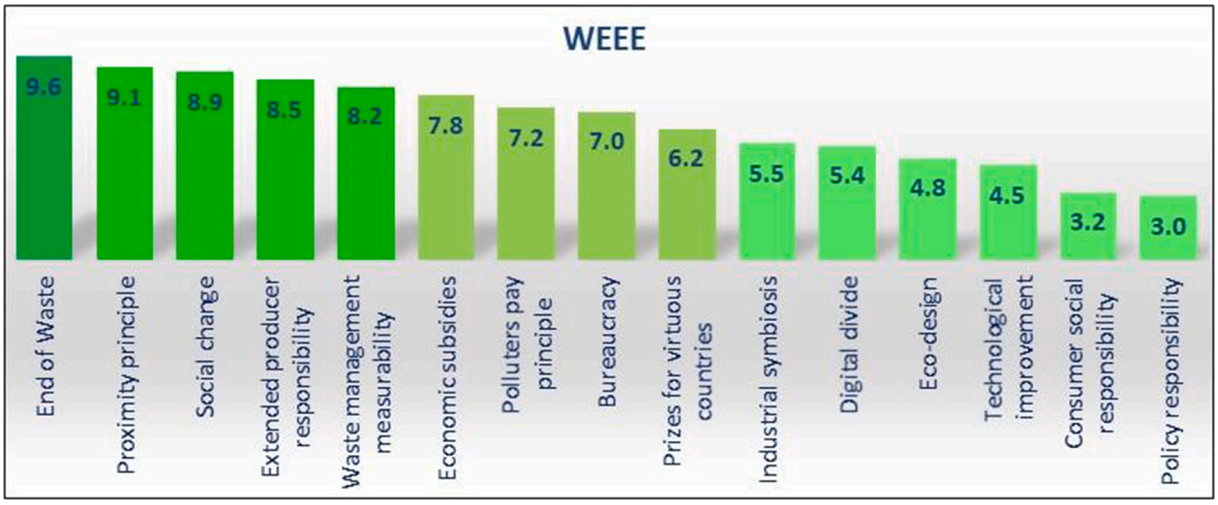

Fig. 1. Ranking of policy actions and recommendations for WEEE.

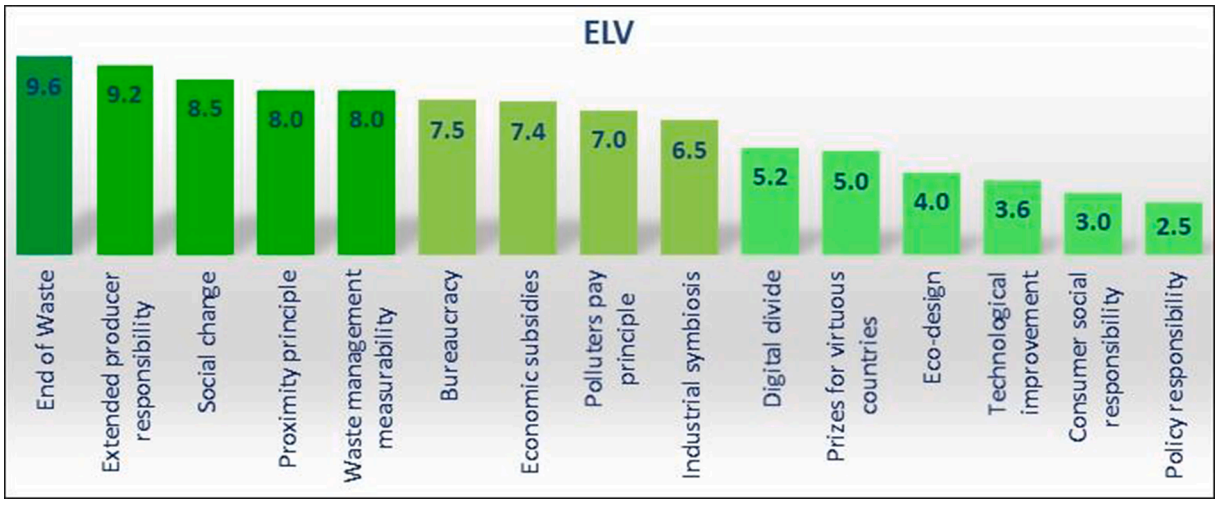

Fig. 2. Ranking of policy actions and recommendations for ELV.

Fig. 3. Ranking of policy actions and recommendations for WEEE.

Waste issues. Also for ELVs, there is an urgent need to clarify how recovered materials could be managed after recycling. Here, both non-metal materials (currently ending in the so-called Automotive Shredder Residue – ASR) and ashes represent an important issue from energetic recovery. All these materials (currently landfilled) could be finally recovered and reused, potentially also in the same automotive industry. A second important issue is represented by the Extended producer responsibility. Car manufacturers should better integrate with EoL actors in order to optimize both materials recovery and car design & development processes. Only through this interaction, materials embedded into cars could be really (and easily) recovered at the end of the car's life cycle. A third element regards social aspects. Also in ELVs (as reported above for WEEEs) as the behaviour of customers is a critical point. Citizens must become more aware about the impact of their obsolete cars on the environment and the benefits related to new forms of mobility systems. In order to better organize the treatment of ELVs, the proximity principle should be followed also in this case. Instead of having few big ELV treatment facilities, a higher number of medium-sized ones could allow maintaining resources in local supply chains and reducing the dependency from imported goods. Finally, waste management measurability is a relevant issue in ELVs. There are still too many obsolete cars disappearing from official registers and sent in eastern and extra European countries. The optimization of the reverse logistic chain could allow reducing these flows and increasing the amount of ELVs legally recovered, with a net advantage to have secondary materials available in the market.

The results regarding WEEE and ELVs show similar priorities, pointing to the necessity to better implement the extended producer responsibility pillar of EU strategies with the support of market based instrument policy mixes. It could be composed of subsidies and taxes/levies/charges in coherence with the institutional framework of the country and the specific value chain (Hemmelskamp et al., 2013; Mazzanti and Zoboli, 2006).

Experts suggest focusing on the core features of European waste policies, as developed out of the first German national policies in the 90′s: use but not priority to economic instruments, necessity to construct operational and effective collection and management systems at local level, which involve key actors on the production side. The role of consumers and related behavioral change is of lesser importance. This is a factor to seriously reflect upon; the role of consumer behavioral change through information campaigns, enhanced communication and pricing does not assume the same relevance across all waste streams. The apparently lower impact of technological improvements is food for further research. It may be linked to a mature stage of waste related technologies, with poor incremental possibilities to advance, or, partially connected to the aforementioned point, to the necessity to set new waste strategies with stronger focus on prevention, given that the 'era' of waste disposal and waste management policies may have already determined its effects over the last 30 years (European Environment Agency, 2019; Nicolli et al., 2012).

MSW's circular strategy is based on a deeper concept than just proper recycling. The social aspect takes on a priority role. In fact, citizen's role is an integral part of the change, as she/he becomes a key player in a circular market in which she/he not only individually carries out actions to protect the environment but also encourages other citizens. Social change, which is also significant for the other two categories of waste, assumes the highest value and is followed by Consumer social responsibility (which instead is considered not significant in both WEEE and ELV). These actions lead to a democratic contrast to phenomena such as Not in My Back Yard (NIMBY) and Not in My Term of Office (NIMTO) because it is the same citizen who asks for a change by adopting actions to protect ecosystems. At the same time, it is necessary to penalize those who obstruct this change. The Polluters Pay Principle has a very high value, much more than that calculated in the other two categories. Therefore, for this type of waste, there is a responsibility on the consumers' side. On the other hand, for the WEEE and ELV categories, the burden is on producers. The result related to the relevance of Waste management measurability could initially be interpreted as a consequential result of this study, however the moderate weight assigned to the awards for the performing countries indicates that this is not the case. It is simply that in a dynamic system, where waste is a resource but where this is not always possible (to this end, see the importance given to the End of Waste), it is necessary to measure and quantify because these types of analysis are able to signal anomalies and identify worrying trends. In addition, economic subsidies do not play a decisive role, a sign therefore that experts recognize that there have been various initiatives that favour this change. Experts here suggest using pricing (e.g. charges, levies, deposit refund systems, etc..) as a key driver which change market prices of green vs brown products and act as a complement to other determinants of social change insisting on intrinsic motivations (Cecere et al., 2014). Subsidies appear of lesser importance but could be useful to mitigate the cost of the transition for specific more fragile social classes. The Next Generation EU is further proof of this with significant weight assigned to sustainable transition. However, in the MSW sector they have a greater relevance as it is the one in which the different types of waste present (organic fraction, paper, glass, plastic) are seen as more critical in terms of actual profitability of reuse and recycling plants.

5. Discussion and policy implications

The analysis conducted in this paper showed several relevant instances for policy actions pointing at behavioural and regulatory aspects as those requiring most urgent interventions - an instance that, with some degree of variation, applies to the three waste streams considered. On the opposite side of the spectrum, technological aspects seem to rank persistently lower in the policy recommendations and actions inventory. Hence, in the experts view, behavioural and regulatory policies are key advantage points to accelerate the transition to a circular and sustainable waste management system. However, even if technological improvement seems to be not so important in terms of policy recommendations, it does not mean that the technological maturity has been already achieved. The message coming from the experts should just to be interpreted like a prioritization of policy actions, preferring to cope with those drivers that, more than others, could accelerate the circular and sustainable transition.

This outcome relates to the EU Waste Framework Directive, which defines the different types of waste processing along with definitions of their meaning for industry (Council directive 2008/98/EC). The Framework Directive led to the development of a Waste Hierarchy that identifies four broad waste management strategies, ranked from most desirable to the least. These can be labelled as follows: reduce, reuse, recycling and recover (disposal being a fifth option, yet to be avoided).

As pointed out by Fletcher et al. (2021), to contribute to the circular economy, waste management strategies should be positioned toward the top of the Waste Hierarchy, while to achieve this within the time frame set by the European targets, strategies should be technologically ready for implementation. To assess both the technological readiness and a strategy's place in the Waste Hierarchy, waste management strategies can be evaluated against the WH-TRL framework originally proposed by Rybicka et al. (2016).

As reported in Fig. 4, the 15 identified policy recommendations and actions can be grouped in the three categories mentioned above (behavioural, regulatory and technological) and related to the Waste Hierarchy. These are then combined (see right panel of Fig. 4) with the technology readiness level, as suggested by Rybicka et al. (2016). Four scenarios are then identified: (1) Desired; (2) High environmental/innovation potential; (3) Rethinking needed; (4) Not viable (low environmental potential).

The analysis developed in this paper suggests that the scenario that best fit the current situation in the three waste streams considered is the third one (Rethinking needed), which combines a high technological

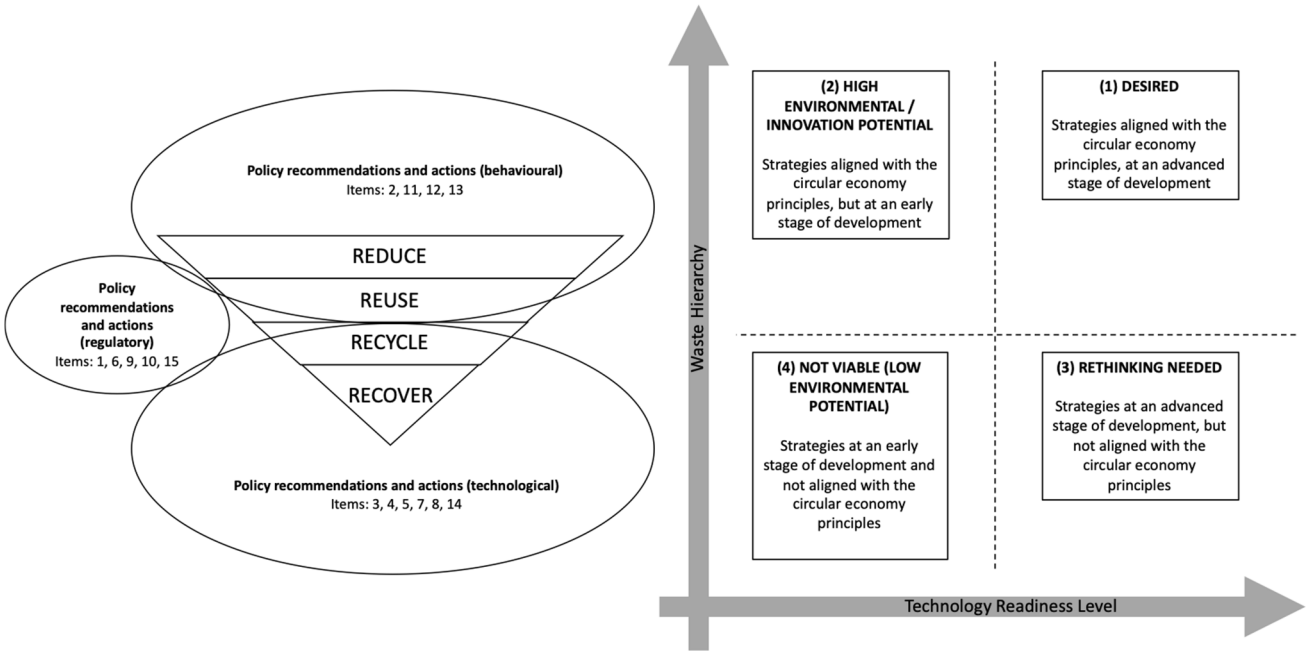

Fig. 4. Waste Hierarchy-TRL framework ().
adapted from Rybicka et al. (2016)

readiness level yet with a certain degree of misalignment from circular economy principles. Hence, behavioural and regulatory changes are needed to reach the desired scenario where strategies are well aligned with the circular economy principles and technologies already reached an advanced stage of development. The EEA report shows that waste related patents have shown a stable trend since the 90′s, compared to other environmental realms where patterns have increased more but also presented stronger volatility. Waste is a relatively more mature and stable 'technological market'. It remains to analyse in the next future whether the circular economy and waste prevention targets will radically change this long run pattern (European Environment Agency, 2019). This paper is unable to provide an assessment on the different role between developed and emerging countries because the analysis framework had the European reference sample. Clearly, additional elements should be considered by assessing the level of technologies used, the presence of subsidies, separate collection, regulations present, and political perceptions.

6. Conclusions

The EU Action Plan for the Circular Economy (COM/2020/98) aims to promote the reduction of waste generation and improve recycling. This work covers a gap in the literature as it analyzes the impact of different actions and policies on three different types of waste. The results show that end of waste has a key relevance for ELVs and WEEEs, while social change assumes a key role for MSW. Thus, the first result of this work is that end of waste and social change are enabling factors for the reuse and recycling practices of these wastes. In addition, it emerges that technological aspects are given secondary importance, while behavioral and regulatory policies are prioritized to foster resource circularity in waste management. In a Waste Hierarchy-TRL framework, the Rethinking needed scenario is the one that best fits the current waste management analyzed.

There are some limitations to the work, as it is unable to capture the interactions between different policies and correlations may prove to be very significant and can be extended to additional waste streams. In addition, the analysis was conducted at the European level and a comparison with other territories would be useful. It might be useful to propose degrees of correlation between different actions and policies and to evaluate dynamic models. However, it can be seen that the circular economy is no longer just a practice in which the benefit of waste is sought, but also becomes a social responsibility, with behaviors consistent with a sharing of resources.

Circular economy models move toward sustainability when there are mutually consistent policy interventions that lead to transparent management systems over the waste collected and processed. In this framework, resource sharing and stakeholders engagement are necessary as the waste sector is highly at risk of crime as it has very interesting valuable resources. The basic idea is that the circular economy can foster the development of new industrial areas, which have available resources and raw materials not originally found in their territories.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2022.09.031.

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