

Universidad San Jorge  
Escuela de Arquitectura y Tecnología



**SOSTENIBILIDAD Y GESTIÓN DE LOS RESIDUOS PELIGROSOS EN EUROPA:  
ANÁLISIS DE LA EFICIENCIA Y  
LOS TRASLADOS DE RESIDUOS PELIGROSOS  
DESDE UNA PERSPECTIVA DE CUMPLIMIENTO NORMATIVO**

**TESIS DOCTORAL**

**Carmen Callao Buatas**

**Villanueva de Gállego. 2021**



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#### **CERTIFICAN**

Que el trabajo de investigación recogido en la presente Tesis titulada: “Sostenibilidad y gestión de los residuos peligrosos en Europa: análisis de la eficiencia y los traslados de residuos peligrosos desde una perspectiva de cumplimiento normativo” Presentada en la Universidad San Jorge, ha sido realizada por Doña Carmen Callao Buatas, bajo su dirección y autorizan la presentación para optar al grado de Doctor.

Y para que conste, firmamos el presente certificado en Villanueva de Gállego (Zaragoza), a 23 de noviembre de 2021.

M<sup>a</sup>. Pilar Latorre Martínez

Margarita Martínez-Nuñez



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*¿Qué es un maestro? Te lo diré: no es alguien que enseña algo, sino alguien que inspira al estudiante a dar lo mejor de sí para descubrir un conocimiento que ya tiene dentro de su alma – Paulo Coelho*



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# INTRODUCCIÓN

*un viaje de mil millas comienza con un solo paso. (Lao Tse)*



# 1. INTRODUCCIÓN

Vivimos en un mundo en el que estamos acostumbrados a consumir rápido, en el que la publicidad y la sociedad nos llevan a consumir más de lo que en muchas ocasiones necesitamos, smart watch, relojes deportivos, teléfonos móviles, moda que cambia cada año y la facilidad de adquirir millones de productos de todos los tipos gracias a la compra online y sin tener que movernos.

Nos hemos acostumbrado a no reparar, se estropea una plancha y automáticamente compramos otra, la obsolescencia programada impide que nuestros electrodomésticos duren muchos años y los precios de las reparaciones y cambio de piezas son en ocasiones superiores a la adquisición de un nuevo producto.

Todos esos productos que deseamos en nuestro día a día (bolsas de plástico, botellas de agua, relojes o lavadoras), deben ser gestionados correctamente si no queremos que acaben en los océanos que ya se encuentran inundados por millones de toneladas de basura o con una gestión insuficiente contaminando la tierra, el aire y el agua que consumimos.

Partiendo de esta necesidad de gestionar residuos, y de la mayor peligrosidad que suponen los residuos peligrosos para el medio ambiente, esta tesis doctoral analiza cómo es esta gestión y qué pasa con los residuos peligrosos que producimos cada día en Europa ¿se gestionan de forma eficiente? ¿los gestionamos en España o los trasladamos?

En esta investigación y a través de un doble análisis, de datos y legislación, vamos a conocer qué sucede con nuestros residuos peligrosos, cómo se gestionan y cómo hay factores culturales, económicos y de innovación que repercuten en esa gestión.

## 1.1- EL DESARROLLO SOSTENIBLE

Naciones Unidas define el Desarrollo Sostenible como *“el desarrollo capaz de satisfacer las necesidades del presente sin comprometer la capacidad de las futuras generaciones para satisfacer sus propias necesidades”*. Es un concepto que comienza a surgir y a tomar forma en la década de los 70 (Pisani, 2007).

Du Pisani explica que el concepto de sostenibilidad nació ligado a la escasez de materiales, y fue a finales de la década de los 60 y en el inicio de los 70 cuando las teorías sobre desarrollo, sostenibilidad y crecimiento convergieron en el concepto de desarrollo sostenible y ello, porque se detectaron tres amenazas principales:

1. El aumento de población.
2. Escasez de recursos.
3. La contaminación.

Estas tres amenazas siguen siendo temas muy estudiados en la actualidad y han dado lugar a numerosa investigación y literatura científica, ya que están profundamente interrelacionadas entre ellas.

Respecto al aumento de población, hay que señalar que la población mundial alcanzó en 2011 los siete mil millones y las previsiones indican que se llegará a entre nueve mil y doce mil millones en 2100 (Gerland et al., 2014; Lee, 2011). Este aumento de población, tal y como indican estos autores, inevitablemente conllevará la necesidad de aumentar la producción tanto agrícola como ganadera, y exigirá aumentar la extracción de materias primas.

El aumento de la necesidad de materias primas genera inevitablemente tensiones que se trasladan a todos los actores de la economía, y así se ha dejado ver durante el año 2021 en la llamada “crisis de los microchips” que ha paralizado la producción en numerosas fábricas españolas, pero también en la ausencia de otras materias primas como el cobre, el aluminio o el gas natural (Feijóo, 2021).

Además de la población, también se prevé que aumente la riqueza per cápita en países como China, India y algunos países africanos, lo que hará que inevitablemente crezca la demanda de materias primas en los países que experimenten un aumento en su riqueza (Allwood et al., 2011; Rosenau-Tornow et al., 2009). El crecimiento de la riqueza de la población se traducirá también en un aumento de la demanda energética (Malinauskaite et al., 2017), es decir, que el aumento de la población y la necesidad de recursos y materias primas va ligada inexorablemente a la escasez de recursos.

La presión sobre las materias primas y los recursos naturales hizo que en el año 2011 se publicase en la Unión Europea la primera lista de materias primas críticas, es decir, materias primas imprescindibles para el desarrollo de la industria y de las nuevas tecnologías, entre las que se encontraba la fluorita, el cobalto o el magnesio. Esta lista, que se actualiza cada tres años, ha pasado de incluir 14 materias primas críticas en 2011 a 30 en 2020, año en el que se ha añadido por primera vez el litio al listado de materias primas críticas, ya que se prevé el aumento exponencial de su demanda por el uso de los coches eléctricos y de las nuevas tecnologías.

Por último y respecto a la contaminación, la preocupación por la emisión de Gases de Efectos Invernadero (GEIs), dio lugar a la firma del Acuerdo de París el 12 de diciembre de 2015 (Unfccc, 2015), adoptado por 197 países y, en el que se reconoce que el cambio climático es un problema para toda la humanidad y es necesario adoptar medidas para hacerle frente, y que recoge los siguientes objetivos:

*“a) Mantener el aumento de la temperatura media mundial muy por debajo de 2°C con respecto a los niveles preindustriales, y proseguir los esfuerzos para limitar ese aumento de la temperatura a 1,5 °C con respecto a los niveles preindustriales, reconociendo que ello reduciría considerablemente los riesgos y los efectos del cambio climático;*

*b) Aumentar la capacidad de adaptación a los efectos adversos del cambio climático y promover la resiliencia al clima y un desarrollo con bajas emisiones de gases de efecto invernadero, de un modo que no comprometa la producción de alimentos; y*

*c) Situar los flujos financieros en un nivel compatible con una trayectoria que conduzca a un desarrollo resiliente al clima y con bajas emisiones de gases de efecto invernadero.”*

El concepto de Desarrollo Sostenible, además de haber sido introducido por Naciones Unidas a través de sus ambiciosos objetivos de desarrollo sostenible, es un objetivo fundamental en la Unión Europea y fue incluido en 1997 en el Tratado de Ámsterdam. Desde entonces la estrategia de desarrollo sostenible ha ido sufriendo cambios hasta experimentar una gran revolución, ya que el concepto de desarrollo sostenible va ligado tanto al medio ambiente como a la actividad económica o a la salud de la población.

### 1.1.1 EL DESARROLLO SOSTENIBLE EN EUROPA

La Directiva Marco de Residuos (Parlamento Europeo y Consejo, 2008) recoge en su artículo 1 el objetivo de *“establecer medidas destinadas a proteger el medio ambiente y la salud humana mediante la prevención o la reducción de los impactos adversos de la generación y gestión de los residuos, la reducción de los impactos globales del uso de los recursos y la mejora de la eficacia de dicho uso”*, objetivo ligado a la sostenibilidad tal como afirma en su artículo 4 *“Los Estados miembros tendrán en cuenta los principios generales de precaución y sostenibilidad en el ámbito de la protección medioambiental, viabilidad técnica y económica, protección de los recursos, así como el conjunto de impactos medioambientales, sobre la salud humana, económicos y sociales”*.

Si bien la sostenibilidad es un objetivo en la Unión Europea, la industria de gestión de residuos muestra un modelo débil de sostenibilidad. Los investigadores afirman respecto a los compromisos con la sostenibilidad de las empresas analizadas, que no está claro si dichos compromisos responden a imperativos de los negocios o si responden a un compromiso real con la sostenibilidad, ya que las empresas ponen el acento en un aumento de la eficiencia ligado entre otros a aspectos económicos, sociales y a medioambientales pero no ligados a la viabilidad e integridad de los ecosistemas naturales y en la reducción de las demandas sobre recursos naturales finitos. Por lo que, en las empresas analizadas, la gestión de residuos refleja un modelo "débil" en lugar de que un modelo "fuerte" de sostenibilidad. Más críticamente, los autores sugieren que los compromisos de las empresas seleccionadas con la sostenibilidad se muestran dentro de los modelos comerciales existentes centrados en el crecimiento continuo (Jones and Comfort, 2019).

La gestión de los residuos es un factor clave para el desarrollo sostenible, afirmación que se encuentra alineada con las tres amenazas de las que habla Du Pisani (Pisani, 2007) y en particular con el aumento de la riqueza per cápita, ya que la generación de residuos aumenta cuando aumenta el PIB, relación que es notoria en el flujo de Residuos de Aparatos Eléctricos y Electrónicos (RAEEs) (Awasthi et al., 2018a; Kusch and Hills, 2017), pero también de residuos industriales (Yanrong et al., 2011). La relación entre aumento de PIB y aumento en la generación de residuos tiene su reflejo en la relación que existe entre el aumento de PIB y el aumento de residuos eléctricos y electrónicos generados, lo que hace que este sea uno de los flujos de más rápido crecimiento, y es que, a mayor renta per cápita mayor es la cantidad de teléfonos, ordenadores o teléfonos móviles que se consumen (Awasthi et al., 2018b).

## 1.1.2 NORMATIVA Y LEGISLACIÓN QUE TIENEN COMO OBJETIVO LA MEJORA DEL MEDIO AMBIENTE Y EL DESARROLLO SOSTENIBLE

Una de las políticas cuyo objetivo es incidir de forma positiva sobre el medio ambiente y por lo tanto en el desarrollo sostenible, es la economía circular (McDowall et al., 2017; Zhu et al., 2019).

La economía circular es un concepto introducido por David Pearce en los años 90, y que fue adoptado en China con su ley de economía circular, publicada en el 2008 y que entró en vigor en el año 2009.

La economía circular, tal y como especificaba la Comisión Europea en su primer plan de acción tenía como objetivo que *“el valor de los productos, los materiales y los recursos se mantenga en la economía durante el mayor tiempo posible, y en la que se reduzca al mínimo la generación de residuos”*.

Es decir, que la economía circular persigue un triple objetivo:

- a) Reducir la demanda de materias primas, tal y como se detalla en la estrategia europea de materiales críticos, ya que la valorización y el reciclaje de estos residuos evitará la extracción y adquisición de nuevas materias primas, permitiendo aprovechar las que ya están en circulación en nuestra economía.
- b) Evitar que los residuos sean eliminados, dándoles valor y una nueva vida a través del reciclaje y la valorización.
- c) Contribuir a la neutralidad climática reduciendo las emisiones.

El término economía circular hace referencia a la transformación de la función de los recursos en la economía (Preston, 2012), haciendo que los residuos sean utilizados como materias primas (Kama, 2015) y de acuerdo al principio de las 3R (reducir, reutilizar y reciclar) (Ranta et al., 2018).

Con este nuevo marco normativo de economía circular es posible que los residuos sean gestionados y reutilizados en el país en el que han sido generados, o que sean trasladados a otro país para su tratamiento, ya que lo importante será la reutilización del mismo y el mantenimiento de esas materias primas, bien sea reciclándolas, o reacondicionando productos para que pueda existir un mercado de productos de segunda mano (lavadoras, coches, teléfonos...).

En Europa, no fue hasta el año 2015 cuando la Comisión Europea publicó un ambicioso paquete de economía circular en el que introdujo los siguientes objetivos para conseguir en el año 2030:

- reciclado del 65 % de los residuos municipales
- reciclado del 75 % de los residuos de envases
- reducción de la eliminación en vertedero a un máximo del 10 %
- prohibición del depósito en vertedero de los residuos recogidos por separado.

Para lograr esos objetivos, el plan de economía circular iba acompañado de propuestas de modificación de las siguientes directivas:

- Propuesta de Directiva sobre los residuos, modificación que fue aprobada en el año 2018 (DIRECTIVA (UE) 2018/851 DEL PARLAMENTO EUROPEO Y DEL CONSEJO de 30 de mayo de 2018 por la que se modifica la Directiva 2008/98/CE sobre los residuos).
- Propuesta de Directiva sobre los residuos de envases, modificación que fue aprobada en el año 2018 (DIRECTIVA (UE) 2018/852 DEL PARLAMENTO EUROPEO Y DEL CONSEJO de 30 de mayo de 2018 por la que se modifica la Directiva 94/62/CE relativa a los envases y residuos de envases).
- Propuesta de Directiva sobre vertederos, modificación que fue aprobada en el año 2018 (Directiva (UE) 2018/850 del Parlamento Europeo y del Consejo, de 30 de mayo de 2018, por la que se modifica la Directiva 1999/31/CE relativa al vertido de residuos).
- Propuesta de Directiva sobre residuos eléctricos y electrónicos, modificación aprobada en el año 2018 (DIRECTIVA (UE) 2018/849 DEL PARLAMENTO EUROPEO Y DEL CONSEJO de 30 de mayo de 2018 por la que se modifican la Directiva 2000/53/CE relativa a los vehículos al final de su vida útil, la Directiva 2006/66/CE relativa a las pilas y acumuladores y a los residuos de pilas y acumuladores y la Directiva 2012/19/UE sobre residuos de aparatos eléctricos y electrónicos).

Es decir, que el paquete de economía circular y la introducción de objetivos están en línea o son una forma de implementar directamente la jerarquía de gestión de residuos que recoge la Directiva Marco de Residuos (Parlamento Europeo y Consejo, 2008) que indica que la jerarquía *“establece en general un orden de prioridad de lo que constituye la mejor opción global para el medio ambiente en la legislación y la política en materia de residuos”* y que se recoge en el artículo 4 de la Directiva *“1. La siguiente jerarquía de residuos servirá de orden de prioridades en la legislación y la política sobre la prevención y la gestión de los residuos:*

*a) prevención;*

*b) preparación para la reutilización;*

*c) reciclado;*

*d) otro tipo de valorización, por ejemplo, la valorización energética; y*

*e) eliminación.”*

A través de la prevención, Europa trata de reducir el contenido de sustancias perjudiciales en materiales y productos y, por lo tanto, la cantidad de residuos peligrosos producidos, flujo de residuos, el de residuos peligrosos que es objeto de análisis en esta tesis doctoral.

Pero incluso, si la prevención está en lo más alto de la jerarquía de gestión de residuos, la Directiva Marco de Residuos establece diferentes operaciones de gestión de residuos y ha considerado que dos ellas, la incineración y la eliminación en vertedero merecían una especial atención y por lo tanto promulgó Directiva (UE) 2018/850 del Parlamento Europeo y del Consejo, de 30 de mayo de 2018, por la que se modifica la Directiva 1999/31/CE relativa al vertido de residuos y la Directiva 2000/76/CE del Parlamento Europeo y del Consejo, de 4 de diciembre de 2000, relativa a la incineración de residuos. Esta Directiva quedó derogada el 7 de enero de 2014

por la Directiva 2010/75/UE de 24 de noviembre de 2010, sobre las emisiones industriales (prevención y control integrados de la contaminación).

Es decir que en Europa y a través de las diferentes normativas se detectan varios temas de especial importancia, por un lado, la existencia de residuos peligrosos y por otro el control en la eliminación de los residuos, bien a través de la incineración o bien a través del depósito en vertederos, de ahí que el análisis de los residuos peligrosos y dónde son eliminados sea un aspecto crucial para el desarrollo sostenible.

Pero en línea con los objetivos de la economía circular, también es importante conocer qué países son los que reciben más residuos para valorizar y si ese flujo de residuos para valorización puede estar ligado a un mayor PIB y a una mayor capacidad de innovación de los países.

Otras operaciones de gestión de residuos como el reciclaje o las operaciones de valorización no están reguladas en directivas, sino que son objetivos que se introducen en la legislación tal y como propuso (Gordon, 1986), y que los Estados Miembros de la UE tienen que alcanzar. Y siempre sin perder de vista el objetivo de una correcta gestión y la optimización de los sistemas de gestión de residuos peligrosos (Nema and Gupta, 1999).

La valorización de los residuos también contribuirá a aumentar el PIB de los países, la Comisión Europea afirma que la inversión privada ligada a la economía circular fue aproximadamente del 0.1 del PIB de Europa (European Commission, 2018). En línea con esta afirmación, la Fundación Ellen McArthur calculó que la economía circular haría crecer la economía europea en un 7% (Ellen MacArthur Foundation and the McKinsey Center for Business and Environment, 2015).

## 1.2. EL AUMENTO EN LA GENERACIÓN DE RESIDUOS

### 1.2.1 LA LEGISLACIÓN COMO MOTOR DE CAMBIO

El aumento en la generación de residuos es una constante en los últimos años, y así lo muestran los datos de Eurostat (Tabla 1).

Tabla 1 – Toneladas de residuos producidas en Europa

**Tabla 1.- TONELADAS DE RESIDUOS (PELIGROSOS Y NO PELIGROSOS) PRODUCIDAS EN EUROPA**

2010	2012	2014	2016	2018
2.454.720.000	2.483.990.000	2.507.100.000	2.536.170.000	2.619.880.000

Con este aumento de 200 millones de toneladas de residuos generados en un periodo de 8 años, la gestión de estos se ha convertido en una materia de creciente interés en todo el mundo

(Andersson and Stage, 2018; Sakai et al., 2017; Um et al., 2018) y ha dado paso a la adopción de diferentes políticas y normativas.

La legislación y los cambios legislativos son usados para intentar lograr mejoras en la gestión de residuos, bien sea para evitar que los residuos acaben en los vertederos o para lograr una mejora en la gestión de ciertos flujos como ocurre con las Directivas que regulan el fin de la vida de los vehículos, los envases o embalajes o los residuos de aparatos eléctricos y electrónicos. Sin embargo estas directivas que se dirigen a una parte del público como pueden ser los productores y los gestores de residuos, olvidan a otra parte, que son los usuarios particulares y que muchas veces y por comodidad acaban tirando una caja de cartón o un despertador al cubo de la basura, sin ser conscientes de cómo una buena gestión en los hogares tendrá una repercusión muy positiva sobre el medio ambiente, pudiendo, por ejemplo, evitar que los lixiviados de los vertederos se contaminen con los restos de pilas y consiguiendo aumentar el reciclado de cartón, vidrio o plástico y, evitando por lo tanto, la extracción de materias primas (Gerrard and Kandlikar, 2007; Mazzanti and Zoboli, 2008; Simões and Marques, 2012).

Sin embargo, también se ha comprobado que el hecho de que la legislación introduzca unas obligaciones y unos objetivos, no siempre asegura la eficiencia de los sistemas, ya que la existencia de unos objetivos marcados por la Directiva de envases y embalajes no aumenta la eficiencia de la gestión debido a los altos costes de la misma, como consecuencia de la falta de incentivos (Simões and Marques, 2012).

En la relación entre legislación y gestión de residuos, no hay que olvidar que la innovación y los aspectos medioambientales están profundamente relacionados. La conocida como “hipótesis de Porter” señaló la importancia de la existencia de unas estrictas normativas medioambientales para la introducción de tecnologías limpias y mejoras medioambientales (Porter and van der Linde, 1995). La relación entre políticas e innovación ha sido ampliamente estudiada (Ashford and Hall, 2011; Cecere and Corrocher, 2016; Chen et al., 2017; Fankhauser et al., 2013; Guo et al., 2017; Melece, 2015) ya que las innovaciones tecnológicas pueden ayudar a alcanzar los objetivos medioambientales (Jordaan et al., 2017), y por lo tanto, a conseguir un desarrollo sostenible (Ashford and Hall, 2011).

A este fenómeno de interrelación entre la existencia de estrictas normas medioambientales y el desarrollo tecnológico se le ha dado diferentes denominaciones crecimiento verde (Guo et al., 2017) o eco-innovación (Chen et al., 2017; Jo et al., 2015; Melece, 2015; Nill and Kemp, 2009).

La normativa y la innovación pueden ayudar a que el crecimiento económico no tenga como consecuencia la producción de un daño medioambiental (Mazzanti and Nicolli, 2011; Nill and Kemp, 2009).

Es decir, que la legislación medioambiental, es sin duda una gran aliada para conseguir los objetivos de desarrollo sostenible a través de la innovación, pero no hay que olvidar, que para conseguir esos objetivos, es importante que la eco-innovación sea medida y existan unos datos fiables y objetivos sobre la misma (Fernando et al., 2013).

En Europa la innovación se mide a través del cuadro europeo de indicadores de la innovación, que en el año 2021 ha celebrado su 10ª edición y *“proporciona un análisis comparativo del rendimiento de la innovación en los países de la UE, otros países europeos y vecinos regionales.*

*Evalúa las fortalezas y debilidades relativas de los sistemas nacionales de innovación y ayuda a los países a identificar las áreas que deben abordar* (“Regional innovation scoreboard 2021 - Publications Office of the EU,” 2021)

### 1.2.3 LA LEGISLACIÓN SOBRE TRASLADO DE RESIDUOS

Hay que tener en cuenta que la gestión de los residuos tiene un alto coste económico que se traduce en dos consecuencias negativas. Por un lado, el coste de gestión de los residuos está en el origen de los traslados ilegales de residuos (Bernard, 2011; Boudier and Bensebaa, 2011), y por otro lado, esos costes son una barrera para que la economía circular se convierta en una realidad, ya que la economía circular busca la reutilización de los residuos y no su eliminación (Golev et al., 2015). Los traslados ilegales se producen, tal y como indica Bernard, cuando se envían residuos de aparatos eléctricos y electrónicos a países de África como si fuesen bienes de segunda mano aptos para ser usados en esos países, cuando la mayoría de las veces se trata de residuos, es decir, de equipos que no se pueden usar y que acabarán tirados en vertederos carentes de gestión y de control, este ejemplo puede ser extensible a otros flujos de residuos (Bernard, 2011).

La preocupación se incrementa cuando los traslados ilegales, tal y como es habitual, son traslados de residuos peligrosos, que van a ser eliminados en vertederos ilegales.

Entre el año 2010 y el 2018 se produjo un aumento de 200 millones en los residuos generados (Tabla 1), y de los residuos que anualmente se generan en Europa hay una parte que son residuos peligrosos. En la Tabla 2 se muestra la cantidad de residuos peligrosos producidas en ese periodo de tiempo.

Según los datos de Eurostat, la generación de residuos peligrosos también presenta una tendencia al alza, tal y como se muestra en la Tabla 2.

Tabla 2 – Toneladas de residuos peligrosos producidas en Europa

TONELADAS DE RESIDUOS PELIGROSOS PRODUCIDAS EN EUROPA				
2010	2012	2014	2016	2018
96.060.000	95.370.000	94.870.000	100.670.000	107.850.000

De hecho, la generación de residuos peligrosos es uno de los problemas más importantes a los que Europa tiene que hacer frente. En el año 2014, se produjeron en Europa 2502 millones de toneladas de residuos, de las cuales, aproximadamente 95 millones de toneladas eran residuos peligrosos.

La definición de residuo y de residuo peligroso las encontramos en la Directiva Marco de Residuos, Directiva 2008/98/CE del Parlamento Europeo y del Consejo, de 19 de noviembre de 2008, sobre los residuos y por la que se derogan determinadas Directivas (Texto pertinente a efectos del EEE) que en su artículo 3 define los residuos como “*cualquier sustancia u objeto del cual su poseedor se desprenda o tenga la intención o la obligación de desprenderse*” y los

residuos peligrosos como *“residuo que presenta una o varias de las características peligrosas enumeradas en el anexo III”*. Esas características son: H 1 «Explosivo», H 2 «Oxidante», H 3-A «Fácilmente inflamable», H 3-B «Inflamable», H 4 «Irritante», H 5 «Nocivo», H 6 «Tóxico», H 7 «Cancerígeno», H 8 «Corrosivo», H 9 «Infeccioso», H 10 «Tóxico para la reproducción», H 11 «Mutagénico», H 12 Residuos que emiten gases tóxicos o muy tóxicos al entrar en contacto con el aire, con el agua o con un ácido., H 13 (\*) «Sensibilizante», H 14 «Ecotóxico».

Según esta Directiva *“Los Estados miembros adoptarán las medidas necesarias para velar por que la producción, la recogida y el transporte de residuos peligrosos, así como su almacenamiento y tratamiento, se lleven a cabo en unas condiciones que aseguren la protección del medio ambiente y de la salud humana”* y ello porque tanto la eliminación de los residuos en vertederos como la incineración de los mismos tiene un alto impacto en la salud (Forastiere et al., 2009) y ha dado lugar a movimientos como el conocido por sus siglas en inglés NIMBY (Not In My Backyard) (O’Neill, 1998), que traducido quiere decir *“no en mi patio trasero”*, y que rechaza por ejemplo la instalación de vertederos o incineradoras cerca de los barrios de las ciudades.

Como ya hemos indicado, hay una clara relación entre el producto interior bruto de cada país y la generación de residuos (Awasthi et al., 2018b).

Pero el PIB es una variable que presenta un doble interés, ya que además de ir unida al aumento en la generación de residuos, (Awasthi et al., 2018c; Kusch and Hills, 2017), los traslados se producen de países ricos a países pobres (Sonak et al., 2008a).

Esto hace que los residuos viajen por todo el mundo y que haya un tráfico de residuos de los países del Hemisferio Norte a los países del Hemisferio Sur.

Los traslados de residuos peligrosos han sido estudiados desde diferentes puntos de vista.

- 1) Los traslados de residuos del hemisferio norte al hemisferio sur han sido estudiados en profundidad (Cotta, 2020; Lucier and Gareau, 2016; Renckens, 2015; Sonak et al., 2008b), dado el riesgo que representan para los países en vías de desarrollo. Sin embargo, hay que tener presente que esa afirmación tiene sus excepciones, y por ejemplo los investigadores han comprobado que Estados Unidos exporta más residuos a Canadá que a México (Moore et al., 2019, 2018).
- 2) También han sido estudiados desde el punto de vista de la representación/visualización de las rutas, ya que esto puede ayudar a entender las características de los destinos de los residuos y a tomar decisiones sobre las mejores rutas (Rosenfeld et al., 2018; Vincent et al., 2019). Los traslados de residuos han sido estudiados con objeto de optimizar las rutas y evitar problemas para las poblaciones que atraviesan (Laurence and Wynne, 2010; Nema and Gupta, 1999; ReVelle et al., 1991) , ya que los autores buscan el mejor *“modelo”* para planificar y reducir los riesgos a la salud y al medio ambiente.
- 3) El transporte de residuos también ha sido estudiado por las emisiones que genera. El estudio de emisiones en el transporte se ha realizado tanto para el transporte aéreo (Morrell, 2007), transporte por carretera (Ong et al., 2011) y el transporte marítimo (Viana et al., 2014).

Para evitar el tráfico ilegal de residuos que hemos recogido en el punto 1), la ONU promulgó la Convención de Basilea, a la que la UE está adherida y que trasladó al REGLAMENTO (CE) No 1013/2006 DEL PARLAMENTO EUROPEO Y DEL CONSEJO de 14 de junio de 2006 relativo a los traslados de residuos.

En Europa, en la regulación de los traslados de residuos, confluyen dos normas que regulan diferentes aspectos y en diferente profundidad los traslados de residuos.

Por un lado, la Directiva Marco de Residuos regula las figuras que actúan en la gestión de los mismos (productor de residuos, gestor, transportista, agente y negociante de residuos), así como ciertos aspectos de su gestión y establece dos principios para la gestión de los residuos peligrosos: el principio de proximidad y el principio de autosuficiencia.

Los principios de proximidad y autosuficiencia están regulados en el artículo 16 de la Directiva Marco de Residuos con el siguiente tenor literal *“1. Los Estados miembros tomarán las medidas oportunas, en cooperación con los demás Estados miembros cuando sea necesario o aconsejable, para establecer una red integrada y adecuada de instalaciones de eliminación de residuos y de instalaciones para la valorización de residuos municipales mezclados recogidos de hogares privados, incluso cuando dicha recogida también abarque tales residuos procedentes de otros productores, teniendo en cuenta las mejores técnicas disponibles.*

*No obstante, lo dispuesto en el Reglamento (CE) no 1013/2006, los Estados miembros, para proteger su red, podrán limitar los traslados entrantes de residuos destinados a los incineradores que estén clasificados como valorización, cuando se haya establecido que dichos traslados tendrían como consecuencia que los residuos nacionales tendrían que ser eliminados o que estos residuos tendrían que ser tratados de una manera que no fuese compatible con sus planes de gestión de residuos. Los Estados miembros notificarán dicha decisión a la Comisión. Los Estados miembros también podrán limitar las salidas de residuos por motivos medioambientales enunciados en el Reglamento (CE) no 1013/2006.*

*2. Dicha red estará concebida de tal manera que permita a la Comunidad en su conjunto llegar a ser autosuficiente en materia de eliminación de residuos, así como de valorización de los residuos mencionados en el apartado 1, y que permita a los Estados miembros avanzar hacia ese objetivo individualmente, teniendo en cuenta las circunstancias geográficas o la necesidad de instalaciones especializadas para determinados tipos de residuos.*

*3. La red deberá permitir la eliminación de los residuos o la valorización de los residuos mencionados en el apartado 1 en una de las instalaciones adecuadas más próximas, mediante la utilización de las tecnologías y los métodos más adecuados para asegurar un nivel elevado de protección del medio ambiente y de la salud pública.*

*4. Los principios de proximidad y autosuficiencia no significan que cada Estado miembros deba poseer la gama completa de instalaciones de valorización final en su territorio.”*

Los principios de proximidad y autosuficiencia pueden aumentar el poder de mercado de los gestores locales tal y como afirman Reggiani y Silvestri (Reggiani and Silvestri, 2017), pero con independencia de los efectos que señalan los autores citados, estos principios son analizados por su importancia legal (Jans, 1999; Reese, 2018).

La aplicación del principio de proximidad disminuye el peligro en el transporte de residuos peligrosos (Alumur and Kara, 2007; ReVelle et al., 1991; Yilmaz et al., 2017) y las emisiones producidas por el transporte de residuos por carretera, además de que la necesidad de cumplir estos principios, puede tener como consecuencia la necesidad de innovación, tal y como señala la hipótesis de Porter (Porter and van der Linde, 1995).

Otra norma europea que regula el traslado de residuos es el Reglamento (EC) No. 1013/2006 que en su exposición de motivos indica *“El objetivo y el componente principal y predominante del presente Reglamento es la protección del medio ambiente, y sus efectos sobre el comercio internacional son meramente incidentales”*, es decir, que comparte el objetivo de protección al medio ambiente que recoge la Directiva Marco de Residuos.

Este Reglamento incide de forma directa sobre los traslados de residuos peligrosos y así lo manifiesta al decir *“Es también importante tener en cuenta el requisito recogido en el artículo 4, apartado 2, letra d), del Convenio de Basilea de reducir los traslados de residuos peligrosos al mínimo, en consonancia con la gestión ambientalmente correcta y eficiente de dichos residuos.*

*(9) Además, es importante tener en cuenta que con arreglo al artículo 4, apartado 1, del Convenio de Basilea cada Parte tiene derecho a prohibir la importación de residuos peligrosos o de los residuos incluidos en la lista del anexo II de ese Convenio.”*

El Reglamento de traslado de residuos fue modificado en el año 2014 por el REGLAMENTO (UE) No 660/2014 DEL PARLAMENTO EUROPEO Y DEL CONSEJO de 15 de mayo de 2014 por el que se modifica el Reglamento (CE) no 1013/2006 relativo a los traslados de residuos y que pone el acento en las inspecciones de estos traslados con objeto de evitar traslados ilícitos y así lo recoge en su parte expositiva *“Los traslados ilícitos de residuos se derivan con frecuencia de la recogida, clasificación y almacenamiento incontrolados. La inspección sistemática de los traslados de residuos debe, por lo tanto, contribuir a detectar y hacer frente a dichas actividades incontroladas, contribuyendo así a la aplicación del Reglamento (CE) no 1013/2006.”*

Sin embargo, y aunque a través de las inspecciones se intentan evitar los traslados ilegales de residuos, incluso después de esta modificación se han encontrado vacíos legales que son aprovechados para traslados ilícitos de residuos (, Morganti manifiesta la necesidad de simplificar el lenguaje usado en la legislación sobre residuos y la necesidad de que se aumenten la tecnología para realizar inspecciones de residuos, ya que cualquier vacío legal puede ser una oportunidad para la comisión de delitos y de ilícitos administrativos(Morganti et al., 2020).

La normativa sobre traslados de residuos fue modificada recientemente como consecuencia de la prohibición China de importar plástico del extranjero desde el año 2018. Esto llevó a una modificación de la Convención de Basilea y a una modificación del Reglamento europeo de traslado de residuos. La principal modificación ( ) fue evitar los traslados ilegales de plásticos dada la contaminación que el plástico produce en el medio ambiente, sin embargo, esta tarea que ha logrado catalogar como residuo peligroso a una parte del plástico que se traslada entre países, deja fuera de su ámbito de aplicación una inmensa mayoría de plástico que es catalogado como residuo no peligroso (Khan, 2020).

La modificación del Reglamento de traslado de residuos se produjo por el REGLAMENTO DELEGADO (UE) 2020/2174 DE LA COMISIÓN de 19 de octubre de 2020 por el que se modifican

los anexos IC, III, IIIA, IV, V, VII y VIII del Reglamento (CE) nº 1013/2006 del Parlamento Europeo y del Consejo, relativo a los traslados de residuos que señalaba el principal cambio en su exposición de motivos *“En lo que respecta a la exportación de residuos de materias plásticas de la Unión a terceros países y a la importación de residuos de materias plásticas en la Unión desde terceros países, deben modificarse los anexos III, IV y V del Reglamento (CE) n.o 1013/2006 para adaptarlos a las enmiendas de los anexos II, VIII y IX del Convenio de Basilea y a las enmiendas del apéndice 4 de la Decisión de la OCDE. En consecuencia, a partir del 1 de enero de 2021, la exportación desde la Unión y la importación en la Unión de residuos de materias plásticas incluidos en las categorías AC300 e Y48 hacia y desde terceros países a los que se aplique la Decisión de la OCDE (3) estarán sujetas al procedimiento de notificación y autorización previas por escrito. De conformidad con el artículo 36, apartado 1, letras a) y b), y el anexo V del Reglamento (CE) n.o 1013/2006, estará prohibida la exportación de desechos plásticos incluidos en las categorías A3210 e Y48 a terceros países a los que no se aplique la Decisión de la OCDE.”*

El cumplimiento de las normas citadas, Directiva Marco de Residuos y Reglamento de traslado de residuos deberá tener como consecuencia una disminución en los traslados de residuos para eliminación y un mayor control del tráfico ilícito de residuos de los países ricos a los países pobres.

### 1.3. LA IMPORTANCIA DE LA MEDICIÓN A TRAVÉS DE LOS DATOS

*“Una meta es absolutamente diferente de un deseo. Es algo claro, escrito y específico. Se puede describir con rapidez y facilidad a otra persona. Se puede medir y se sabe cuándo se ha alcanzado y cuándo no se ha alcanzado” (Tracy, 2004)*

Partiendo del aforismo de Brian Tracy (Tracy, 2004) vemos la importancia de que los objetivos de reciclaje recogidos en las diferentes directivas de residuos se reflejen en los datos que cada país comunica a Eurostat, centro encargado de elaborar estadísticas y cuyas funciones son:

- *desarrollar definiciones, clasificaciones y metodologías armonizadas para la elaboración de las estadísticas oficiales europeas, en colaboración con las autoridades estadísticas nacionales*
- *calcular los datos agregados para la Unión Europea y la zona del euro a partir de la información recopilada por las autoridades estadísticas nacionales según normas armonizadas*
- *poner estadísticas europeas a libre disposición de los responsables y los ciudadanos a través de la web de Eurostat y otros canales”.*

La comunicación de los datos relativos a los residuos, no es algo voluntario para los Estados Miembro de la Unión Europea, sino que se trata de una obligación recogida en el REGLAMENTO (CE) No 2150/2002 DEL PARLAMENTO EUROPEO Y DEL CONSEJO de 25 de noviembre de 2002 relativo a las estadísticas sobre residuos que en su parte expositiva manifiesta *“La Comunidad*

*necesita estadísticas comunitarias periódicas sobre la producción y gestión de los residuos procedentes de las empresas y hogares para llevar a cabo un seguimiento de la aplicación de la política de residuos.*

*De este modo se sientan las bases para controlar si se cumplen los principios de maximización de la recuperación y eliminación segura. No obstante, es necesario seguir desarrollando instrumentos estadísticos para evaluar el grado de cumplimiento del principio de prevención de residuos y poder relacionar los datos sobre la generación de residuos y un inventario de la utilización de los recursos a escala global, nacional y regional”.*

La obligación que establece ese Reglamento europeo nos ha permitido disponer de una fuente de datos, Eurostat, de la que obtener datos fiables que nos ayuden a estudiar a través de los datos el cumplimiento normativo de los países.

La presente introducción comienza hablando de sostenibilidad que es un concepto transversal y muy ligado a la generación y gestión de residuos y se cierra volviendo a ese concepto, ya que a través del cumplimiento de la normativa europea y alcanzando los objetivos y metas que recogen las diferentes normativas podremos saber si los países europeos son eficientes en la gestión de los residuos. En este sentido, análisis previos publicados en la revista de investigación Cleaner Production (Almeida et al., 2017, 2013; Bonilla et al., 2010) han analizado cómo la transición al desarrollo sostenible implica la realización de cambios en la gestión de residuos. En esa transición las políticas de residuos y de gestión de los mismos se consideran un factor fundamental (Hoornweg and Bhada-Tata, 2012; Kemp et al., 2007).

La obligación de aportar datos por parte de los Estados Miembros de la Unión Europea, hace que Eurostat sea una base de datos muy rica, sin embargo, los datos existentes no han sido analizados todavía desde el punto de vista del cumplimiento normativo de la legislación en materia de gestión y transporte de residuos peligrosos. La presente tesis aporta un análisis desde el punto de vista del Derecho que nos indicará no sólo la necesidad de nuevas o diferentes políticas, sino que también si los datos que se recogen son suficientes o si es precisa una nueva forma de medir y tomar los datos.



# JUSTIFICACIÓN

“El hombre de ciencia ha aprendido a creer en la justificación, no por la fe, sino por la verificación.”

THOMAS HENRY HUXLEY



## 2. JUSTIFICACIÓN

El estudio de la eficiencia en la gestión de residuos peligrosos en relación con la legislación es un elemento importante a la hora de alcanzar los objetivos de desarrollo sostenible. Para alcanzar la sostenibilidad, hay que cumplir ciertas Directivas europeas y normativa con objeto de asegurar que los residuos son gestionados de forma correcta y sin causar daños al medio ambiente ni a la salud humana.

La gestión de los residuos peligrosos no sólo es una preocupación europea, sino una preocupación mundial, en particular en lo que concierne a su eliminación, por lo que será imprescindible, tal y como se ha indicado asegurar que su eliminación y los traslados hasta los lugares en que los residuos van a ser eliminados, o valorizados, se hacen respetando las diferentes normativas, puesto que la eliminación de residuos tiene un fuerte impacto en el desarrollo sostenible (Duan et al., 2021; Sauve and van Acker, 2020; Wang et al., 2020) y el transporte de residuos también tiene un impacto directo en el desarrollo sostenible ya que como se ha indicado se producen gran cantidad de gases de efecto invernadero (Santos, 2017) .

La investigación sobre políticas y desarrollo sostenible están ligadas a la eficiencia de la gestión de los residuos peligrosos, esto hace que se necesiten nuevos análisis sobre la gestión de los residuos peligrosos, y en particular un análisis que se capaz de englobar diferentes perspectivas:

- El análisis de la normativa de gestión de residuos y su cumplimiento, con objeto de analizar su eficiencia.
- El análisis de la normativa de traslados de residuos y los traslados de residuos entre países tanto para valorización como para eliminación.
- El análisis del cumplimiento normativo de cada país y el análisis de las relaciones que se establecen entre los países en los traslados de residuos.

Partiendo de la necesidad de realizar nuevos análisis sobre la gestión de los residuos peligrosos, esta tesis doctoral, analiza las cuestiones antedichas a través de tres artículos.

El primero de los artículos que compone esta tesis, y partiendo del hecho de que en Europa se comparte una legislación común, analiza la situación de los países europeos desde una perspectiva de gestión de residuos, enfocando el análisis principalmente en la gestión de residuos peligrosos, con la finalidad de conocer si el hecho de compartir una misma legislación hace que los países sean más eficientes en la gestión de los residuos.

A continuación, y a la vista de los numerosos traslados de residuos peligrosos que realizan los países europeos, vamos a analizar en dos artículos los traslados de residuos peligrosos, traslados de residuos peligrosos para valorización en un artículo y traslados de residuos peligrosos para eliminación en otro artículo.

Ambos artículos dedicados a los traslados de residuos peligrosos, tienen una metodología común, si bien en cada uno se analiza un aspecto que no se analiza en el otro. En el análisis de residuos para eliminación se introduce un breve análisis de cómo afectan las tasas de los vertederos a los traslados, y en el artículo dedicado a los traslados de residuos para valorización se introduce un análisis de cómo la innovación afecta a estos traslados.

Por último, indicar que, el traslado de residuos para eliminación está muy regulado por la normativa mencionada, Convención de Basilea y Reglamento para el traslado de residuos, sin embargo, consideramos importante averiguar, si al igual que ocurre entre hemisferio norte y hemisferio sur, los residuos se trasladan a los países europeos que tienen un PIB más bajo y conocer si en los traslados se cumplen los principios de eficiencia y proximidad, así como las relaciones entre los países.

En esta tesis se analizan los datos del año 2014, que resultan claves por ser el año anterior a la publicación de la estrategia de Economía circular, por lo que análisis y estudios posteriores, podrán indicar si las nuevas medidas adoptadas realmente han tenido la repercusión esperada en la gestión de los residuos.

## OBJETIVOS

“No existen preguntas sin respuesta, solo  
preguntas mal formuladas.”

LAURENCE FISHBURNE - Morfeo



### 3.OBJETIVOS

#### OBJETIVO GENERAL:

El objetivo general es el análisis de los residuos peligrosos en Europa desde una visión holística que abarca el cumplimiento normativo desde dos perspectivas, la eficiencia en la gestión y cómo afecta la normativa a los traslados, a la vez que estudia la interrelación de los países europeos para alcanzar el cumplimiento normativo.

#### OBJETIVOS ESPECÍFICOS.

O.E 1: Analizar la situación en Europa desde la perspectiva de gestión de residuos, con un enfoque predominante en la gestión de residuos peligrosos para responder a la pregunta de si una legislación común garantiza una gestión correcta de los residuos.

O.E 2: Analizar el cumplimiento normativo, en particular el cumplimiento de los principios de autosuficiencia y proximidad, en los traslados de residuos para su eliminación y la influencia del PIB en los mismos.

O.E 3: Analizar los traslados de residuos para su valorización desde una perspectiva política, económica y de innovación.



# MATERIAL, MÉTODO Y RESULTADOS

*Lo que con mucho trabajo se adquiere,  
más se ama.*

*Aristóteles*



## 4. MATERIAL, MÉTODO Y RESULTADOS

Como resultado de la presente tesis, se han publicado los siguientes artículos:

- Artículo 1

Callao, C., Martínez-Nuñez, M., & Latorre, M. P. (2019). European Countries: Does common legislation guarantee better hazardous waste performance for European Union member states?. *Waste Management*, 84, 147-157.

Factor de impacto de la revista: 7.145 (2020)

- Artículo 2

Latorre, M. P., Martínez-Nuñez, M., & Callao, C. (2021). Modelling and analysing the relationship between innovation and the European Regulations on hazardous waste shipments. *International Environmental Agreements: Politics, Law and Economics*, 1-20.

Factor de impacto de la revista: 2.649 (2020)

- Artículo 3

Callao, C., Latorre, M. P., & Martínez-Núñez, M. (2021). Understanding hazardous waste exports for disposal in europe: A contribution to sustainable development. *Sustainability*, 13(16), 8905.

Factor de impacto de la revista: 3.251 (2020)





## European Countries: Does common legislation guarantee better hazardous waste performance for European Union member states?



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### ABSTRACT

The study of efficiency in hazardous waste management has been proved to be a driving factor for sustainable development (SD). This study focuses on a performance assessment of European countries, most of them European Union (EU) member states and candidate countries that share a common legislative framework through European regulations, in order to provide a general understanding of hazardous waste performance. In this paper, we use Data Envelopment Analysis (DEA) to examine the efficiency of 32 countries in Europe by using novel input/output environmental parameters to study the efficiency of the different waste management operations from an environmental point of view. This analysis contrasts the efficiency in the management of total waste versus hazardous waste and studies three operations with hazardous wastes: incineration and incineration with energy recovery, disposal and recovery. Results show that there are differences in the achievement of efficiency, not only among countries, but also among the different waste management operations analysed.

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### 1. Introduction

Hazardous waste has become one of the most serious problems Europe has to face. In 2014, 2502 million tons of waste was produced in Europe (Eurostat, 2014), of which 95 million tons were hazardous waste.

To deal with this problem, the European Union (EU) has developed a set of regulations concerning environmental protection. In this regard, the Waste Framework Directive (WFD) (Directive, 2008) tries to protect the environment and human health from negative effects produced by hazardous waste, and establishes waste prevention at the top of the waste management hierarchy. Through waste prevention, Europe tries to “reduce the content of harmful substances in materials and products” and, therefore, the amount of hazardous waste produced.

But even if waste prevention is at the top of the waste management hierarchy, the WFD establishes different waste management operations and has considered it necessary to regulate two of them: landfill (Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste, 1999) and incineration (Directive, 2010).

Other waste management operations, such as recycling and other recovery operations, are not regulated by directives: instead they are targets introduced by the legislation, as proposed by Gordon (1986), that member states have to achieve. And always having in mind to ensure the objective of hazardous waste management and the optimization of the systems (Nema and Gupta, 1999).

These targets are introduced in the Directives, either in the Directives that regulate the operations, as with Landfill Directive; in the WFD, which contains the objectives for household waste and construction and demolition waste or in Directives that regulate different waste streams, Packaging and Packaging Waste Directive (European Parliament and Council Directive 94/62/EC of 20 December 1994 on packaging and packaging waste, 1994), WEEE Directive (“Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE) Text with EEA relevance,” 2012), Directive 2006/66/EC of the European Parliament and of the Council of 6 September 2006 on batteries and accumulators and waste batteries and accumulators) or Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of life vehicles.

Although the analysis of the fixed targets and their evolution does not fall under the scope of this research, it is important to

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mention that research has begun important analysis and evaluations of processes in the search for improvement and technology development, such as for end-of-life-vehicles (Edwards et al., 2006; Ene and Öztürk, 2015; Gerrard and Kandlikar, 2006; Johnson and Wang, 2002; Tasala Gradin et al., 2013; Zameri et al., 2006), WEEE (Bigum et al., 2013; Jha et al., 2013; Ylä-Mella et al., 2014b, 2014a; Zotos et al., 2009), batteries and accumulators (Bernardes et al., 2004; Espinosa et al., 2004) or packaging waste (da Cruz et al., 2012; Guerrini et al., 2017; Luijsterburg and Goossens, 2014).

But given that countries must achieve objectives, numerous analysis have also been carried out in different territorial areas such as China (Zhang et al., 2011), United Kingdom (Edwards et al., 2006), Denmark (Bigum et al., 2013), the Nordic Countries (Ylä-Mella et al., 2014b, 2014a), Greece (Zotos et al., 2009) or Portugal (da Cruz et al., 2012; Marques et al., 2014).

Legislation may be a driver for improvements of the systems and for technological developments (Gerrard and Kandlikar, 2006; Mazzanti and Zoboli, 2008; Simões and Marques, 2012a), however, legislation and the existence of targets to achieve do not guarantee the efficiency of the systems (Marques et al., 2012).

Nevertheless, this analysis and the fulfilment of the European targets and regulations by European Countries, do not show whether European countries are efficient in their performance of waste management. In this sense, previous experiences of the Workshops on Advances in Cleaner Production (Almeida et al., 2017, 2013; Bonilla et al., 2010) have explored how the transition to sustainable development (SD) involves changes in waste management and improvements in efficiency of use, a transition in which waste policies and waste management policies are considered key factors (Hoorweg and Bhada-Tata, 2012; Kemp et al., 2007).

Research about policies and sustainable development, efficiency of hazardous waste management operations and hazardous waste policies needs new approaches that are capable of analysing hazardous waste management from three different perspectives: (1) individual countries, (2) the global continent, and (3) hazardous waste management efficiency.

With this in mind, and knowing that European Union Member States share common environmental legislation, the objective of this article is to analyse the current situation in Europe from the perspective of waste management, focusing the analysis mainly on hazardous waste management, in order to look more closely at those countries that are more efficient and to answer the question whether the common legislation guarantee efficiency in the performance of hazardous waste management. This study is focused on the performance assessment of 32 European countries, using data envelopment analysis (DEA) with the aim of providing information about performance of five different models: total waste management (M1), hazardous waste management (M2), incineration and incineration with energy recovery of hazardous waste (M3), some hazardous waste disposal operations (M4) and finally hazardous waste recovery (M5).

Our contribution aims to provide information on efficiency measures and will help to deliver specific knowledge from local to global scales. These measures provide important estimates for further hazardous waste management in relation to the three perspectives presented: hazardous waste management of the individual countries, hazardous waste management of a specific continent (Europe) and hazardous waste management according to the management operation. As a result, this work can be used as a valuable source of information for EU policies and policies within member states and should contribute to sustainability.

The paper is structured as follows. In Section 2, we motivate our work by reviewing some related work in the literature; then in Section 3 we present the methodology we use to study efficiency

throughout the paper. Section 4 sets out the data collected in relation to European countries. We present the results obtained in Section 5. Finally, we draw some conclusions and sketch some future avenues for research in Section 6.

## 2. Background

The use of DEA is not new in the analysis of the performance of the waste sector. Literature shows that this methodology has been used in many environmental aspects. A review of the economic performance of the waste sector (Simões and Marques, 2012b) shows the representativeness of DEA among the quantitative techniques used by researchers.

From waste to water, DEA analysis has been found in many research articles as a result.

Regarding waste, DEA studies analyse waste services and waste utilities (Benito-López et al., 2011; Bosch et al., 2000; Gaiola, 2002; Moore et al., 2005; Pedro Simões et al., 2012; Simões et al., 2010), others study the efficiency of recycling (Lozano et al., 2004; Marques et al., 2012), and they even analyse the performance of private partners in the provision of this services (P. Simões et al., 2012). Table 1 lists examples of DEA studies conducted for the analysis of waste services. Many works assessing performance in waste generation can be found in the literature. Some researchers (Halkos and Papageorgiou, 2016; Halkos and Petrou, 2017) use DEA to show the disparities in waste generation between European countries, and even within the same member state, and they reach the conclusion that the different regulations are the cause of the differences.

Some of the aforementioned studies in which DEA are focused on the study of a single country (da Cruz et al., 2012; Dijkgraaf and Vollebergh, 2003; Gaiola, 2002; Garcia-Sanchez and García-Sánchez, 2008; Marques et al., 2012; Sarkis and Dijkshoorn, 2007; Scrimgeour et al., 2005; Simões et al., 2012), and studies covering European Union countries focus mainly on waste generation efficiency (Halkos and Papageorgiou, 2016; Halkos and Petrou, 2017). These studies have brought about some important advances in gaining a better understanding of the functioning of waste generation efficiency.

Regarding solid waste management, researches have used DEA for its study (García-Sánchez, 2008; Huang et al., 2011; Marques and Simões, 2009; Rogge and De Jaeger, 2012; Sarkis and Dijkshoorn, 2007; Worthington and Dollery, 2001). Analysing the inputs and outputs chosen by these authors, while some of them (Marques et al., 2012; Rogge and De Jaeger, 2012; Sarkis and Dijkshoorn, 2007; P. Simões et al., 2012; Worthington and Dollery 2001), include the costs in the inputs, others, (García-Sánchez, 2007; García-Sánchez, 2008) includes staff, vehicles and containers. Also other inputs, such as population density are include by these authors (Marques and Simões, 2009; Worthington and Dollery, 2001).

Though the outputs chosen vary greatly, total waste generated and recycled waste is considered by (Marques and Simões, 2009; Sarkis and Dijkshoorn, 2007; Worthington and Dollery, 2001). Sarkis and Dijkshoorn (2007) also include hazardous waste generated as an output, while García-Sánchez (2008) uses variables like tonnage and collection points, collection points density, kilometres of surface area washing and number of waste containers emptied. Through these articles, we see how DEA is a proven method for efficiency analysis; at the same time, they prove the validity of some of the inputs and outputs we will use, like waste generated or population density. However, they also highlight the opportunity to use new variables in the analysis.

Incineration, which is one of the waste management operations regulated by a directive (Directive, 2010), has also been subject to

**Table 1**  
Summary of literature related to DE in waste sector.

Reference	Sector/study	Input	Output
(Bosch et al., 2000)	Efficiency of Spanish municipal refuse collection services	<ul style="list-style-type: none"> <li>• Number of containers</li> <li>• Number of vehicles</li> <li>• Direct non-offices workers</li> </ul>	<ul style="list-style-type: none"> <li>• Tons of collected organic material refuse</li> </ul>
Worthington and Dollery (2001)	Analysis of New South Wales municipalities domestic waste management function	<ul style="list-style-type: none"> <li>• Nondiscretionary inputs: <ul style="list-style-type: none"> <li>• Properties receiving DWMS</li> <li>• Occupancy rate</li> <li>• Population density</li> <li>• Population distribution</li> <li>• Cost of disposal index</li> </ul> </li> <li>• Discretionary inputs: <ul style="list-style-type: none"> <li>• Collection expenditure</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• Discretionary outputs: <ul style="list-style-type: none"> <li>• Total garbage collected</li> <li>• Total recyclables collected</li> <li>• Implied recycling rate</li> </ul> </li> </ul>
(Gaiola, 2002)	Efficiency evaluation in the Urban Solid Waste Systems of Portugal using Data Envelopment Analysis	<ul style="list-style-type: none"> <li>• Costs of the service</li> <li>• Personnel costs</li> <li>• Number of USW Systems employees</li> </ul>	<ul style="list-style-type: none"> <li>• Total USW production</li> <li>• Quantity of selective collection</li> <li>• USW Systems beneficiaries</li> </ul>
(Lozano et al., 2004)	Performance of a number of Spanish municipalities in terms of the amount of glass recycled	<ul style="list-style-type: none"> <li>• Number of glass containers</li> <li>• Population</li> <li>• Number of bars and restaurants</li> </ul>	<ul style="list-style-type: none"> <li>• Glass recycled</li> </ul>
(Moore et al., 2005)	Performance of municipal services	<ul style="list-style-type: none"> <li>• In solid waste services: <ul style="list-style-type: none"> <li>• Number of FTE staff</li> <li>• Solid waste budget</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• Number of citizens served.</li> </ul>
Sarkis and Dijkshoorn (2007)	Relationships between solid waste management performance and environmental practice adoption in Welsh small and medium sized enterprises (SMEs)	<ul style="list-style-type: none"> <li>• Environmental efficiency model: <ul style="list-style-type: none"> <li>• Employees</li> </ul> </li> <li>• Economic efficiency model: <ul style="list-style-type: none"> <li>• Waste management expenses</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• Environmental efficiency model: <ul style="list-style-type: none"> <li>• Recycled material</li> <li>• Total waste generated</li> </ul> </li> <li>• Economic efficiency model: <ul style="list-style-type: none"> <li>• Total waste generated</li> <li>• Total waste recycled</li> </ul> </li> <li>• Hazardous waste generated</li> </ul>
García-Sánchez (2008)	Performance of Spanish solid waste collection	<ul style="list-style-type: none"> <li>• Total full-time workers</li> <li>• Vehicles and containers</li> </ul>	<ul style="list-style-type: none"> <li>• Tonnage and collection points</li> <li>• Collection point density</li> <li>• Kilometres of surfaces area washing</li> <li>• Number of waste containers emptied</li> <li>• Treated solid waste</li> <li>• Recycled waste</li> </ul>
Marques and Simões (2009)	Portuguese solid waste management services	<ul style="list-style-type: none"> <li>• Operational expenses (OPEX)</li> <li>• Capital costs (CAPEX)</li> </ul>	<ul style="list-style-type: none"> <li>• Contaminants removed</li> </ul>
Hernández-Sancho and Sala-Garrido (2009)	Cost analysis in wastewater treatment processes	<ul style="list-style-type: none"> <li>• Energy cost</li> <li>• Labour cost</li> <li>• Maintenance cost</li> <li>• Waste management cost</li> <li>• Other costs</li> </ul>	<ul style="list-style-type: none"> <li>• NOx</li> <li>• SOx</li> <li>• COx</li> <li>• HCl</li> <li>• Suspended solid</li> <li>• Opacity</li> <li>• Incinerator ash</li> <li>• Dioxin emission</li> <li>• Treated solid waste</li> <li>• Recycled solid waste</li> </ul>
Chen et al. (2010)	Environmental performance evaluation of large scale municipal solid waste incinerators using data envelopment analysis.	<ul style="list-style-type: none"> <li>• Electricity consumption</li> <li>• Municipal solid waste incinerated</li> <li>• Operation time</li> <li>• Shutdown time</li> </ul>	<ul style="list-style-type: none"> <li>• The model also includes 8 explanatory factors.</li> <li>• Annual production of residues</li> <li>• QUALITY – Suitability of the service+ Exogenous factors were considered in the second stage model</li> </ul>
(Simões et al., 2010)	Measures the performance of solid waste utilities.	<ul style="list-style-type: none"> <li>• OPEX</li> <li>• CAPEX</li> </ul>	<ul style="list-style-type: none"> <li>• WASTPC (per capita cost)</li> </ul>
(Benito-López et al., 2011)	Efficiency determinants of Spanish local entities in the provision of public street-cleaning and refuse collection services	<ul style="list-style-type: none"> <li>• WASTPC (per capita cost)</li> </ul>	<ul style="list-style-type: none"> <li>• Residual household waste</li> <li>• Packaging waste</li> <li>• Paper and cardboard</li> <li>• Glass</li> <li>• Other</li> </ul>
De Jaeger et al. (2011)	Test if the most commonly implemented local policy initiatives in MSW management have an influence on average efficiency scores.	<ul style="list-style-type: none"> <li>• Costs</li> <li>• Background variables: <ul style="list-style-type: none"> <li>• Total population (heads)</li> <li>• Population density</li> <li>• Median income</li> <li>• Old (%)</li> <li>• Young (%)</li> <li>• Left wing vote share</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• Dummy input equal to one</li> </ul>
Huang et al. (2011)	Performance assessment for municipal solid waste collection in Taiwan	<ul style="list-style-type: none"> <li>• Dummy input equal to one</li> </ul>	<ul style="list-style-type: none"> <li>• Cost per unit volume of MSW collected</li> <li>• Quantity of MSW collected per unit collection time</li> <li>• Quantity of MSW collected per collection vehicle</li> <li>• The population served per collector</li> <li>• Quantity of MSW collected per vehicle mile</li> <li>• Residential waste collected</li> </ul>
(Pedro Simões et al., 2012)	Efficiency of refuse collection services	<ul style="list-style-type: none"> <li>• Staff</li> <li>• Vehicles</li> <li>• Operational costs (OOPEX)</li> </ul>	<ul style="list-style-type: none"> <li>• Retail services: <ul style="list-style-type: none"> <li>• Residential waste collected</li> </ul> </li> <li>• Wholesale services: <ul style="list-style-type: none"> <li>• Tonnage of waste for treatment</li> <li>• Tonnage of waste for recycling</li> </ul> </li> </ul>
(P. Simões et al., 2012)	Evaluation of the impact of private sector participation in the Portuguese waste sector	<ul style="list-style-type: none"> <li>• Retail services: <ul style="list-style-type: none"> <li>• Staff</li> <li>• Vehicles</li> <li>• Other operational expenditures (OOPEX)</li> </ul> </li> <li>• Wholesale services: <ul style="list-style-type: none"> <li>• Staff</li> <li>• Capital expenditure (CAPEX)</li> <li>• OOPEX</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>• Retail services: <ul style="list-style-type: none"> <li>• Residential waste collected</li> </ul> </li> <li>• Wholesale services: <ul style="list-style-type: none"> <li>• Tonnage of waste for treatment</li> <li>• Tonnage of waste for recycling</li> </ul> </li> </ul>

(continued on next page)

Table 1 (continued)

Reference	Sector/study	Input	Output
(Marques et al., 2012)	Efficiency of Portuguese recycling companies	<ul style="list-style-type: none"> <li>Operating expenses (OPEX)</li> <li>Capital expenses (CAPEX)</li> </ul>	<ul style="list-style-type: none"> <li>M1 outputs: <ul style="list-style-type: none"> <li>Glas collectec</li> <li>Plastic collected</li> <li>Paper collected</li> </ul> </li> <li>M2 outputs: <ul style="list-style-type: none"> <li>Total economic revenues</li> <li>Financial transfers from SPV</li> </ul> </li> <li>Residual waste</li> <li>Other municipal waste</li> <li>Packaging waste</li> <li>Other EPR waste</li> <li>Green waste</li> <li>Bulky waste</li> </ul>
Rogge and De Jaeger (2012)	Efficiency of municipalities in collecting and processing municipal solid waste	<ul style="list-style-type: none"> <li>Waste costs</li> </ul>	<ul style="list-style-type: none"> <li>Regional waste generation</li> <li>Regional GDP</li> </ul>
Halkos and Papageorgiou (2016)	Environmental efficiency indicators in regional waste generation	M1 inputs: <ul style="list-style-type: none"> <li>Total regional labour force</li> <li>Regional capital stock</li> </ul> M2 inputs: <ul style="list-style-type: none"> <li>Total regional labour force</li> <li>Regional capital stock</li> </ul> M3 inputs: <ul style="list-style-type: none"> <li>Regional waste generation</li> </ul>	M1 outputs: <ul style="list-style-type: none"> <li>Regional GDP</li> </ul> M2 outputs: <ul style="list-style-type: none"> <li>Regional waste generation</li> </ul> M3 outputs: <ul style="list-style-type: none"> <li>Regional GDP</li> </ul>
Sasao (2016)	Efficiency of disaster waste disposal after the East Japan earthquake	Inputs: <ul style="list-style-type: none"> <li>Disposal costs</li> <li>Total number of workers for waste management</li> </ul>	Outputs: <ul style="list-style-type: none"> <li>Disposal and recycled amount of wastes</li> <li>Tsunami sediments</li> </ul>
Halkos and Petrou (2017b)	Waste generation efficiency in EU regions	M1 inputs: <ul style="list-style-type: none"> <li>Regional labour</li> <li>Regional investment</li> </ul> M2 inputs: <ul style="list-style-type: none"> <li>Regional labour force</li> <li>Regional investment</li> </ul> M3 inputs: <ul style="list-style-type: none"> <li>Regional waste generation</li> <li>Regional labour</li> <li>Regional investment</li> <li>Regional waste generation</li> </ul> M4 inputs: <ul style="list-style-type: none"> <li>Regional population density</li> <li>Regional waste generation</li> </ul>	M1 outputs: <ul style="list-style-type: none"> <li>Regional GDP</li> <li>Waste</li> </ul> M2 outputs: <ul style="list-style-type: none"> <li>Regional GDP</li> </ul> M3 outputs: <ul style="list-style-type: none"> <li>Regional GDP</li> </ul> M4 outputs: <ul style="list-style-type: none"> <li>Regional GDP</li> </ul>

DEA (Chen et al., 2010), including costs in the inputs (operation cost, electricity consumption, municipal solid waste incinerated, operation time and shutdown time) and data related to emissions in the output.

In this study, and in order to increase the robustness of the results, bootstrapping is applied.

### 3. Methodology

In this work, DEA has been chosen as non-parametric technique to measure the relative efficiency (Martínez-Núñez and Pérez-Aguilar, 2014) of a set of units. The main advantage of DEA is that it allows the comparison of homogeneous units (decision making units; DMU). A total of  $m$  inputs are used in the production process of each DMU to produce  $s$  outputs. One of the limitations of this methodology is to obtain robust data as the number of DMUs will limit the number of inputs/outputs used.

In this context the measurement of the technical efficiency with which countries act has been measured with a DEA model assuming variable returns to scale (Banker et al., 1984) and orientation to output. In microeconomic theory of production, the concept of returns to scale is related to the physical size of the productive unit. For this reason, variable returns to scale have been chosen. All models have been created with an output orientation. This technique aims to maximize outputs with the same set of input values (Cooper et al., 2006), this is logical with the evaluated management model.

This methodology deals with organizational dimensions that produce measurable and recognisable outputs from measurable inputs, but they generally lack market price for certain inputs or

outputs. This methodology can also show what are the best practices that organizations can follow to achieve their most efficient organizational structure as (Simoes et al., 2010) have observed.

Supposing that there are  $N$  firms each producing  $m$  outputs from  $n$  inputs, firm  $t$  uses the input bundle  $x^t = (x_{1t}, x_{2t}, \dots, x_{nt})$  to produce the output bundle  $Y^t = (y_{1t}, y_{2t}, \dots, y_{mt})$ . As noted above, measurement of average productivity requires aggregation of inputs and outputs. Eq. (1) shows how solve efficiency scores can be computed,

$$\begin{aligned}
 & \min \theta \\
 \text{s. t. } & \sum_{j=1}^N \lambda_j x^j \leq \theta x^t; \\
 & \sum_{j=1}^N \lambda_j y^j \geq y^t; \\
 & \sum_{j=1}^N \lambda_j = 1; \quad \lambda_j \\
 & \lambda_j \geq 0 (j = 1, 2, \dots, N).
 \end{aligned} \tag{1}$$

The BCC model (Banker et al., 1984) assumes the convex combination of the observed DMUs as the production possibility set, where in the VRS score is called local pure technical efficiency (PTE). The problem is to solve PTE  $\theta$  and lambda value  $\lambda_j$  for an observed DMU: PTE = 1 means the DMU is technically efficient; PTE < 1 means DMU is technically inefficient.

For an observed DMU, the solution of lambda value  $\lambda_j$  indicates whether DMU  $j$  works as a role model (peer) for the observed DMU  $k$ . If  $\lambda_{jk} = 0$ , DMU  $j$  is not a role model. If  $\lambda_{jk} > 0$ , DMU  $j$  is a role model of the observed DMU  $k$ .  $\lambda_{ij}$  represents the weight that the observed DMU  $k$  references DMU  $j$ , so as to reach target efficiency.

### 3.1. Bootstrapping DEA technique

DEA efficiency is highly sensitive to errors in the data. Given that the DEA method uses a sample for the analysis of efficiency, specific differences in estimations may be due solely to sampling noise rather than true differences in the levels of efficiency of the units. In this paper, we address this problem by using a bootstrap approach. Bootstrapping, introduced by Efron (Efron, 1992), is based on the idea of resampling from an original sample of data to create replica datasets from which we can make statistical inferences. The smoothed bootstrap approach of Simar and Wilson (Simar and Wilson, 2000; Simar and Wilson, 1998) is used in this study. Theoretical underpinnings can be found also in (Simar and Wilson, 1998).

One of the most noteworthy benefits of bootstrapping DEA technique is to determine confidence intervals to the corrected efficiencies estimated (Simoes et al., 2012). On the other hand, this technique presents a relevant drawback: the possible detection of outliers in the sample, such as the order-m procedure developed by Simar (2003), based on the work of Cazals et al. (2002) or methods that attend to the influence of atypical observations in the sample (Charnes et al. (1985) or to the importance of individual variables (Torgersen et al., 1996).

The key assumption behind this approach is that the known bootstrap distribution will imitate the original unknown distribution if the known data generating process (DGP) is a consistent estimator of the unknown DGP. The common approach is to estimate non-parametrically the original densities of the performance scores using kernel smoothing methods, combined with a reflection method (Silverman and Young, 1987). The bootstrap process will therefore generate values that imitate the distributions which would be generated from the unobserved and unknown DGP (Simar and Wilson, 2000).

Following Simões et al. (2012), the bootstrap estimate bias of the DEA estimator is computed by Eq. (2) in which  $\{\theta_i^*; i = 1, 2, \dots, n\}$  corresponds to the average of the bootstrap efficiency result and  $\{\hat{\theta}_i; i = 1, 2, \dots, n\}$  to the DEA estimate original results. The bootstrap estimate of the DEA bias is obtained through

$$bias_i = \frac{1}{B} \sum_{b=1}^B \hat{\theta}_{i,b}^* - \hat{\theta}_i, \quad i = 1, 2, \dots, n \quad (2)$$

A bias corrected efficiency estimator is then obtained by defining by Eq (3):

$$\tilde{\theta}_i = 2\hat{\theta}_i - \frac{1}{B} \sum_{b=1}^B \hat{\theta}_{i,b}^*, \quad i = 1, 2, \dots, n \quad (3)$$

Accepting that  $\hat{\theta}_{i,b}^*; i = 1, 2, \dots, n; b = 1, 2, \dots, B$  is the bootstrap efficiencies empirical distribution function after a new bias correction.

### 4. Model data

We have used data from 32 European countries. We used Eurostat (2014) as the only source of information. We collected information concerning waste for the year 2014.

In this analysis, we have chosen the BCC output-oriented DEA models. According to these orientation models, efficient units obtain the maximum number of outputs using a fixed amount of inputs and are assigned an efficiency score of 1.

Table 2 shows the descriptive analysis of the collected variables. There is a rule of thumb when defining a DEA model, that the model should not contain redundant information. For this reason, a correlation analysis of the aspirant variables was carried out to ensure consistency and reasonability of the selection of inputs and outputs.

Appendix A shows the pearson's correlation coefficients of the performed analysis.

In Table 3, we present the variables selected in each of the five models analysed.

We type of waste (M1 total waste, M2 hazardous waste) and hazardous waste management operation (M3, M4, M5).

In this analysis, DEA costs have not been taken into account, as the aim is to find out if a common legislation can guarantee efficiency in the performance, taken into account that countries have different characteristics (different quantities of waste and hazardous waste to manage, and different GDPs and population density).

#### 4.1. Input-output data for total waste management model BCC\_M1

Model BCC\_M1 tells us the efficiency of each country based on its population density and waste generation and how it treats or recycles that waste, taking into account the country's GDP.

Regarding inputs, in this study a combination of these countries' economic and human resource data was collected; these inputs were used in previous works, among other purposes, to analyse the best practice frontier performance. We selected the variables of population density—that is, persons per km<sup>2</sup>, a variable that has been used as input in DEA by (Ali et al., 2015; Halkos and Petrou, 2017; Worthington and Dollery, 2001).

In the inputs of this model we have included waste generated, a variable that can be treated as an input (Halkos and Papageorgiou, 2016; Halkos and Petrou, 2017) or as an output in DEA (Halkos and

**Table 2**  
Descriptive analysis of collected variables.

Index	Mean	Sum	Std. Dev.	Variance	Minimum	Maximum	Range
Total waste (Tons)	80006432.9	2,640,212,286	99581219.1	9.92E+15	1,164,024	387,504,241	386,340,217
Total hazardous waste (Tons)	3442953.18	113,617,455	5087853.91	2.59E+13	36,654	21,812,660	21,776,006
Population Density (Persons per km <sup>2</sup> )	157.71	5204.3	237.27	56297.88	16.9	1352.4	1335.5
Recyclable waste (Tons)	6821416.27	225,106,737	11190639.3	1.25E+14	0	38,860,736	38,860,736
Total waste Treatment (Tons)	74,617,452	2,462,375,915	93,642,908	8.77E+15	952,447	370,740,801	369,788,354
Recyclable hazardous waste (Tons)	57964.88	1,912,841	192170.62	3.693E+10	0	1,081,826	1,081,826
Total waste treatment (Tons)	2951247.27	97,391,160	4,793,885	2.30E+13	438	20,521,107	20,520,669
Deposit onto or into land (Tons)	1717801.39	56,687,446	3424849.44	1.17E+13	0	13,434,944	13,434,944
Land treatment and release into water bodies (Tons)	21398.27	706,143	69223.62	4,791,909,622	0	363,431	363,431
Incineration disposal	141846.45	4,680,933	338625.67	1.15E+11	0	1,520,287	1,520,287
Incineration energy recovery (Tons)	187231.3	6,178,633	506434.37	2.56E+11	0	2,788,642	2,788,642
Recovery other than energy recovery backfilling (Tons)	72762.27	2,401,155	379805.4	1.44E+11	0	2,178,280	2,178,280
Recovery other than energy recovery except backfilling (Tons)	810216.76	26,737,153	1745466.65	3.05E+12	0	9,641,160	9,641,160

**Table 3**  
Variables selected for each DEA model.

	Waste-waste treatment model BCC_M1	Hazardous waste-hazardous waste treatment model BCC_M2	Incineration and incineration with energy recovery model BCC_M3	Disposal model BCC_M4	Recovery operations model BCC_M5
<i>INPUTS</i>					
Total waste generation	✓				
Population density	✓	✓	✓	✓	✓
Hazardous waste generation		✓	✓	✓	✓
<i>OUTPUTS</i>					
GDP	✓	✓	✓	✓	✓
Recycling	✓				
Recycled hazardous waste		✓			
Incineration			✓		
Incineration with energy recovery			✓		
Deposit onto or into land				✓	
Land treatment and release into water bodies				✓	
Recovery other than energy recovery - backfilling					✓
Recovery other than energy recovery - except backfilling					✓

Papageorgiou, 2016; Halkos and Petrou, 2017; Rogge and De Jaeger, 2012; Sarkis and Dijkshoorn, 2007; Zhang et al., 2008).

In the outputs, two new variables have been introduced: wastes that are recycled, a variable that can be found in DEA by authors like Sarkis and Dijkshoorn (Sarkis and Dijkshoorn, 2007) and Worthington and Dollery (Worthington and Dollery, 2001), and GDP, which is also used in some DEA analysis related to the efficiency of environmental aspects (Ramanathan, 2006), and the linkages among CO<sub>2</sub> emissions, GDP and energy consumption (Halkos and Papageorgiou, 2016; Halkos and Petrou, 2017).

#### 4.2. Input-output data for hazardous waste management BCC\_M2

In this model—and in order to study the differences when we talk about recycling efficiency with hazardous and total wastes—we have simply replaced one of the outputs (recycled hazardous waste) and one of the inputs (total hazardous waste).

Recycled hazardous waste has not been used in literature so far as an output; however, if we want to know not only if countries recycle waste efficiently, but also if they are efficient in the recycling of hazardous waste, we have to use this output.

#### 4.3. Input-output data for incineration and incineration with energy recovery BCC\_M3

Model BCC\_M3 tells us the efficiency of each country based on its population density and hazardous waste generation, taking into account their GDP and trying to ascertain the efficiency of incineration.

Observing the evolution of hazardous waste incineration, it is important to differentiate between incineration with energy recovery (R1), which is a recovery operation, and incineration without energy recovery (D10), which is a disposal operation.

The efficiency of incineration has been measured when studying the performance of incinerators (Chen et al., 2010, 2012; Parmar and Rai, 2017).

It is important to know if this waste management operation is efficient in the context of hazardous waste, as there is controversy. While some researchers consider the recycling of waste into energy in a positive way (Cheng and Hu, 2010; Porteous, 2005, 2001), other approaches with environmental and economic perspectives are not so clear (Dijkgraaf and Vollebergh, 2003; Turconi et al., 2011). Finally, others present the illness incidence of waste incineration, especially with reference to cancer (Elliott et al., 1996; García-Pérez et al., 2013; Gatrell and Dunn, 1995; Hu and Shy, 2001).

#### 4.4. Input-output data for disposal model BCC\_M4

Model BCC\_M4 tells us the efficiency of each country based on its population density and hazardous waste generation, taking into account the country's GDP and seeking to ascertain the efficiency of disposal operations.

This DEA analysis has been made with data on deposit into land (D1, D5 and D12) and land management and release into water bodies (D2, D3, D4, D6 and D7).

Most of the studies on disposal operations concern hazardous waste landfill, and especially the health effects near hazardous waste landfills (Dolk et al., 1998; Elliott et al., 2008; Vrijheid, 2000; Zornberg et al., 2003), but there are no studies about the efficiency of its performance.

#### 4.5. Input-output data for other recovery operations model BCC\_M5

Model BCC\_M5 tells us the efficiency of each country based on its population density and waste generation, taking into account the country's GDP and trying to find out the efficiency of other recovery operations.

The Waste Framework Directive defines waste management as “recovery or disposal operations, including preparation prior to recovery or disposal”.

Differentiation of the efficiency of these recovery operations from recycling has not been analysed using DEA.

This DEA analysis has been conducted with data on recovery other than energy recovery backfilling and recovery other than energy recovery except backfilling (R2-R11).

It should be noted that the backfilling concept has been subject to analysis, as it was introduced in the Waste Framework Directive for the first time.

## 5. Results

In this section, we first present the results obtained by utilizing the DEA BCC model—that is, the variable returns-to-scale assumption with the different models culled to analyse the efficiency of European countries. For the DEA and the bootstrapped DEA PIM-DEA, software was utilized.

Given that, the data used in this work come from official institutions, such as Eurostat, and after the implementation of DEA models, the application of outlier detection techniques has not been necessary since the scores obtained do not suggest presence of any atypical values.

We present in Table 4 the average technical original efficiency score (a percentage) for models BCC\_M1, BCC\_M2, BCC\_M3, BCC\_M4 and BCC\_M5. The efficiency scores rank between 0 and 100. Those countries that do not reach efficiency values of 100 are considered inefficient

In Model 1, the waste-waste management model BCC\_M1, the efficiency has an average efficiency of nearly 60 per cent. This indicates that countries in Europe, given their current inputs levels, could on average improve their output by 40 per cent.

In Model M2, the hazardous waste-hazardous waste management model BCC\_M2, the average efficiency is 31 per cent—that is, the capacity of waste management at European level could be improved in terms of hazardous waste management by 69 per cent. Only seven countries achieve efficiency (Germany, Latvia, Malta, Portugal, Sweden, Norway and Macedonia). Most of these seven countries have a percentage of Recycled Hazardous Waste out of Total Hazardous Waste higher than 5 per cent.

On the other hand, from the perspective of incineration and incineration with energy recovery (model BCC\_M3), we can observe significant differences in efficiency: the average efficiency is 54.29 per cent. Only eight countries operate at optimum capacity (Germany, France, Latvia, Malta, Romania, Finland, Norway and Macedonia). Most of these countries have a relationship between incineration of hazardous waste (both with energy recovery and disposal) and total hazardous waste higher than 17 per cent and they incinerate with energy recovery more than 10 per cent of the total hazardous waste.

Furthermore, in Model BCC\_4, the disposal model, is the one with the lowest average efficiency at European Level with 25.5 per cent. Only five countries are efficient (Bulgaria, Estonia, Finland, Norway and Serbia). Most of these countries deposit onto or into land more than 60 per cent of the total hazardous waste. Hazardous waste disposal is the more inefficient treatment of haz-

ardous waste management and produces the highest differences in efficiency between countries of all models.

Finally, the average efficiency for model BCC\_M5, recovery operations, is 54.5 per cent. Eight countries are efficient (Czech Republic, Germany, Estonia, Latvia, Malta, Poland, Norway and Macedonia). The efficient countries in this model are the only that make other recovery than energy recovery backfilling.

There is only one country that operate at the most efficient level, that is, Norway. Countries such as Germany and Macedonia are efficient in four of the five models analysed. All the efficient countries in M2 (Hazardous Waste Model) are also efficient in M1 (Waste Management Model) except Malta, probably due to its small surface and the low generation of hazardous waste regarding the rest of waste generation.

Due to the deterministic nature of the DEA method, the next phase is the examination of efficiency estimates in the presence of sample variations through the bootstrapping DEA (Silverman and Young, 1987; Simar and Wilson, 2000) reports the summary results for the efficiency scores using 2,500 bootstrap replications ( $B = 2500$ ) (under BCC DEA orientation) obtained by models BCC\_M1, BCC\_M2, BCC\_M3, BCC\_M4 and BCC\_M5. In the second column, we report the bias-corrected DEA efficiency scores; column three reports the bias of the DEA efficiency scores, while the fourth column reports the median. Finally, columns five and six display the basic bootstrap (Simar and Wilson, 2000) 95 per cent confidence intervals, lower and upper bounds (Table 5).

This bootstrapping method allows us to obtain confidence intervals for the value of the parameter of the efficiency. These results reveal reduced sensitivity of the efficiency measures with respect to sampling variation. The use of bootstrapping confirms the stability of our result.

All models decrease in efficiency scores once corrected. Model M1 is the one with the highest average efficiency, which means that

**Table 4**  
Results of the five models applied.

Name	BCC_M1	BCC_M2	BCC_M3	BCC_M4	BCC_M5
Belgium	100	37.89	81.52	5.09	41.92
Bulgaria	0.43	0.43	1.12	100	5.52
Czech Republic	77.18	18.8	47.48	13.39	100
Denmark	61.78	14.98	63.33	13.87	29.89
Germany	100	100	100	44.24	100
Estonia	66.06	0.26	3.4	100	100
Ireland	0.98	1.17	38.37	5.85	1.47
Greece	11.29	1.74	13.81	0.78	55.62
Spain	85.97	3.95	28.41	6.62	98.74
France	100	11.57	100	24.07	56.71
Croatia	6.09	6.88	58.05	1.49	60.08
Italy	100	5.59	32.38	13.26	41.64
Cyprus	32.26	0.64	4.65	1.05	15.53
Latvia	100	100	100	0.34	100
Lithuania	81.49	3.5	17.16	0.4	39.62
Luxembourg	15.62	91.22	79.07	0.15	1.7
Malta	0.8	100	100	0.03	100
Netherlands	37.18	18.5	52.94	11.65	91.6
Austria	59.92	24.12	67.69	1.41	14.82
Poland	61.38	5.34	57.86	7.04	100
Portugal	100	100	20.34	0.64	60.66
Romania	2.56	2.69	100	9.9	39.37
Slovenia	69.99	0.66	59.57	0.18	66.75
Slovakia	0.47	0.39	35.82	23.38	14.19
Finland	100	6.92	100	100	34.24
Sweden	100	100	93.04	72.58	82.45
United Kingdom	100	15.27	29.78	11.3	49.8
Norway	100	100	100	100	100
Montenegro	100	0.05	0.05	2.56	2.37
Macedonia	100	100	100	2.12	100
Serbia	16.09	16.09	16.08	100	16.51
Turkey	6.66	6.66	35.25	44.47	24.82
Average for Europe	59.19	31.10	54.29	25.56	54.56

**Table 5**  
Summary results for the efficiency scores using bootstrapping.

	Original eff. Score	Bootstrap (2500)				
		Bias-corrected eff.	Bias	Median	Lbound	Ubound
BCC_M1	0.60	0.48	−0.13	0.47	0.41	0.64
BCC_M2	0.33	0.06	−0.27	0.05	−0.11	0.38
BCC_M3	0.56	0.28	−0.28	0.26	0.18	0.63
BCC_M4	0.28	0	−0.31	−0.06	−0.19	0.36
BCC_M5	0.56	0.44	−0.12	0.45	0.32	0.57

**Table 6**  
Country classification based on efficiency scores using bootstrapping.

	Efficient countries	Inefficient countries (<0.005)
Waste-waste management	(N = 12) BELGIUM; GERMANY; FRANCE; ITALY; LATVIA; PORTUGAL; FINLAND; SWEDEN; UNITED KINGDOM; NORWAY; MONTENEGRO; MACEDONIA;	(N = 12) BULGARIA; IRELAND; GREECE; CROATIA; CYPRUS; LUXEMBOURG; MALTA; NETHERLANDS; ROMANIA; SLOVAKIA; SERBIA; TURKEY
Hazardous waste-hazardous waste management	(N = 7) GERMANY; LATVIA; MALTA; PORTUGAL; SWEDEN; NORWAY; MACEDONIA	(N = 24) BELGIUM; BULGARIA; CZECH REPUBLIC; DENMARK; ESTONIA; IRELAND; GREECE; SPAIN; FRANCE; CROATIA; ITALY; CYPRUS; LITHUANIA; NETHERLANDS; AUSTRIA; POLAND; ROMANIA; SLOVENIA; SLOVAKIA; FINLAND; UNITED KINGDOM; MONTENEGRO; SERBIA; TURKEY;
HW Incineration and incineration with energy recovery	(N = 8) GERMANY; FRANCE; LATVIA; MALTA; ROMANIA; FINLAND; NORWAY; MACEDONIA	(N = 15) BULGARIA; CZECH REPUBLIC; ESTONIA; IRELAND; GREECE; SPAIN; ITALY; CYPRUS; LITHUANIA; PORTUGAL; SLOVAKIA; UNITED KINGDOM; MONTENEGRO; SERBIA; TURKEY;
HW Disposal model	(N = 5) BULGARIA; ESTONIA; FINLAND; NORWAY; SERBIA;	(N = 27) BELGIUM; CZECH REPUBLIC; DENMARK; GERMANY; IRELAND; GREECE; SPAIN; FRANCE; CROATIA; ITALY; CYPRUS; LATVIA; LITHUANIA; LUXEMBOURG; MALTA; NETHERLANDS; AUSTRIA; POLAND; PORTUGAL; ROMANIA; SLOVENIA; SLOVAKIA; SWEDEN; UNITED KINGDOM; MONTENEGRO; MACEDONIA; TURKEY;
HW Recovery operations model	(N = 9) CZECH REPUBLIC; GERMANY; ESTONIA; SPAIN; LATVIA;; MALTA; POLAND; NORWAY; MACEDONIA;	(N = 3) IRELAND; MONTENEGRO; SERBIA

the total waste management (hazardous and non hazardous waste) in the different EU countries is still more efficient than the management of hazardous waste regardless of the management system operated. Model M4 has the biggest corrections of efficiency the variation of the bound intervals is the widest. In this model, the average efficiency is zero once corrected, which indicates that the landfill hazardous waste management system is not considered as an optimal system. So, it would not be considered as a viable waste management alternative in the European Union.

Table 6 shows country classification based of efficiency scores using bootstrapping.

Classification shows efficient countries in contrast with countries which efficiency is below 0.005.

## 6. Conclusions

This study proposed a performance evaluation focused on hazardous waste management, as 4 out of 5 models analysed hazardous waste. From the perspective of neo-classical production, an output-oriented approach indicates the estimation of capacity and capacity utilization.

The first conclusion is that European Union Member States are not more efficient than non European Union Countries.

The second conclusion is that a common legislation does not guarantee efficiency in the performance of waste management, taking into account the inputs and outputs chosen for this study.

It is remarkable, how efficiency decreases in Model 4, but European Union has already begun working to change this result through the objectives proposed by the Circular Economy Package. Member states will have to accomplish reforms to achieve the objective of reducing municipal waste sent to landfill to ten per cent (EUR-Lex - 52015PC0594 - EN - EUR-Lex, n.d.).

Despite the efforts made by the EU in terms of the creation of regulations of industrial and consumption systems, in view of the results obtained, it can be concluded that one way to improve environmental performance is through a strategic waste management process—that is, according to Porter (Porter, 1985) on waste management strategic analysis, the formulation of strategies and implementation of strategies. Specifically, the DEA is a tool that can be used in the waste management strategic analysis phase: through analysis of the efficiency of the countries, we can identify in which areas of their resource management they should improve.

Another way to improve the efficiency may be through the different alternatives legislation offers:

1.- Controlling the transposition of Directives: The reason is that even if the Directives must be transposed in all Member States, the truth is that this transposition varies. For example, regarding Industrial Emissions Directive while Finland uses 70 different regulations in the transposition, according the information in Eur-lex, other countries such as Greece or Italy might use just one regulation, and for example, just France has a regulation for the incineration of hazardous wastes.

Regarding the major differences in the measures communicated in the national transposition of European directives, it remains necessary to continue working together in efforts to achieve more efficient and sustainable management models.

2.- Another way to improve environmental performance through regulation is the use of tariff regulation, as it has already been proposed for the waste sector (Marques et al., 2018), and may be a way to improve the efficiency of the less efficient models.

Appendix A

		Total Waste	Total Hazardous Waste	Density	Recyclable Wastes	Total Waste Management	GDP (Gross Domestic Product)	Recyclable Hazardous Wastes	Total Waste Management	Deposit onto or into Land	Land Management and Release into Water Bodies	Incineration Disposal	Incineration Energy Recovery	Recovery other than Energy Recovery Backfilling	Recovery other than Energy Recovery except Backfilling
Total Waste	C. Pearson	1	0.706**	0.001	0.837**	0.996**	-0.021	0.587**	0.611**	0.231	0.132	0.797**	0.697**	0.545**	0.744**
	Sig. (bilateral)		0.000	0.996	0.000	0.000	0.907	0.000	0.000	0.197	0.460	0.000	0.000	0.001	0.000
Total Hazardous Waste	C. Pearson	0.706**	1	-0.023	0.606**	0.705**	-0.005	0.618**	0.966**	0.730**	0.106	0.656**	0.697**	0.640**	0.748**
	Sig. (bilateral)	0.000		0.901	0.000	0.000	0.980	0.000	0.000	0.000	0.556	0.000	0.000	0.000	0.000
Density	C. Pearson	0.001	-0.023	1	0.089	-0.011	-0.067	0.055	-0.042	-0.122	-0.131	0.049	0.054	0.051	0.093
	Sig. (bilateral)	0.996	0.901		0.621	0.954	0.710	0.761	0.818	0.500	0.468	0.787	0.764	0.779	0.606
Recyclable Waste	C. Pearson	0.837**	0.606**	0.089	1	0.797**	0.023	0.539**	0.444**	0.008	-0.049	0.809**	0.665**	0.511**	0.743**
	Sig. (bilateral)	0.000	0.000	0.621		0.000	0.897	0.001	0.010	0.963	0.788	0.000	0.000	0.002	0.000
Total Waste Management	C. Pearson	0.996**	0.705**	-0.011	0.797**	1	-0.023	0.597**	0.626**	0.249	0.147	0.788**	0.704**	0.557**	0.746**
	Sig. (bilateral)	0.000	0.000	0.954	0.000		0.901	0.000	0.000	0.162	0.414	0.000	0.000	0.001	0.000
GDP (Gross Domestic Product)	C. Pearson	-0.021	-0.005	-0.067	0.023	-0.023	1	0.023	-0.007	-0.024	-0.096	0.045	0.022	0.036	0.010
	Sig. (bilateral)	0.907	0.980	0.710	0.897	0.901		0.900	0.970	0.893	0.595	0.806	0.902	0.844	0.956
Recyclable Hazardous Waste	C. Pearson	0.587**	0.618**	0.055	0.539**	0.597**	0.023	1	0.609**	0.103	0.003	0.591**	0.905**	0.948**	0.886**
	Sig. (bilateral)	0.000	0.000	0.761	0.001	0.000	0.900		0.000	0.570	0.989	0.000	0.000	0.000	0.000
Total Waste Management	C. Pearson	0.611**	0.966**	-0.042	0.444**	0.626**	-0.007	0.609**	1	0.811**	0.135	0.553**	0.675**	0.648**	0.706**
	Sig. (bilateral)	0.000	0.000	0.818	0.010	0.000	0.970	0.000		0.000	0.453	0.001	0.000	0.000	0.000
Deposit onto or into Land	C. Pearson	0.231	0.730**	-0.122	0.008	0.249	-0.024	0.103	0.811**	1	0.177	0.099	0.140	0.143	0.166
	Sig. (bilateral)	0.197	0.000	0.500	0.963	0.162	0.893	0.570	0.000		0.324	0.582	0.437	0.428	0.355
Land Management and Release into Water Bodies	C. Pearson	0.132	0.106	-0.131	-0.049	0.147	-0.096	0.003	0.135	0	1.000	0.010	-0.004	0.036	-0.025
	Sig. (bilateral)	0.460	0.556	0.468	0.788	0.414	0.595	0.989	0.453	0.324		0.954	0.982	0.843	0.891
Incineration Disposal	C. Pearson	0.797**	0.656**	0.049	0.809**	0.788**	0.045	0.591**	0.553**	0.000	0.010	1	0.818**	0.590**	0.762**
	Sig. (bilateral)	0.000	0.000	0.787	0.000	0.000	0.806	0.000	0.001	0.582	0.954		0.000	0.000	0.000
Incineration Energy Recovery	C. Pearson	0.697**	0.697**	0.054	0.665**	0.704**	0.022	0.905**	0.675**	0.000	-0.004	0.818**	1	0.916**	0.932**
	Sig. (bilateral)	0.000	0.000	0.764	0.000	0.000	0.902	0.000	0.000	0.437	0.982	0.000		0.000	0.000
Recovery other than Energy Recovery Backfilling	C. Pearson	0.545**	0.640**	0.051	0.511**	0.557**	0.036	0.948**	0.648**	0.143	0.036	0.590**	0.916**	1	0.901**
	Sig. (bilateral)	0.001	0.000	0.779	0.002	0.001	0.844	0.000	0.000	0.428	0.843	0.000	0.000		0.000
Recovery other than Energy Recovery except Backfilling	C. Pearson	0.744**	0.748**	0.093	0.743**	0.746**	0.010	0.886**	0.706**	0.166	-0.025	0.762**	0.932**	0.901**	1
	Sig. (bilateral)	0.000	0.000	0.606	0.000	0.000	0.956	0.000	0.000	0.355	0.891	0.000	0.000	0.000	

alfa > 0.995.

\*\* The correlation is significant at the 0.01 level (bilateral).

3.- If one looks at the targets included in the Directives, the recycling objectives are generic, with no specific objectives according to whether the waste is hazardous or non-hazardous. Regulation would be a good instrument to set specific targets for hazardous waste.

4.- Regulation would also be a key instrument to control hazardous household waste according to research (Inglezakis and Moustakas, 2015).

New researches should also be carried out to determine whether or not European countries have a good waste management infrastructure and to ascertain how shipments of waste affect the efficiency of waste management. In this new approaches to sustainable waste management, DEA efficiency analysis could be combined with life cycle assessment, a tool that has been used in the analysis of waste management (Bovea et al., 2010; Hung et al., 2007) from different perspectives and with different uses and has proved to be a useful tool.

Also, future lines of research should deepen analysis of the reasons for the low efficiency rates in waste management operations in European countries and see if the measures of the circular economy contribute to a more efficient management of hazardous waste and therefore if they help to achieve a sustainable world.

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## Article

# Understanding Hazardous Waste Exports for Disposal in Europe: A Contribution to Sustainable Development

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**Abstract:** The concept of sustainable development was introduced in Europe by the Treaty of Amsterdam (1997) and was extended to waste management in the Waste Framework Directive. In order to achieve sustainable development, hazardous waste (HW) must be managed safely and in accordance with regulations. This also applies to worldwide HW transport, especially when HW is shipped for disposal. The United Nations, through the Basel Convention, aims to prevent the export of HW from developed countries to developing countries for disposal. In Europe, HW shipments are regulated by Regulation (EC) No. 1013/2006 of the European Parliament and by the Council of 14 June 2006 on shipments of waste. Additionally, all HW shipments must be in accordance with two principles contained in the Waste Framework Directive: proximity and self-sufficiency. Using data from 2014 and network analysis methodology, this paper fills the gaps in the scientific literature by looking at how shipments of HW travel for disposal in Europe, how the regulations affect these shipments and how GDP per capita influences the shipment of waste. The results show that countries with a high GDP per capita play an important role in the network (having the highest in-degree) and that the absence of landfill taxes for HW does not influence HW shipments for disposal. Therefore, countries in the EU act in accordance with the proximity and self-sufficiency principles.

**Keywords:** hazardous waste shipment; network analysis; gross domestic product per capita; disposal; proximity principle; self-sufficiency principle



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## 1. Introduction

Sustainable development is a fundamental objective of the EU and was included in the 1997 Treaty of Amsterdam [1]. Since then, the Sustainable Development Strategy has gone through a great revolution.

Sustainable development includes waste management as the Waste Framework Directive (WFD) urges Member States to “promote and support sustainable production and consumption models” and introduces the United Nations Sustainable Development Goals in its objectives, showing the relation between waste management and sustainability.

Although sustainability is an aim of the European Union, the European waste management industry shows a weak model of sustainability [2].

The study of efficient hazardous waste (HW) management in relation to legislation can be a driving force towards the achievement of sustainable development [3]. It should be noted that, in order to achieve sustainability, certain regulations and directives must be met and fulfilled to ensure safe and environmentally sound practices are implemented. The implementation of the two environmental principles included in the WFD, proximity and self-sufficiency, affect HW exports in Europe. However, HW is not only a European concern but also a worldwide concern, especially regarding its disposal. HW disposal must

be carried out safely and controlling HW shipments is essential to determine where and how such disposal takes place.

In the analysis of HW shipments transported for disposal, one must take into account how they affect sustainability. On the one hand, shipments of HW affect sustainability through carbon emissions, as road transport has a great impact on greenhouse gas (GHG) emissions [4–6]. However, an analysis of the regulations applying to the shipment of waste is also important, as transboundary waste shipments contribute to efficient waste management [7], and trade policies also affect environmental quality [8] and shipments.

Understanding these regulations and policy implications is key to achieving the Sustainable Development Goals [9].

Finally, disposal in landfill sites or in incineration facilities has a great impact on the environment and therefore on sustainability [10–14].

The main research problem is the lack of information on how HW is transported and disposed of in Europe, and the relationship between HW disposal shipments and compliance with European environmental laws. This article analyses different aspects of sustainability related to HW management and HW shipments and contributes by: (1) deepening the analysis of waste shipments in Europe and the way in which landfill taxes affect waste shipments; (2) analysing HW regulations and the adherence to the principles of proximity and self-sufficiency, and; (3) presenting a qualitative analysis of HW shipments for disposal using different variables – GDP, HW generation and the amount of HW shipped for disposal. To fulfil these aims, network analysis is used to display the importance of networks, giving us a picture of HW shipments, and showing the communities which arise in relation to HW exports for disposal.

Before the methodology is set out, there is a review of key aspects of HW shipments for disposal: a legislative review, including logistics, and a brief analysis of costs and capacity as they relate to the disposal of HW.

## 2. Objectives and Scope to Present Legislative and Literature Review

### 2.1. Objectives

Research literature shows how hazardous waste travels worldwide for disposal from rich countries to poor countries [15], making GDP an important element in HW shipments. European countries cannot export HW for disposal to countries outside the Organization for Economic Co-operation and Development. In order to achieve their objectives and fulfill regulations, countries can use different policies and landfill taxes.

In this research we answer the following questions, not yet analyzed by researchers:

- Does HW travel within Europe for disposal to countries with a low or high GDP?
- How do countries interact to fulfill self-sufficiency and proximity principles?

With these questions we try to fill the gap in the research literature about how HW travels and the relationship between HW shipments and legal compliance with European environmental laws.

### 2.2. Scope

The geographical scope of the research is Europe.

Regarding waste management the scope is Hazardous Waste exports for disposal. The year analyzed is 2014.

It must be pointed out that the scope of this research has several limitations. Firstly, due the research time, only 2014 data of hazardous waste shipments for disposal have been used in the network analysis. Secondly, not all European countries are studied, as Eurostat only has data for the countries included in the table. Thirdly, no data on number of landfills in each country have been used. Finally, the network is made from legal and official data from Eurostat, even if data from illegal shipments are important to understand the impact on sustainability.

### 2.3. Literature Review: The Origin of the Restriction of HW Exports

The Basel Convention controls HW transport for disposal worldwide. The EU, as part of the Basel Convention, has incorporated its provisions through the European Waste Shipment Regulation (EWSR) [16].

The EWSR was modified in 2014 by Regulation (EU) No 660/2014 of the European Parliament and by the Council of 15 May 2014, amending Regulation (EC) No 1013/2006 on shipments of waste and aiming to strengthen inspections of waste shipments, in order to discourage illegal shipping. Even after this amendment, loopholes in the legislation have been found [17].

Recently, and after China's plastic waste ban, the EWSR has been modified by the Commission Delegated Regulation (EU) 2020/2174 of 19 October 2020 amending Annexes IC, III, IIIA, IV, V, VII and VIII of Regulation (EC) No 1013/2006 of the European Parliament and of the Council on shipments of waste. China's ban was caused by plastic pollution [18] and will affect the plastic waste trade networks which have been hereto established [19], as well as the global circular economy [20].

Besides the Basel Convention and the EWSR, Directive 2008/98/EC on waste management includes two principles connected with waste shipments, as described in Article 16 of the WFD: self-sufficiency and proximity. The self-sufficiency principle indicates that "Member States shall take appropriate measures, in cooperation with other Member States where this is necessary or advisable, to establish an integrated and adequate network of waste disposal installation. The network shall be designed to enable the Community as a whole to become self-sufficient in waste disposal." The proximity principle states that "the network shall enable waste to be disposed of or recovered in one of the nearest appropriate installations by means of the most appropriate methods and technologies to ensure a high level of protection for the environment and public health."

The proximity and self-sufficiency principles can increase the market power of local disposers [21], as Reggiani and Silvestri state, but these principles are also analyzed because of their legal importance [22,23].

Compliance with both sets of regulations, the EWSR and the WFD and its principles, should lead to fewer exports of HW for disposal, and better control the illegal traffic in waste to poor countries [17,18,24,25].

The application of the proximity principle decreases the dangers in the transport of HW [26–28] and the GHG emissions caused by the transport of waste by road, and the self-sufficiency principle can lead countries and companies to innovate in order to comply with the regulations [29–32].

### 2.4. HW Management: Costs and GDP

Waste management costs have been indicated as one of the reasons for illegal shipments [33,34] and a barrier to a circular economy in which recovery is prioritized over disposal [35,36].

GDP is an important variable in this analysis for two reasons: on the one hand, there is a link between GDP and waste generation [37,38], and, on the other, as HW travel worldwide from rich countries to poor countries, it is important to know how GDP affects the export of waste in Europe, and if HW is disposed in countries with a high or a low GDP.

### 2.5. HW Shipment for Disposal and Disposal Taxes

Disposal operations are classified by the WFD into 15 categories, identified with the codes D1 to D15. In research on disposal taxes and their effects, not all papers distinguish between different disposal operations [39–41]. Instead, they discuss disposal in general. However, Sigman's analysis of HW taxes [42] establishes a difference between landfill disposal and incineration. Dinan [39] proposed the taxation of disposal and the establishment of a reuse subsidy. Levinson [40] studied the effect of disposal taxes on HW shipments for disposal, finding that HW disposal taxes increase the decentralisation of HW disposal. The

literature on this topic has developed widely, studying not only the impact of landfill and disposal taxes [43–45] but also the impact of environmental taxes [46–48].

It is important to determine what kind of disposal operations should be taxed if the right effect is to be achieved and there is to be sustainable development. Incineration (D10) increases in countries with landfill taxes, which causes landfills (D1) to decrease [49–51]. Taxes and regulations that ban the landfill disposal of some types of waste have allowed the Netherlands to reduce its number of landfills [52]. Interestingly, Scharff (2014) points out that “underground storage” in Germany is in a grey area between disposal and recovery, while others recognise underground storage as a common disposal practice [53].

According to a study on landfill taxes in Europe [54], landfill prices vary among and within European countries according to waste classification (e.g. HW, non-HW and municipal solid waste). Bulgaria, Finland and Norway have no landfill taxes for HW, while in the Belgian region of Wallonia, HW is partially banned. In other countries HW is taxed, with rates ranging from less than 10 euros/tonne (Portugal) to more than 60 euros/tonne (UK, Ireland, Denmark, Czech Republic and Estonia), which may be one of the causes of the shipment of waste for disposal. Some of these countries have also established taxes on incineration to promote waste recycling (Austria, Denmark, France, The Netherlands and Norway), whereas in countries where only landfill disposal is taxed, incineration has increased.

The variation of landfill taxes is also verified by the information provided by the Confederation of European Waste-to-Energy Plants (CEWEP) [55], updated to December 2017.

### 3. Materials and Methods

#### 3.1. Network Analysis for HW Shipment for Disposal in Europe

This research uses network analysis to determine the relationships among nodes (countries) and uses Gephi to show the relevance of these nodes in the network or the communities formed by the countries, in the framework of HW exports for disposal among EU Member States. Gephi is used not only to create a trade network to discover whether the self-sufficiency and proximity principles are being adhered to, but also to relate trade/shipments to GDP per capita and HW production. This paper analyzes how these variables affect HW shipments for disposal in Europe.

The stages of this research are presented in the following diagram (Figure 1):

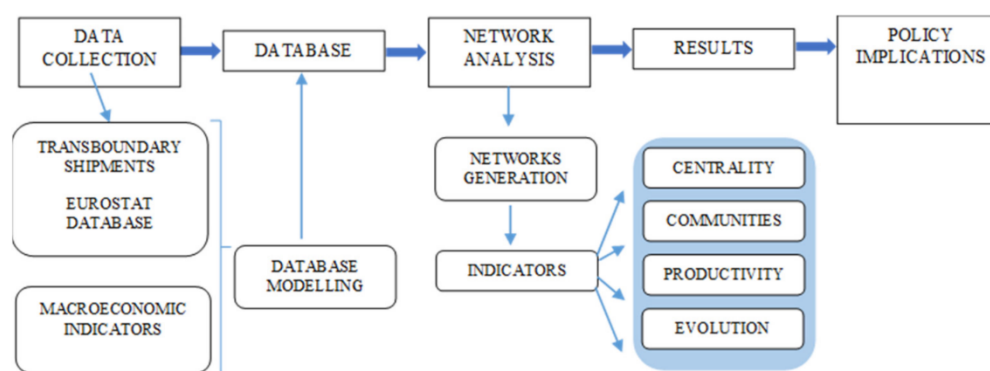


Figure 1. Block diagram.

Gephi is a piece of software designed to explore networks and has previously been used in scientific studies related to waste management. Lepawsky [56,57] used Gephi to evaluate e-waste trade and to determine its evolution and patterns. In his research he used e-waste data import transactions reported by territories and available from United Nations Comtrade. Chen et al. [58] and Wang et al. [59] used Gephi in an analysis of the literature related to waste. While the former used data from the WoS Collection Database on the most cited publications on construction and demolition waste, the latter used data on the literature on incinerating waste to produce energy.

### 3.2. Network Model

Different metrics, like degree centrality, eigenvector centrality and modularity, are used to analyze how European countries are linked to HW shipments for disposal. In the networks with origins in European countries in 2014,  $V$  represents the set of countries from Europe and  $E$  represents the shipments for disposal. Let  $(v_i, v_j) \in E$ , with  $v_i, v_j \in V$  as an edge (i.e., export) in  $G$ , representing HW shipments among countries  $v_i$  and  $v_j$ . This analysis assumes that countries' relationships are unidirectional—that is, from exporter to importer—and, therefore, the graph is directed.

#### 3.2.1. Centrality Network Metrics

Centrality metrics measure how important a country is in the European network. In this analysis, centrality shows the importance and the role of a given country in HW exports for disposal. Centrality includes 'micro' measures that show how a given node relates to the overall network [60,61]. Knowing the importance of countries (i.e., nodes) in the generated network indicates the relationships between these countries in the shipment of HW for disposal.

##### Degree Centrality

Degree centrality [62] represents the number of links each country/node has in the network, using the following formula:

$$DC^{v_i} = \frac{d(v_i)}{|V| - 1} \quad (1)$$

where  $d(v_i)$  denotes the degree centrality ( $DC$ ) of node  $v_i$  in the network. This metric counts the direct links of each country in the network.

##### Eigenvector Centrality

Eigenvector centrality was proposed by Bonacich [63], as follows:

$$\lambda \cdot EC^{v_i}(G) = \sum_{v_j} g_{ij} EC^{v_j}(G) \quad (2)$$

in which  $g_{ij}$  takes the value 1 if  $(v_i, v_j) \in E$  and 0 otherwise (retrievable if  $G$  is represented using an adjacency matrix) and  $\lambda$  is a proportional factor (i.e., the eigenvalue).

Eigenvector centrality measures the influence of a node on a network. In other words, nodes that have high values of this measurement are well connected. Also, in this sense, they are good connectors as waste exporters and importers from a large number of countries and in large amounts. When the degree of centrality of the eigenvectors is greater, the cohesion of the group is greater.

#### 3.2.2. Structural Analysis of the Network through Modularity

Modularity is another technique used to observe the relationships of HW shipments among European countries. This notion of community partition using modularity was first proposed by Newman and Girvan in [64]. The vertices in networks create groups or communities, which means that some countries in the analyzed network have many edges (exports) while other countries have few edges. Countries in the same community are better connected, while those in different communities are less likely to be connected.

$$M(\Pi, G) = \sum_{\pi \in \Pi} e_{\pi\pi}(G) - \sum_{\pi \in \Pi, \pi' \in \Pi, \pi'' \in \Pi} e_{\pi\pi'}(G) e_{\pi'\pi''}(G)$$

where  $\Pi$  represents any community structure and  $e_{\pi\pi}(G)$  represents the fraction of all edges in the network that connect nodes in  $\pi$  to nodes in  $\pi'$ .

#### 4. Results

The network analysis was performed with the disposal data obtained through Eurostat for the year 2014. As established in Regulation (EC) No. 2150/2002 of the European Parliament and the council of 25 November 2002 on waste statistics, Member States are obliged to provide data to Eurostat. The main reasons for analyzing the year 2014 are that in 2014 (1) the Circular Economy Package was presented and (2) the EWSR was modified. The Circular Economy Package was the starting point for legislative modifications in the Directives to regulate different waste streams and try to increase recovery and recycling. It is a key year to give a picture of HW shipments before the implementation of new recycling targets and new regulatory changes.

Table 1 shows tonnes exported for disposal from 2011 to 2015.

**Table 1.** Tonnes exported for disposal 2010–2015.

Year	Tonnes Exported for Disposal
2011	1,712,608
2012	1,509,190
2013	1,480,184
2014	1,528,391
2015	1,025,445

In 2015, a decrease in the quantities exported can be observed. The reason for this may be the change in landfill tax policies in some Member States, as CEWEP shows [55]. The Netherlands reintroduced its landfill tax, Norway repealed its landfill tax and Sweden established a fee in 2015. These changes in landfill taxes may have affected the exports of HW for disposal.

This study analyzes the shipments made in 2014 on the basis of the following scientific assumptions: countries are adhering to the proximity and self-sufficiency principles; as has been shown in research, there are difficulties in finding sites for HW facilities for disposal in the case of landfills and incinerators [65–67] because these must meet environmental, economic and social criteria; and countries must find the best routing model for their exports to minimize transportation costs and risks [26].

##### 4.1. From Data to Network Generation

Taking the current network model (Section 4.1), let  $G = (V, E)$  be the graph representing the network for European waste disposal analysis, in which  $V$  is the set of operating countries and  $E$  is the set of existing shipments among them.

The figures show two different networks. Figure 2 shows the network based on the effective shipments of waste and the GDP per capita and Figure 3 shows the communities formed in the network.

In the export analysis, Italy (573,614 tonnes), Germany (237,777 tonnes) and the Netherlands (195,969 tonnes) were the countries with the greatest amounts of HW exported for disposal. The countries that generated the most HW were Germany (21,812,660 tonnes), Bulgaria (12,206,169 tonnes) and France (10,783,405 tonnes).

Table 2 shows that countries with the highest GDP per capita or with a GDP per capita above 40,000 euros in 2014, according to Eurostat, exported the most HW for disposal to other countries with a high GDP per capita.

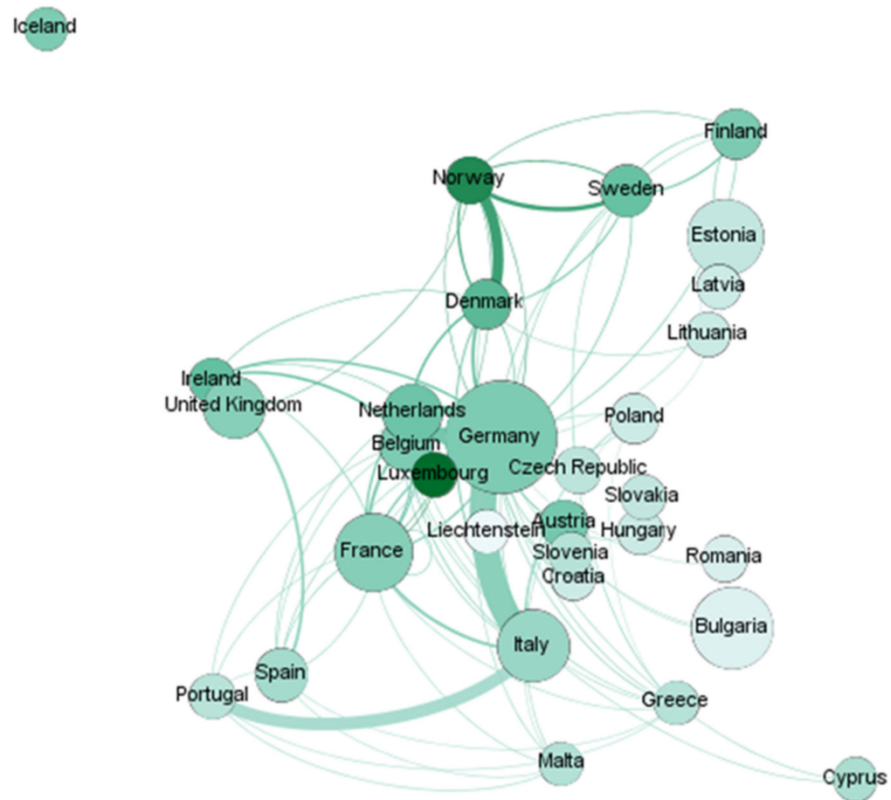


Figure 2. Network of HW shipments for disposal in Europe.

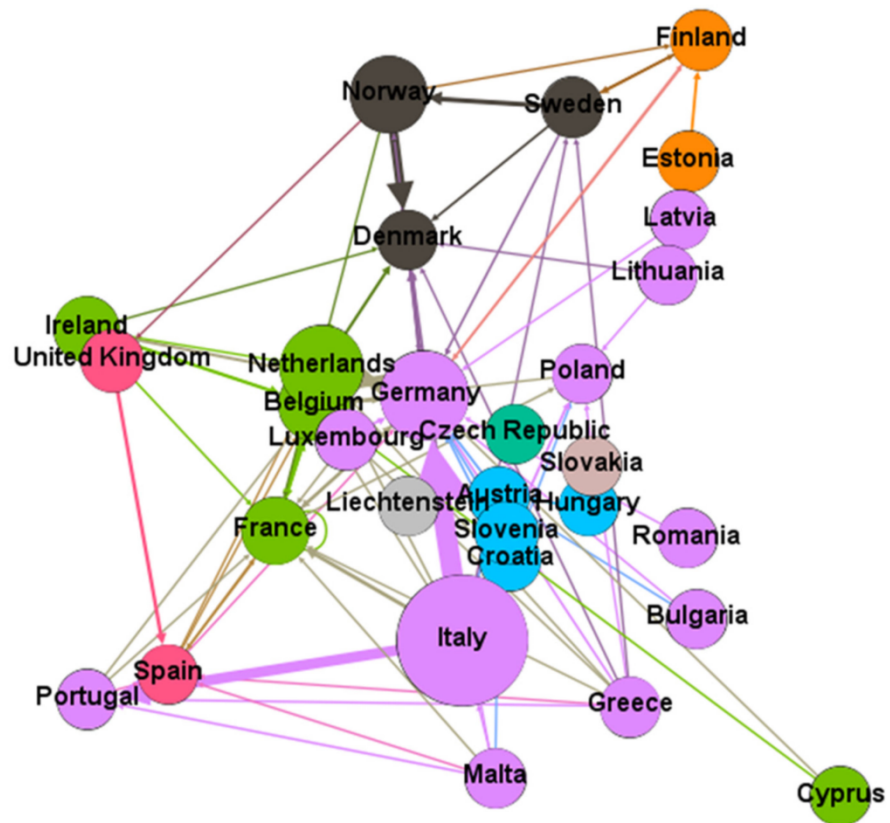


Figure 3. Network for HW shipments for disposal in Europe (2014), displayed by modularity.

**Table 2.** HW exports from high-income countries.

Exporting Countries	Importing Countries
Denmark	Germany Norway
Ireland	Belgium Germany France Denmark The Netherlands UK
Luxembourg	Belgium Germany France The Netherlands
Sweden	Denmark Germany Finland
Norway	Denmark Germany France Finland Sweden UK

The countries with the lowest GDP per capita or with GDP per capita lower than 15,000 euros did not receive HW for disposal, except Lithuania, which received HW for disposal from Latvia. Only two countries exported as much as 19% of the HW they produced (Malta and Slovenia), while the countries with the next highest exports exported under 10% of the waste they produced.

No data for HW landfill taxes were found from 2014. It is therefore not possible to assess whether these influenced HW shipments. However, in 2012, only three countries (Bulgaria, Finland and Norway) did not have landfill taxes for HW, and this did not appear to affect waste shipments—that is, European countries did not look to export to countries with no landfill taxes.

For degree centrality, three main nodes were considered (Germany with 26 relationships, France with 18 relationships and Belgium with 15 relationships). These countries are in central Europe, and, following the proximity principle, the logistics connectivity for these countries may have been greater. Furthermore, these three countries correspond to the highest in-degree values.

The results are shown in Tables 3 and 4 and Figures 2 and 3. Table 3 shows the amount of HW produced, the GDP per capita, the amount of HW exported, the in-degree (from how many countries waste is received or imported), the out-degree (to how many countries HW is exported), the degree (in-degree + out-degree) and the ratio of exports to generation.

Figure 2 highlights the waste tonnage generated by each node (i.e., the node size corresponds to the tonnage generated). The nodes are green, with their shades varying according to GDP per capita (a darker color corresponds to a higher GDP per capita). Finally, the thickness of the line corresponds to the amount of export flow between the countries.

Figure 3 shows the network displayed by modularity; each color represents a different community.

**Table 3.** Results from the Network Analysis for HW Shipments for Disposal in Europe in 2014.

Label	Export	GDP per Capita	Generated	Ratio Exp/Gen (%)	Indegree	Outdegree	Degree
Belgium	98,391	33,800	2,946,195	3.34	11	4	15
Bulgaria	1157	5500	12,206,169	0.01	0	2	2
Czech Republic	100	15,400	1,162,342	0.01	0	0	0
Denmark	2637	44,900	1,718,394	0.15	8	2	10
Germany	237,777	34,000	21,812,660	1.09	20	6	26
Estonia	11,504	13,200	10,410,321	0.11	1	1	2
Ireland	50,738	41,300	482,907	10.51	0	6	6
Greece	10,759	17,000	221,041	4.87	0	9	9
Spain	2984	22,300	2,984,518	0.10	5	4	9
France	69,386	31,300	10,783,405	0.64	12	6	18
Croatia	12,393	10,300	130,239	9.52	0	3	3
Italy	573,614	25,400	8,923,548	6.43	1	9	10
Cyprus	67	20,400	173,377	0.04	0	2	2
Latvia	107	10,300	104,142	0.10	0	2	2
Lithuania	765	11,300	165,477	0.46	1	3	4
Luxembourg	14,934	80,600	237,180	6.30	1	4	5
Hungary	174	10,700	596,554	0.03	0	1	1
Malta	6997	17,900	36,654	19.09	0	6	6
The Netherlands	195,969	38,600	4,830,495	4.06	8	4	12
Austria	7854	36,200	1,272,288	0.62	6	1	7
Poland	21	10,500	1,679,051	0.00	5	1	6
Portugal	1596	16,300	701,228	0.23	3	3	6
Romania	69	7000	590,300	0.01	0	1	1
Slovenia	29,628	17,500	155,229	19.09	0	2	2
Slovakia	100	13,600	371,214	0.03	0	0	0
Finland	15,036	34,200	1,998,693	0.75	4	2	6
Sweden	11,503	40,500	2,568,154	0.45	4	4	8
United Kingdom	29,597	31,000	5,755,258	0.51	2	1	3
Iceland	100	33,800	1000	10.00	0	0	0
Liechtenstein	100	1000	1204	8.31	0	0	0
Norway	142,734	67,400	1,368,049	10.43	3	6	9

**Table 4.** Communities in the European Disposal Network.

Modularity Class	Countries (Eigencentality)
0	Belgium (0.764), Ireland (0), France (0.968), Cyprus (0), The Netherlands (0.715)
1	Czech Republic (0)
2	Denmark (0.524), Norway (0.388), Sweden (0.173)
3	Bulgaria (0), Germany (1), Greece (0), Italy (0.002), Latvia (0), Lithuania (0.002), Luxembourg (0.170), Malta (0), Poland (0.224), Portugal (0.008), Romania (0.008)
4	Estonia (0.004), Finland (0.360)
5	Spain (0.246), United Kingdom (0.087)
6	Croatia (0), Hungary (0), Austria (0.015), Slovenia (0)
7	Slovakia (0)
8	Iceland (0)
9	Liechtenstein (0)

The node size is proportional to the waste tonnage that the country exports. The thickness of the line corresponds to the size of the export flow between the countries.

The modularity shows groups/communities in the network. These groups account for GDP per capita and show how the European countries apply the proximity and self-sufficiency principles.

Table 4 shows the communities formed in the network. The reasons for these communities are discussed in Section 6.

The largest community is the third (purple), which is composed of 10 countries: Bulgaria, Germany, Greece, Italy, Latvia, Lithuania, Luxembourg, Malta, Poland, Portugal and Romania. Germany has the highest eigencentrality score but the other members of this community have a score of nearly 0. Germany is also the country with the highest in-degree, which indicates that it receives the highest volume of HW. The second most important community is the first (green), which is composed of five countries: Belgium, Ireland, France, Cyprus and the Netherlands. Community six (blue) consists of Croatia, Hungary, Austria and Slovenia. The other communities are small.

## 5. Discussion

This paper analyses HW shipments for disposal, the effect of the regulations on the shipment of waste, the application of the two principles contained in the Waste Framework Directive—proximity and self-sufficiency—and the way in which GDP affects these shipments.

The adherence to these principles shows a low density network, while HW for recovery in the same year shows a high density network [68]. The density of the networks represents the links between the nodes, showing there are many fewer shipments for disposal than shipments for recovery.

The communities formed by some of the countries show that there is one country with a higher eigencentrality value [63], that is, a country that has a bigger relevance to the network.

The centrality shown by Germany can also be seen in the literature, as there has been a thorough analysis of waste treatment facilities in this country [69].

The countries with the highest in-degree (Germany 20, France 12, Belgium 15 and the Netherlands 12) are, except Belgium, countries with a high incineration capacity. These countries also have a GDP per capita above 30,000 euros.

In contrast with the “Pollution Havens” described in the research literature, in which waste travels from rich to poor countries [70,71], in Europe, HW is sent to be disposed of in countries with a high GDP.

This shows that high GDP makes these countries more able to use the best available techniques for wastes incineration [13].

The countries with high incineration capacity (France, Germany, Sweden, Denmark, the Netherlands, Austria and Finland) have a GDP per capita above 30,000 euros. These countries also have an important value for in-degree. It must be taken into account that, Sora [72] states that the opening of the incineration market threatens the application of the proximity principle.

## 6. Conclusions

One of the novelties of this study was the use of network analysis to fill in the gaps in the research literature about how HW travels for disposal in Europe and the relationship between HW shipments and legal compliance with environmental laws in relation to sustainability and sustainable development in Europe.

Network analysis is a useful tool to answer these research questions and to find out if HW travels for disposal to European countries with a low or high GDP and how countries interact to fulfil the principles of self-sufficiency and proximity.

HW is shipped for disposal to countries with a high GDP and high incineration capacities, which means that when countries must apply proximity and self-sufficiency principles, waste is shipped to countries with a high GDP, because these countries have better treatment facilities. This demonstrates how GDP is a determining factor in the export of waste.

Countries with a high GDP per capita have more incineration facilities; they are better prepared for the disposal of HW.

Good practices for the environment and for sustainable development are demonstrated by networks, showing coherence in the fulfilment of the principles of self-sufficiency and proximity, and the adherence to legal regulations.

The absence of a landfill tax does not affect the export of waste; countries with no landfill tax did not have higher in-degrees than countries that applied a landfill tax.

The network analysis demonstrated the relationships between countries when HW is shipped for disposal, and the association between countries generated from the adherence to the proximity and self-sufficiency principles.

Degree centrality demonstrated that countries in central Europe (Germany, France and Belgium) were the main nodes. Following the proximity principle, this may be because of better logistics connectivity. The application of these principles helps to improve efficiency in HW management systems, since it minimizes emissions from HW transport and indicates that countries have sufficient capacity for the disposal of the HW they generate.

Further research should be undertaken to establish the quantities of HW exported and imported for landfill and incineration in each country. Additionally, two circumstances may affect HW shipments: (1) the exit of the UK from the EU may affect waste shipments to and from this country and (2) the plastic waste ban imposed by China. New data may show how these circumstances affect waste trade and the stability of the communities.

The control of compliance with the analyzed regulations will be fundamental to avoid illegal waste trafficking and to protect the environment and citizens' health.

The capacities for waste management in Europe (i.e., landfill and incineration capacities) should also be determined. In future, Europe should establish appropriate regulations that take into account all these circumstances, in order to make a better contribution to sustainable development.

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# Modelling and analysing the relationship between innovation and the European Regulations on hazardous waste shipments

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## Abstract

In Europe, there are different regulations regarding hazardous waste management with which European Union Member States must comply. On the one hand, Member States must meet the recovery targets that are set in the different waste Directives, and they have two options here: material recovery facilities in the country of origin, or recovery through the shipment of waste. In addition, EU Member States must comply with the regulations governing the shipment of hazardous waste (HW), that is, the Basel Convention and the European Regulation on the shipment of waste. Two main questions arise: where is hazardous waste sent, and why? We analyse the European regulation on the shipment of waste, and we consider the above questions by combining network analysis methodology, to examine which countries in the network can be grouped in HW-trading communities, and ANOVA technique to study how the groups created in the network behave in different contexts. These HW-trading communities can be assessed according to European Innovation Indicators, GDP, and other variables. The results allow us to understand the drivers behind the shipment of HW for recovery in Europe. First, this study provides a descriptive overview of the relationships between European countries, the way in which they cooperate and describes how each country is positioned in the joint network. Second, the study is able to identify the most relevant countries in the network. Third, the HW-trading communities are analysed to discover whether they behave differently from the other groups according to GDP and other variables, amongst which we have included the following Europe Innovation Indicators: innovation index, research systems, innovation friendly environment, or innovators. The results show that the Nordic countries are outstanding in the way in which their waste is managed with other countries and reveal a community that works both in the context of hazardous waste shipment and innovation.

**Keywords** Regulation on the shipment of waste · Network analysis · Innovation context · ANOVA · HW-trading communities and political relationships

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## 1 Introduction

The world population has reached 7 billion and is expected to grow to 9 billion people (Gerland et al., 2014; Lee, 2011), and wealth per capita will also grow in countries like China, India, and some African countries (Tukker & Butter, 2007); therefore, the need for raw materials will also grow (Allwood et al., 2011; Rosenau-Tornow et al., 2009). Another need that will increase in the future is the demand for energy, as there is a correlation between the increase of wealth and energy consumption (Malinauskaite et al., 2017).

Higher wealth per capita is closely related to increases in waste, particularly e-waste (Awasthi et al., 2018; Kusch & Hills, 2017) but also solid industrial waste (Yanrong et al., 2011). With this increase of waste, waste management has been a subject of increased interest all over the world (Andersson & Stage, 2018; C. Callao et al., 2019a, 2019b; Sakai, 2017; Um et al., 2018), leading to policies targeting the circular economy (McDowall et al., 2017; Zhu et al., 2019). The term circular economy refers to the transformation of the function of resources in the economy (Prescston 2012) so that waste has to be processed close to the point of origin (Kama, 2015) and in accordance with the principles of the 3Rs (reduce, reuse, recycle) (Ranta et al., 2018). In this new policy framework, it is important to take into account whether waste is managed in the place where it is produced, or whether it is shipped to another country for treatment.

The shipment of hazardous waste has been studied from different environmental perspectives. The shipment of HW from the north to the south has been thoroughly studied (Cotta, 2020; Lucier & Gareau, 2016; Renckens, 2015; Sonak et al., 2008) as it represents a risk for developing countries. Waste shipment is not always from north to south as researchers have proven that the USA exports more HW to Canada than to Mexico (Moore et al., , 2018, 2019).

Route visualisation can help in understanding the socio-economic characteristics of waste destinations and in decision making (Moore et al., , 2018, 2019; Rosenfeld et al., 2018; Vincent et al., 2019). Waste shipments have been examined with a view to aiding the process of route optimisation, that is, routing problems (Laurence and Wynne, 1989; Nema and Gupta, 1999; ReVelle et al., 1991) as authors look for the best model for planning and routing in HW management systems to minimize the risks. Waste transport is also important because of emissions, and transport emissions have been studied in the case of air transport (Morrell, 2007), road transport (Ong et al., 2011) and maritime transport (Viana et al., 2014).

Regarding the regulations that apply, the shipping of waste is controlled and regulated in the case of HW by the Basel Convention (“Basel Convention,” 1989), and the OECD Decision Control System for waste recovery (OECD Council, 2004). Both these regulations have been implemented in Europe by Regulation (EC) No 1013/2006 on shipments of waste (European Parliament, 2007).

In Europe, there is one regulation for waste management and another for waste transport. Waste transport is regulated in Europe by Regulation (EC) No. 1013/2006. The definition and types of waste, the actors involved with waste and the way in which waste must be managed and treated are regulated by the Waste Framework Directive (WFD) (European Parliament & the Council of the European Union, 2008). Waste Framework Directive aims “to protect the environment and human health by preventing or reducing the adverse impacts of the generation and management of waste and by reducing overall impacts of resource use and improving the efficiency of such use” (Article 1).

WFD defines hazardous waste (HW) as “waste which displays one or more of the hazardous properties listed in Annex III”. Hazardous wastes pose a danger to human health and the environment (Sonak et al., 2008; Yilmaz et al., 2017). Therefore, depending on the waste stream there are different protocols and possible treatments (Nema & Gupta, 1999).

Taking into account that facilities that process HW generate externalities and are controversial (Hamilton, 1993), it is important to study HW exports for recovery in Europe, in order to find the elements of these shipments of HW and to develop better policies. Waste transport has been studied on the basis of the Basel Convention and of GHG emissions, and from the point of view of its routing, but it has not been studied by looking at the links and relations it creates between different European countries as a form of further cooperation. It is important to fill this gap, as the transport of waste gives us information about how each country manage its waste, but also shows the informal coalitions or alliances between countries; a thorough analysis can therefore lead to better policies and to a better understanding of the relationships between European countries.

This paper analyses the shipment of HW for recovery from the complex networks perspective and looks at how this relates to Regulation (EC) No 1013/2006 and Europe innovation indicators. Network analysis has been used in waste management, as, municipal waste collection and the optimisation of transporting and routing HW have been analysed through networks (Cerqueti et al., 2021; Jennings & Sholar, 1984; Karadimas & Loumos, 2007; Seadon, 2010). These studies showed the importance of finding not only the optimal routes but also the best waste collection and management systems. Network analysis has also been used to study HW shipments between Canada, Mexico, and the USA (Moore et al., 2018).

HW shipments can be for disposal or for recovery, none of the previous research has studied HW exports for recovery in Europe from a network analysis perspective, and neither has the network structure, that is created in HW shipment for recovery, been studied.

This research has a twofold target: To analyse two different waste trading networks obtained with two different analytical techniques, and to analyse the role of EU countries in managing waste from a political perspective.

To achieve the set objectives, in section two we will analyse and study the recovery<sup>1</sup> targets and how hazardous waste is recovered. In section three, we will present Europe Innovation Indicators. The methodology will be presented in section four, and finally we will analyse the results of the network and see if there is a relation between the network results and innovation in European countries.

## 2 Common recovery targets for hazardous and non-hazardous waste

Waste trade has been documented since 1970 (O’Neill 2001). It is a symptom of the problems faced by the waste management sectors in industrialised countries (O’Neill, 1998). Researchers have reported how even within Europe there are substantial differences in levels of waste trade. The United Kingdom and France were identified as the largest importers of HW within the EU, while Germany was a waste exporter (Bernard & Chang, 1994; O’Neill, 1997). Waste trade is conducted to minimise disposal costs (Bernard & Chang,

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<sup>1</sup> The definition that will be used for recovery, will include recycling as it is based on the recovery definition included in the WFD.

1994) and to meet the demands of the regulatory system (O'Neill, 1997). Waste exports may play an important role in the transition towards a circular economy. This process (including the associated policies, such as circular economy, and actions of the European countries involved) has been studied by a number of scholars (Domenech & Bahn-Walkowiak, 2019; Hartley et al., 2020). The circular economy package has introduced new recycling targets for the different waste streams (Official Journal of the European Union, L 150, 14 June 2018), but these targets do not consider if the wastes are hazardous or not. According to European regulations, if the wastes are shipped, for recovery or recycling, to other European countries then they must be counted in the country where they were collected from. Waste shipment regulations state that hazardous waste for recovery can be exported to non-European Union States (European Parliament, 2007).

In waste shipment for recovery, more developed countries have better recycling rates, but studies do not indicate if there is a difference depending on whether or not the waste is hazardous (Higashida and Managi, 2008; van Beukering & Bouman, 2001). The high recycling rates in developed countries may be due to the value of the wastes (Cucchiella et al., 2015) and the obligation for European Union member states to reach the objectives of the different waste directives.

Different reports have also shown that recovery is beneficial for the GDP, European Commission states that private investment for a circular economy was estimated to be around 0.1% of GDP in Europe (European Commission, 2018). Also, the Ellen McArthur Foundations calculated that a circular economy will grow the European economy by 7% (Ellen MacArthur Foundation and the McKinsey Center for Business and Environment, 2015). Apart from the positive economic impact of recovery, it has become necessary, as there is also a relation between GDP and waste generation, the higher the GDP is, the more wastes a country produces (Lee et al., 2017; Malinauskaite et al., 2017).

According to Eurostat, the top treatment recovery operations for hazardous waste in 2014 were R4 (recycling/reclamation of metals and metal compounds—1.635 (1000 tonnes), R5 (recycling/reclamation of other inorganic materials—807 (1000 tonnes), R1 (use as a fuel other than in direct incineration) or other means to generate energy—649 (1000 tonnes), and R12 (Exchange of wastes for submission to any of the operations numbered R1-R11- 448 (1000 tonnes). When there are no metals or inorganic materials to recover, waste to energy (R1) seems to be the most used recovery operation. Waste to energy diverts waste from landfill and turns it into energy, thus saving emissions (Porteous, 2001; Psomopoulos et al., 2009; Tan et al., 2014).

Recovery must be done safely, and innovation can contribute towards this aim, as has already been shown (Gohlke & Martin, 2007; Potdar et al., 2016).

### 3 Europe innovation indicators

Innovations and environmental issues are closely related, (Porter and Van der Linde 1995). The Porter hypothesis highlighted the importance of strict environmental regulations for the introduction of innovation in cleaner technologies and environmental improvements. The relationship between policies and innovation has been widely studied (Ashford and Hall, 2011; Cecere and Corrocher, 2016; Chen et al., 2017; Fankhauser et al., 2013; Guo et al., 2017; Jo et al., 2015; Melece, 2015) as technological innovations can help with reaching environmental targets (Jordaan et al., 2017), and therefore with sustainable development (Ashford and Hall, 2011). Taking this into account, the authors use different

terminology such as green growth (Guo et al., 2017) or eco-innovation (Chen et al., 2017; Jo et al., 2015; Melece, 2015; Nill and Kemp, 2009) when talking about innovation that is connected to sustainability or environmental improvements.

Regulation and innovation can help with decoupling economic growth and environmental damage (Mazzanti and Nicolli, 2011; Nill and Kemp, 2009). Environmental regulation can be done through subsidy schemes (Georg et al., 1992) and analysing the impact on firms in order to reduce it (Hernandez-Sancho et al., 2000). To achieve this purpose, innovation and eco-innovation must be measured (Basso et al., 2013).

Regarding innovation, the European Commission has created the European Innovation Scoreboards (EIS), whereby innovation indicators can measure not only innovation but also other important results, such as an innovation friendly environment. From 2011, Europe elaborated on its innovation index whereby 27 different indicators are used to analyse the performance in different innovation areas.

The results from 2014 are summarised in the following choropleth maps: innovation index, innovators, innovation friendly environment, and research systems.

- Innovation index represents the results from the 27 indicators used by the European Commission in its report (Directorate-General for Enterprise and Industry).
- Innovators index shows the results from four indicators: share of firms that have introduced innovations onto the market or with their organisations, covering both product and process innovators, marketing and organisational innovators, Small and medium-sized enterprises (SMEs) that innovate in house.
- Innovation friendly environment uses two indicators: broadband penetration among enterprises and opportunity driven.
- Research systems shows the results from three indicators: scientific publications, most cited publications, and doctorate students.

The values of each of the four groups are represented in the following choropleth maps (Fig. 1).

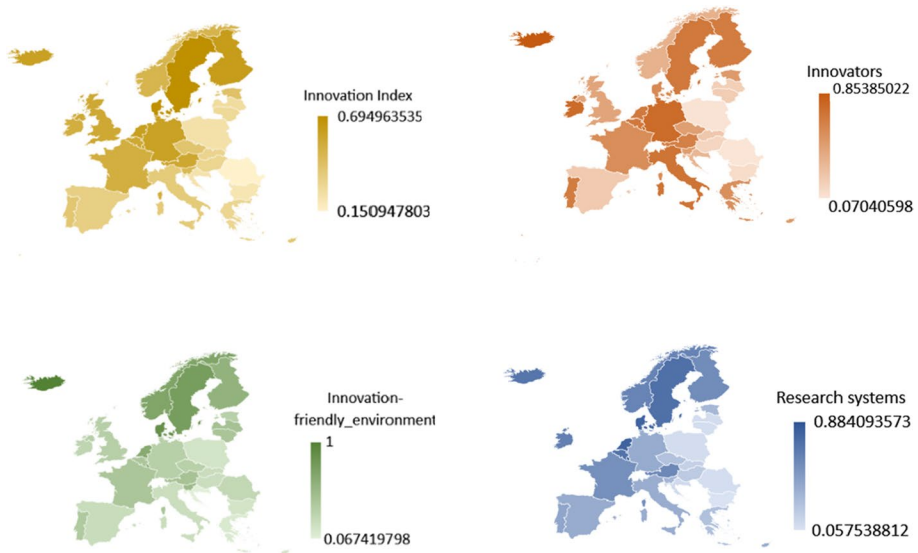
We investigate the relationship between HW trade and innovation. Using ANOVA, the aforementioned indicators are studied in relation to the HW-trading communities that emerge from the network analysis of HW shipments for recovery. This has enabled us to examine the behaviour of these HW-trading communities with regard to HW.

## 4 Methodology and network representation

All the data in this research are published in Eurostat (“Eurostat—Data Explorer”), the statistical office of the European Union as this is the official information European countries provide to the European Commission.

We have built and analysed the network of hazardous waste shipment for recovery by applying the tools and methodologies of the discipline of Complex Networks (Boccaletti et al., 2006). The advantages of using network analysis in our research are threefold: (1) it allows a better understanding of the European scenario on HW shipment, (2) it can be used as a resource to allow individual countries to study their own relationships, and (3) we can identify the HW-trading communities and see what characterises them.

Network analysis has its origin in graph theory (Barnes, 1983; Butts, 2009), vertices/nodes and edges are common elements in both, and networks are represented by graphs.



**Fig. 1** Choropleth maps of Innovation index, Innovators index, Innovation friendly environment and Research systems. Own elaboration based on European Commission has created the European Innovation Scoreboards

Network analysis can show meaningful relations (Prell et al., 2009a) by using different network concepts, such as centrality, density, or modularity. In this research, we have used directed graphs (Börner et al., 2007) centrality, and modularity.

The concept of centrality was extensively developed by Freeman (Freeman, 1977, 2004) who made a compendium and analysed the following types of centrality: degree centrality, closeness centrality, betweenness centrality, and eigenvector centrality. These concepts and its measures have been extensively developed and used in social network analysis (Brandes, 2001; Hage & Harary, 1995; Yan & Ding, 2009).

Regarding degree centrality, we will see which country holds the majority of ties with others in the network (Prell et al., 2009b), and through degree centrality we will see how the countries are connected to each one of the actors and which one has more connections and therefore plays a major role. For this purpose, we will also use eigenvector centrality to establish the importance of a country in the network (Bonacich, 1987). As Bonacich stated “eigenvector is an appropriate measure when one believes that actors status is determined by those with whom they are in contact”.

Outdegree centrality shows to how many countries each member exports hazardous wastes. The results will show which countries occupy the most relevant positions.

Let  $G=(V, E)$  be a graph in which  $V$  represents the set of countries (we use the term nodes, countries with the same meaning) participating in recovery shipment and  $E$  represents the set of links of shipment between them. Let  $(v_i, v_j) \in E$ , with  $v_i, v_j \in V$ , as an edge in  $G$  that represents any kind of shipment between countries  $v_i$  and  $v_j$ .

The observations of the degree centrality reveal that four countries have the highest centrality: Germany, Belgium, Netherlands, and France. With the exception of Germany, the rest of the countries are between the countries that export the largest amounts for recovery.

The results of the centrality metrics are shown in Table 1, which provides some interesting findings. Indegree centrality shows how many nodes/countries each member receives

**Table 1** Results obtained using centrality metrics

Id	Label	Export	GDP	Generated	Indegree	Outdegree	Modularity_class	Eigencentrality
1	Belgium	524,650	33,800	2,946,195	18	12	1	0.876125
2	Bulgaria	2,374	5,500	12,206,169	6	3	3	0.184315
3	Czech Republic	33,728	15,400	1,162,342	6	6	0	0.298495
4	Denmark	129,744	44,900	1,718,394	7	8	4	0.370225
5	Germany	366,725	34,000	21,812,660	29	16	2	1.000000
6	Estonia	1,699	13,200	10,410,321	5	6	4	0.159824
7	Ireland	180,826	41,300	482,907	1	9	4	0.070881
8	Greece	9,093	17,000	221,041	2	10	3	0.021239
9	Spain	38,608	22,300	2,984,518	12	9	1	0.595103
10	France	1,075,755	31,300	10,783,405	19	11	1	0.857168
11	Croatia	9,276	10,300	130,239	0	9	0	0.000000
12	Italy	373,152	25,400	8,923,548	11	11	2	0.610052
13	Cyprus	2,585	20,400	173,377	1	5	3	0.003652
14	Latvia	18,093	10,300	104,142	2	5	2	0.033515
15	Lithuania	20,291	11,300	16,477	5	6	0	0.153449
16	Luxembourg	69,824	80,600	237,180	4	5	2	0.292839
17	Hungary	28,704	10,700	596,554	4	11	0	0.122130
18	Malta	11,016	17,900	36,654	0	6	1	0.000000
19	Netherlands	574,261	38,600	4,830,495	18	12	2	0.847686
20	Austria	253,438	36,200	1,272,288	18	9	2	0.843815
21	Poland	23,634	10,500	1,679,051	19	5	0	0.764753
22	Portugal	53,355	16,300	701,228	3	6	1	0.063085
23	Romania	25,164	7,000	590,300	6	6	3	0.223013
24	Slovenia	27,560	17,500	155,229	7	5	0	0.406910
25	Slovakia	11,947	13,600	371,214	3	7	0	0.143415
26	Finland	99,442	34,200	1,998,693	6	10	4	0.377701
27	Sweden	139,340	40,500	2,568,154	16	13	4	0.650768
28	United Kingdom	217,259	31,000	5,755,258	16	13	1	0.718951
29	Iceland	12,272	33,800	36,250	0	4	1	0.000000
30	Liechtenstein	3,835	100,000	5,744	0	2	2	0.000000
31	Norway	887,507	67,400	1,368,049	7	11	4	0.301826

hazardous wastes from. In this case, Germany (29), France (19), Poland (19), Belgium (18), Netherlands (18) and Austria (18) are the countries with the highest indegree. Again, Belgium, Netherlands, and France appear in this list, that is, not only do they produce the largest amounts of hazardous wastes, but they also receive wastes from more than half of the countries in the table.

According to the degree eigenvector centrality, countries with the highest eigenvector centrality are Germany (1), Belgium (0.87), France (0.85), Netherlands (0.84), and Austria (0.84). All of these countries belong to HW-trading communities 1 (Belgium and France) and 2 (Germany, Netherlands and Austria), as it is shown in Table 1.

**Table 2** Modularity Class—HW-trading communities

Modularity class	Countries (Eigencentrality)
0	Czech Rep, Croatia, Lithuania, Hungary, Poland, Slovenia, Slovakia
1	Belgium, Spain, France, Malta, Portugal, United Kingdom, Iceland
2	Germany, Italy, Latvia, Luxembourg, Netherlands, Austria, Liechtenstein
3	Bulgaria, Greece, Cyprus, Romania
4	Denmark, Estonia, Ireland, Finland, Sweden, Norway

**Fig. 2** Hazardous waste shipment flow for recovery

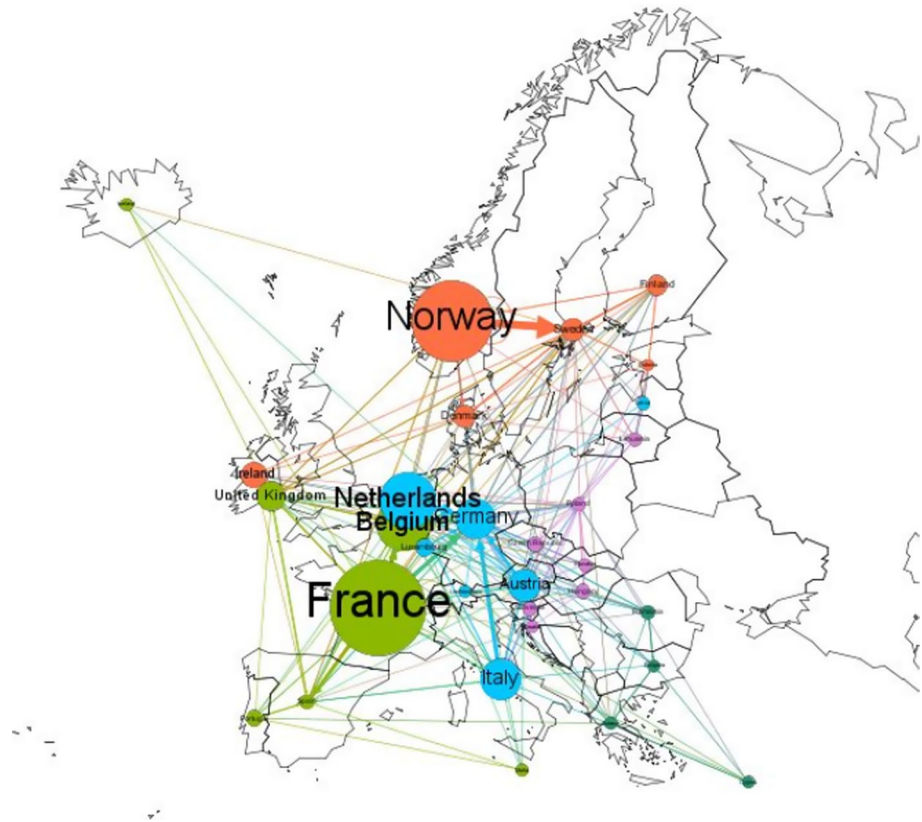
As was previously mentioned, Belgium, Germany, France, and Netherlands are the countries that export the largest amounts of hazardous wastes for recovery and also have the highest indegree and degree values regarding centrality.

We will also look for modularity in the network. This concept has been widely used in biology when looking for “connected molecular components” (Yoon et al., 2006) or “loosely linked islands of densely connected nodes” (Sauro, 2008). Modularity has been widely used in health sciences (Alexander et al., 2009; Stevens et al., 2012; Taylor et al., 2009). It has also been applied in social network analysis and was defined by Newman (Newman & Girvan, 2004) as “the detection and characterization of community structure in networks, meaning the appearance of densely connected groups of vertices”.

Table 2 shows that five HW-trading communities emerge in this network, as we mentioned before, is related to the emergence of densely connected groups.

Figure 2 displays HW shipment flows for recovery, we emphasize two different metrics, firstly, the number of tonnes generated by each country is represented by the size of the node. Secondly the GDP is represented by the colour of the node, that is, countries with a higher GDP are represented in a darker colour. The thickness of the link represents the quantity of HW shipment flows between countries, and the edge colour indicates the node of origin. According to this figure, countries with the highest GDP are not the countries that produce the largest amount of hazardous wastes.

In Fig. 3, we can observe the modularity of the network, that is, its structure and which HW-trading communities are formed. The size of the node represents the number of tonnes



**Fig. 3** Network displaying the modularity

that each country exports. The thickness of the lines represents the amount of wastes sent to another country; a high amount of exports is represented by a thick line between the nodes. In this figure, the thickest line is between Norway and Sweden, where both countries have a GDP above 40.000 euros/capita, and with a high degree of centrality (29) and also a high indegree (16). The colours in Fig. 3 represent the HW-trading communities that arise in the network.

## 5 Discussion

Every three years, the European Commission publishes reports on the implementation of Regulation (EC) No 1013/2006 of 14 June 2006 on shipments of waste; reports have been published in the years 2018, 2015, 2012, 2009 and 2006. These reports contain an analysis of waste shipments based on the data. It is interesting to discover how Regulation (EC) No 1013/2006 of 14 June 2006 on shipments of waste works from another perspective, based not only on the data provided by the European countries but also taking into account other variables such as GDP, the nodes we find in network analysis, and the HW-trading communities that arise in this analysis.

The HW-trading communities obtained are analysed below to see how they behave. Matching those HW-trading communities with other variables could be relevant to understand how waste shipment takes place. The discussion will lead us to look at our results in the light of these waste politics.

We use a new perspective to analyse Regulation (EC) No 1013/2006 of 14 June 2006 on shipments of waste, with data from 2014 and using network analysis we have generated two networks (Figs. 2 and 3) in which we can evaluate hazardous wastes exports for recovery between European countries. In Table 1, we present the results obtained for centrality metrics, as well as other data, such as GDP or the amount of wastes exported for recovery. Both networks are formed by 31 countries and 251 edges, which represent the number of exports of hazardous waste shipments for recovery.

If we compare the countries that generate the largest amounts of hazardous wastes, Germany (21,812,660 tonnes), Bulgaria (12,206,169 tonnes), France (10,783,405 tonnes), and Estonia (10,410,321 tonnes) with the countries that export the largest amount of wastes, France (1,075,755 tonnes), Norway (887,507 tonnes), Netherlands (574,261 tonnes) and Belgium (524,650 tonnes), we can observe that the countries that generate the largest amounts of hazardous wastes are not the countries that export the largest amounts for recovery.

If we analyse the percentage of hazardous wastes exports, we find that the countries with the higher percentages are Liechtenstein (66.76%), Norway (64.87%), and Iceland (33.85%).

The data show the importance of the hazardous waste market in Europe, in which safety is guaranteed by compliance with the Regulation for the shipment of waste and the WFD. They also show the importance of waste transport in meeting the targets of the circular economy, since not all the countries have the technology or capacity for waste treatment in the place of origin. This gives rise to a market that, no doubt, contributes to creating employment and wealth in different sectors, from waste management machinery, to trucks, drivers and mechanical workshops.

## 6 Analysis of network HW-trading communities

The next step is to understand the main characteristics of the five HW-trading communities generated by the network and represented in Table 2 and in different colours in Fig. 3. The first approach is to know if these groups/communities behave as such and differently from the rest of the groups according to the different variables we are studying for year 2014. We want to know what their behaviour is regarding the GDP per capita, the total hazardous waste generated, greenhouse gases generated, recovery (energy recovery), and Waste to energy plants by classified countries. It is also of interest to know their behaviour regarding the indicators defined by the EU for innovation. We have also studied the cloropath maps in Fig. 1 that are linked to innovation and research, with a special emphasis on eco-innovation.

For this purpose, as a second stage, the analysis of variance (ANOVA) of a factor has been studied. This analysis allows the comparison of several groups as a quantitative variable. This test is a generalisation of the equality of means contrast for two independent samples. It is applied to contrast the equality of means of three or more independent populations. This analysis is inter- and intragroup, that is, no individual country's behaviour

**Table 3** One-factor ANOVA

Dependency relationship		DOF	F Value	Significant relationship (p-value)
GDP	Inter-groups	4	5.126	Yes
	Intra-groups	25		0.004
	Total	29		
Hazardous Waste Generated	Inter-groups	4	1.027	No
	Intra-groups	25		0.413
	Total	29		
Innovation Index	Inter-groups	4	7.343	Yes
	Intra-groups	25		0.000
	Total	29		
Research Systems	Inter-groups	4	6.563	Yes
	Intra-groups	25		0.001
	Total	29		
Innovation Friendly Environment	Inter-groups	4	3.706	Yes
	Intra-groups	25		0.017
	Total	29		
Innovators	Inter-groups	4	4.474	Yes
	Intra-groups	25		0.007
	Total	29		
Greenhouse Gases	Inter-groups	4	1.556	No
	Intra-groups	25		0.217
	Total	29		
Recovery	Inter-groups	4	1.029	No
	Intra-groups	25		0.412
	Total	29		
Waste to Energy	Inter-groups	4	1.507	No
	Intra-groups	24		0.232
	Total	28		

NO: There is no functional relationship. YES: There is a functional relationship. Number in parentheses corresponds to the critical level of test

DOF Degree of Freedom

is assessed. These groups are the five HW-trading communities, shown in Table 2, that emerge from the network analysis carried out in this work.

This index requires  $k$  independent samples of the variable of interest. This grouping variable is called a factor and it seeks to classify the observations of the variable in the different samples. Table 3 shows the possible two-to-two combinations between the levels of the factor variable and the differences between the categories of the variable in each group. The groups whose means differ significantly (at the 0.05 level of p-value) are those that show statistically significant differences from each other. As a Post Hoc contrast, the Scheffé Test has been used.

As given in Table 3, there are five variables highlighted in bold that can be defined as independent indicators. Therefore, these groups, the five HW-trading communities shown in Table 2, behave significantly differently in the GDP per capita and in the innovation and

**Table 4** Descriptive analysis based on flow characterisation

	N	Mean	Standard deviation	Minimum	Maximum	
GDP (Euros/capita)	G0	7	12,757.14	2,818.90	10,300.00	17,500.00
	G1	7	26,628.57	7,587.21	16,300.00	33,800.00
	<b>G2</b>	<b>6</b>	<b>37,516.67</b>	<b>23,490.46</b>	<b>10,300.00</b>	<b>80,600.00</b>
	G3	4	12,475.00	7,346.37	5,500.00	20,400.00
	<b>G4</b>	<b>6</b>	<b>40,250.00</b>	<b>17,482.65</b>	<b>13,200.00</b>	<b>67,400.00</b>
Total	30	26,406.67	17,433.12	5,500.00	80,600.00	
Innovation Index*	G0	7	0.32264	0.08471	0.23679	0.46926
	G1	7	0.48315	0.09901	0.34375	0.59994
	<b>G2</b>	<b>6</b>	<b>0.50168</b>	<b>0.14564</b>	<b>0.26923</b>	<b>0.60740</b>
	G3	4	0.26517	0.10194	0.15094	0.38527
	<b>G4</b>	<b>6</b>	<b>0.57168</b>	<b>0.11488</b>	<b>0.41447</b>	<b>0.69496</b>
Total	30	0.43805	0.15126	0.15094	0.69496	
Research Systems*	G0	7	0.17099	0.08694	0.08551	0.31377
	<b>G1</b>	<b>7</b>	<b>0.51737</b>	<b>0.19334</b>	<b>0.20568</b>	<b>0.71193</b>
	<b>G2</b>	<b>6</b>	<b>0.51727</b>	<b>0.29703</b>	<b>0.09052</b>	<b>0.88409</b>
	G3	4	0.19228	0.14876	0.05754	0.37277
	G4	6	0.60452	0.16908	0.30591	0.79567
Total	30	0.41061	0.25504	0.05754	0.88409	
Innovation Friendly Environment*	G0	7	0.27839	0.15256	0.06742	0.50461
	<b>G1</b>	<b>7</b>	<b>0.45512</b>	<b>0.24894</b>	<b>0.23101</b>	<b>1.00000</b>
	<b>G2</b>	<b>6</b>	<b>0.46233</b>	<b>0.17159</b>	<b>0.22029</b>	<b>0.65506</b>
	G3	4	0.18011	0.06400	0.12029	0.27079
	<b>G4</b>	<b>6</b>	<b>0.59257</b>	<b>0.23586</b>	<b>0.29009</b>	<b>0.87500</b>
Total	30	0.40615	0.22834	0.06741	1.00000	
Innovators*	G0	7	0.27716	0.15159	0.07829	0.47336
	<b>G1</b>	<b>7</b>	<b>0.56806</b>	<b>0.20118</b>	<b>0.22007</b>	<b>0.85385</b>
	<b>G2</b>	<b>6</b>	<b>0.62298</b>	<b>0.21933</b>	<b>0.18915</b>	<b>0.78538</b>
	G3	4	0.30771	0.24840	0.07041	0.54855
	<b>G4</b>	<b>6</b>	<b>0.58621</b>	<b>0.14399</b>	<b>0.35731</b>	<b>0.75259</b>
Total	30	0.48008	0.23204	0.07041	0.85385	

Functional relationship are given in bold

\*For definition see Directorate-General for Enterprise and Industry (European Commission), 2014 In bold Groups with higher means in each variable

research indicators: innovation index, research systems, innovation friendly environment, innovators.

Next, in Table 4, a descriptive analysis of the network HW-trading communities is carried out according to the factors that characterise the sample, based on the results in Table 3.

As shown in Table 4, the groups G4 formed by Denmark, Estonia, Ireland, Finland, Sweden, and Norway, and G2 formed by Germany, Italy, Latvia, Luxembourg, Netherlands, Austria, and Liechtenstein are the ones that have higher means for all the analysed variables. The G4 group has typical deviations that are smaller than the G2, so the behaviour of

these countries is more homogeneous. This group has higher average values, except for the innovator indicator. It should be noted that the G1 group (Belgium, Spain, France, Malta, Portugal, United Kingdom, Iceland), has a similar behaviour to the G2 Group regarding the research systems and innovation friendly environment variables.

## 7 Discussion of ANOVA analysis

Hazardous waste management has always been analysed in great depth (Chang & Wang, 1995; Cucchiella et al., 2015; He et al., 2006; Marques et al., 2012). For this reason, it is important to go beyond data and carry out a deeper analysis to understand not only how hazardous wastes move, but also what other variables, such as GDP or the hazardous waste generated, affect these exports. It is also important to establish which HW-trading communities are formed, and how they go beyond HW exports to interact through innovation. These issues are examined using network analysis, the European Innovation Scoreboard (2020), and the ANOVA technique, providing information that arises from the implementation of Regulation (EC) 1013/2006 on the transport of waste.

The analysis of the HW shipments for recovery network revealed 251 connections between European countries. From the network analysis, it is observed that exports between them produce HW-trading communities. These HW-trading communities are made up of countries with common characteristics. An ANOVA analysis was carried out in order to identify variables that lead to common behaviours within each community and that distinguish them from other HW-trading communities. The results show the importance of countries like France, Germany, Netherlands, or Belgium, but the HW-trading communities formed show that GDP may be an important variable; the proximity of the HW-trading communities also appears to be an important factor.

Germany is the country with the highest degree, as it receives HW from 29 countries (indegree 29) and sends HW to 16 countries (outdegree 16), showing how powerful it is in relation to the shipment of HW for recovery. Its leadership and importance in Europe has been subject to research (Bulmer & Paterson, 1996, 2010; Hyde-Price & Jeffery, 2001).

However, HW-trading communities, and the countries within them, can also be analysed from other political perspectives; these perspectives arise as a consequence of the shipment of HW for recovery but may have their roots in other forms of cooperation such as coalitions or cooperation in European macro-regions.

Coalitions show power distributions (Aleskerov et al., 2002). Our results demonstrate that HW-trading communities are formed by countries that are not distant. Proximity has already been signalled as one of the roots of coalitions, as coalitions may be culturally based, associated with geographical proximity or show a division between north and south (Elgstrom et al., 2001). HW-trading communities therefore show cooperation that may go beyond the exchange of HW for recovery.

Coalitions also show how “greener countries” in Europe work together towards a common target (Liefferink & Andersen, 1998) and the importance of the Nordic block is shown in the results of this research.

Denmark, Sweden, Finland and Norway, all members of G4 and leaders in innovation, also cooperate in two other fields—in the Baltic Sea macro-region, and in two important forums, the Nordic Council of Ministers and the Nordic Council.

Once more, network analysis has revealed the importance of cooperation, and shows how cooperation in other domains leads to cooperation in HW shipment and how countries work with countries that are partners in other fields.

It is not only the Baltic Sea macro-region that has its reflection in these HW-trading communities; other macro-regions (such as the Alpine macro-region) are formed by countries that belong to G2 (Austria, Germany, Italy and Liechtenstein), with the exception of France in community 1.

In this line, the results also show the importance of and the relation between HW-trading communities and innovation. In fact, the countries in community 4 (Denmark, Estonia, Ireland, Finland, Sweden, Norway) are the countries with the highest innovation scores in all fields.

When analyzing the HW-trading communities obtained by the network according to their modularity, this highlights how the GDP per capita characterizes them, since those with a higher GDP per capita perform better regarding the innovation and research indicators. Although the networks generated may be justified by their proximity, there are other variables that characterize them and suggest that they also influence this type of exchange. The operation of the groups regarding the innovation friendly environment show very differentiated behaviours between groups G1, G2, G4 with values greater than 45% compared to groups G0 and G3 with values below 30%. This same behaviour is also observed for the research systems and innovators indicators. Therefore, the networks that are generated are characterised by geographical proximity but also by the proximity in their levels of innovation and research, and their capacity for an innovation friendly environment.

Finally, as was previously mentioned, waste to energy was the most used recovery option, which is an important novelty as other studies, only focused on Municipal Solid Waste (not exclusively for HW) (Scarlat et al., 2019), conclude that MSW as an energy source is underexploited as only 6% was sent to incineration, including energy recovery in incineration. However, further research should be done as this does not explain the amount of exports between Norway and Sweden, or the high indegree of Poland.

## 8 Conclusions

The first conclusion is that the implementation of Regulation (EC) 1013/2006 goes beyond the quantities of HW that are shipped, creating a network of different HW-trading communities, and showing the importance of relations between European countries.

This research can contribute to different debates in the scholarly community. On the one hand, it can improve the regulation of waste transport, as it may be possible through regulation to influence HW-trading communities in order to extend the benefits of such regulation. On the other hand, it can help to give an understanding of how different policies, such as innovation policies, influence the behaviour of countries in different areas such as waste transport, and vice versa.

The study also shows how cooperation in other domains and proximity between countries may be relevant in HW management.

All European countries export hazardous wastes in different percentages because they lack the innovation needed or because they do not have enough treatment facilities or because of legislative barriers to HW recovery facilities. If we want European countries to improve their HW recovery, it is not only prevention and innovation that are important;

a limit on hazardous waste exports may push countries to innovate and look for recovery options at home.

France and Germany have a high indegree: Germany (29), France (19), and in 2014 both had a high number of waste to energy plants, (Germany 99 plants and France 126 plants according to CEWEP), however, we cannot state that hazardous waste recovery operation is energy recovery, so further research should be done.

Countries with a high GDP are also countries with high scores in the different innovation indexes, especially Scandinavian countries (Finland, Sweden, and Norway), even if their eigenvector centrality is not very high in this network, which not only highlights the relationship between GDP and innovation, but also how countries that form HW-trading communities when trading in HW shipment for recovery interact. Based on the ANOVA results, we can conclude that the countries with similar levels of eco-innovation share similar behaviours in HW exports for recovery. In the different HW-trading communities we can observe that they share proximity, similar GDP levels, and also similar innovation environments and policies, see for example Nordic countries. It is important to note that Nordic countries have always been concerned about wastes and the environment (Richter & Koppejan, 2016; Watson et al., 2013; Ylä-Mella et al., 2014). In particular, Norway is the most efficient country regarding HW management (Carmen Callao et al., 2019a, 2019b). The amount of HW produced or greenhouse gases do not affect the behaviour of the HW-trading communities. Consequently, the transfer of knowledge between countries and groups should be encouraged in Europe.

This analysis of Regulation (EC) 1013/2006 can give a new perspective on the development of policies to achieve the new Green Deal and the sustainable development goals. It shows the importance of HW-trading communities, not only in the transport of waste, but also in cooperation and in the context of innovation, where funding is necessary to promote innovation and development in line with these objectives. In the context of the new European Green Deal and Horizon Europe, hazardous waste management seems to be of great relevance, and policies should not ignore the importance of waste transport.

It must be noted that this research began before the publication of the European Green Deal (December 2019), however, waste management has always been one of the priorities of European Commission which began this path in 2015 with the circular economy package. However, the conclusions from this study could be useful in future European Green Deal policies.

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## DISCUSIÓN

Lo que impresiona de un hombre no es su mente, sino el resultado de ésta.

Walter Bagehot



## 5. DISCUSIÓN

Se ha realizado un análisis desde una perspectiva de cumplimiento normativo de la gestión de los residuos peligrosos en Europa.

En el análisis, en primer lugar, abordaremos la eficiencia de los países europeos y a continuación realizaremos la discusión de los estudios sobre traslados de residuos peligrosos para eliminación y para valorización.

### 5.1 EFICIENCIA EN LA GESTIÓN DE RESIDUOS PELIGROSOS

Para dar respuesta al Objetivo Específico 1: analizar la situación en Europa desde la perspectiva de gestión de residuos, con un enfoque predominante en la gestión de residuos peligrosos para responder a la pregunta de si una legislación común garantiza una gestión correcta de los residuos, se ha analizado la eficiencia de cinco modelos diferentes, usando para ello Data Envelopment Analysis (DEA).

Los cinco modelos analizados han sido los siguientes: gestión de residuos totales (Modelo 1), gestión de residuos peligrosos (Modelo 2), incineración y recuperación de energía a través de la incineración de residuos peligrosos (Modelo 3), operaciones de eliminación de residuos peligrosos (Modelo 4) y valorización de residuos peligrosos (Modelo 5) se describen a continuación para cada uno de los modelos:

- En el Modelo 1, de gestión de residuos totales, incluyendo residuos peligrosos y no peligrosos, la eficiencia tiene una media de casi el 60%, lo que indica que existe un margen de un 40% para mejorar la eficiencia de la gestión de los residuos.
- En el Modelo 2, que analiza la eficiencia en la gestión de los residuos peligrosos, la eficiencia se reduce a un 31%, hay que decir que de los países que muestran mejor eficiencia (Alemania, Letonia, Malta, Portugal, Suecia, Noruega o Macedonia) tienen un porcentaje de reciclaje de residuos peligrosos superior al 5%, es decir, que en el tratamiento de los residuos peligrosos tienen un porcentaje de reciclaje superior a otros países que optarán por otras formas de valorización o por la eliminación de los mismos.

Indicamos la importancia del reciclaje ya que uno de los outputs usados es el reciclaje de residuos peligrosos y como input se usó el total de residuos peligrosos generados.

Es decir, que cuando hablamos de gestión de residuos peligrosos la eficiencia desciende considerablemente.

- En el Modelo 3 que analiza la incineración y la incineración con recuperación de energía los países con mayor eficiencia usan la incineración con recuperación de energía en el tratamiento de más de un 10% de sus residuos peligrosos.

- En el Modelo 4 de eliminación de residuos, muestra como resultado una menor eficiencia y muestra como muchos países eliminan en vertederos más del 60% de sus residuos.

Por lo que los resultados muestran que la eliminación de residuos en vertederos es la forma más ineficiente de tratamiento de residuos peligrosos y es la que produce mayores diferencias en la eficiencia de los países.

- En el Modelo 5 se analizan otras formas de valorización entre las que se encuentra las operaciones de relleno tiene una eficiencia del 54.5%

A continuación, mostramos en la Tabla 3 los países que son eficientes o ineficientes en cada uno de los modelos analizados.

**Tabla 3 – Clasificación de eficiencia por países usando bootstrapping**

	Países eficientes	(<0,005) – Países ineficientes
M1 – Gestión		
residuos	BELGIUM; GERMANY; FRANCE; ITALY; LATVIA;	BULGARIA; IRELAND; GREECE; CROATIA; CYPRUS; LUXEMBOURG;
totales	PORTUGAL; FINLAND; SWEDEN; UNITED KINGDOM;	MALTA; NETHERLANDS; ROMANIA; SLOVAKIA; SERBIA; TURKEY
	NORWAY; MONTENEGRO; MACEDONIA;	
M2- Gestión		BELGIUM; BULGARIA; CZECH REPUBLIC; DENMARK; ESTONIA;
residuos	GERMANY; LATVIA; MALTA; PORTUGAL; SWEDEN;	IRELAND; GREECE; SPAIN; FRANCE; CROATIA; ITALY; CYPRUS;
peligrosos	NORWAY; MACEDONIA	LITHUANIA; NETHERLANDS; AUSTRIA; POLAND; ROMANIA;
		SLOVENIA; SLOVAKIA; FINLAND; UNITED KINGDOM; MONTENEGRO;
		SERBIA; TURKEY;
M3 –		
Incineración +		BULGARIA; CZECH REPUBLIC; ESTONIA; IRELAND; GREECE; SPAIN;
recuperación	GERMANY; FRANCE; LATVIA; MALTA; ROMANIA;	ITALY; CYPRUS; LITHUANIA; PORTUGAL; SLOVAKIA; UNITED
energía	FINLAND; NORWAY; MACEDONIA	KINGDOM; MONTENEGRO; SERBIA; TURKEY;
M4-		BELGIUM; CZECH REPUBLIC; DENMARK; GERMANY; IRELAND;
Eliminación de		GREECE; SPAIN; FRANCE; CROATIA; ITALY; CYPRUS; LATVIA;
residuos	BULGARIA; ESTONIA; FINLAND; NORWAY; SERBIA;	LITHUANIA; LUXEMBOURG; MALTA; NETHERLANDS; AUSTRIA;
		POLAND; PORTUGAL; ROMANIA; SLOVENIA; SLOVAKIA; SWEDEN;
		UNITED KINGDOM; MONTENEGRO; MACEDONIA; TURKEY;
M5 – Otras		
formas de	CZECH REPUBLIC; GERMANY; ESTONIA; SPAIN;	IRELAND; MONTENEGRO; SERBIA
valorización	LATVIA;; MALTA; POLAND; NORWAY; MACEDONIA;	

En los resultados del estudio de eficiencia, destaca la eficiencia de Noruega y los países Bálticos, así como la eficiencia de Alemania que son países que en el ámbito de los traslados de residuos destacan tal y como muestran los resultados que se muestran a continuación, resultado que está en línea con estudios más recientes (Gökgöz and Yalçın, 2021).

La importancia de Alemania y de los países con mayor tasa de reciclado destaca también al analizar la eficiencia de los países de la UE en relación con la producción de residuos y emisión de gases de efecto invernadero (Halkos and Petrou, 2019).

Los resultados del estudio de eficiencia ponen de relieve la importancia de profundizar en el estudio de la gestión de los residuos peligrosos y la importancia del análisis de los traslados de los residuos peligrosos para valorización y eliminación, y los retos y desafíos que dicho transporte conlleva (Healy, 2021).

A pesar de los esfuerzos realizados por la Unión Europea en términos de promulgación de normativa, a la vista de los resultados obtenidos, una forma de mejorar la eficiencia es a través de las diferentes alternativas que ofrece la legislación y en concreto:

- 1.- Controlando la transposición de las Directivas: La razón es que incluso si existe una obligación de transponer las Directivas, la realidad muestra cómo los Estados Miembro realizan la transposición de muy diferente manera. Por ejemplo, en Finlandia la transposición de la Directiva de Emisiones Industriales se realizó en 70 normas diferentes según la información que refleja el portal de la UE Eux-lex, mientras que otros países como Grecia o Italia sólo usan una norma para transponer. Otro ejemplo sería el hecho de que el único país que cuenta con una normativa para la incineración de residuos peligrosos sea Francia.
- 2.- Otra forma de mejorar la eficiencia a través de la regulación es a través de a través de regulación de tasas (Marques et al., 2018), lo que podría ayudar a mejorar la eficiencia de los modelos menos eficientes.
- 3.- Los objetivos de reciclado son genéricos, y no tienen en cuenta si el reciclaje es de residuos peligrosos o no peligrosos. La regulación puede ser un buen instrumento para fijar unos objetivos específicos para residuos peligrosos.
- 4.- A través de la normativa también se podría controlar el flujo de residuos peligrosos que es producido en los hogares (Inglezakis and Moustakas, 2015).

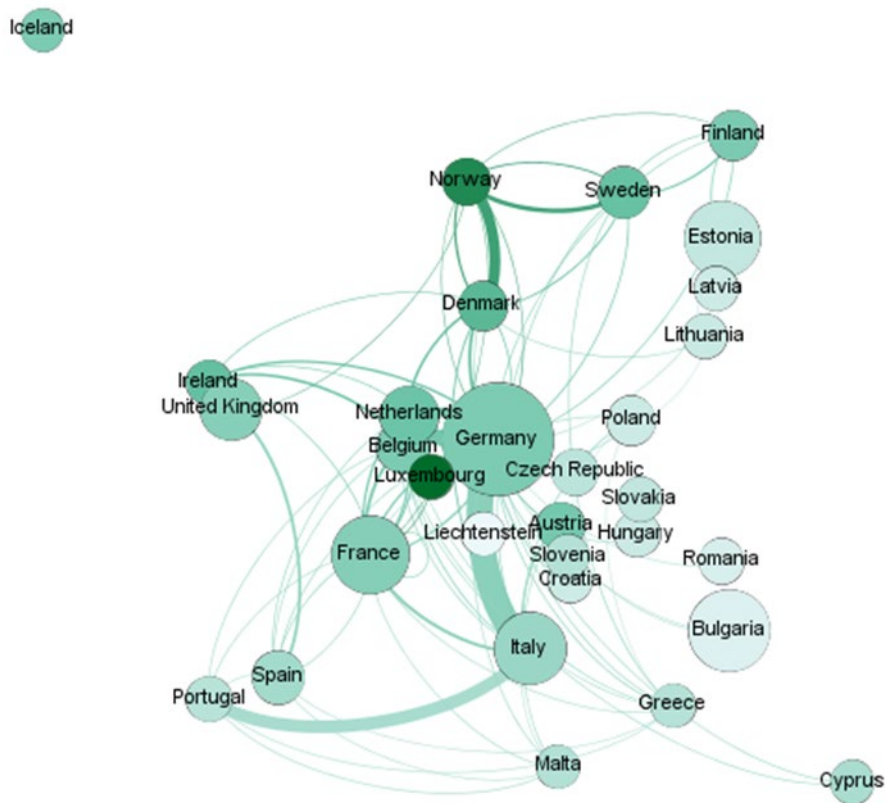
## 5.2 ANÁLISIS DE LOS TRASLADOS DE RESIDUOS PELIGROSOS PARA ELIMINACIÓN

Para dar respuesta al Objetivo Específico 2: analizar el cumplimiento normativo, en particular el cumplimiento de los principios de autosuficiencia y proximidad, en los traslados de residuos para su eliminación y la influencia del PIB en los mismos se han analizado los datos de las exportaciones de residuos peligrosos para eliminación.

Los principales resultados de los traslados de residuos se pueden presentar a través de la “foto” que se realiza con el análisis de redes y cuya interpretación mostramos a continuación.

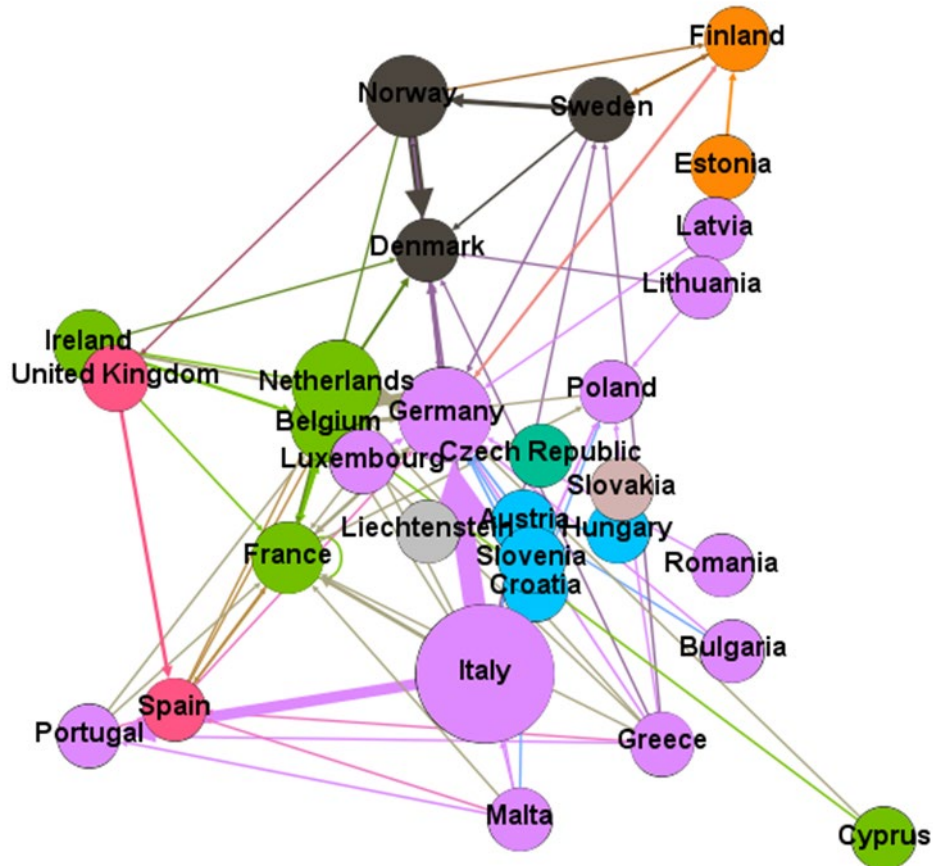
La Figura 1 muestra la cantidad de residuos producida por cada nodo. El tamaño del nodo se corresponde con la cantidad de residuos peligrosos producida. Los nodos son de color verde de diferentes tonalidades. Las tonalidades de verde varían según el PIB per cápita (cuanto más oscuro es el tono verde mayor es el PIB per cápita). El grosor de la línea representa la cantidad de residuos exportados entre países.

**Figura 1.** Red de traslado de residuos peligrosos para eliminación en Europa.



La Figura 2 muestra las comunidades creadas, cada comunidad aparece representada por un color diferente.

**Figura 2.** Red de traslados de residuos peligrosos para eliminación por modularidad



En la figura 2, el tamaño del nodo es proporcional a las toneladas que cada país exporta, y el grosor de las líneas muestra el flujo de las exportaciones entre países.

La modularidad muestra los grupos o comunidades en la red, estos grupos se forman según el PIB per cápita y muestran cómo los países aplican los principios de autosuficiencia y proximidad y que se reflejan en la Tabla 4.

**Tabla 4.** Comunidades en los traslados de residuos para eliminación.

<b>Modularidad clasificación</b>	<b>Países (centralidad vector propio)</b>
0	Belgium (0.764), Ireland (0), France (0.968), Cyprus (0), The Netherlands (0.715)

1	<i>Czech Republic (0)</i>
2	<i>Denmark (0.524), Norway (0.388), Sweden (0.173)</i>
3	<i>Bulgaria (0), Germany (1), Greece (0), Italy (0.002), Latvia (0), Lithuania (0.002), Luxembourg (0.170), Malta (0), Poland (0.224), Portugal (0.008), Romania (0.008)</i>
4	<i>Estonia (0.004), Finland (0.360)</i>
5	<i>Spain (0.246), United Kingdom (0.087)</i>
6	<i>Croatia (0), Hungary (0), Austria (0.015), Slovenia (0)</i>
7	<i>Slovakia (0)</i>
8	<i>Iceland (0)</i>
9	<i>Liechtenstein (0)</i>

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La Tabla 4, muestra que la mayor comunidad es la 3 (color púrpura), que está formada por 10 países: Bulgaria, Alemania, Italia, Letonia, Lituania, Luxemburgo, Malta, Polonia, Portugal y Rumanía. Alemania tiene la mayor centralidad, y el resto de países de esa comunidad tienen una centralidad próxima a cero. Alemania es además el país con el in-degree (número de países/nodos de los que recibe), más alto de la red, lo que indica que es el país que recibe el volumen más alto de residuos peligrosos para eliminación. La segunda comunidad en importancia es la número 1 (en color verde) que está compuesta por seis países: Bélgica, Irlanda, Francia, Chipre y Países Bajos. Otra comunidad importante es la número 6 (en azul) formada por Croacia, Hungría, Austria y Eslovenia. La importancia de otras comunidades es pequeña.

En este análisis de redes de los traslados de residuos peligrosos para eliminación, se analizan los datos de exportación de residuos para comprobar si se cumplen los principios de proximidad y autosuficiencia y cómo el PIB afecta a los traslados.

El cumplimiento de estos principios tiene como consecuencia la creación de una red de traslados de baja densidad, frente a la red de traslados de residuos para valorización. La densidad de la red se muestra a través de las conexiones entre los nodos, mostrando que hay menos traslados para eliminación que para valorización.

En estos traslados se forman comunidades en las que hay un país que tiene una especial relevancia en la red. Este país es Alemania, que es el país que más conexiones tiene en la red y el que más cantidad de residuos para eliminación recibe.

Los países con mayor in-degree, que reciben de más nodos/países, son Alemania (20), Bélgica (15) y Francia y Países Bajos (12). Es importante indicar que todos estos países tienen una alta capacidad de incineración y que todos ellos tienen un PIB por encima de los 30.000 euros.

Al contrario de lo que sucede en los traslados de residuos para eliminación entre el hemisferio norte y el hemisferio sur, en los que los residuos viajan de países ricos a países pobres, en Europa, los residuos peligrosos son enviados para eliminación a países con un alto PIB, mostrando que el PIB más alto permite a los países usar las Mejores Técnicas Disponibles (MTD).

Los países con una alta capacidad de incineración (Francia, Alemania, Suecia, Dinamarca, Países Bajos, Austria y Finlandia) tienen un PIB per cápita superior a 30000 euros, estas comunidades tienen un alto in-degree, es decir, reciben residuos de muchos nodos, a pesar de que según Sora la apertura a la incineración es una amenaza al principio de proximidad (Jofra Sora and Puig Ventosa, 2014)

### 5.3 ANÁLISIS DE LOS TRASLADOS DE RESIDUOS PELIGROSOS PARA VALORIZACIÓN

Para dar respuesta al Objetivo Específico 3: Analizar los traslados de residuos para su valorización desde una perspectiva política, económica y de innovación se han analizado los datos de los traslados de residuos para valorización.

De dicho análisis, al igual que en el estudio de los traslados de residuos para eliminación, surgen dos figuras y varias comunidades de países.

La Tabla 5 muestra que de esta red surgen 5 comunidades de traslados y los grupos están densamente conectados por un alto número de traslados.

**Tabla 5.-** Comunidades en los traslados de residuos para valorización

Modularidad Clasificación	Países (centralidad vector propio)
0	Czech Rep, Croatia, Lithuania, Hungary, Poland, Slovenia, Slovakia
1	Belgium, Spain, France, Malta, Portugal, United Kingdom, Iceland
2	Germany, Italy, Latvia, Luxembourg, Netherlands, Austria, Liechtenstein
3	Bulgaria, Greece, Cyprus, Romania
4	Denmark, Estonia, Ireland, Finland, Sweden, Norway

La Figura 3 muestra los flujos de traslados para valorización. La cantidad de residuos peligrosos generada por cada país está representada por el tamaño del nodo, mientras que el color de cada nodo, representa el PIB de cada país, es decir, que los países con un PIB más alto tienen un color más oscuro. El grosor de las líneas muestra la cantidad de residuos exportados entre países, observándose que los países con el PIB más alto no son los países que producen la mayor cantidad de residuos peligrosos.



Figura 3. Red de traslados de residuos peligrosos para valorización

En la figura 4 se observa la modularidad de la red, es decir, su estructura y las comunidades que se forman. El tamaño del nodo representa la cantidad de toneladas que cada país exporta. El grosor de las líneas representa la cantidad de residuos que se envían a otro país, un envío de una gran cantidad de residuos peligrosos a otro país está representado por una línea gruesa. En este gráfico, la línea más gruesa es el flujo de residuos que se trasladan entre Noruega y Finlandia, ambos países con un PIB por encima de los 40.000 euros per cápita y con un alto grado de centralidad (29) y un alto in-degree, que reciben de más nodos/países, (16). Los colores de la figura 4 representan las comunidades que se forman en los traslados de residuos para valorización.

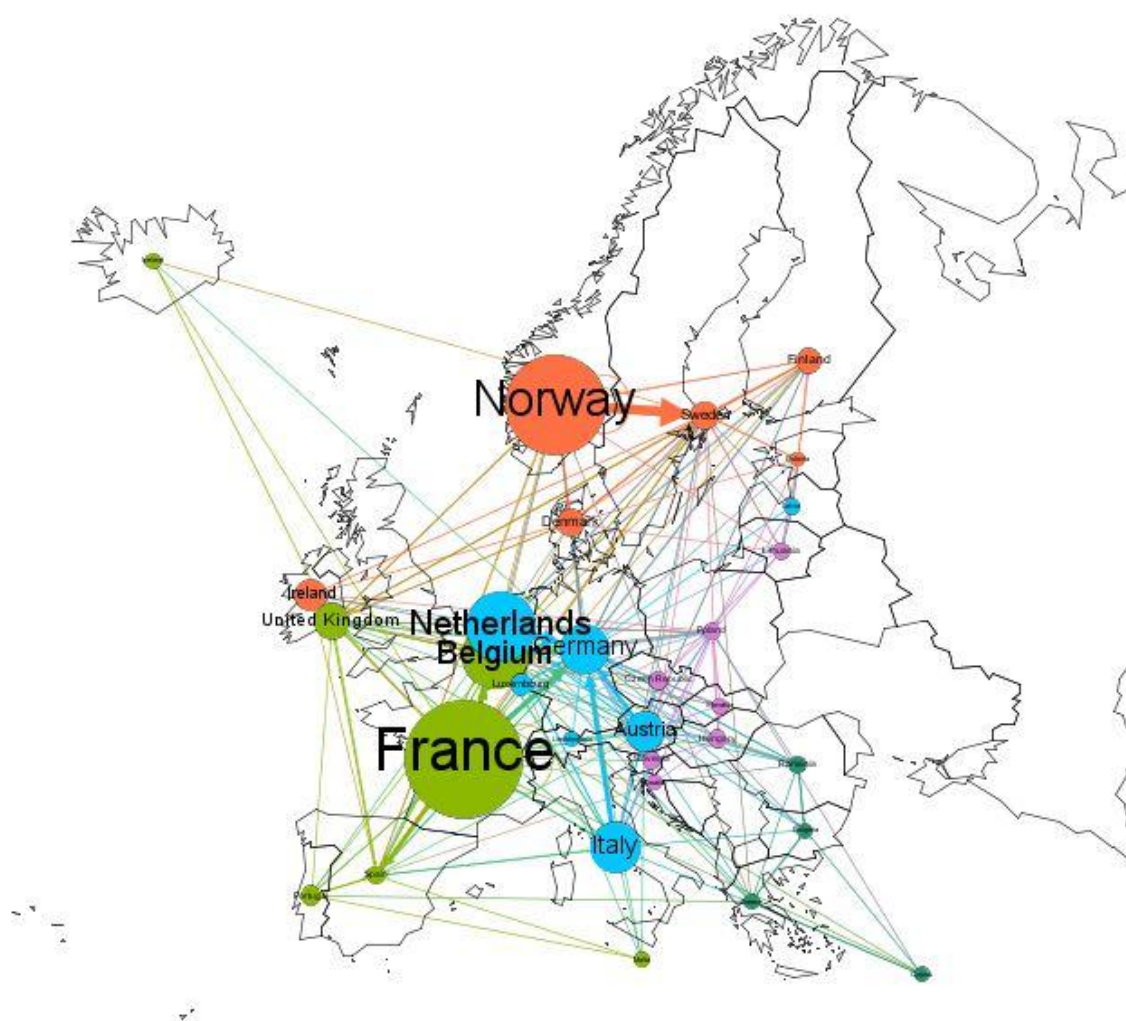


Figure 4. Red de traslados de residuos peligrosos para valorización por modularidad

La gestión de los residuos peligrosos ha sido analizada en profundidad por diferentes autores (Chang and Wang, 1995; Cucchiella et al., 2015; He et al., 2006; Marques et al., 2012). Por este motivo es importante ir más allá de los datos y realizar un análisis más profundo para comprender no sólo cómo se mueven los residuos peligrosos, sino también qué otras variables, como el PIB o la cantidad de residuos peligrosos generados afectan a la exportación de residuos peligrosos. También es importante establecer qué comunidades se forman en los traslados de residuos peligrosos y cómo estas relaciones van más allá de la exportación de residuos peligrosos e interactúan a través de la innovación. Estos aspectos son analizados usando análisis de redes, European Innovation Scoreboard y ANOVA, y nos proporcionan información sobre la aplicación del Reglamento de traslado de residuos y sobre la importancia de un entorno innovador en los países.

El análisis de redes de los transportes de residuos para valorización reveló la existencia de 251 conexiones entre países europeos, es decir que se producen muchas más conexiones que en las exportaciones para eliminación. La exportación de residuos provoca la creación de comunidades de transporte de residuos peligrosos.

Los resultados muestran la importancia de países como Francia, Alemania, Países Bajos o Bélgica, pero las comunidades que se forman muestran que el PIB es una variable importante. La proximidad de los países que forman las comunidades también aparece como un factor relevante.

Alemania es el país con el in-degree más alto (29) y envía a 16 países, mostrando lo poderoso que es en relación los traslados de residuos para valorización. El liderazgo de Alemania en Europa ha sido objeto de investigación (Bulmer and Paterson, 2010; Hyde-Price and Jeffery, 2001).

Sin embargo, las comunidades formadas y los países que las integran también pueden ser analizadas desde otras perspectivas políticas, estas perspectivas pueden ser consecuencia de los traslados de residuos peligrosos para valorización pero también pueden ser consecuencia de la colaboración o cooperación que se genera dentro de las macro-regiones europeas.

Estas coaliciones muestran una distribución de poder (Aleskerov et al., 2002).

Los resultados muestran que las comunidades creadas por los traslados de residuos peligrosos están formadas por países cercanos. La proximidad puede ser una de las raíces de esas coaliciones, pero también puede haber una base cultural asociada a la proximidad geográfica y que muestra una división norte-sur en Europa (Elgström et al., 2001).

Las alianzas muestran como “los países verdes” en Europa trabajan junto por un objetivo común (“Strategies of the ‘Green’ Member States in EU Environmental,” 2012) y la importancia del bloque nórdico se muestran claramente en esta investigación.

Dinamarca, Suecia, Finlandia y Noruega forman parte de la Comunidad 4 son líderes en innovación y también cooperan en otros ámbitos como la macro-región del Báltico, el Nordic Council of Ministers y el Nordic Council.

Una vez más el análisis de redes muestra la importancia de la cooperación y cómo los países trabajan con países con los que cooperan en otras áreas.

La cooperación o colaboración de países que integran otras macro-regiones también es patente en las comunidades, así, países de la macro-región Alpina está formada mayoritariamente por países que pertenecen a la comunidad 2 (Austria, Alemania, Italia y Liechtenstein).

En esta línea, los resultados muestran la importancia de la relación entre las comunidades de los traslados de residuos peligrosos para valorización y la innovación. De hecho, los países de la comunidad 4 (Dinamarca, Estonia, Irlanda, Finlandia, Suecia y Noruega) son los países con los resultados más altos de innovación en todos los campos.

En el análisis de las comunidades obtenidas en los traslados de residuos peligrosos para valorización se observa que se caracterizan por el PIB per cápita, dado que los países con el PIB más alto tienen mejores resultados en los indicadores de innovación.

Aunque las redes generadas pueden justificarse por la proximidad, hay otras variables que las caracterizan y sugieren también la influencia de interacciones en innovación, por lo que uno de los principales resultados es ver cómo la red generada se caracteriza por la proximidad, pero también por los niveles de investigación e innovación y por el entorno innovador.

Finalmente, indicar que “de residuo a energía” fue la operación de valorización más importante. Sin embargo, es necesario que existan investigaciones sobre el alto índice de Polonia o el alto número de exportaciones entre Noruega y Suecia.

## 5.4 LIMITACIONES DEL ESTUDIO

Debe indicarse que esta investigación comenzó antes de la publicación del Green Deal europeo en diciembre de 2019. Sin embargo, la gestión de los residuos siempre ha sido una de las prioridades de la Comisión Europea que comenzó en el año 2015 con el paquete de economía circular, por lo que las conclusiones de la presente tesis pueden ser trasladadas al Green Deal Europeo.



## CONCLUSIONES

*Sí la razón hace al hombre, el sentimiento lo conduce. - Jean Jacques Rousseau*



## 6. CONCLUSIONES

Las conclusiones de la tesis son las siguientes:

- 1.- Los países miembros de la Unión Europea no son más eficientes que los países europeos que no pertenecen a la misma.
- 2.- Compartir una misma legislación no garantiza la eficiencia en la gestión de residuos, teniendo en cuenta los inputs y los outputs elegidos.
- 3.- El análisis de redes es una herramienta eficaz para el estudio de las exportaciones de residuos peligrosos y para comprobar el cumplimiento de la normativa.
- 4.- Los residuos peligrosos se trasladan para eliminación y para valorización a países con un alto PIB y con una capacidad de incineración alta.
- 5.- Los principios de proximidad y autosuficiencia influyen en las redes de traslados de residuos peligrosos, generando una red de baja densidad en los traslados de residuos para eliminación y una red densa en los traslados de residuos peligrosos para valorización
- 6.- Los países con un alto PIB per cápita tienen mayor número de instalaciones de incineración y por tanto mayor preparación para la eliminación de residuos peligrosos.
- 7.- Los países con un alto PIB per cápita son países que tienen altos valores en los índices de innovación.
- 8.- Los países que no tienen una tasa de vertedero no tienen un in-degree más alto que los países que sí lo tienen, no afectando a la exportación de residuos.
- 9.- La centralidad de la red (degree centrality) ha demostrado que los países situados en centro Europa (Alemania, Francia y Bélgica) son los principales nodos. Siguiendo el principio de proximidad, esto es consecuencia de una mejor conectividad en logística.
- 10.- La aplicación de los principios de proximidad y autosuficiencia ayuda a mejorar la eficiencia en la gestión de residuos peligrosos, ya que minimiza las emisiones que produce el transporte de residuos e indica que los países tienen una capacidad suficiente para tratar los residuos que generan.
- 11.- El control del cumplimiento con las regulaciones analizadas es fundamental para evitar el transporte ilegal de residuos y proteger la salud de los ciudadanos.
- 12.- La aplicación del Reglamento (EC) 1013/2006 va más allá de las cantidades de residuos peligrosos que son trasladados y crean diferentes comunidades mostrando la importancia de las relaciones entre los países europeos.
- 13.- El análisis del Reglamento (EC) 1013/2006 y las comunidades que surgen de su aplicación pueden generar nuevas políticas que ayuden a conseguir los objetivos perseguidos por el nuevo Green Deal y los objetivos de desarrollo sostenible, por lo que en este contexto el transporte de residuos puede tener un papel importante.



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Los libros sólo tienen valor cuando  
conducen a la vida y le son útiles.

Hermann Hesse



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# ANEXO I – TABLAS Y FIGURAS



## 8. ANEXO I - TABLAS Y FIGURAS

### 8.2 TABLAS

**Tabla 1** – Toneladas de residuos (peligrosos y no peligrosos) producidas en Europa

**TONELADAS DE RESIDUOS (PELIGROSOS Y NO PELIGROSOS) PRODUCIDAS EN EUROPA**

<b>2010</b>	<b>2012</b>	<b>2014</b>	<b>2016</b>	<b>2018</b>
<b>2.454.720.000</b>	2.483.990.000	2.507.100.000	2.536.170.000	2.619.880.000

**Tabla 2** - Toneladas de residuos peligrosos producidas en Europa

**TONELADAS DE RESIDUOS PELIGROSOS PRODUCIDAS EN EUROPA**

<b>2010</b>	<b>2012</b>	<b>2014</b>	<b>2016</b>	<b>2018</b>
<b>96.060.000</b>	95.370.000	94.870.000	100.670.000	107.850.000

**Tabla 3 – Clasificación de eficiencia por países usando bootstrapping**

	Países eficientes	(<0,005) – Países ineficientes
M1 – Gestión		
residuos	BELGIUM; GERMANY; FRANCE; ITALY; LATVIA;	BULGARIA; IRELAND; GREECE; CROATIA; CYPRUS; LUXEMBOURG;
totales	PORTUGAL; FINLAND; SWEDEN; UNITED KINGDOM; NORWAY; MONTENEGRO; MACEDONIA;	MALTA; NETHERLANDS; ROMANIA; SLOVAKIA; SERBIA; TURKEY
M2- Gestión		BELGIUM; BULGARIA; CZECH REPUBLIC; DENMARK; ESTONIA;
residuos	GERMANY; LATVIA; MALTA; PORTUGAL; SWEDEN;	IRELAND; GREECE; SPAIN; FRANCE; CROATIA; ITALY; CYPRUS;
peligrosos	NORWAY; MACEDONIA	LITHUANIA; NETHERLANDS; AUSTRIA; POLAND; ROMANIA; SLOVENIA; SLOVAKIA; FINLAND; UNITED KINGDOM; MONTENEGRO; SERBIA; TURKEY;
M3 –		
Incineración +		BULGARIA; CZECH REPUBLIC; ESTONIA; IRELAND; GREECE; SPAIN;
recuperación	GERMANY; FRANCE; LATVIA; MALTA; ROMANIA;	ITALY; CYPRUS; LITHUANIA; PORTUGAL; SLOVAKIA; UNITED
energía	FINLAND; NORWAY; MACEDONIA	KINGDOM; MONTENEGRO; SERBIA; TURKEY;
M4-		BELGIUM; CZECH REPUBLIC; DENMARK; GERMANY; IRELAND;
Eliminación de		GREECE; SPAIN; FRANCE; CROATIA; ITALY; CYPRUS; LATVIA;
residuos	BULGARIA; ESTONIA; FINLAND; NORWAY; SERBIA;	LITHUANIA; LUXEMBOURG; MALTA; NETHERLANDS; AUSTRIA; POLAND; PORTUGAL; ROMANIA; SLOVENIA; SLOVAKIA; SWEDEN; UNITED KINGDOM; MONTENEGRO; MACEDONIA; TURKEY;
M5 – Otras		
formas de	CZECH REPUBLIC; GERMANY; ESTONIA; SPAIN;	IRELAND; MONTENEGRO; SERBIA
valorización	LATVIA;; MALTA; POLAND; NORWAY; MACEDONIA;	

**Table 4.** Comunidades en los traslados de residuos para eliminación

<b>Modularidad clasificación</b>	<b>Países (centralidad vector propio)</b>
0	<i>Belgium (0.764), Ireland (0), France (0.968), Cyprus (0), The Netherlands (0.715)</i>
1	<i>Czech Republic (0)</i>
2	<i>Denmark (0.524), Norway (0.388), Sweden (0.173)</i>
3	<i>Bulgaria (0), Germany (1), Greece (0), Italy (0.002), Latvia (0), Lithuania (0.002), Luxembourg (0.170), Malta (0), Poland (0.224), Portugal (0.008), Romania (0.008)</i>
4	<i>Estonia (0.004), Finland (0.360)</i>
5	<i>Spain (0.246), United Kingdom (0.087)</i>
6	<i>Croatia (0), Hungary (0), Austria (0.015), Slovenia (0)</i>
7	<i>Slovakia (0)</i>
8	<i>Iceland (0)</i>
9	<i>Liechtenstein (0)</i>

**Tabla 5.-** Comunidades en los traslados de residuos para valorización

Modularidad Clasificación	Países (centralidad vector propio)
0	Czech Rep, Croatia, Lithuania, Hungary, Poland, Slovenia, Slovakia
1	Belgium, Spain, France, Malta, Portugal, United Kingdom, Iceland
2	Germany, Italy, Latvia, Luxembourg, Netherlands, Austria, Liechtenstein
3	Bulgaria, Greece, Cyprus, Romania
4	Denmark, Estonia, Ireland, Finland, Sweden, Norway

## 8.3 FIGURAS

**Figura 1.** Red de traslado de residuos peligrosos para eliminación en Europa.

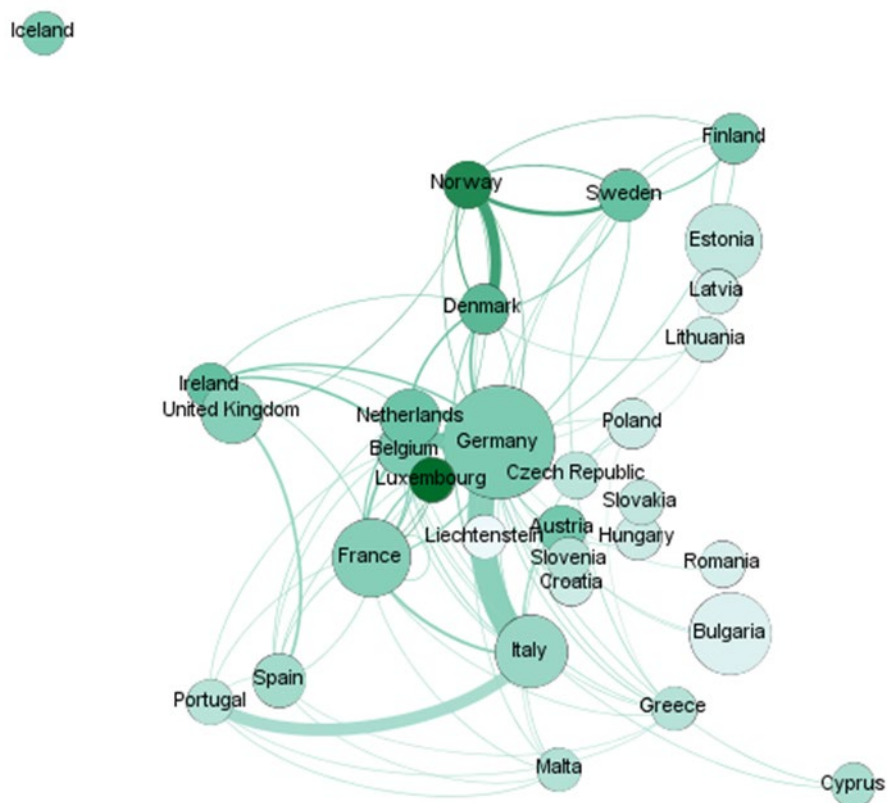


Figura 2. Red de traslados de residuos peligrosos para eliminación por modularidad

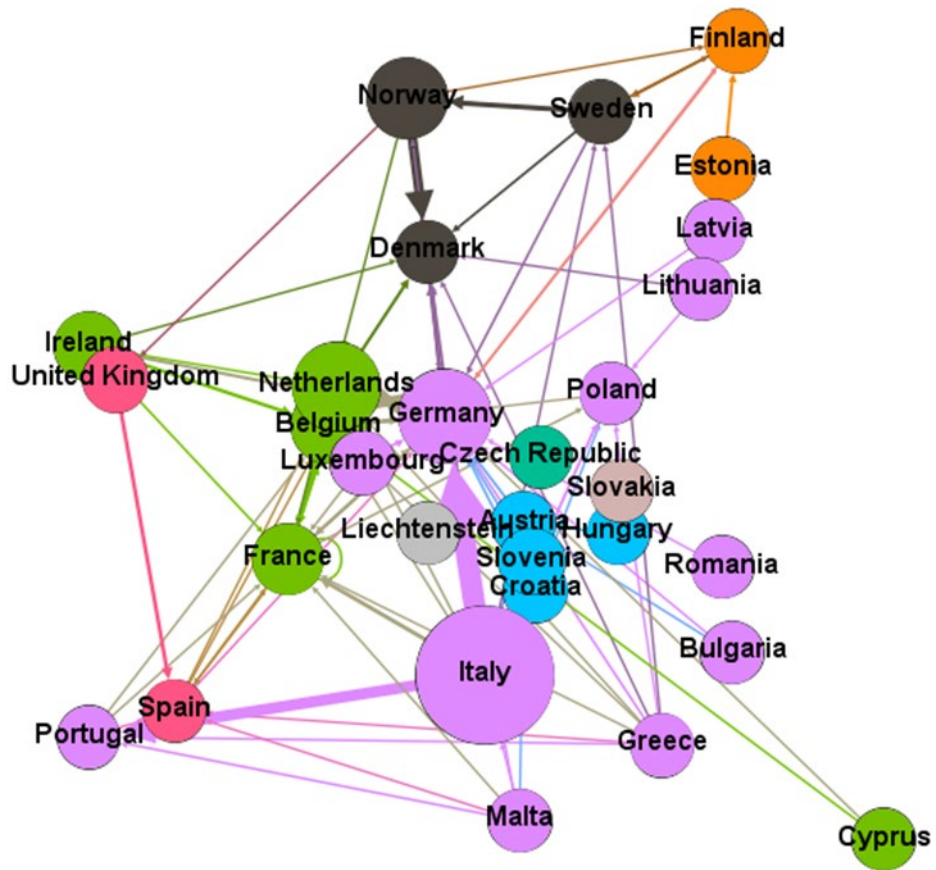


Figura 3 – Red de traslados de residuos peligrosos para valorización



Figura 4 – Red de traslados de residuos peligrosos para valorización por modularidad

