UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

# Sistemas de Gestión de Residuos Sólidos Urbanos (RSU)

## Metodología para el análisis técnico-económico con valoración de las externalidades y casos de estudio

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UNIVERSITAT POLITÈCNICA DE CATALUNYA
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Programa de Doctorado en Ingeniería Ambiental

# "Sistemas de Gestión de Residuos Sólidos Urbanos (RSU). Metodología para el análisis técnico-económico con valoración de las externalidades y Casos de Estudio"


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*Para mi amada madre y mi esposo*
*Harry por su apoyo y amor infinito.*

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# Resumen


Actualmente, existe un grave problema debido a la gran generación de residuos sólidos urbanos (RSU), a causa de las altas tasas de consumo de la población y el corto tiempo de uso de los productos. Por otro lado, se observa una deficiente gestión de residuos, debido a que, en diversos países y ciudades, todavía es usado en gran medida el depósito de residuos en vertederos, sistema que puede ocasionar diversos daños al medio ambiente y a la sociedad. A nivel mundial, aproximadamente el 69.7% de los RSU generados son depositados en algún tipo de vertedero.

Generalmente, cuando se implementa un sistema de gestión de RSU, este ocasiona impactos que pueden verse reflejados como costes o ingresos, dependiendo si estos impactos tienen un efecto negativo o positivo, respectivamente. Los aspectos económicos son de gran relevancia debido a que la mayoría de las decisiones relacionadas con los sistemas de gestión de RSU se toman en base a los resultados económicos. Mediante el análisis del estado del arte se determinó que diversos autores consideran únicamente los impactos privados, los cuales están relacionados con los costes e ingresos de Inversión, Operación y Mantenimiento. Por otro lado, los autores que han analizado las externalidades (costes e ingresos relacionados con aspectos ambientales y sociales) generalmente se enfocan en casos específicos o sólo consideran unos cuantos impactos externos.

La presente Tesis Doctoral tiene como objetivo el desarrollo de una metodología basada en el análisis coste-beneficio sostenible, ya que tiene en consideración los impactos privados y externos ocasionados por los sistemas de gestión de RSU. Además, bajo los principios de la sostenibilidad, se considera que el mejor proyecto será aquel que equilibre sus tres dimensiones: económica, ambiental y social. Una parte fundamental de la metodología desarrollada es la determinación y discusión de los impactos más relevantes relacionados con los sistemas de gestión de RSU. Constituyendo una guía de consulta para futuros investigadores y tomadores de decisiones que deseen analizar económicamente cualquier sistema de gestión de RSU. Estos impactos se clasifican en diferentes grupos como: infraestructura, reutilización, reciclaje y valorización de los residuos, uso de los materiales, medio ambiente, salud pública, educación y calidad de vida. El principal objetivo de la metodología es la determinación del Beneficio Privado ($B_P$) y el Beneficio Total ($B_T$), para concluir si el sistema o proyecto evaluado es económicamente rentable o viable desde el punto de vista privado y/o externo. Un proyecto será viable desde el punto de vista privado si $B_P$ es mayor a 0, por otro lado, si $B_T$ es mayor a 0 se puede concluir que el proyecto es viable desde el punto de vista económico, ambiental y social.

Finalmente, se han analizado unos casos de estudio donde se aplicó la metodología desarrollada a una planta de valorización energética (PVE) y una planta de clasificación y tratamiento de residuos de envases ligeros y residuos voluminosos (PCT) en Barcelona, España. Los resultados muestran que ambas instalaciones son rentables desde una perspectiva privada y externa, es decir, son rentables económica, social y ambientalmente. Además, se observa que la PCT es una instalación con mayores beneficios sociales y ambientales respecto a la PVE, lo cual coincide con la actual jerarquía de residuos establecida por el Parlamento Europeo.

**Palabras clave:** *Metodología, Análisis técnico-económico, Residuos sólidos urbanos, Impactos privados, Costes e ingresos, Externalidades, Análisis coste-beneficio sostenible, Casos de estudio*

# Abstract

Currently, there is a serious problem due to the large generation of municipal solid waste (MSW) due to the high consumption rates of the population and the short time of use of the products. Moreover, there is poor waste management, because, in various countries and cities, the deposit of waste in landfills is still used to a great extent, a system that can cause various damages to the environment and society. Worldwide, approximately 69.7% of the MSW generated is deposited in some type of landfill.

Generally, when a MSW management system is implemented, it causes impacts that can be reflected as costs or revenues, depending on whether these impacts have a negative or positive effect, respectively. The economic aspects are of great relevance because most of the decisions related to MSW management systems are made based on economic results. Through the analysis of state of the art, it was determined that various authors only consider the private impacts, which are related to the costs and revenues of Investment, Operation and Maintenance. Furthermore, authors who have analyzed externalities (costs and revenues related to environmental and social aspects) generally focus on specific cases or only consider a few external impacts.

This doctoral thesis aims to develop a methodology based on sustainable cost-benefit analysis, since it considers the private and external impacts caused by MSW management systems. In addition, under the principles of sustainability, it is considered that the best project will be the one that balances its three dimensions: economic, environmental and social. A fundamental part of the methodology developed is determining and discussing the most relevant impacts related to MSW management systems. It constituted a reference guide for future researchers and decision-makers who economically analyze any MSW management system. These impacts are classified into different groups such as infrastructure, reuse, recycling and recovery of waste, use of materials, environment, public health, education and quality of life. The methodology's main objective is to determine the Private Benefit (*BP*) and the Total Benefit (*BT*) to conclude if the evaluated system or project is economically profitable or viable from the private and/or external point of view. A project will be viable from a private point of view if *BP* is greater than 0, and if *BT* is greater than 0, the project is viable from an economic, environmental, and social perspective.

Finally, some case studies were analyzed where the methodology developed was applied to an energy recovery facility (ERF) and a sorting and treatment facility of light packaging waste and bulky waste (STF) in Barcelona, Spain. The results show that both facilities are profitable from a private and external perspective, that is, they are economically, socially and environmentally profitable. In addition, it is observed that the STF is a facility with greater social and environmental benefits compared to the ERF, which coincides with the current waste hierarchy established by the European Parliament.

**Keywords:** *Methodology, Technical-economic analysis, Municipal solid waste, Private impacts, Costs and revenues, Externalities, Sustainable cost-benefit analysis, Case studies*

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## Abreviaturas

| | |
|---|---|
| ACB | Análisis Coste- Beneficio |
| AVW | Volumen anual de residuos tratados |
| $B_E$ | Beneficio Externo |
| $B_P$ | Beneficio Privado |
| $B_T$ | Beneficio Total |
| FC | Costes Financieros |
| IC | Costes de Inversión |
| J | Impactos Totales |
| j | Índice de Impacto (j = 1, …, J) |
| LCA | Análisis de Ciclo de Vida |
| LCC | Coste del Ciclo de Vida |
| N | Duración total del proyecto |
| n | Índice de año del proyecto (n = 0, …, N) |
| NE | Externalidades Negativas |
| OC | Coste de oportunidad |
| OMC | Costes operativos y de mantenimiento |
| PCT | Planta de Clasificación y Tratamiento de residuos |
| PE | Externalidades Positivas |
| PVE | Planta de Valorización Energética |
| RSU | Residuos Sólidos Urbanos |
| SP | Precio de venta por unidad |
| T | Impuestos |
| TMB | Planta de Tratamiento Mecánico- Biológico |

# Capítulo 1: Introducción a los Residuos Sólidos Urbanos

## 1.1 Sistemas de gestión de Residuos Sólidos Urbanos

La economía global opera tradicionalmente a través de un modelo lineal, donde los recursos y las materias primas se consideran ilimitados, siguiendo el esquema de tomar, usar y desechar o como coloquialmente se denomina "de la cuna a la tumba", generando un desperdicio significativo porque los recursos se utilizan y se desechan después de un breve uso, residuos que generalmente terminan en vertederos, como se muestra en la Figura 1.


Figura 1. Diagrama de los procesos de la economía lineal. Fuente: Elaboración propia.

El término de residuo puede definirse como "*cualquier sustancia u objeto del cual su poseedor se desprenda o tenga la intención o la obligación de desprenderse*" (European Parliament, 2008) p. 15. De lo anterior podemos señalar que cualquier producto que deje de tener un valor o utilidad para el consumidor, se convertirá en un residuo, ocasionando que el consumidor tenga que deshacerse de este. De esta manera, surge la necesidad de determinar cuál es la mejor alternativa para la gestión de estos residuos.

Por otro lado, los residuos municipales se definen como "*los residuos generados en los domicilios particulares, los comercios, las oficinas y los servicios, y también los que no tienen la consideración de residuos especiales y que por su naturaleza o composición se pueden asimilar a los que se producen en dichos lugares o actividades*" (BOE, 2009) p. 11. También, son conocidos como residuos sólidos urbanos (RSU).

La gran generación de residuos ha ocasionado que sea necesario el establecimiento de un conjunto de operaciones para su gestión. En European Parliament (2008) se define a la gestión de residuos como "*la recogida, el transporte, la valorización y la eliminación de los residuos, incluida la vigilancia de estas operaciones, así como el mantenimiento posterior al cierre de los vertederos, incluidas las actuaciones realizadas en calidad de negociante o agente*" p. 15.

Dentro de la definición de gestión de residuos encontramos diversos elementos definidos de la siguiente manera:

- Recogida: operación consistente en la recolección de residuos, incluida su clasificación y almacenamiento inicial, con el objeto de transportarlos a una instalación de tratamiento de residuos (BOE, 2009).
- Transporte y transferencia: Este proceso comprende dos pasos: 1) transferencia de residuos desde un vehículo de recogida pequeño hasta un equipo de transporte más

grande; y 2) el transporte subsiguiente de los residuos, normalmente a través de grandes distancias, a un lugar de procesamiento o eliminación (Tchobanoglous et al., 1994).

- Valorización: cualquier operación cuyo objetivo es la reutilización de los residuos para diversas finalidades, aumentando su vida útil y permitiendo que permanezcan más tiempo en la economía, así como evitar el uso de materias primas vírgenes (European Parliament, 2008). Entre las operaciones de valorización podemos encontrar diversos tipos como: preparación para la reutilización, reciclado y compostaje (valorización material), así como la valorización energética.
- Eliminación y disposición final: cualquier operación que no sea la valorización de los residuos, incluso cuando la operación tenga como consecuencia secundaria el aprovechamiento de sustancias o energía, se incluye el depósito en vertederos controlados y no controlados (European Parliament, 2008).

Estos procesos de gestión varían dependiendo del país o ciudad donde se realicen. En el caso de los países en desarrollo, generalmente se observan procesos más simples (Figura 2), donde los residuos son recogidos de manera mezclada y son directamente depositados en vertederos sanitarios o vertederos a cielo abierto. Los vertederos son una instalación de eliminación de residuos mediante su depósito subterráneo o en superficie, por períodos de tiempo superiores a los considerados para el almacenamiento temporal (MITECO, 2021). Además, hay una gran presencia de los recolectores informales, quienes se encargan de recoger los residuos directamente de los hogares o de los vertederos para después venderlo a empresas recicladoras, obteniendo un beneficio económico pero poniendo en riesgo su salud (Ezeah et al., 2013).

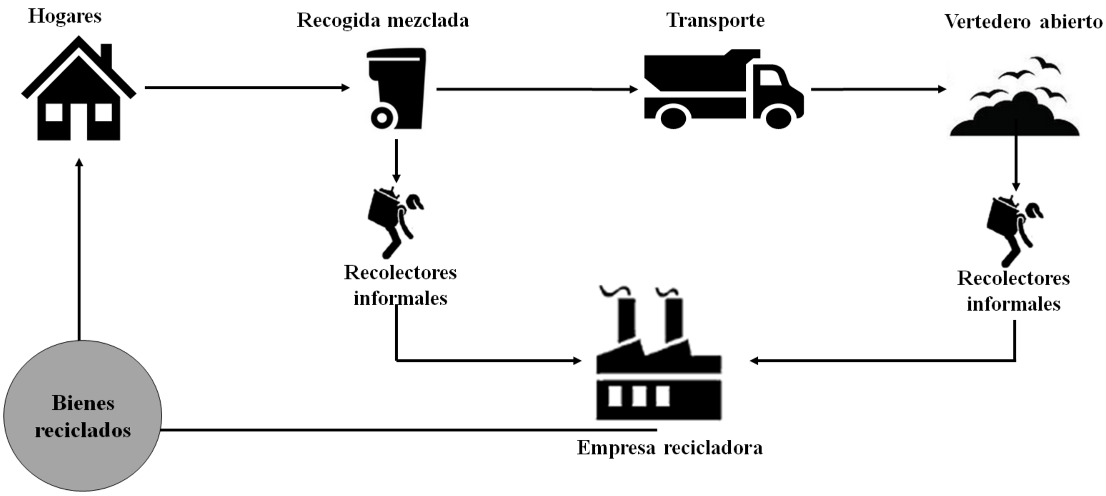


Figura 2. Prácticas de gestión de residuos realizadas habitualmente en países en desarrollo. Fuente: Elaboración propia a partir de Ezeah et al. (2013) y Steuer et al. (2017).

Por otro lado, en el caso de los países desarrollados se observan procesos más complejos y sofisticados, donde generalmente los residuos son recogidos de manera separada dependiendo del tipo de residuo (materia orgánica, envases ligeros, papel/cartón, vidrio) mediante diversos sistemas de recolección como:

- Recogida puerta a puerta (*Curbside/ Kerbside collection*), donde los residuos son clasificados según su tipo o fracción en contenedores, bolsas, sacos, cubos, etc., y colocados junto a la propiedad por los residentes, resultando el sistema donde los usuarios deben de recorrer la menor distancia (González-Torre and Adenso-Díaz, 2005).
- Recogida por contenedores (*Neighborhood/ Drop off collection*), consiste en una serie de contenedores para la recolección de varios tipos de residuos, localizados en puntos estratégicos, aumentado así la distancia que los usuarios deben de recorrer en comparación con el sistema puerta a puerta (González-Torre and Adenso-Díaz, 2005). Estos pueden ser superficiales, que como su nombre indica consiste en colocar los contendores sobre el pavimento; o subterráneos, donde los contenedores se ubican bajo el nivel del suelo, de manera que únicamente queda en la superficie un buzón a través del cual se depositan los residuos.
- Puntos verdes (*Clean point/ Green point*), este es un sitio de grandes dimensiones diseñado para la recolección selectiva de residuos que no se puedan recolectar en los otros tipos de sistemas de recolección (González-Torre and Adenso-Díaz, 2005). Este sistema generalmente es el más lejano a los usuarios y puede clasificarse en móvil o fijo. Los puntos fijos, son instalaciones fijas de gran tamaño que suelen estar ubicadas en zonas no centrales de los municipios. Los puntos móviles consisten en un vehículo de recogida, dotado de compartimentos para los diferentes residuos, que se desplaza a distintos puntos establecidos (con lugar y horario establecido).
- Recogida neumática, consiste en una serie de buzones de vertido conectados mediante tuberías subterráneas al punto de captura desde donde se realiza una aspiración del circuito. Existen dos tipos de sistemas de recogida neumática: los estacionarios y los móviles. En los sistemas estacionarios, también conocidos como estáticos, los residuos se disponen en los puntos de recogida de residuos, los cuales son transportados a través de tuberías subterráneas por medio del uso de vacío a una terminal de recolección de residuos, donde cada fracción se desvía a su propio contenedor. Los contenedores llenos son transportados por camiones hasta el procesamiento final y sitios de eliminación. En los sistemas móviles, los desechos se transportan neumáticamente, pero sólo a una distancia corta a varios puntos de succión, donde un camión equipado con una unidad neumática recoge los residuos (Teerioja et al, 2012).

Además, existen diversos tipos de tratamiento según la fracción a tratar, como se presenta en la Figura 3. En el caso de los residuos de envases ligeros, cartón/papel y vidrio, estos generalmente son transportados a plantas de separación y clasificación, donde mediante una combinación de procesos de separación mecánicos y automatizados, así como procesos manuales se recuperan diversos materiales valorizables (MITECO, 2021).

En el caso de la materia orgánica, esta puede ser sometida a dos tipos de tratamientos biológicos diferentes, por un lado, el compostaje, que es un proceso aerobio (en presencia de oxígeno) que, bajo condiciones de ventilación, humedad y temperatura controladas, transforma la materia prima en un material estable e higienizado llamado compost, favoreciendo el retorno de la materia orgánica al suelo y su reinserción a los ciclos naturales (MITECO, 2021). Por otro lado, la biometanización o digestión anaerobia, es un proceso en ausencia de oxígeno, y a lo largo de varias etapas en las que intervienen una población heterogénea de microorganismos, permite transformar la fracción más degradable de la materia orgánica en biogás y digestato (MITECO, 2021). El biogás es una mezcla de gases formada principalmente por metano y dióxido de carbono que se aprovecha energéticamente. En el caso del digestato, material residual de la digestión, este puede ser utilizado para fines agrícolas.

En el caso de la fracción resto, esta es enviada directamente a incineración o es sometida a tratamientos previos como los realizados en las plantas de tratamiento mecánico-biológico. El tratamiento mecánico-biológico es una combinación de procesos físicos y biológicos para el tratamiento de las fracciones de residuos con contenido significativo de materia orgánica como en el caso de la fracción resto, que generalmente contiene materia orgánica, así como diversos tipos de materiales todavía valorizables (MITECO, 2021). En estos procesos se obtienen diferentes productos como el digestato, biogás, así como materiales valorizables. Por último, los residuos rechazo (los cuales ya no se pueden valorizar materialmente) son enviados a incineración, donde tiene lugar la combustión de los residuos mediante una reacción química que se basa en la oxidación térmica. Este proceso térmico puede generar. 1) calor que se puede aprovechar para calentar agua para la calefacción; 2) vapor para usos industriales; o 3) energía eléctrica mediante un conjunto de turbinas de vapor para autoconsumo o venta a la red eléctrica de energía (MITECO, 2021). Como subproducto se generan residuos sólidos, compuestos fundamentalmente por escorias inertes y cenizas, que generalmente son enviados a vertederos.

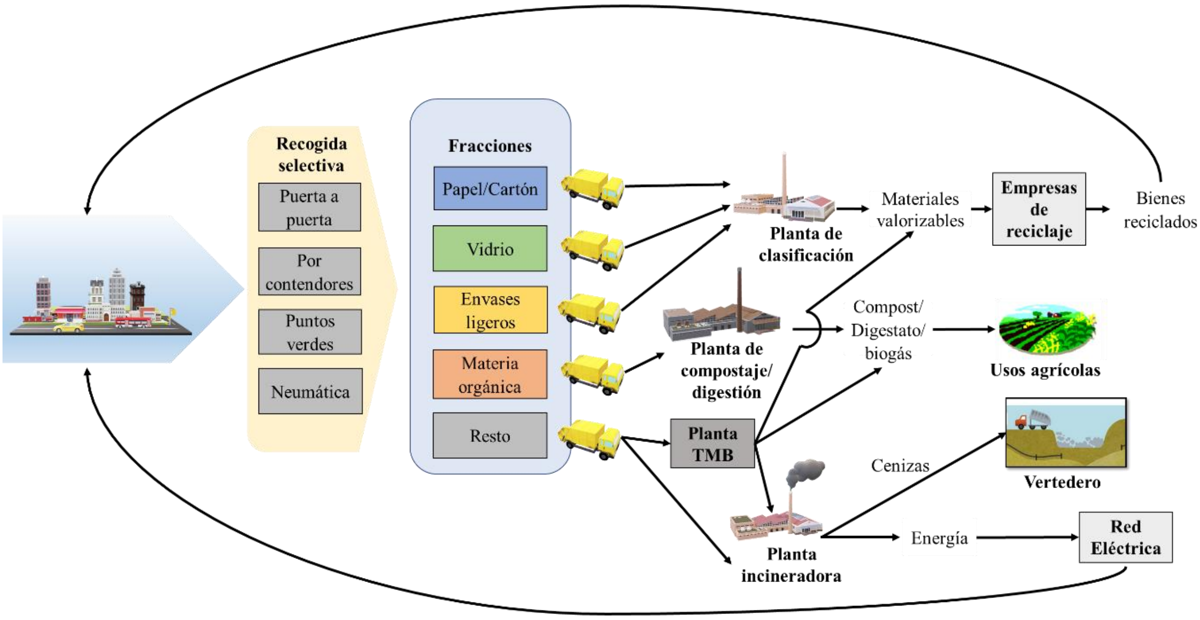


Figura 3. Sistemas de gestión de residuos habitualmente utilizados en países desarrollados. Fuente. Elaboración propia a partir de Winkler and Bilitewski (2007), Da Cruz et al. (2012) y Simon et al. (2016). TMB: Tratamiento Mecánico-Biológico.

La gran generación de residuos es un asunto de creciente interés y preocupación. Por lo que la Directiva 2008/98/CE del Parlamento Europeo, señala que el primer objetivo de cualquier política de residuos debería ser minimizar los efectos negativos de la generación y gestión de residuos sobre la salud humana y el medio ambiente, así como reducir el uso de recursos, además de seguir la siguiente jerarquía de residuos como orden de prioridades en la legislación y la política sobre la prevención y la gestión de los residuos (European Parliament, 2008):

- Prevención;
- Preparación para la reutilización;
- Reciclado;
- Otro tipo de valorización;
- Eliminación.

La jerarquía de residuos generalmente establece un orden de prioridad de lo que constituye la mejor opción ambiental en cuanto a la gestión de los residuos, sin embargo, otras opciones que se aparten de dicha jerarquía pueden considerarse, siempre y cuando se justifique por razones, de viabilidad técnica, viabilidad económica y protección del medio ambiente (European Parliament, 2008).

Por otro lado, en European Commission (2015) se presentan unos objetivos prioritarios en materia de residuos sólidos municipales:

- Aumento del objetivo de preparación para la reutilización y el reciclaje de residuos municipales al 65% para 2030;
- Aumento del objetivo de preparación para la reutilización y el reciclaje de residuos de envases al 75% para 2030;
- Limitación gradual de los vertidos de residuos municipales al 10 % para 2030.

Estos objetivos buscan mejorar las prácticas de gestión de residuos, estimular la innovación en el reciclaje, limitar el uso de vertederos y crear incentivos para cambiar el comportamiento de los consumidores, lo que a su vez, traerá beneficios significativos como el crecimiento sostenible y la creación de empleo, reducción de las emisiones de contaminantes, ahorros directos vinculados con mejores prácticas de gestión de residuos y un mejor medio ambiente (European Commission, 2015).

El modelo de economía lineal tiene como resultado impactos evitables en el medio ambiente y la salud humana, un uso ineficiente de los recursos naturales y una dependencia excesiva de los recursos de fuera de Europa (European Parliament, 2017). En oposición al modelo lineal surge la economía circular, el cual es un modelo de producción y consumo que busca asegurar que los materiales permanezcan más tiempo en la economía, reduciendo la utilización de materias primas vírgenes, así como la generación de residuos y consecuentemente, la reducción de los daños a la sociedad y al medio ambiente.

De acuerdo con Kirchherr et al. (2017) *p. 224*: "*Una economía circular describe un sistema económico que se basa en modelos de negocio que reemplazan el concepto de 'fin de vida útil' con la reducción, reutilización, reciclaje y recuperación de materiales en procesos de producción/distribución y consumo, operando así a nivel micro (productos, empresas, consumidores), nivel meso (parques eco-industriales) y a nivel macro (ciudad, región, nación), con el objetivo de lograr un desarrollo sostenible, que implica crear calidad ambiental, prosperidad económica y equidad social, en beneficio de las generaciones actuales y futuras*".

La economía circular se basa en el diseño duradero, mantenimiento, reparación, reutilización, remanufactura, restauración y reciclaje de los productos como se muestra en la Figura 4. El establecimiento de una economía circular podría generar beneficios como reducir la presión sobre el medio ambiente, mejorar la seguridad del suministro de materias primas, aumentar la competitividad, estimular la innovación, impulsar el crecimiento económico, crear puestos de trabajo, entre otros.

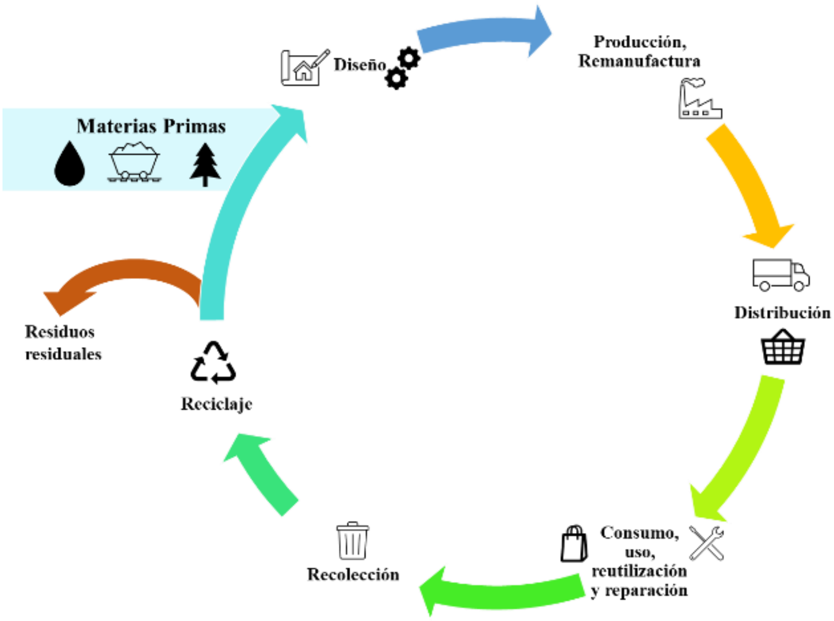


Figura 4. Diagrama de los procesos de la economía circular. Fuente: European Parliament (2020).

Esta jerarquía y objetivos, así como la economía circular priorizan la adopción de opciones para reducir la generación de residuos, aumentar la preparación para la reutilización y reciclado, y desalienta el uso de otro tipo de valorización (como la valorización energética), pero sobre todo, el depósito en vertederos, práctica que todavía es realizada en gran porcentaje en varios países del mundo y de Europa, como se muestra en la Figura 5 y 6, así como en las estadísticas presentadas en el Anexo A.

De acuerdo con Kaza et al. (2018) a nivel mundial se generaron aproximadamente 2.01 mil millones de toneladas de residuos sólidos urbanos en 2016, y se espera que este número crezca a 3.40 mil millones de toneladas para el año 2050, si se continua con el modelo actual de consumo. Por otro lado, en todo el mundo, el 69.7% de los residuos se depositan en algún tipo de vertedero. Alrededor del 19% experimenta la recuperación de materiales a través del reciclaje y el compostaje, y el 11% se trata a través de la incineración moderna (Figura 5). Aunque a nivel mundial, el 33 por ciento de los desechos aún se depositan en vertederos abiertos, los gobiernos están reconociendo cada vez más los riesgos (ambientales y social) y costes de los vertederos.

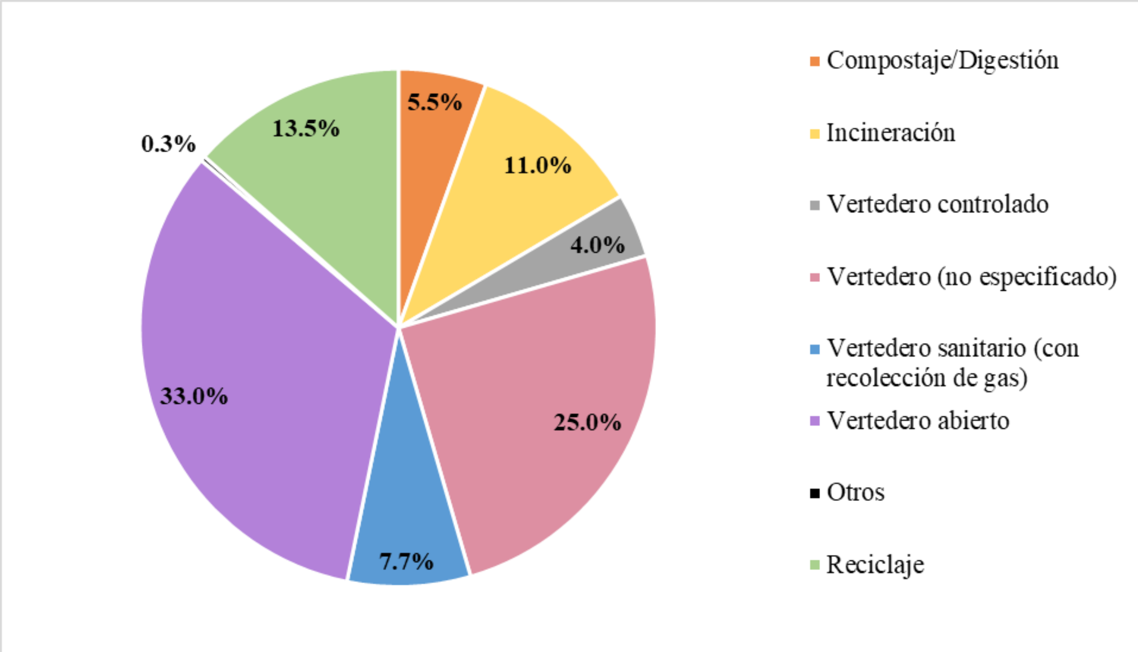


Figura 5. Tratamiento y eliminación de residuos a nivel global. Fuente: Kaza et al. (2018)

En el caso de España, en 2018, de las 22,222 miles de toneladas generadas aproximadamente 11,325 miles de toneladas de los residuos fueron enviados a vertederos (51.0% del total), 4,057 miles de toneladas fueron recicladas (18.3%), 3,942 miles de toneladas se convirtieron en compost o digestato (17.7%) y con 2,898 miles de toneladas se obtuvo energía por medio de la incineración de residuos (13.0%) (Eurostat, 2020). Por otro lado, la generación anual por habitante fue de 475 kg/hab., es decir, 1.30 kg/hab. por día.

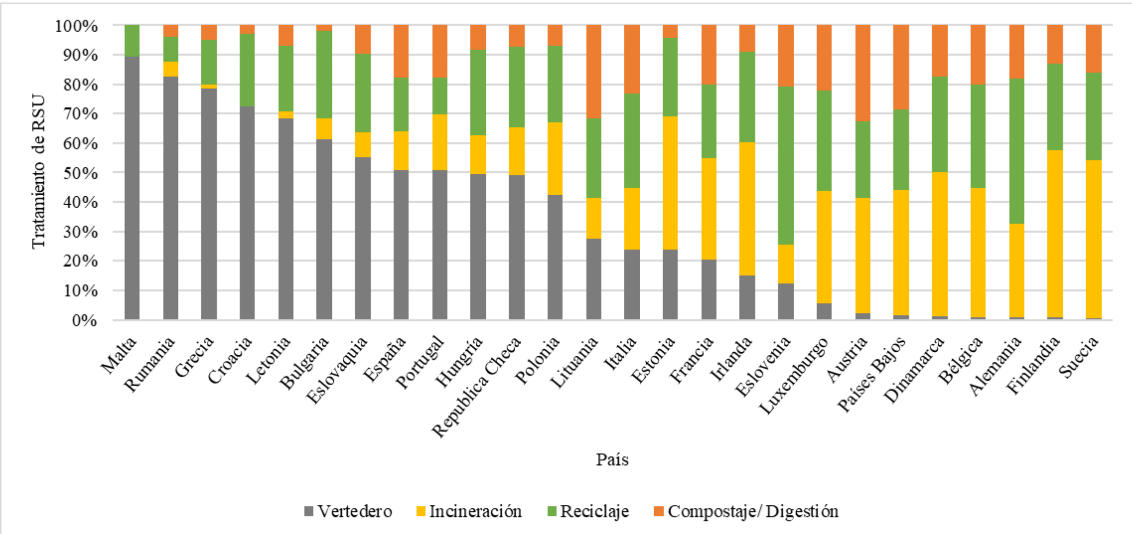


Figura 6. Porcentaje de tratamiento y eliminación de residuos en los países de la Unión Europea en 2018. Fuente: Elaboración propia a partir de Eurostat (2020). No se ha incluido Chipre por falta de datos.

## 1.2 Métodos para el análisis económico de los sistemas de gestión de RSU

En Allesch and Brunner (2014) se realiza una descripción general de los diferentes métodos de evaluación para el manejo de residuos sólidos utilizados en 151 estudios revisados. Entre los métodos que consideran los aspectos económicos se mencionan el Coste del Ciclo de Vida (*Life Cycle Costing*), el Análisis Coste-Beneficio, el Análisis Coste-efectividad, el Análisis de Ecoeficiencia, el Análisis *Emergy*. Los métodos más utilizados en la literatura son el Coste del Ciclo de Vida y el Análisis Coste-Beneficio, los cuales se detallan a continuación.

### 1.2.1 Coste del Ciclo de Vida

El Coste del Ciclo de Vida (LCC) es un método utilizado para evaluar los aspectos económicos de los sistemas de gestión de RSU. El LCC es el método utilizado para contabilizar todos los costes de un producto o servicio durante su vida útil (Reich, 2005). Generalmente se utilizan y se conocen tres variantes de LCC; estos son LCC convencional, LCC ambiental y LCC social.

- El LCC convencional o LCC financiero presenta evaluaciones financieras tradicionales (sobre bienes y servicios comercializados) que se centran en los costes privados o internos de un actor (empresa o consumidor) (Martinez-Sanchez et al., 2015; Nessi et al., 2012).
- El LCC ambiental amplía el LCC convencional para ser coherente con los límites del sistema LCA. Esta es una evaluación financiera, que incluye los costes incurridos por todas las partes interesadas (Martinez-Sanchez et al., 2015).
- El LCC social se refiere a todos los costes sociales asociados con el ciclo de vida completo de un producto o servicio dentro de los límites definidos en el LCA. En este se consideran dos tipos de costes: costes directos o internos (costes de inversión, mano de obra, energía, etc.) y costes externos (Dahlbo et al. 2007; Martinez-Sanchez et al., 2015).

Algunos estudios donde se usa el LCC son: Dahlbo et al. (2007), Massarutto et al. (2011), Teerioja et al. (2012), Martinez-Sanchez et al. (2015), Woon and Lo (2016) y Edwards et al. (2018).

### 1.2.2 Análisis Coste-Beneficio

El Análisis Coste-Beneficio (ACB) es una herramienta analítica para juzgar las ventajas o desventajas económicas de una decisión de inversión, evaluando sus costes e ingresos con el fin de evaluar el cambio de bienestar atribuible a ella (European Commission, 2014). El ACB es un enfoque establecido de la economía del bienestar, aplicado para estimar y comparar los costes e ingresos totales generados por políticas y escenarios alternativos (European Commission, 2014).

En el caso de Análisis Coste-Beneficio existen tres tipos de variaciones, las cuales se describen a continuación.

- ACB Financiero (ACBf). Es una herramienta para la evaluación de la rentabilidad privada. Solo se consideran los flujos de efectivo de un actor. Solo en un mercado perfecto, la ACBf sería suficiente para evaluar la sostenibilidad (Hoogmartens et al., 2014).
- ACB ambiental (ACBa). El concepto central de ACBa es el de los costes externos causados por los impactos ambientales. Generalmente, expresar el daño causado por los impactos ambientales en valores monetarios suele ser todo un desafío. Además, el impacto monetizado suele ser externo al productor, porque no asume ese coste. Ejemplos de costes externos son los impactos de la contaminación, las pérdidas de ecosistemas y los daños a la propiedad de los vecinos. Como ACBa contiene aspectos financieros, la información en ACBf está integrada. (Hoogmartens et al., 2014).
- ACB Social (ACBs). Evalúa un proyecto desde el punto de vista de la sociedad en su conjunto. En este caso, el dinero se utiliza como unidad común en la que se pueden expresar los costes y beneficios sociales y ambientales, la atención se centra en el bienestar. Los beneficios se definen como aumentos en el bienestar humano (utilidad) y los costes se definen como reducciones en el bienestar humano. Para que un proyecto o una política califique por motivos de coste-beneficio, sus beneficios sociales deben exceder sus costes sociales (D. Pearce et al., 2006; Hoogmartens et al., 2014).

Algunos estudios en los que se utiliza el ACB son: Ibenholt and Lindhjem (2003), donde se realiza un análisis coste-beneficio para evaluar si la política noruega de reciclaje para envases de cartón es realmente rentable; y Kumar et al. (2004), donde se utiliza un análisis coste-beneficio para evaluar un caso de estudio sobre un sistema de relleno sanitario con opción de recuperación de gas, que se ha llevado a cabo en la ciudad de Port Blair, Islas Andaman, India. En Jamasb and Nepal (2010) se utiliza el análisis coste-beneficio social para evaluar los aspectos económicos y ambientales de las opciones de gestión de residuos centradas en la conversión de residuos en energía (WtE) en Reino Unido.

El ACB ha sido elegido para el desarrollo de la metodología, por su simplicidad y fácil comprensión para cualquier tomador de decisiones. Por otro lado, a diferencia del LCC, el cual está relacionado con la evaluación de los productos, el ACB se enfoca principalmente en proyectos o políticas. El propósito de ACB es facilitar una asignación de recursos más eficiente, demostrando la conveniencia para la sociedad de un proyecto o política en particular, en lugar de otras posibles alternativas.

*1.2.2.1 Análisis Coste-Beneficio sostenible*

La industrialización y el crecimiento poblacional han generado consecuencias negativas al medio ambiente y a la sociedad, por lo que diversos organismos internacionales, como la ONU y el Parlamento Europeo, hacen un llamamiento para lograr un desarrollo sostenible que permita el crecimiento económico pero que garantice la inclusión social y la protección ambiental. La sostenibilidad o desarrollo sostenible puede definirse de diversas maneras, a continuación, se incluyen definiciones de diferentes autores:

> "*Es la distribución eficiente y equitativa de recursos intrageneracional e intergeneracional con el funcionamiento de actividades socioeconómicas dentro de los confines de un ecosistema finito*" (Stoddart, 2011; Mensah, 2019).
>
> "*Un equilibrio dinámico en el proceso de interacción entre una población y su entorno, de tal manera que la población desarrolle todo su potencial sin producir efectos adversos irreversibles sobre la capacidad de carga del medio ambiente del que depende*" (Ben-Eli, 2018) p. 1340.
>
> "*Desarrollo que satisfaga las necesidades del presente sin comprometer la capacidad de las generaciones futuras para satisfacer sus propias necesidades*" (United Nations, 2015).

Por otro lado, en la legislación española se presenta un concepto relacionado con el desarrollo sostenible conocido como economía sostenible, el cual se define como:

> *"Un patrón de crecimiento que concilie el desarrollo económico, social y ambiental en una economía productiva y competitiva, que favorezca el empleo de calidad, la igualdad de oportunidades y la cohesión social, y que garantice el respeto ambiental y el uso racional de los recursos naturales, de forma que permita satisfacer las necesidades de las generaciones presentes sin comprometer las posibilidades de las generaciones futuras para atender sus propias necesidades"* (BOE, 2011) p. 10.

Se considera que el desarrollo sostenible tiene tres pilares como se muestra en la Figura 7: a) medio ambiente: garantía de la integridad continua de los recursos naturales; b) sociedad: garantía continua de salud y bienestar humano; y c) economía: garantía de prosperidad económica continua (Fiksel et al. 2012). Para lograr la sostenibilidad se debe de equilibrar los factores económicos, ambientales y sociales en igual armonía. Estos elementos están interconectados y son cruciales para la prosperidad y bienestar de las sociedades.

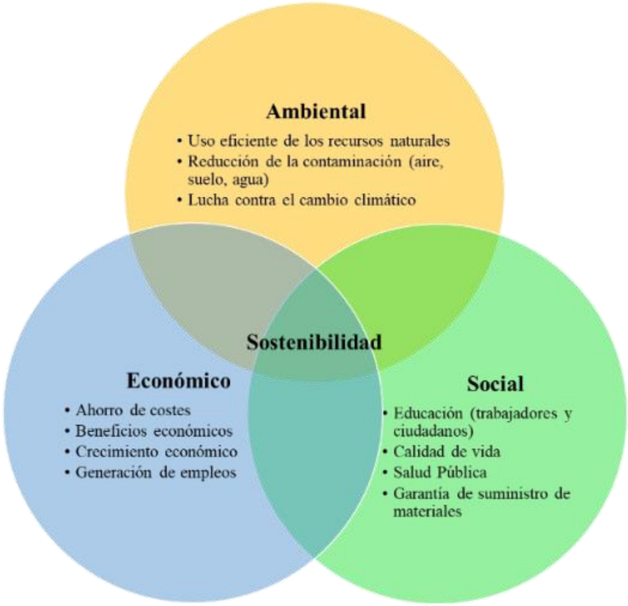


Figura 7. Pilares de la sostenibilidad. Fuente: Elaboración propia a partir de Fiksel et al. (2012).

La metodología desarrollada utilizará lo que denominamos análisis coste-beneficio sostenible porque se basa en los principios de la sostenibilidad y sus tres pilares, al considerar los posibles impactos económicos, sociales y ambientales de los sistemas o proyectos evaluados. En la metodología desarrollada se presentan diferentes impactos clasificados en diversos grupos: 1) infraestructura, 2) reutilización, reciclaje y valorización de los residuos, 3) uso de los materiales, 4) medio ambiente, 5) salud pública, 6) educación, y 7) calidad de vida. De esta manera, se evaluará los sistemas o proyectos incluyendo la mayor cantidad de impactos, y si se cumplen con las condiciones o lineamientos establecidos en la metodología se podrá concluir que los sistemas o proyectos son sostenibles.

Además, se implica que la mejor opción es aquella que satisfaga las necesidades de la sociedad, y sea ambiental y económicamente viable, económica y socialmente equitativa, así como social y ambientalmente soportable (Mensah, 2019), como se muestra en la Figura 8. De acuerdo con lo anterior, se considera que estos 3 pilares son sinérgicos e interdependientes, y la mejor alternativa será aquella que asegure una armonía y equilibrio de estas 3 pilares o dimensiones.

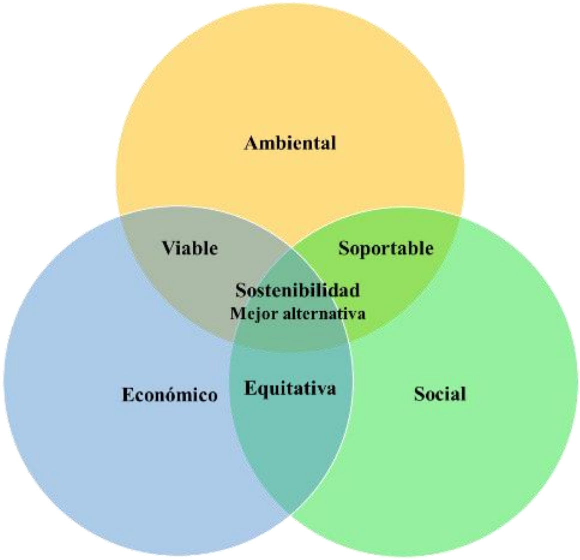


Figura 8. Evaluación de los proyectos o sistemas de gestión considerando los 3 pilares de la sostenibilidad. Fuente: Elaboración propia a partir de Mensah (2019).

## 1.3 Tipos de costes e ingresos

Cualquier sistema de gestión de residuos puede ocasionar diferentes impactos, los cuales pueden ser definidos como cualquier consecuencia del establecimiento de un sistema de gestión de RSU, deseada o no, generalmente susceptible de medición (Seguí-Amórtegui et al., 2014). Estos pueden generar impactos positivos o negativos que se verán reflejados como ingresos o costes, respectivamente.

De acuerdo a Aleluia and Ferrão (2017), los costes internos o privados corresponden a los costes e ingresos asociados con la inversión, operación y mantenimiento de los sistemas de tratamiento y recolección de residuos. Estos son costes e ingresos en los que incurre el inversionista o el desarrollador del proyecto (ya sea una entidad pública o privada). Estos están restringidos al límite espacial de una instalación de tratamiento de residuos.

Los costes de inversión, operación y mantenimiento de los sistemas de gestión de residuos están relacionados con los costes de construcción, costes de equipos y maquinaria, costes laborales, materias primas e insumos, entre otros (Figura 9). Por otro lado, los ingresos privados están relacionados con la venta de los materiales recuperados (plástico, compost, vidrio, entre otros) por las instalaciones de gestión de residuos, así como la energía y el vapor generados por las plantas de incineración. También, se obtienen ingresos debido a las tasas de entrada (*gate fees*), que corresponden a la cantidad pagada por las autoridades locales a las instalaciones de tratamiento y disposición de residuos. La tasa de entrada se cobra por cada tonelada de residuos que se recibe para el tratamiento en una determinada instalación con el fin de compensar los costes operativos totales de los sistemas.

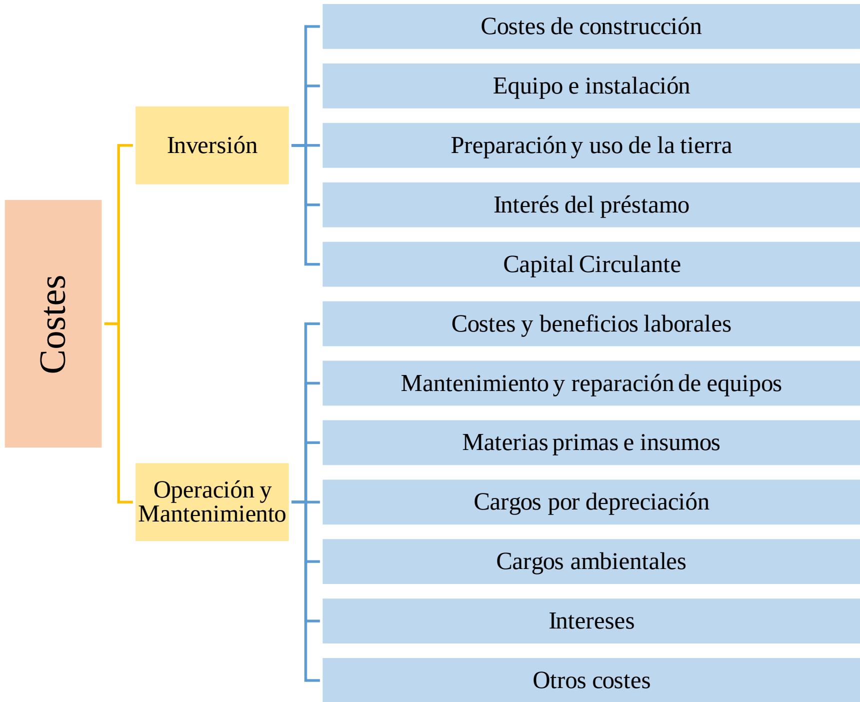


Figura 9. Costes de inversión y operación de los sistemas de gestión de residuos. Fuente: Aleluia and Ferrão (2017).

Generalmente, los estudios solo centran su atención en los costes privados de los sistemas gestión de residuos como en Aleluia and Ferrão (2017) y Al-Salem et al. (2014). De acuerdo con Nahman (2011), esto resulta en un sesgo en contra de alternativas como el reciclaje, que puede ser más caro que los vertederos desde una perspectiva puramente financiera, pero preferible desde un punto de vista ambiental y social. Lo ideal, sería comparar diferentes opciones de gestión de residuos sobre la base de sus costes netos globales para la sociedad (ingresos privados - costes privados + ingresos externos - costes externos) por tonelada de residuos. Sin embargo, a diferencia de los costes privados, los costes e ingresos externos son a menudo intangibles y difíciles de cuantificar en términos monetarios y, por lo tanto, generalmente no se reflejan en los análisis económicos de los sistemas de gestión de residuos y no se tiene en cuenta en la toma de decisiones sobre las opciones de gestión de residuos.

De acuerdo con Eshet et al. (2006), las externalidades pueden definirse como "*Los costes e ingresos externos que surgen cuando las actividades sociales o económicas de un grupo de personas tienen un impacto en otro, y cuando el primer grupo no tiene en cuenta plenamente su impacto*" p. 336. Por otro lado, Aleluia and Ferrão (2017) señala que los costes externos o las externalidades se refieren a aquellos costes causados directa o indirectamente por la operación de una planta de tratamiento, pero cuyos efectos son asumidos por una parte que no sea su propietario u operador. Estos costes están esencialmente relacionados con los impactos sociales y ambientales. Ejemplos de costes ambientales externos son la descarga de agua de lixiviado no tratada de una planta de compostaje, la liberación a la atmósfera de exceso de biogás de una instalación de digestión anaeróbica, que contribuye así a las emisiones de gases de efecto invernadero, o la emisión de toxinas de una instalación de incineración que no puede ser equipado con tecnologías de control de emisiones. Los costes sociales podrían incluir, por ejemplo, la afectación del precio de venta de las viviendas que se ubican cerca de las instalaciones de tratamiento como vertederos o incineradora, la destrucción de empleos del sector informal en los países en desarrollo como resultado de la implementación de sistemas de gestión de tratamiento de residuos o la mayor incidencia de enfermedades relacionadas con las vías respiratorias en las comunidades que se encuentran cerca de las plantas de incineración. Todos estos impactos inducen costes en la sociedad, que no se tienen en cuenta en las decisiones de gestión de residuos y en la fijación de precios y, por lo tanto, constituyen las externalidades ambientales y sociales de la gestión de residuos.

## 1.4 Métodos de valoración económica

La definición de costes externos requiere la aplicación de métodos específicos desarrollados en la economía ambiental y de recursos (Dahlbo et al. 2007). De acuerdo con Atkinson and Mourato (2015), los economistas han desarrollado una serie de enfoques para estimar el valor económico de los impactos intangibles (externalidades). Existen varios procedimientos que comparten la característica común de utilizar la información y el comportamiento del mercado para determinar el valor económico de un impacto no relacionado con el mercado; estos procedimientos se conocen como los métodos de valoración económica. De acuerdo con Eshet et al. (2005), los métodos de valoración se clasifican en 5 categorías, las cuales son:

1. Función de respuesta a la dosis (*Dose response function)*, relaciona la cantidad de un contaminante que afecta a un receptor (por ejemplo, la población) con el impacto físico en este receptor (por ejemplo, el número incremental de hospitalizaciones) (Rabl et al., 2010; Eshet et al., 2006). Como receptor puede considerarse también a los edificios, cultivos, cuerpos de agua, entre otros. En la Figura 10, se muestran las posibles vías de exposición a las emisiones de contaminantes, que pueden ser por inhalación (vía respiratoria), ingestión (vía oral) y contacto directo (vía dermis). También, se puede observar que la contaminación del aire, suelo y aire puede afectar a los ecosistemas acuáticos y terrestres, y consecuentemente, afectar a la salud de las personas.

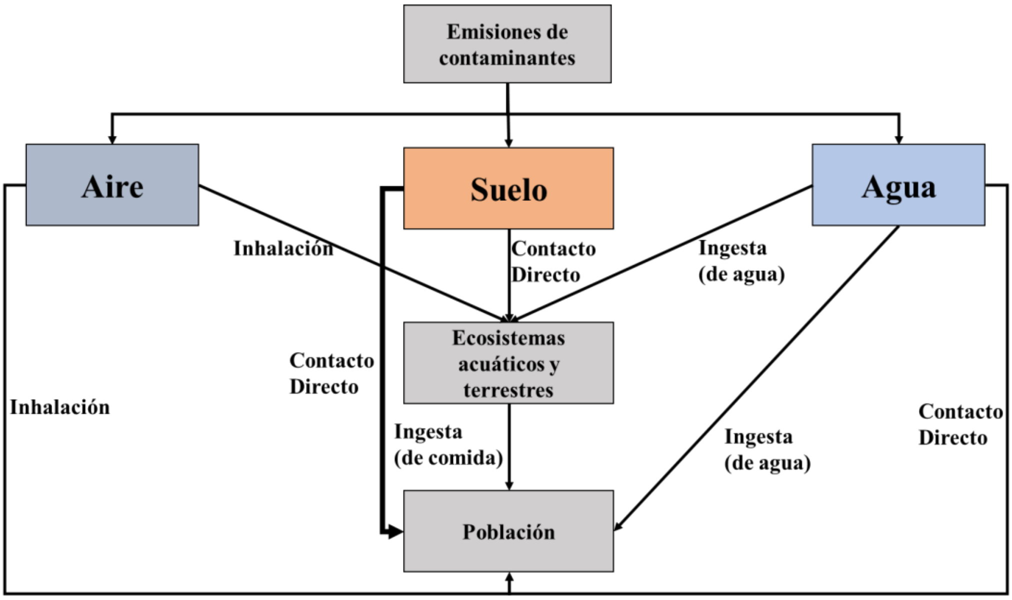


Figura 10. Vías de exposición a las emisiones de contaminantes. Fuente: Rabl et al. (2010).

2. Métodos directos (preferencia declarada), asume que el consumidor es el mejor juez de sus intereses y que es capaz de tomar decisiones realistas en función de sus preferencias, aunque no realice ningún cambio de comportamiento (Eshet et al., 2005).

   - Método de valoración contingente (*Contingent valuation method*), se basa en información recopilada de individuos y/o hogares de la región afectada por el proyecto investigado, donde se calcula la contribución financiera que las personas están dispuestas a hacer para prevenir o remediar el daño ambiental, es decir, su disposición a pagar o DAP (*WTP o Willingness to Pay*) o la compensación económica que las personas están dispuestas a aceptar (DAA), a cambio de asumir una nueva carga ambiental, (*Willingness to Accept o WTA*) (Stigka et al., 2014).

   - Experimento de elección (*Choice experiment*), es un método que consiste en cuestionarios, donde las personas tienen que clasificar, calificar o elegir alternativas según sus preferencias. Cada alternativa se caracteriza por una serie de atributos, de los cuales, uno será monetario (Eshet et al., 2005). Por lo general, se incluye una alternativa que contiene atributos relacionados con la situación actual (status quo), para que los encuestados puedan establecer las otras alternativas en relación con su contexto actual (Lim et al., 2014).

3. Evaluación de expertos de los costes de los daños (*Experts' assessment of damage costs*), los daños ambientales a menudo se valoran de acuerdo con el conocimiento, la experiencia y principalmente la intuición y el juicio de los profesionales, que estiman los costes de reparar, restaurar o reemplazar un activo dañado o disminuir los impactos (Eshet et al., 2005).

- Método de control de costes (*Control cost method*) —coste de abatimiento, coste de evitación, coste de remediación. Pretende inferir el valor (costes de los impactos) que se le atribuyen a la contaminación, a partir, de la implementación de regulaciones económicas que los gobiernos imponen para evitar o abatir la contaminación y sus daños (Eshet et al., 2005).

- Método de coste de reemplazo *(Replacement cost method),* utiliza el coste de reemplazar o restaurar un activo dañado a su estado original (D.W. Pearce and Howarth, 2000).

- Método del coste de limpieza (*Clean-up cost method*), asume que una vez que se produce el daño resultante de la contaminación, los costes de rehabilitación para lograr la situación anterior al daño aparecerán como un valor económico indirecto (mínimo) del daño causado (Eshet et al., 2005).

4. Métodos indirectos (preferencia revelada), son métodos que determinan las preferencias y el valor implícito de las externalidades, a partir de observaciones reales del mercado. Las preferencias se revelan indirectamente cuando las personas compran bienes y servicios comercializados que se supone que resuelven o reducen el problema ambiental generado (Eshet et al., 2006).

   - Método del precio hedónico (*Hedonic Price method*), es un método estadístico mediante el cual se analiza el efecto de la proximidad de determinada instalación de tratamiento de residuos sobre los precios de la propiedad, basándose en datos sobre precios y características de la vivienda para un gran número de propiedades, utilizando regresión múltiple (Eshet et al., 2005). La variable dependiente (precio o valor de la vivienda) se analiza respecto a una serie de variables independientes como las características que afectan los precios o valores de la vivienda, incluida la variable de calidad ambiental en cuestión, como la proximidad a una instalación de tratamiento; así como otras características. De esta manera, se puede determinar la influencia específica de la proximidad de una instalación de tratamiento en los precios de la vivienda, manteniendo constantes todas las demás características. Una vez aislado de esta manera, la influencia de la instalación en los precios de la propiedad se puede utilizar para determinar (en términos monetarios) el impacto en el bienestar humano de los inconvenientes asociados con la proximidad a esta instalación (Hite et al., 2001; Zhao et al., 2016).

   - Método de evitación del comportamiento (*Averting behaviour method*), asume que el valor de un impacto ambiental es igual a la cantidad de dinero que los hogares gastan para compensar el impacto (por ejemplo, el gasto en filtros de agua) por el daño causado por determinado sistema de gestión de residuos (contaminación del agua subterránea causado por el lixiviado de vertederos) (Eshet et al., 2005).

- Método del coste de enfermedad (*Cost of illness method*), estima los cambios en el gasto público y privado en salud y el valor de la producción perdida (ganancias perdidas debido a días no trabajados), sobre la base de la relación entre el exceso de morbilidad o mortalidad y los niveles de contaminación ambiental (Shechter, 1999).
- Función de producción de salud (*Health production function*), se asume que el estado de buena salud (output) se produce debido a la combinación de diversos factores (inputs), incluidos los gastos para evitar problemas de salud (D.W. Pearce and Howarth, 2000).
- Método del coste de viaje *(Travel cost method*), este método no es generalmente utilizado para la valoración de las externalidades de los sistemas de RSU. El principal objetivo de este método es determinar los gastos familiares e individuales que se relacionan con viajes a sitios recreativos, teniendo en cuenta los costes de transporte, las tarifas de entrada, los gastos realizado en el sitio (alimentación, hospedaje, entre otras) y así como el tiempo utilizado (Seguí et al., 2009; Eshet et al., 2005).
- Método de evaluación de quejas (*Complaint assessment method*), se basa en la observación de los gastos reales involucrados en las demandas judiciales de los ciudadanos contra instalaciones nocivas, incluye varios costes gubernamentales o municipales involucrados en la investigación de una queja, costes de las actividades de los grupos de ciudadanos, honorarios de abogados ambientales y costes de defensa de las empresas (Eshet et al., 2005).

5. Transferencia de beneficios (*Benefit transfer*) —transferencia del valor ambiental/ transferencia de información. Implica aprovechar los valores existentes de estimaciones de cálculo de otros estudios, y aplicarlas al sitio de estudio en cuestión, haciendo los ajustes apropiados entre el sitio de estudio original y el sitio de estudio nuevo, requiriendo que los estudios de donde se extraen las estimaciones sean sólidos y fiables (Nahman, 2011). En la Figura 11 se muestran los métodos de valoración económica. Se puede observar que tanto los métodos directos, indirectos, evaluación de expertos y función de respuesta a la dosis, contribuyen a la información utilizada en el método de transferencia de beneficios, debido a que utiliza los resultados de estudios previos.

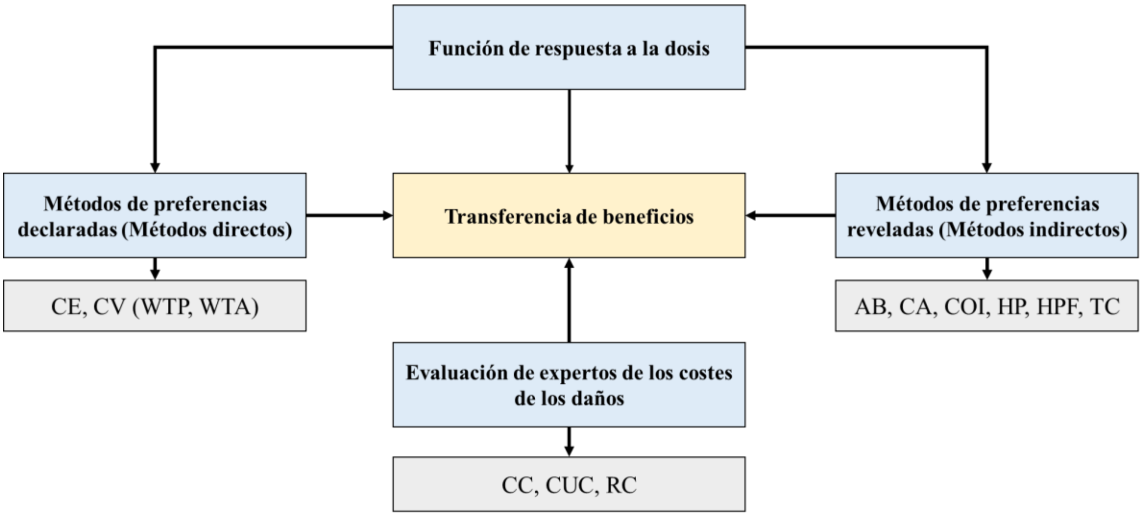


Figura 11. Métodos de valoración económica. Fuente: Eshet et al. (2005). AB: Método de evitación del comportamiento; CA: Método de evaluación de quejas; CC: Método de control de costes; CE: Experimento de elección; COI: Método del coste de enfermedad; CUC: Método del coste de limpieza; CV: Método de valoración contingente; HP: Método del precio hedónico; HPF: Función de producción de salud; RC: Método de coste de reemplazo; TC: Método del coste de viaje; WTA: Disposición a aceptar; WTP: Disposición a pagar.

## 1.5 Estado del arte

Mediante la realización del análisis del estado del arte, a través de un análisis bibliométrico, se observa un creciente interés de los investigadores en temas relacionados con el análisis económico de los sistemas de gestión de RSU. Esto es debido a que las cuestiones económicas son una parte fundamental en la toma de decisiones de los gestores, ya que la mayoría de las decisiones relacionadas con la implementación de sistemas y tecnologías de gestión de RSU en la sociedad moderna se ven afectadas por restricciones económicas.

En específico, se observa un aumento en el número de publicaciones enfocadas en el análisis económico de los sistemas de conversión de residuos en energía. La valorización energética de residuos brinda la oportunidad de reducir la cantidad de residuos enviados a vertederos, además, puede ayudar a reducir la dependencia de los países a la energía generada a partir de combustibles fósiles. Sin embargo, el aumento de publicaciones no está en consonancia con la jerarquía de residuos y los principios de la economía circular, que prioriza la adopción de métodos para reducir la generación de residuos, aumentar la reutilización y el reciclaje, y desalienta el uso de incineradoras y vertederos. Algunas de las publicaciones enfocadas principalmente en los sistemas de conversión de residuos a energía son: Panepinto et al. (2016), Murphy and McKeogh (2004), Tan et al. (2015), Leme et al. (2014), Jamasb and Nepal (2010), Massarutto et al. (2011), entre otros.

Diversos artículos en la literatura se enfocan principalmente en el análisis de los impactos privados como en Aleluia and Ferrão (2017). Los autores realizan un análisis de los costes de los sistemas de gestión de residuos sólidos urbanos de los países asiáticos en desarrollo, enfocándose en los costes privados, al considerar los costes de inversión, operación y mantenimiento. En los costes de inversión incluyen: costes de construcción, equipo e instalación, uso y preparación del suelo, intereses del préstamo, capital circulante. Por otro lado, los costes de operación incluyen: costes y beneficios laborales, mantenimiento y reparación de equipos, materias primas e insumos, cargos por depreciación, cargos ambientales, intereses y otros costes. Al-Salem et al. (2014) realiza una evaluación del desempeño tecno-económico de tres escenarios diferentes, que reflejan las estrategias de gestión de residuos y el tratamiento de plásticos en el área de Londres. Los autores consideran principalmente los costes e ingresos privados como: los costes de capital, de recolección, de funcionamiento, de operación y mantenimiento, tarifas de entrada, intereses e impuestos, así como diversos ingresos como: la venta de calor, electricidad, materiales recuperados, entre otros.

Por otro lado, los autores que han analizado las externalidades, generalmente se enfocan en aspectos o casos específicos de los sistemas de RSU o solo consideran unos cuantos impactos externos. Un ejemplo es Teerioja et al. (2012), donde se analizan los sistemas de recolección en Helsinki (Finlandia), teniendo en consideración las emisiones de $CO_2$, $SO_2$ y NOx. Woon and Lo (2016) analizan los impactos de los sistemas de gestión de RSU en Hong Kong, comparando un vertedero y una incineradora, al considerar como externalidades: el coste de oportunidad de la tierra, el coste debido a las molestias generadas (olores, ruidos, intrusión visual, etc.), y el coste por la contaminación del aire. Edwards et al. (2018) analizan los sistemas de gestión de residuos de comida, al considerar principalmente los costes relacionados con las emisiones de contaminantes al aire y al suelo. Sasao (2004) examina las preferencias de los residentes (público) sobre la ubicación de los vertederos, mediante un experimento de elección a través de cuestionarios, se centra en los posibles efectos negativos para los residentes considerando una ubicación hipotética de un vertedero. Sun et al. (2017) aplica un modelo de precios hedónicos para evaluar el impacto del establecimiento de incineradoras en el valor de mercado de las viviendas ubicadas cerca de estas instalaciones en China.

A continuación, se detalla los estudios donde se han desarrollado alguna metodología para el análisis económico de los sistemas de gestión de RSU, señalando los impactos (costes e ingresos) que son considerados. En Mavrotas et al. (2015) se desarrolla un modelo de programación matemática con optimización multiobjetivo de los sistemas de gestión de RSU con el objetivo de proporcionar la solución óptima para un sistema de gestión de RSU, generando una optimización estructural, de diseño y operativa. En este artículo se incorpora los costes e ingresos externos asociados con: a) los impactos de la contaminación atmosférica, b) los impactos en el suelo y las aguas subterráneas, c) los impactos en la calidad de vida, d) el uso o desplazamiento de electricidad, y e) la reducción del uso de fertilizantes de compost.

En Rabl et al. (2008) se presenta una metodología para evaluar los impactos y los costes de los daños debido a la contaminación del tratamiento de residuos. Se comparan los costes de los daños del vertido y de la incineración de RSU, teniendo en cuenta los impactos a la salud pública, a los cultivos, materiales y edificios por las emisiones de contaminantes como: $PM_{2.5}$, $PM_{10}$, $SO_2$, $NO_2$, dioxinas y metales pesados (Cd, Cr, Ni, As, Pb, Hg). Además, de los impactos ocasionados por el calentamiento global (emisiones de $CO_2$ generadas y evitadas por la recuperación de energía y de materiales), así como la generación de molestias (ruido, polvo, olores, etc.).

En Martinez-Sanchez et al. (2015) se desarrolla un modelo de costes para la evaluación económica de los sistemas de gestión de RSU. El modelo se basa en los principios del Coste del Ciclo de Vida donde se proporciona los costes detallados para las tecnologías clave dentro de los sistemas de residuos modernos. Los costes se clasificaron como: a) costes presupuestarios, b) transferencias y c) costes externos. Donde los costes presupuestarios pueden clasificarse como: costes de capital, así como costes de operación y mantenimiento, que puede ser coste fijo, por ejemplo, mano de obra, mantenimiento y seguro; o coste variable, por ejemplo, consumo de electricidad. Las transferencias se refieren a tasas, impuestos, subsidios, entre otros. Y las externalidades donde se consideran principalmente los daños por las emisiones de contaminantes generadas.

En Yedla (2003) se desarrollaron modelos integrados para conocer el coste de disposición de los RSU, analizado dos sistemas en específico: sistema de relleno sanitario con recuperación de gas y el compostaje aeróbico. Para el análisis económico se realiza una distinción entre costes e ingresos. En el caso de los costes se incluyen: precio del terreno, costes de preparación de vertederos, costes de gestión, costes de recolección, transporte y vertido de residuos, costes de conversión y distribución de energía, costes administrativos. En el caso de los ingresos se incluyen: reducción del gasto en salud pública, generación de gas metano, reducción en el uso de combustibles fósiles, reducción del gasto en medidas de control de la contaminación, reducción de la contaminación por quema de residuos, reducción del uso del suelo para la eliminación de RSU, utilización de materiales reciclables, nivelación y rejuvenecimiento de tierras abandonadas, mejora de la imagen pública.

En Massarutto et al. (2011) se compara escenarios alternativos de gestión de residuos, considerando diferentes tipos de sistemas de recolección y niveles de separación de residuos, mediante el desarrollo de un modelo de simulación de escritorio. Se aplican varios escenarios alternativos basados en diferentes combinaciones de recuperación de energía y materiales, en dos áreas imaginarias modeladas para representar un entorno típico del norte de Italia. En el caso de los costes externos se consideran las emisiones a la atmósfera (por incineración, vertido y vehículos recolectores), el cambio climático ($CO_2$) y las molestias generadas (ruido, intrusión visual, etc.). Por otro lado, en el caso de los ingresos externos se consideran las emisiones evitadas debido a que la generación de energía a partir de residuos desplaza a las plantas termoeléctricas alimentadas por petróleo y carbón y a los sistemas de calefacción domésticos alimentados por petróleo y gas; el reciclaje de los materiales seleccionados y recuperados (vidrio, papel, plásticos, metales y madera), que representan ahorros en términos de energía primaria y $CO_2$.

En Weng and Fujiwara (2011) se enfocan principalmente en el desarrollo de una metodología generalizada para evaluar la rentabilidad financiera de los sistemas de gestión de RSU, considerando los costes financieros de operación y mantenimiento. Además, presenta un marco de referencia basado en el análisis coste-beneficio (ACB) para evaluar la efectividad de los sistemas de gestión de RSU, donde se describen los costes e ingresos financieros, ambientales y sociales entre los que se incluye los impactos debido a la contaminación del aire, suelo y agua, al tráfico, al ruido, al desarrollo regional, a la reducción de los residuos, a la recuperación de los residuos, al paisaje.

En la Tabla 1 se muestra a modo de resumen los estudios que presentan metodologías para el análisis económico de los sistemas de RSU, los cuales consideran las externalidades. En términos generales, se puede observar que todos los estudios analizan los impactos relacionados con el medio ambiente. Sin embargo, otros impactos como los relacionados con la salud pública, el uso de los materiales y la calidad de vida han sido analizados en menor medida. En el caso de los impactos relacionados con la educación, estos no han sido incluidos en ninguno de los estudios.

Tabla 1. Artículos que presentan metodologías para el análisis de los sistemas de RSU con consideración de externalidades. Fuente: Elaboración propia.

| **Referencia** | **Método** | **Uso de materiales** | **Medio ambiente** | **Salud Pública** | **Educación** | **Calidad de vida** | **Desarrollo económico** |
|---|---|---|---|---|---|---|---|
| Mavrotas et al. (2015) | Modelo de optimización multiobjetivo | X | X | | | X | |
| Rabl et al. (2008) | ExternE (LCA y *impact pathway analysis*) | | X | X | | X | |
| Martinez-Sanchez et al. (2015) | Coste del Ciclo de Vida | | X | | | | |
| Yedla (2003) | Modelos funcionales multivariados | X | X | X | | | X |
| Massarutto et al. (2011) | Modelo de escritorio | | X | | | X | |
| Weng and Fujiwara (2011) | Análisis coste-beneficio integrado | X | X | X | | X | X |

De acuerdo con lo anterior, se identificó la necesidad de desarrollar una metodología que permitiera el análisis económico de los sistemas gestión de RSU. Donde se incluyera los impactos internos y externos relacionados con los sistemas de gestión de RSU y mediante la cual se pudiera visualizar por separado, si el sistema de gestión de RSU es viable o rentable desde el punto de vista privado. Y también, si el sistema de gestión de los RSU es financiera, económica, social y ambientalmente viable o rentable.

### 1.6 Descripción de la zona de estudio de las instalaciones de tratamiento de RSU

La zona de estudio corresponde al Área Metropolitana de Barcelona (AMB) compuesta por 36 municipios, entre los que se incluye Barcelona, Badalona, Sant Adrià de Besòs, entre otros. La AMB cuenta con aproximadamente 3,239,337 habitantes (AMB, 2021). En 2018, se generaron 1,556,908 toneladas de residuos, que corresponden a 1.26 kg/día por habitante. Como se puede observar en la Figura 12, donde se muestra como la generación total ha aumentado considerablemente en los últimos años, sin embargo, la generación de residuos por habitante se mantiene relativamente estable.

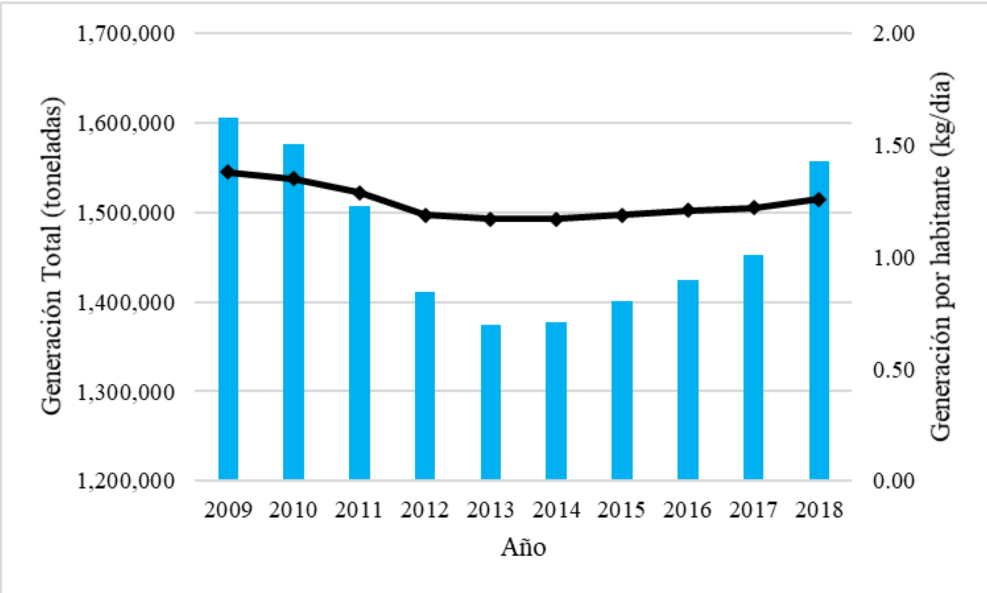


Figura 12. Generación de total y por habitantes de RSU en Barcelona. Fuente: Elaboración propia a partir de AMB (2021). La línea negra representa la generación per cápita (kg/hab. y día) y las barras azules representa la generación total (toneladas).

En el AMB se llevan a cabo diferentes procesos para la gestión de los RSU. Los RSU se recogen mediante recogida selectiva a través de 5 tipos de contenedores: 1) contenedor amarillo para la recogida de residuos de envases ligeros; 2) contenedor azul para residuos de papel y cartón; 3) contenedor verde para residuos de vidrio; 4) contenedor marrón para residuos orgánicos; y 5) contenedor gris para la fracción resto (residuos que no han sido recogidos selectivamente). Por otro lado, existen recogidas especiales para algunos tipos de residuos como los voluminosos, los residuos de aparatos eléctricos y electrónicos (RAEE), entre otros. Cada tipo de fracción es sometida a diferentes tipos de tratamientos como se muestra en la Tabla 2.

Tabla 2. Sistemas de tratamiento por tipo de fracción utilizados en España. Fuente: Elaboración propia a partir de MITECO (2021).

| Fracción | Contenedor | Tratamiento | Resultado |
|---|---|---|---|
| **Orgánica** | Marrón | Instalación de compostaje | Compost |
| | | Instalación de biometanización | Digestato |
| **Resto** | Gris | Instalación de selección y clasificación | Materiales valorizables |
| | | Instalación de tratamiento mecánico-biológico | Materiales valorizables - Compost/Digestato-biogás |
| | | Incineradora (valorización energética o eliminación) | Energía |
| | | Depósito controlado con recuperación energética | Energía |
| | | Depósito controlado sin recuperación energética | |
| **Envases Ligeros** | Amarillo | Instalación de clasificación y tratamiento de envases | Materiales valorizables |
| **Vidrio** | Verde | Instalación de clasificación y tratamiento de vidrio | Materiales valorizables |
| **Papel y Cartón** | Azul | Instalación de clasificación y tratamiento de papel y cartón | Materiales valorizables |
| **Voluminosos** | Recogida especial o puntos verdes | Instalación de clasificación y tratamiento de voluminosos | Materiales valorizables |
| **RAEE** | Recogida especial o puntos verdes | Instalación de tratamiento de RAEE | Materiales valorizables |

En el caso específico del AMB, existen 10 instalaciones para el tratamiento de los RSU, como se puede ver en la Tabla 3, distribuidas en diferentes municipios de la AMB. Para la realización de los casos de estudio se eligieron dos instalaciones de tratamiento de RSU ubicadas en el AMB. El objetivo de la realización de los casos de estudio son demostrar la aplicabilidad de la metodología desarrollada, considerando los diferentes impactos identificados y descritos para el análisis económico de estas instalaciones, ya que la lista de los diferentes impactos funciona como una guía para los gestores de los sistemas de RSU. Las instalaciones elegidas fueron la planta de tratamiento compuesta por la instalación de clasificación y tratamiento de envases y la instalación de clasificación y tratamiento de voluminosos ubicada en Gavà, así como, la incineradora (planta de valorización energética) ubicada en Sant Adrià de Besòs.

En estos casos de estudio solo se consideraron los impactos generados por las plantas de tratamiento, sin considerar los impactos generados durante la recolección y transporte de los residuos a las instalaciones. Las instalaciones analizadas realizan la valorización material de los residuos y, por otra parte, la valorización energética.

Para la obtención de los datos se utilizó información pública disponible en la página web de las empresas analizadas (declaraciones ambientales, estudios técnicos, cuentas anuales, entre otros). Además, de la base de datos SABI que contiene información financiera y económica sobre empresas españolas y portuguesas. También, se trabajó con información y resultados presentados en diferentes artículos científicos sobre estudios de diversas instalaciones de gestión de RSU.

Tabla 3. Instalaciones de tratamiento de RSU, número de instalaciones y ubicaciones en el Área Metropolitana de Barcelona. Fuente: Elaboración propia a partir de AMB (2020).

| Tratamiento | Nº de instalaciones | Ubicación |
|---|---|---|
| Instalación de clasificación y tratamiento de envases | 3 | Gavà * |
| | | Montcada i Reixac |
| | | Molins de Rei |
| Instalación de compostaje | 2 | Sant Cugat del Vallès |
| | | Torrelles de Llobregat |
| Instalación de tratamiento mecánico-biológico | 3 | Sant Adrià de Besòs |
| | | Barcelona |
| | | Montcada i Reixac |
| Incineradora (valorización energética) | 1 | Sant Adrià de Besòs * |
| Instalación de clasificación y tratamiento de voluminosos | 1 | Gavà * |

* Instalaciones analizadas en los casos de estudio.

### 1.6.1 Planta de Valorización Energética de Residuos Sólidos Urbanos en Sant Adrià de Besòs, Barcelona, España

La Planta de Valorización Energética (PVE) analizada en esta tesis doctoral está ubicada en Sant Adrià de Besòs (Barcelona, España), y forma parte de la Planta Integral de Valorización de Residuos (PIVR) de Sant Adrià de Besòs, conformada por la Planta de Valorización Energética (PVE) y la Planta de Tratamiento Mecánico-Biológico (PTMB).

Esta instalación se encarga del tratamiento térmico de los residuos municipales provenientes de Barcelona y de su zona metropolitana. En específico, de la recogida no selectiva de los residuos realizada por medio de los contenedores grises, así como de los residuos rechazo (es decir, aquellos residuos que ya no pueden ser valorizados materialmente) de otras instalaciones de tratamiento como las plantas de tratamiento mecánico-biológico o las plantas de clasificación y separación de residuos de envases ligeros (Figura 13).

Esta instalación tiene una capacidad de tratamiento de aproximadamente 360,000 toneladas de residuos al año, obteniendo energía para su autoconsumo y para la venta a la red eléctrica; y vapor, para el suministro de calor y frio a la red urbana (en específico, de la zona Fórum y 22@). En 2017, se generó 198,471 MWh de energía eléctrica y 95,509 toneladas de vapor (17,122 MWhe).

Los beneficios de la incineración son la recuperación de energía, debido a la generación de calor y electricidad, reduciendo la dependencia del uso de combustibles fósiles para la producción de electricidad, así como, la dependencia energética exterior. Por consiguiente, la reducción de las emisiones de $CO_2$.

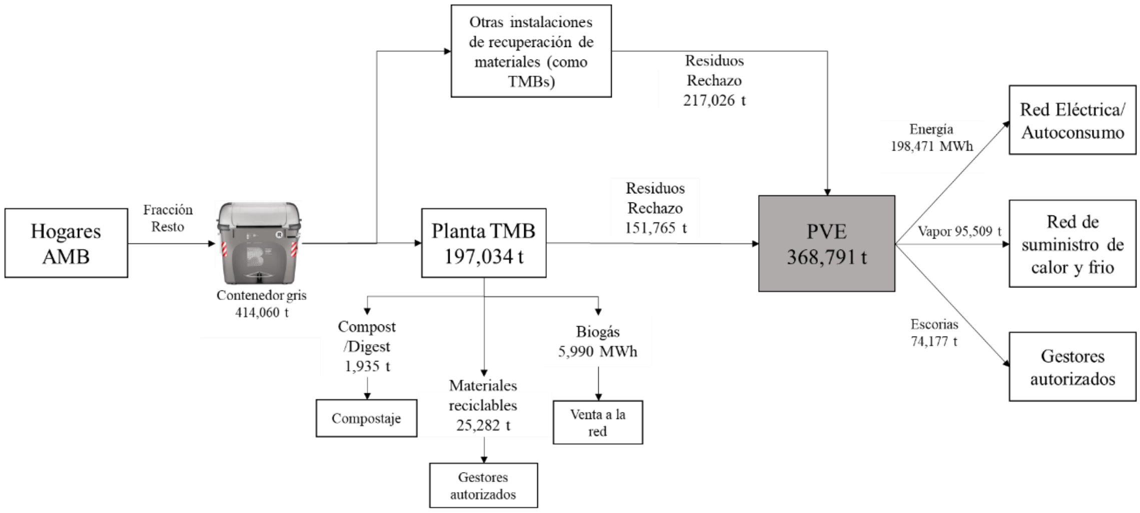


Figura 13. Flujo de los procesos de gestión de los residuos rechazo en la AMB en 2017. Fuente: Elaboración propia. TMB: Tratamiento Mecánico-Biológico; PVE: Planta de Valorización Energética

Sin embargo, las incineradoras se han asociado a emisiones de sustancias químicas tóxicas al suelo, aire y agua, principalmente de dioxinas (PCDD/Fs) y metales pesados, que pueden significar riesgos cancerígenos y no cancerígenos para la población que vive a los alrededores de las instalaciones (Domingo et al., 2017), así como daños al medio ambiente. En específico, en el caso de la PVE, las asociaciones vecinales de la zona del Fórum, pertenecientes a los municipios de Sant Adrià de Besòs, Barcelona y Badalona crearon la coordinadora *Aire Net* para denunciar elevadas emisiones contaminantes y malos olores procedentes presuntamente de la incineradora de Sant Adrià de Besòs (Agència de Salut Pública de Barcelona, 2018).

### 1.6.2 Planta de clasificación y tratamiento de residuos de envases ligeros y voluminosos en Gavà-Viladecans, Barcelona, España

La Planta de tratamiento de residuos de envases ligeros y voluminosos (PCT) analizada en esta tesis doctoral está ubicada en Gavà-Viladecans (Barcelona, España). Esta instalación se encarga de la clasificación y separación de los residuos municipales provenientes de Barcelona y de su zona metropolitana. En específico, de la recogida selectiva de los residuos realizada por medio de los contenedores amarillos, así como de las recogidas especiales de los residuos voluminosos y de los residuos provenientes de los puntos limpios (Figura 14).

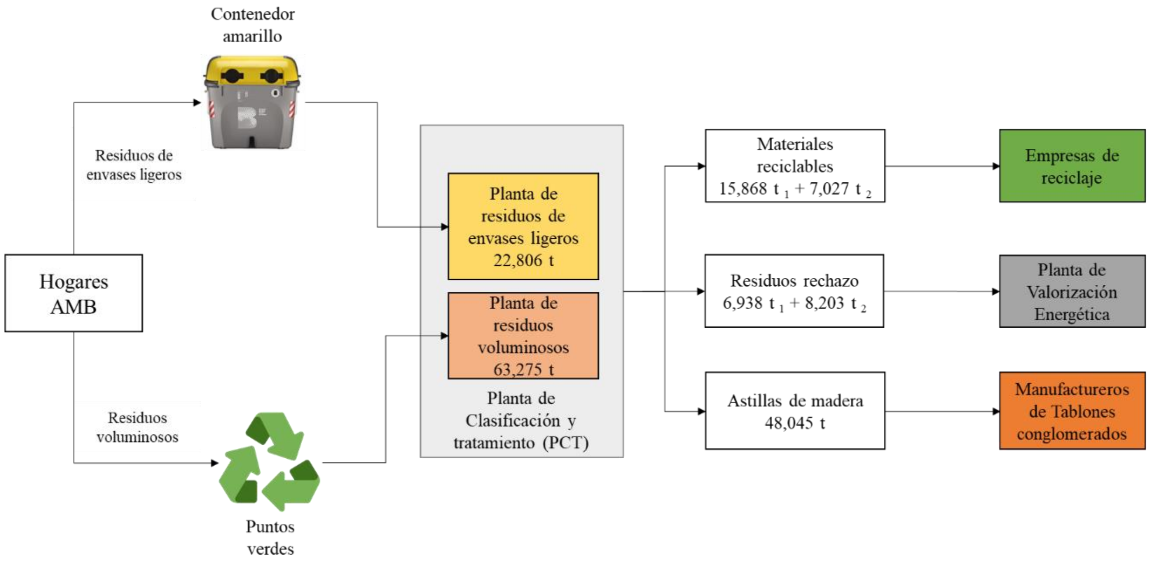


Figura 14. Flujo de los procesos de gestión de los residuos rechazo de la Planta de clasificación y tratamiento de residuos de envases ligeros y residuos voluminosos. Fuente: Elaboración propia. AMB: Área Metropolitana de Barcelona; [1] producto generado por la planta de residuos de envases ligeros; [2] producto generado por la planta de residuos voluminosos.

Esta instalación tiene una capacidad de tratamiento aproximada de 24,000 toneladas de residuos de envases ligeros y 63,000 toneladas de residuos voluminosos. Obteniendo materiales valorizables que son vendidos a gestores autorizados, así como madera con la cual se genera astillas para la producción de tablones conglomerados.

Este tipo de instalación de gestión de RSU es de gran importancia debido a que muchos países carecen de recursos naturales primarios, por lo tanto, el reciclaje de los productos permite reducir la dependencia en materiales importados, realizar un ahorro de energía considerable debido a que se reduce la extracción e importación de materias primas (madera, plástico, metal) y por consiguiente, se contribuye a la conservación del medio ambiente (Risch, 1978). Además, se evita la emisión de $CO_2$ que se hubiera generado durante la producción de materias primas vírgenes.

En específico, los impactos evitados por la correcta gestión de los envases de plástico son: degradación de los sistemas naturales como resultado de fugas, especialmente en el océano. La ONU señala que para el 2050 puede haber más plástico que peces en el mar. Además, de emisiones de gases de efecto invernadero resultantes de la producción de los envases; e impactos en la salud y el medio ambiente de sustancias preocupantes (Ellen MacArthur Foundation, 2016).

# Capítulo 2: Justificación, Objetivos y Metodología

## 2.1 Justificación

En el capítulo anterior se planteó el problema existente relacionado con los RSU, así como el estado del arte de los estudios económicos en el campo de los residuos municipales. A partir de la información presentada nos planteamos un conjunto de problemas abiertos que nos sitúan ante la justificación del trabajo de investigación que se ha realizado en la presente tesis doctoral.

- Los aspectos económicos son de gran importancia debido a que generalmente las decisiones relacionadas con los sistemas de RSU se toman a partir de los resultados obtenidos en los análisis económicos, pero cobran mayor relevancia cuando los resultados demuestran que los proyectos realizados o a realizar fomentan el desarrollo sostenible y armonizan sus tres pilares: medio ambiente (garantía de la integridad continua de los recursos naturales), sociedad (garantía de la salud y el bienestar humanos continuos) y economía (garantía de una prosperidad económica continua) (Fiksel et al., 2012). Mediante la inclusión de los impactos privados y externos es posible tomar una decisión que considere los aspectos económicos, ambientales y sociales, y, por consiguiente, demostrar que fomenta la sostenibilidad.
- El análisis del estado del arte ha permitido identificar la necesidad de una metodología que permita el análisis económico de los sistemas de gestión de RSU, debido a que los autores generalmente solo consideran los impactos privados relacionados con estos sistemas, o cuando incluyen las externalidades se enfocan en aspectos específicos o solo incluyen unos cuantos impactos externos.
- Autoridades como el Parlamento Europeo señalan la importancia de tener en cuenta los principios generales de protección del medio ambiente y sostenibilidad, viabilidad técnica y económica, protección de los recursos, así como los impactos económicos, sociales, al medio ambiental y a la salud humana que pudieran ocasionar los sistemas de gestión de RSU. El desarrollo de una metodología permitiría evaluar los sistemas asegurando que se cumplen con los principios establecidos por las Directivas Europeas.

## 2.2 Objetivo General

El objetivo general de la presente tesis doctoral es desarrollar una metodología que permita realizar el análisis técnico-económico de los sistemas de gestión de residuos sólidos urbanos. Dicha herramienta permitirá a los tomadores de decisiones y legisladores, analizar y comparar diferentes sistemas de gestión teniendo en cuenta los impactos privados y externos generados por los sistemas de gestión de RSU.

### 2.2.1 Objetivos específicos

Los objetivos específicos de la tesis doctoral son:

1) Analizar y documentar el estado actual de los estudios realizados en el área del análisis económico de los sistemas de gestión de residuos sólidos urbanos y en específico, de los artículos que han desarrollado metodologías para la evaluación económica. Además, se determinará los estudios realizados sobre el análisis económico de las externalidades generadas por los sistemas de gestión de RSU, así como los principales métodos o herramientas para el análisis económico de los sistemas de gestión.

2) Desarrollar una metodología basada en el Análisis Coste-Beneficio sostenible, que permita analizar cualquier tipo de sistemas de recolección y tratamiento de residuos municipales, tanto en países en vías de desarrollo como en países desarrollados. Se determinarán los principales impactos (privados y externos) relacionados con los sistemas de gestión de residuos soportado en las más recientes investigaciones, así como los posibles métodos de valoración económica para cada tipo de impacto.

3) Validar la aplicabilidad de la metodología desarrollada mediante la realización de diversos casos de estudio. Demostrando que la metodología y los impactos descritos en ella, podrían constituir una guía de consulta para futuros investigadores y tomadores de decisiones que deseen analizar económicamente cualquier sistema de gestión de RSU.

## 2.3 Metodología

La metodología para el desarrollo de la presente tesis doctoral ha seguido el siguiente procedimiento compuesto por fases teóricas y prácticas, además de una combinación de técnicas cuantitativas y cualitativas:

***Fase 1: Exploratoria***

1) Caracterización de la gestión de residuos sólidos urbanos y los métodos de recogida y tratamiento mediante la revisión del estado del arte. Así como, la identificación y análisis de los principales agentes implicados en la gestión de residuos municipales y sus competencias.

2) Revisión bibliográfica para determinar las características fundamentales de los métodos o herramientas de análisis económico. Por otro lado, se realizará la revisión bibliográfica de las investigaciones existentes sobre metodologías para el análisis económico de los sistemas de gestión de RSU, y en específico, de la evaluación económica de las externalidades.

3) Análisis bibliométrico para determinar las publicaciones más relevantes en el área de investigación, además de evaluar el desempeño de autores, instituciones o países; descubrir

las redes de colaboración entre revistas, autores y palabras clave en este campo; identificar las principales áreas de interés y revelar futuras tendencias de investigación.

***Fase 2: Desarrollo de metodología de análisis técnico- económico***

1) Determinación de los elementos más relevantes a considerar en el análisis técnico-económico, que permita el establecimiento de los pasos a seguir para realizar el análisis de los proyectos o sistemas de gestión de RSU.
2) Determinación a modo de inventario de los principales impactos implicados en la gestión de residuos, así como la descripción de las principales características de los impactos y elementos a considerar.
3) Revisión de la literatura para determinar los posibles métodos de valoración económica para cada tipo de impacto a considerar.
4) Establecimiento de los procedimientos de agregación de costes e ingresos.

***Fase 3: Desarrollo de casos de estudio***

1) Análisis de casos de estudio para verificar la validez de la metodología mediante la evaluación de distintos escenarios de gestión de residuos municipales: el caso de una planta de valorización energética en Barcelona (España), y el caso de una planta de clasificación y tratamiento de residuos de envases ligeros y residuos voluminosos en Barcelona (España).
    a) Definición de los objetivos y el ámbito de estudio del sistema a analizar.
    b) Identificación de los agentes implicados.
    c) Recolección/recopilación de datos mediante entrevistas, cuestionarios, observación directa, revisión de literatura, datos financieros públicos y estudios técnicos y ambientales.
    d) Determinación de los impactos privados y externos a considerar para cada caso de estudio.
    e) Valoración de los impactos externos identificados para cada caso de estudio, a partir de los métodos de valoración señalados.
    f) Agregación de los costes e ingresos obtenidos.
    g) Análisis de los resultados para determinar la rentabilidad de las instalaciones.

# Capítulo 3: Resultados

La presente sección muestra los resultados más relevantes de la presente tesis doctoral, que demuestran que los objetivos establecidos se han cumplido.

## 3.1 Metodología para el análisis técnico-económico de los sistemas de los RSU mediante el análisis coste-beneficio sostenible

La metodología presentada en la presente tesis doctoral fue adaptada del trabajo desarrollado por Seguí et al. (2009), donde se desarrolló una metodología para el análisis técnico-económico de los sistemas de regeneración y reutilización de aguas residuales.

La metodología tiene una visión multidisciplinaria e interdisciplinaria, debido a que considera diversos campos de estudio como: los aspectos técnicos, económicos, ambientales, sociales, de la salud, entre otros. Esta metodología representa una herramienta útil para reducir la incertidumbre y tomar decisiones más acertadas. La metodología está conformada por siete etapas, las cuales son: i) Definición del objetivo, ii) Definición del ámbito de estudio, iii) determinación de los impactos del proyecto, iv) identificación de los agentes implicados, v) estudio de las necesidades y posibilidades financieras vi) agregación de coste e ingresos, y vii) análisis de sensibilidad. Para mayor detalle sobre las diferentes etapas se recomienda consultar el artículo titulado "A methodology for the technical-economic analysis of municipal solid waste systems based on social cost-benefit analysis with a valuation of externalities" (Medina-Mijangos et al., 2021).

El objetivo del análisis técnico-económico es evaluar los sistemas de gestión de RSU, mediante la obtención de Beneficio Total (la diferencia entre ingresos y costes) de un grupo específico de interesados y para un determinado sistema de gestión de RSU, considerando los impactos privados y externos.

La función objetivo a optimizar se presenta en la Ec. (1). Es recomendable que los valores obtenidos estén expresados en unidades monetarias por tonelada de residuos tratados (um/t) o unidades monetarias por año (um/año).

$$B_T = B_P + B_E - OC \tag{1}$$

$B_T$ = Beneficio Total

$B_P$ = Beneficio Privado

$B_E$ = Beneficio Externo

OC = Coste de oportunidad

Para obtener el Beneficio Privado ($B_P$) se utilizará la Ec. (2). En este caso, los ingresos se obtienen multiplicando AVW por SP, en cambio los costes corresponden a la suma de IC, OMC, FC y T.  Es importante señalar que en el caso de los residuos sólidos existe un precio de mercado establecido por los principales actores involucrados (gestores autorizados, organizaciones privadas o autoridades gubernamentales) para la venta de los materiales recuperados, la energía generada, así como, para las tarifas de entrada de los residuos a las instalaciones de tratamiento.

$$B_P = \sum_{n=0}^{N}[(AVW_n * SP) - (IC_n + OMC_n + FC_n + T_n)] \quad (2)$$

Donde:

AVW = Volumen anual de residuos tratados

SP = Precio de venta por unidad

IC = Costes de Inversión

OMC = Costes operativos y de mantenimiento

FC = Costes Financieros

T = Impuestos

N = Duración total del proyecto

n = Índice de año del proyecto (n = 0, …, N)

Para obtener el Beneficio Externo ($B_E$), se utilizará la Ec. 3, 3.1 y 3.2, que corresponde a la diferencia entre PE y NE. En el caso de PE, se obtiene sumando los ingresos generados por las externalidades positivas. En cambio, NE se obtiene sumando los costes generados por las externalidades negativas.

$$B_E = \sum_{\boldsymbol{n=0}}^{\boldsymbol{N}}(PE_n - NE_n) \quad (3)$$

$$PE = \sum_{\boldsymbol{j=1}}^{\boldsymbol{J}}(pe_j);\ \ For\ j = 1, \dots, J\ impactos \quad (3.1)$$

$$NE = \sum_{\boldsymbol{j=1}}^{\boldsymbol{J}}(ne_j);\ \ For\ j = 1, \dots, J\ impactos \quad (3.2)$$

Donde:

NE = Externalidades Negativas

PE = Externalidades Positivas

OC = Coste de oportunidad

J = Impactos Totales

j = Índice de Impacto (j = 1, …, J)

N = Duración total del proyecto

n = Índice de año del proyecto (n = 0, …, N)

Por último, el coste de oportunidad (OC) se define como el valor de la acción alternativa renunciada. Este concepto solo puede surgir en un mundo donde los recursos disponibles para satisfacer los deseos son limitados. Si los recursos fueran ilimitados, ninguna acción sería a expensas de ninguna otra y todas podrían emprenderse, y por consiguiente, el coste de oportunidad sería cero (Pearce, 1992). El concepto de coste de oportunidad aplicado a los sistemas de RSU, se puede explicar a partir de dos condiciones principales. En primer lugar, cuando existen varias alternativas para el uso de los residuos, el coste de oportunidad vendrá dado por el uso que proporcione el mejor desempeño económico, siempre que estos rendimientos sean superiores a los de un instrumento financiero. En segundo lugar, cuando no existen usos alternativos, el coste de oportunidad proviene del desempeño que brinda algún instrumento financiero, cuando se invierten los costes de inversión en este (Medina-Mijangos et al., 2021).

Tradicionalmente, el coste de oportunidad solo tiene en cuenta la maximización de los beneficios económicos. Sin embargo, bajo el concepto de desarrollo sustentable y sus tres pilares, la mejor alternativa será aquella que no solo brinde el mejor desempeño económico, sino también el mejor desempeño social y ambiental (Medina-Mijangos et al., 2021).

Una vez que se han obtenido todos los costes e ingresos, tanto internos como externos, se deben de agregar utilizando la Ec. 2 y 4. La Ec. 4 se obtiene a partir de la sustitución de la Ec. 2 y 3 en la Ec. 1.

$$\boldsymbol{B}_P = \sum_{\boldsymbol{n=0}}^{\boldsymbol{N}} [(AVW_n * SP) - (IC_n + OMC_n + FC_n + T_n)] \quad (2)$$

$$\boldsymbol{B_T} = \sum_{\boldsymbol{n=0}}^{\boldsymbol{N}} [(AVW_n * SP) - (IC_n + OMC_n + FC_n + T_n) + (PE_n - NE_n) - OC_n] \quad (4)$$

Una vez agregados los costes e ingresos se pueden llegar a diferentes conclusiones dependiendo de los resultados obtenidos. Por un lado, si $B_P$ es mayor a 0, se puede señalar que el proyecto o instalación para la gestión de RSU es rentable o viable desde el punto de vista privado, es decir, el sistema de gestión de residuos obtiene ingresos internos suficientes para cubrir los gastos incurridos en la inversión, operación y mantenimiento de la instalación.

Por otro lado, si $B_T$ es mayor a 0, se puede señalar que el proyecto es viable o rentable desde el punto de vista privado y externo, esto significa que los ingresos totales son mayores que los costes totales, por lo tanto, esta instalación es rentable desde el punto de vista financiero, económico, ambiental y social. Además, con la inclusión del término del coste de oportunidad se asegura que el sistema evaluado es la mejor opción posible bajo los principios de la sostenibilidad.

Otra evaluación que se debe de efectuar es el análisis de sensibilidad, donde se evalúa la robustez que tiene el sistema o proyecto evaluado, debido a que se observa cómo se modifica el resultado al cambiar algunas variables críticas. El análisis de sensibilidad tiene como objetivo evaluar cómo varia el resultado al modificar de modo marginal y por separado el valor de cada uno de los parámetros que intervienen en el cálculo (Seguí-Amórtegui et al., 2014). Si después de realizar este análisis, el resultado de $B_T$ es mayor a 0, se puede concluir que el sistema es económicamente confiable, debido a que a pesar de posibles escenarios pesimistas el proyecto continúa siendo rentable.

La metodología desarrollada puede ser utilizada para la evaluación a priori. De esta forma, determinar si un proyecto que va a ser implementado es viable, así como, evaluar diferentes proyectos alternativos y elegir la mejor opción desde el punto de vista financiero, económico, ambiental y social. Por otro lado, permite analizar la rentabilidad privada y externa de una instalación que ya está en funcionamiento, es decir, un análisis a posteriori de su implementación.

## 3.2 Impactos relacionados con los sistemas de gestión de residuos sólidos urbanos

Una de las contribuciones más significativas de la presente metodología es la recopilación, inventario y discusión de los impactos más relevantes relacionados con los sistemas de gestión de RSU. Estos impactos se han dividido en diferentes grupos, los cuales están relacionados con la infraestructura, reutilización, reciclaje y valorización de residuos, uso de materiales, medio ambiente, salud pública, educación y calidad de vida, como puede verse en la Tabla 4. Estos impactos pueden clasificarse en privados o externos, así como negativos o positivos. La lista de impactos representa una guía para futuros investigadores y tomadores de decisiones interesados en la valoración económica de los sistemas de gestión de RSU, ya que permite a los investigadores considerar los mismos tipos de impactos descritos, pero adaptados a contextos específicos para reducir la incertidumbre de los tomadores de decisiones.

En la Tabla 4 se muestra la frecuencia del impacto, que señala en qué momento ocurre cada impacto. Un proyecto puede presentar impactos al comienzo del proyecto, durante o después de la vida útil del proyecto. En el caso de la cuantificación de los impactos, se deben de definir las unidades físicas que permitirán traducir estos impactos a valores monetarios. Es importante señalar que algunos impactos pueden ser cuantificados directamente en unidades monetarias (por ejemplo, a partir de los costes de inversión y operación). Sin embargo, en el caso de los impactos externos es necesario definir las unidades físicas de cuantificación de los impactos ambientales y sociales. Por último, se presenta los métodos de valoración económica de los impactos, donde el valor monetario de algunos de los impactos puede ser calculados, a partir de los costes de inversión y operación o a través de métodos específicos desarrollados en la economía ambiental (Dahlbo et al. 2007).

Tabla 4. Resumen de los impactos considerados para el análisis económico de los sistemas de gestión de RSU. Fuente: Elaboración propia a partir de Medina-Mijangos et al. (2021).

| **Grupo de impacto** | **Descripción de los impactos** | **Frecuencia** | **Cuantificación** | **Valoración monetaria (um/t)** | | **Tipo de impacto** |
|---|---|---|---|---|---|---|
| | | | | **Costes** | **Ingresos** | |
| Infraestructura | Recolección de los residuos | Al inicio y durante toda la vida útil del proyecto | Toneladas de residuos tratados | Costes de inversión y operación | | Negativo/Privado |
| | Transporte de los residuos | | | | | Negativo/Privado |
| | Tratamiento de los residuos | | | | | Negativo/Privado |
| | Disposición final de los residuos | | | | | Negativo/Privado |
| Reutilización, reciclaje y valorización de residuos | Venta de materiales y energía | Durante toda la vida útil del proyecto | Toneladas de residuos tratados | | MP | Positivo/ Privado |
| | Tarifas del servicio de gestión | | | | | Positivo/ Privado |
| Uso de materiales | Materiales (residuos) los cuales se ha evitado se envíen a vertederos o incineradoras | Durante toda la vida útil del proyecto | Toneladas de residuos tratados | | EAD (CC, CUC), OC | Positivo/ Externo |
| | Garantía de suministro de material o energía | | % de confiabilidad | | PS, CV, CE (WTP por materiales reciclados o energía), BTR | Positivo/ Externo |
| | Calidad de los materiales | | % de pureza | | | Positivo/ Externo |
| Medio ambiente | Emisiones al aire | Durante toda la vida útil del proyecto | Kg de contaminantes | DR, BTR, AB, CC, EAD | | Negativo/ Externo |
| | Emisiones al agua | | Partículas suspendidas | | | Negativo/ Externo |
| | Emisiones al suelo | | Hectáreas afectadas | | | Negativo/ Externo |
| Salud Pública | Riesgos Físicos | Durante toda la vida útil del proyecto | Personas expuestas | DR, COI, CV (WTP para evitar enfermedades), YOLL, VSL | | Negativo/ Externo |
| | Riesgos Químicos | | | | | Negativo/ Externo |
| | Riesgos Biológicos | | | | | Negativo/ Externo |
| Educación | Cultura 3R de residuos de la población | Durante toda la vida útil del proyecto | Personas | Costes por programas de entrenamiento | DR | Positivo/ Interno-Externo |
| | Técnica de los trabajadores (reducción de accidentes laborales, aumento de productividad). | | % de productividad | | PC | Positivo/ Interno-Externo |
| Calidad de vida | Molestias: olor, polvo, basura arrastrada por el viento, intrusión visual, ruido, trafico | Durante toda la vida útil del proyecto | Km del sitio/ valor de mercado de los bienes | CE, CV, HP, BTR | | Negativo/ Externo |

AB: Método de evitación del comportamiento; BTR: Transferencia de beneficios; CA: Método de evaluación de quejas; CC: Método de control de costes (/coste de abatimiento); CE: Experimento de elección; COI: Método del coste de enfermedad; CUC: Método del coste de limpieza; CV: Método de valoración contingente; DR: Función de respuesta a la dosis; EAD: Evaluación de expertos de los costes de los daños; HP: Método del precio hedónico; HPF: Función de producción de salud; MP: Precio de Mercado; OC: Coste de Oportunidad; PS: Precio Sustituto; PC: Cambio de productividad; RC: Método de coste de reemplazo; RP: Preferencias Reveladas; SPR: Preferencias Declaradas; TC: Método del coste de viaje; YOLL: Años de vida perdidos; VSL: Valor de una vida estadística; WTA: Disposición a aceptar; WTP: Disposición a pagar.

## 3.3 Comparación de los resultados de los casos de estudio

A continuación, se presentan y comparan los resultados obtenidos en los casos de estudio realizados tanto en la planta de valorización energética (PVE) como en la planta de clasificación y tratamiento de residuos de envases ligeros y voluminosos (PCT). En la Tabla 5 se detallan los impactos considerados para el análisis económico de los sistemas de gestión de RSU, donde se indica el tipo de impacto (privado o externo), así como los valores monetarios de cada impacto analizado.

Una vez obtenidos los resultados, se prosiguió a agregar todos los costes e ingresos mediante la utilización de las Ec. 2 y 4.

$$\boldsymbol{B}_P = \sum_{\boldsymbol{n=0}}^{\boldsymbol{N}}[(AVW_n * SP) - (IC_n + OMC_n + FC_n + T_n)] \quad (2)$$

$$\boldsymbol{B_T} = \sum_{\boldsymbol{n=0}}^{\boldsymbol{N}}[(AVW_n * SP) - (IC_n + OMC_n + FC_n + T_n) + (PE_n - NE_n) - OC_n] \quad (4)$$

De esta manera, para el caso de la PVE, se obtienen los valores presentados en la Ec. 5 y 6. Los resultados obtenidos del análisis muestran que esta instalación tiene un $B_P$ de 9.90 €/t y un $B_T$ de 24.93 €/t.

$$B_P = \sum_{n=1}^{1}[(147.44) - (140.81 - 5.13 + 0 + 1.86)] = 9.90\ €/t \quad (5)$$

$$B_T = \sum_{n=1}^{1}[(147.44) - (140.81 - 5.13 + 0 + 1.86) + (25.88 - 5.78) - 5.07] = 24.93\ €/t \quad (6)$$

Por otro lado, para el caso de la PCT, se obtienen los valores presentados en la Ec. 7 y 8, donde se muestra que esta instalación tiene un $B_P$ de 7.06 €/t y un $B_T$ de 55.72 €/t.

$$B_P = \sum_{n=1}^{1}[(103.26) - (0 + 96.18 + 0 + 0.015)] = 7.06\ €/t \quad (7)$$

$$B_T = \sum_{n=1}^{1}[(103.26) - (0 + 96.18 + 0 + 0.015) + (49.69 - 0.21) - 0.82] = 55.72\ €/t \quad (8)$$

Tabla 5. Resumen de los impactos considerados en el análisis económico de la Planta de Valorización Energética de Sant Adrià de Besòs y la Planta de clasificación y tratamiento de envases ligeros y voluminosos de Gavà. Fuente: Elaboración propia a partir de Medina-Mijangos et al. (2021).

| **Tipo de impacto** | **Grupo de impacto** | **Descripción** | **Valoración de los impactos (€/t)** | | | |
|---|---|---|---|---|---|---|
| | | | **Planta Valorización energética** | | **Planta de clasificación y tratamiento de envases ligeros y voluminosos** | |
| | | | **Costes** | **Ingresos** | **Costes** | **Ingresos** |
| Privado | Infraestructura | Costes laborales | 14.09 | | 19.70 | |
| | | Costes de mantenimiento y reparación | 13.29 | | 13.54 | |
| | | Costes de aprovisionamiento | 92.24 | | 19.68 | |
| | | Depreciación de activos fijos | 4.92 | | 19.02 | |
| | | Otros costes | 16.27 | | 24.24 | |
| Privado | Reutilización, reciclaje y valorización de los residuos | Venta de materiales o energía | | 26.86 | | 9.74 |
| | | Tarifa por la provisión de servicios | | 97.71 | | 91.62 |
| | | Otros ingresos | | 22.83 | | 1.90 |
| Externo | Uso de los materiales | Materiales no enviados a vertederos | | 23.50 | | 38.82 |
| | | Calidad de los materiales (ecológicos) | | 6.65 | | 0.86 |
| Externo | Medio ambiente | Emisión al aire generadas | 5.78 | | | |
| | | Emisión al aire evitadas | | 2.28 | | 8.09 |
| | | Emisión al agua evitadas | | | | 1.20 |
| Externo | Salud Pública | Accidentes con daños físicos | 0.04 | | 0.21 | |
| | | Incendios | | | 0 | |
| | | Generación de cáncer | 0 | | | |
| Externo | Educación | Cultura 3R de los ciudadanos | | No cuantificado | | 0.52 |
| | | Técnica de los trabajadores | | 0.57 | | 0.21 |
| Externo | Calidad de vida | Molestias generadas | 8.00 | | 0 | |
| **Impactos internos totales** | | | 140.81 | 147.40 | 96.18 | 103.26 |
| **Impactos externos totales** | | | 13.82 | 33.00 | 0.21 | 49.69 |
| **Impactos Totales** | | | 154.63 | 180.40 | 96.39 | 152.95 |

Como se puede visualizar en la Figura 15, la PVE presenta altos costes internos, sin embargo, tiene ingresos internos más altos, lo que la hace rentable desde el punto de vista privado. Si analizamos los costes e ingresos externos podemos visualizar que esta instalación tiene más ingresos que costes, permitiendo que el Beneficio Total de la instalación aumente y, por lo tanto, la confiabilidad del sistema aumenta, haciéndola menos susceptible a los factores críticos.

Se puede observar que este sistema presenta diversas externalidades negativas relacionadas con el medio ambiente por la emisión de $CO_2$, daños a la salud debido a los riesgos físicos y la calidad de vida debido a las molestias generadas (olor, intrusión visual, ruido, etc.).

Es importante señalar que en el caso de las emisiones de dioxinas (PCDD/Fs) de la PVE existen estudios contradictorios. En el análisis realizado se consideró el estudio de la Agència de Salut Pública de Barcelona (2018), donde se señala que no hay una asociación significativa entre la mortalidad y la proximidad a la PVE, por lo que se considera que los costes relacionados con los daños a la salud debido a las dioxinas es igual a 0. Sin embargo, el estudio de Domingo et al. (2017), señala que los residentes de la zona cercana a la PVE tienen entre 3 y 4 veces más probabilidades de desarrollar cáncer a lo largo de su vida, debido a la exposición a dioxinas de los residentes de ciudades como Girona, Mataró y Tarragona, donde también hay incineradoras en funcionamiento.

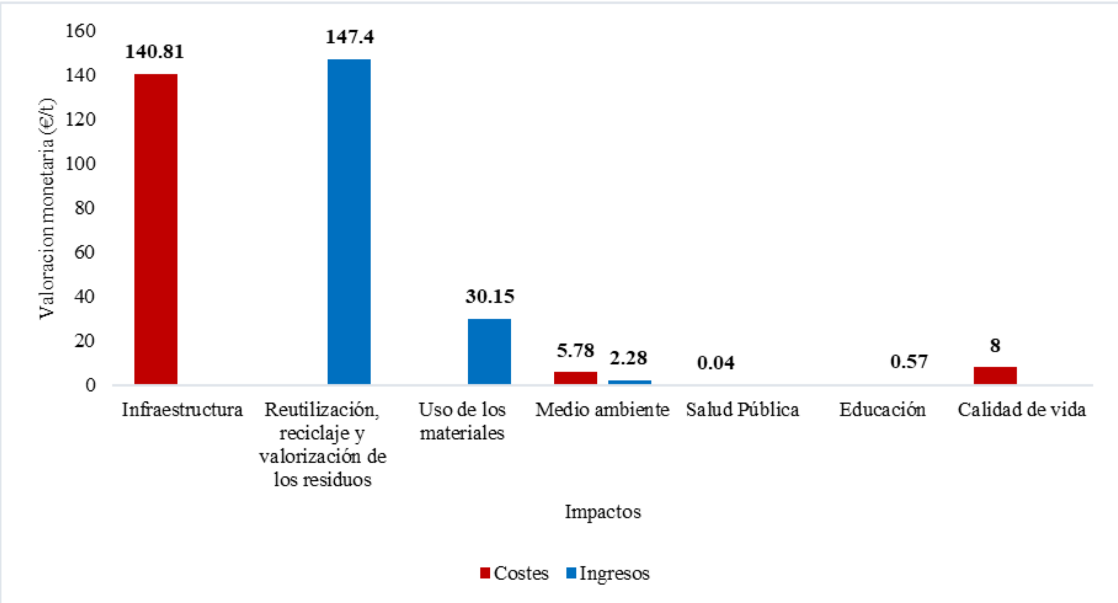


Figura 15. Coste e ingresos en €/t de residuos generados por la Planta de Valorización Energética de residuos. Fuente: Elaboración propia.

Como se puede visualizar en la Figura 16, la PCT presenta altos costes internos, sin embargo, tiene ingresos internos más altos, lo que la hace rentable desde el punto de vista privado. Si se analizan los impactos externos se pude concluir que se trata de una instalación rentable desde el punto de vista financiero, económico, ambiental y social. El efecto de las externalidades es todavía mayor que en el caso de la PVE, de esta manera se podría señalar que esta instalación proporciona mayores ventajas sociales y ambientales respecto a la PVE. En este caso, se observa solamente una externalidad negativa relacionada con la salud publica debido a los riesgos físicos.

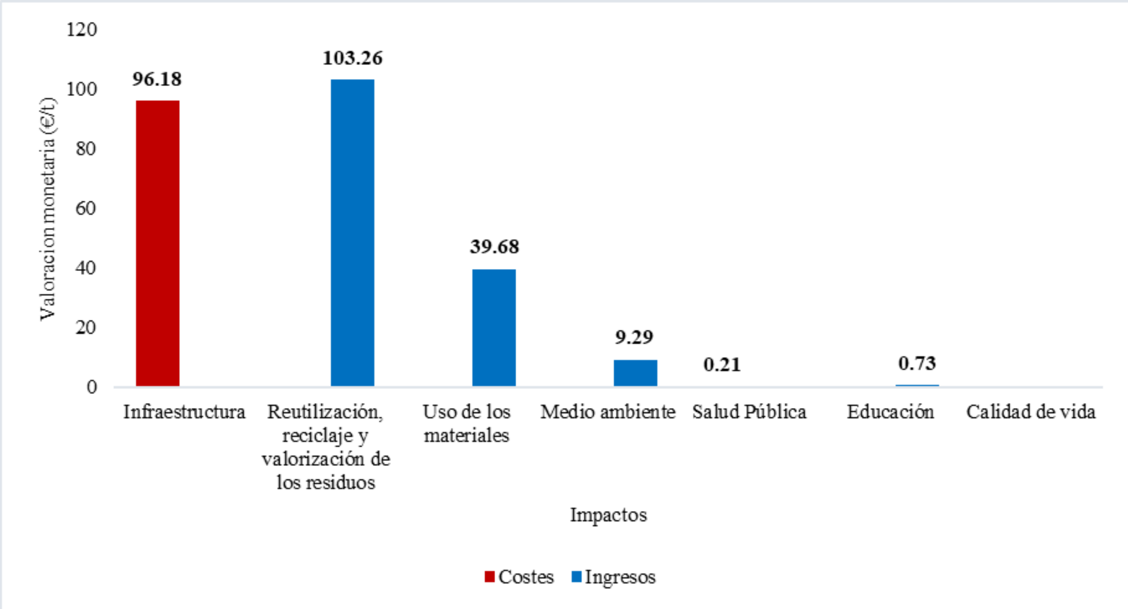


Figura 16. Coste e ingresos en €/t de residuos generados por la Planta de clasificación y tratamiento de residuos de envases ligeros y residuos voluminosos. Fuente: Elaboración propia.

Mediante la realización de los casos de estudio y la comparación de los resultados, se puede concluir que, si se evalúa únicamente los impactos privados de ambas instalaciones, la PVE resulta ser más rentable, ya que genera un mayor beneficio privado. Esta situación podría suceder con otro tipo de instalaciones, como en el caso de los vertederos según señala Nahman (2011), ya que, al considerar únicamente los costes e ingresos privados, puede generar un sesgo en contra de alternativas o sistemas que fomenten el reciclaje, que puede ser más caro que los vertederos desde una perspectiva puramente financiera, pero preferible desde un punto de vista ambiental y social. Al incluir las externalidades, la situación se invierte, como se puede visualizar, ya que la PCT resulta más rentable, debido a los diversos beneficios sociales y ambientales que genera. Por ejemplo, las emisiones de $CO_2$ evitadas debido a la reutilización y reciclaje de los materiales, reducción de los residuos que son enviados a vertederos o incineradoras, reducción de los residuos que son abandonados en cuerpos de agua y otros ecosistemas, entre otros.

## 3.4 Publicaciones derivadas de la tesis doctoral

Como resultado de la tesis doctoral se han desarrollado cuatro artículos, de los cuales tres se han publicado y un cuarto artículo se encuentra en proceso de publicación. Además del desarrollo de un capítulo de libro que se encuentra en proceso de revisión. Estas publicaciones son presentadas en el Anexo B, C y D del presente documento.

a. **Research Trends in the Economic Analysis of Municipal Solid Waste Management Systems: A Bibliometric Analysis from 1980 to 2019** (Medina-Mijangos and Seguí-Amórtegui, 2020)

   - **Estado:** Publicado
   - **DOI:** 10.3390/su12208509
   - **Revista:** Sustainability
   - **Factor de impacto:** 2.576 (JCR 2019)
   - **Área de conocimiento:** Environmental Sciences. Ranking 120 de 265 (Segundo Cuartil)

**Descripción:** En la primera etapa de la investigación se realizó una revisión de la literatura donde se analizó los artículos publicados entre 1980 y 2019, los cuales consideran los aspectos económicos de los sistemas de gestión de RSU. Después, se determinó los artículos que han desarrollado metodologías para el análisis económico de los sistemas de RSU. Y finalmente, se determinó las publicaciones que han desarrollado metodologías para la valoración monetaria de las externalidades. Los resultados demuestran que existe un aumento en el interés por el análisis económico de los sistemas de gestión de RSU, sin embargo, pocos artículos han desarrollado metodologías para el análisis económico de las externalidades, donde generalmente pocas externalidades son consideradas. También, se determinó que los principales métodos utilizados son el Coste del Ciclo de Vida y el Análisis Coste-Beneficio. El estudio mostró que se han publicado 563 artículos sobre aspectos económicos relacionados con los sistemas de gestión de RSU, 229 sobre el desarrollo de metodologías para el análisis económico, y solo 21 han desarrollado metodologías para el análisis económico que consideren las externalidades generadas por los sistemas de gestión de RSU. Mediante el desarrollo de este artículo se han cumplido con el objetivo específico 1, a través del desarrollo de la Fase 1 de la metodología de investigación.

b. **A methodology for the technical-economic analysis of municipal solid waste systems based on social cost-benefit analysis with a valuation of externalities** (Medina-Mijangos et al., 2021).

- **Estado:** Publicado
- **DOI:** 10.1007/s11356-020-09606-2
- **Revista:** Environmental Science and Pollution Research
- **Factor de impacto:** 3.056 (JCR 2019)
- **Área de conocimiento:** Environmental Sciences. Ranking 99 de 265 (Segundo Cuartil)

**Descripción:** Debido a que se determinó la necesidad de una metodología que permita el análisis económico de los sistemas de gestión de RSU y de sus impactos tanto privados como externos, se desarrolló una metodología basada en el análisis Coste-Beneficio sostenible, que considera los impactos económicos, ambientales y sociales. Esta metodología permite determinar los beneficios totales (la diferencia entre ingresos y costes) generados por los sistemas de gestión RSU y comprobar si son rentables desde el punto de vista privado, así como rentable desde el punto de vista económico, social y ambiental. El punto clave de la metodología es la identificación, periodicidad, cuantificación y valoración monetaria de los impactos generados por las instalaciones de gestión de RSU. Proporcionando una guía para los futuros investigadores y tomadores de decisiones interesados en la valoración económica de los sistemas de gestión de RSU. Se determinaron los principales impactos (costes privados y externos) a modo de inventario, que deberán ser considerados al analizar los sistemas de gestión de RSU. Mediante el desarrollo de este artículo se han cumplido con el objetivo específico 2, a través del desarrollo de la Fase 2 de la metodología.

c. **Technical-economic analysis of a municipal solid waste energy recovery facility in Spain: A case study** (Medina-Mijangos and Seguí-Amórtegui, 2021)**.**

- **Estado:** Publicado
- **DOI:** 10.1016/j.wasman.2020.09.035
- **Revista:** Waste Management
- **Factor de impacto:** 5.448 (JCR 2019)
- **Área de conocimiento:** Environmental Sciences. Ranking 35 de 265 (Primer Cuartil)

**Descripción:** Para evaluar la aplicabilidad de la metodología desarrollada se analizó económicamente casos de estudio sobre diferentes instalaciones de gestión de RSU. En específico, en este artículo se realizó el análisis de una incineradora ubicada en la zona metropolitana de Barcelona para determinar si la instalación es rentable desde el punto de vista privado, así como rentable desde el punto de vista económico, social y ambiental. Permitiendo a futuros investigadores extrapolar los impactos considerados en este caso de estudio para el análisis económico de otras instalaciones de gestión. Aplicando la metodología, se pudo comprobar que la instalación es rentable desde el punto de vista privado ($B_P$ = 9.86 €/t) así como, desde el punto de vista económico, social y ambiental ($B_T$ = 23.97 €/t). Los resultados muestran que la incineradora tiene altos costes privados, sin embargo, debido a sus altos ingresos por la venta de energía y servicios, la instalación es rentable desde el punto de vista privado, pero con un beneficio privado bajo por tonelada de residuo tratada. Las externalidades juegan un papel importante ya que aumentan el Beneficio Total haciendo la instalación más rentable y confiable. Mediante el desarrollo de este artículo se han cumplido con el objetivo específico 3, a través del desarrollo de la Fase 3 de la metodología.

**d. The economic assessment of the environmental and social impacts generated by a light packaging and bulky waste sorting and treatment facility in Spain: A circular economy example**

- **Estado:** Aceptado en proceso de publicación
- **DOI:** 10.1186/s12302-021-00519-6
- **Revista:** Environmental Sciences Europe
- **Factor de impacto:** 5.394 (JCR 2019)
- **Área de conocimiento:** Environmental Sciences. Ranking 38 de 265 (Primer Cuartil)

**Descripción:** En este artículo se realizó el análisis de una instalación de clasificación y tratamiento de residuos de envases ligeros y residuos voluminosos ubicada en la zona metropolitana de Barcelona (Gavà-Viladecans, Barcelona) para determinar si la instalación es rentable. Las instalaciones de clasificación y tratamiento de residuos juegan un papel importante en la gestión de los Residuos Sólidos Municipales (RSU), ya que permiten preparar los materiales para su posterior reutilización y reciclaje. Aplicando la metodología, se ha podido demostrar que esta planta es rentable el punto de vista privado (BP = 7.06 €/t) así como, desde el punto de vista económico, social y ambiental (BT = 55.72 €/t). La planta es altamente rentable desde una perspectiva social y ambiental. Mediante el desarrollo de este artículo se han cumplido con el objetivo específico 3, a través del desarrollo de la Fase 3 de la metodología.

**e. Capítulo de Libro: Waste-to-energy plant in Spain: a case study using a Techno-economic analysis.**

- **Estado:** En revisión
- **Libro:** “Waste-to-Energy: Recent developments and future perspectives towards circular economy”

- **Editorial:** Springer International Publishing AG
- **Factor de impacto:** ICEE 33.060 (SPI 2018)
- **Editores:** Abd El-Fatah Abohomohra, Qingyuan Wang, Jin Huang

**Descripción:** Este capítulo discute los datos tecno-económicos de plantas de conversión de residuos en energía en Europa, es especifico de una planta de incineración en España. El capítulo tiene como objetivo evaluar la viabilidad económica y discutir los impactos ambientales y sociales de estas plantas de tratamiento y ofrecer sugerencias para mejorar la recuperación de energía a partir de los residuos en países europeos. Este capítulo ampliará el análisis técnico-económico realizado en Medina-Mijangos and Seguí-Amórtegui (2021)**.**

## 3.5 Presentaciones en Congresos Internacionales y simposios

Como parte de la divulgación científica de los resultados obtenidos en la tesis doctoral se ha participado en Congresos Internacionales y simposios, los cuales se mencionan a continuación.

**1. 8º Simposio Becarios CONACYT en Europa (Presentación individual)**

- **Participación:** Comunicación oral
- **Fecha del evento:** 3- 5 de Abril de 2019
- **Lugar:** Parlamento Europeo, Estrasburgo, Francia

**Descripción:** El Simposio Becarios CONACYT en Europa es una manifestación científica anual organizada desde el 2011 por la Casa Universitaria Franco-Mexicana (MUFRAMEX), organismo bilateral al servicio de la cooperación universitaria y científica, dependiente del Ministerio de Educación Nacional, de Educación Superior y de Investigación de Francia y de la Secretaria de Educación Pública de México, en colaboración con el Consejo Nacional de Ciencia y Tecnología (CONACYT) y el Parlamento Europeo.

**2. 5th International Congress on Water, Waste and Energy Management (WWEM-19)**

- **Participación:** Comunicación oral
- **Fecha del evento:** 22-24 de Julio de 2019
- **Lugar:** Paris, Francia

**Descripción:** El 5th International Congress on Water, Waste and Energy Management (WWEM-19) está organizado por académicos e investigadores pertenecientes a diferentes áreas científicas de la Universidad de Trás-os-Montes e Alto Douro, Universidad de Extremadura, Universidad de Granada, Universidad de Jaén, Universidad de Santiago de Compostela y Universidad de Las

Palmas de Gran Canaria con el apoyo técnico de Sciknowledge European Conferences. El evento tiene el objetivo de crear un foro internacional para académicos, investigadores y científicos de todo el mundo para discutir resultados y propuestas a nivel mundial sobre los temas más sólidos relacionados con la Gestión del Agua, Residuos y Energía.

3. **4th Doctoral Congress in Engineering (DCE21)**

- **Participación:** Póster y Comunicación Oral
- **Fecha del evento:** 28 y 29 de Junio de 2021
- **Lugar:** Porto, Portugal (Online)

**Descripción:** DCE21 es un congreso para estudiantes de doctorado de las diversas áreas de la ingeniería, con el objetivo de discutir la investigación en curso con compañeros, profesores e industrias/empresas. En específico, el simposio en ingeniería ambiental tiene como principales temas: a) Agua limpia: contaminantes emergentes, monitoreo y tratamiento; b) Calidad del aire: emisiones, evaluación y seguridad sanitaria; c) Gestión de residuos y economía circular; d) Energía, sostenibilidad e innovación: productos, tecnologías y mitigación del cambio climático.

## 3.6 Premios y Reconocimientos

1. **Concurso “Tesis en 4 minutos”. Final Institucional organizada por la Universitat Politecnica de Catalunya (UPC)**

- **Fecha del evento:** 16 de mayo de 2019
- **Lugar:** Edificio Vertex, Barcelona, España
- **Premio:** Primer Premio

**Descripción:** La final del concurso “Tesis en 4 minutos” se ha realizado en el marco de la jornada de puertas abiertas de la Escuela de Doctorado de la UPC, donde participaron doctorandos y doctorandas de la UPC de diferentes especialidades con el objetivo de explicar su tema de investigación en un máximo de cuatro minutos ante un público no especializado.

2. **Concurso “Presenta la teva tesi en 4 minuts”. Final Interuniversitaria organizada por la Fundació Catalana per a la Recerca i la Innovació (FCRi)**

- **Fecha del evento:** 4 de junio de 2019
- **Lugar:** Espacio Endesa, Barcelona, España
- **Premio:** Tercer Premio (Premio del Público)

**Descripción:** El concurso “Presenta la teva tesi en 4 minuts” es una convocatoria impulsada por la Fundación Catalana para la Investigación y la Innovación (FCRi) y en la que participan las 12 universidades catalanas. El certamen plantea a los doctorandos y doctorandas de cualquier disciplina científica el reto de explicar oralmente, de manera individual, su investigación en un máximo de cuatro minutos ante un público no especializado.

# Capítulo 4: Conclusiones y Futuras vías de investigación

## 4.1 Conclusiones

Las conclusiones generales que se extraen de esta tesis doctoral, de acuerdo con los objetivos planteados y los resultados obtenidos, son las que se presentan a continuación:

1. El análisis bibliométrico permitió visualizar el creciente interés de los investigadores en temas relacionados con el análisis económico de los sistemas de gestión de RSU. Debido a que las cuestiones económicas son una parte fundamental en la toma de decisiones de los gestores e investigadores, ya que la mayoría de las decisiones relacionadas con la implementación de sistemas y tecnologías de gestión de RSU en la sociedad moderna se ven afectadas por restricciones económicas.
2. En general, se observa un aumento en el número de publicaciones enfocadas en el análisis económico de los sistemas de conversión de residuos en energía. La valorización energética de residuos brinda la oportunidad de reducir la cantidad de residuos que son enviados a vertederos. Sin embargo, el aumento de publicaciones no está en consonancia con la jerarquía de residuos y los principios de la economía circular, la cual prioriza la adopción de métodos para reducir la generación de residuos, aumentar la reutilización y el reciclaje, y desalienta el uso de incineradoras y vertederos.
3. En la literatura, los impactos ambientales relacionados con los sistemas de gestión de RSU han sido analizados y discutidos en diversos estudios. Sin embargo, los impactos sociales relacionados con los riesgos físicos, educación y calidad de vida han sido analizados en pocas ocasiones o incluso no han sido considerados por los autores.
4. Además, se identificó la necesidad de una metodología que permitiera el análisis económico de los sistemas gestión de RSU, debido a que hay diversos artículos en la literatura que se enfocan principalmente en el análisis de los impactos privados. Por otro lado, los autores que han analizado las externalidades generalmente se enfocan en aspectos o casos específicos de los sistemas de RSU o solo consideran unos cuantos impactos externos.
5. Una de las contribuciones significativas de la presente metodología es la recopilación e inventario de los impactos más relevantes relacionados con los sistemas de gestión de RSU. Además, se incluyó los posibles métodos de valoración económica que podrán ser utilizados para dar un valor monetario a los principales impactos identificados. En la metodología presentada se incluye diversos impactos privados y externos que pueden ser considerados para cualquier sistema de gestión de RSU. Se han incluido impactos relacionados con la infraestructura, la venta de los materiales, la reutilización, reciclaje y valorización de los residuos, el medio ambiente, la salud pública, la educación y la calidad de vida.

6. La metodología para el análisis técnico-económico de los sistemas de gestión de RSU está basada en el Análisis de Coste-Beneficio sostenible. Este método ha sido elegido para el desarrollo de la metodología debido a su simplicidad y fácil comprensión para cualquier tomador de decisiones. Además, representa un método óptimo para la cuantificación de los beneficios relacionados con los sistemas de gestión, ya que es una herramienta útil para la evaluación de proyectos y políticas.
7. La inclusión de los impactos privados y externos permite evaluar los proyectos y sistemas considerando los principios de la sostenibilidad y sus tres pilares, al considerar los posibles impactos económicos, sociales y ambientales. Además, se considera que estos 3 pilares son sinérgicos e interdependientes, y la mejor alternativa será aquella que asegure una armonía y equilibrio de estas 3 dimensiones o pilares.
8. Los principales objetivos de la metodología son determinar los costes e ingresos totales del proyecto y visualizar dos situaciones por separado: primero, si el sistema de gestión de RSU es viable o rentable desde el punto de vista privado para su operación, lo cual se define por la determinación del Beneficio Privado ($B_P$); y segundo, si el sistema de gestión de los RSU es financiera, económica, social y ambientalmente viable o rentable, lo cual se define por la determinación del Beneficio Total ($B_T$).
9. Esta metodología se puede aplicar para la evaluación económica de diferentes infraestructuras de gestión de RSU (vertederos, plantas de incineración, instalaciones de reciclaje y compostaje), sistemas de recogida (recogida por contenedores, recogida puerta a puerta, puntos limpios) y para diferentes tipos de residuos (envases ligeros, materia orgánica, voluminosos, entre otros).
10. Los resultados obtenidos del análisis realizado sobre la planta de valorización energética (PVE) muestran que esta instalación tiene un $B_P$ de 9.90 € y un $B_T$ de 24.93 €, lo que demuestra que se trata de una instalación rentable desde el punto de vista privado y externo. Además, permite visualizar la importancia de las externalidades, debido a que, al analizar los impactos externos, el beneficio de la instalación aumenta y, por lo tanto, la confiabilidad del sistema aumenta, haciéndola menos susceptible a los factores críticos.
11. Los resultados obtenidos del análisis realizado sobre la planta de clasificación y tratamiento de residuos de envases ligeros y residuos voluminosos (PCT) muestran que esta instalación tiene un $B_P$ de 7.06 € y un $B_T$ de 55.72 €, lo que demuestra que se trata de una instalación rentable desde el punto de vista financiero, económico, ambiental y social. El efecto de las externalidades es todavía mayor que en el caso de la PVE. De esta manera se podría señalar que esta instalación proporciona mayores ventajas sociales y ambientales respecto a la PVE.

12. Mediante la realización de los casos de estudio y la comparación de los resultados, se puede concluir que, si se evalúa únicamente los impactos privados de ambas instalaciones, la PVE resulta ser más rentable, ya que genera mayores beneficios privados. Sin embargo, al incluir las externalidades, la PCT resulta más rentable, ya que los beneficios sociales y ambientales son mayores, debido a que fomenta la valorización material reduciendo el uso de materias primas vírgenes, así como las emisiones de contaminantes al aire y agua. Esta situación podría suceder con otros tipos de instalaciones o proyectos, como en el caso de los vertederos, que, desde un punto de vista privado, es más rentable. Sin embargo, al incluir las externalidades, la instalación puede llegar a ser no rentable, a causa de sus diversos impactos negativos al medio ambiente y a la sociedad.
13. La metodología propuesta puede ser utilizada como una herramienta para la evaluación a priori. De esta forma, determinar si un proyecto que va a ser implementado es viable, así como, evaluar diferentes proyectos alternativos y elegir la mejor opción desde el punto de vista financiero, económico, ambiental y social. Por otro lado, también permite analizar la rentabilidad de una instalación que ya está en funcionamiento, es decir, un análisis a posteriori de su implementación, como es el caso de las dos infraestructuras analizadas en la tesis doctoral.
14. Por otro lado, mediante la realización de los casos de estudio se demostró la aplicabilidad de la metodología, ya que permite utilizar fácilmente esta metodología para cualquier tipo de sistema de gestión, representando una oportunidad para que los gestores de los RSU tomen decisiones acertadas y se reduzca la incertidumbre. Aunque los detalles presentados en los casos de estudio son específicos para el contexto español, la metodología utilizada puede ser de aplicación universal. Esta metodología determina y analiza varios impactos potenciales resultantes del tratamiento de RSU (privados y externos), y pueden ser extrapolados para el análisis de otras plantas de tratamiento, permitiendo a los investigadores considerar los mismos tipos de impactos, pero adaptados a contextos específicos.

## 4.2 Futuras vías de investigación

A pesar de que se han cumplido con los objetivos de la presente tesis doctoral, se tiene planeado seguir desarrollando otros estudios relacionados con el tema de investigación. A continuación, se detallan las posibles futuras vías de investigación:

1. Se recomienda ampliar los casos de estudio realizados incluyendo el análisis de los impactos generados por los procesos de recogida, transporte, así como otras instalaciones de tratamiento previos o posteriores a los procesos presentados, por ejemplo, en el caso de la

Planta de Valorización Energética incluir los impactos generados por la planta de tratamiento mecánico-biológica (proceso previo a esta planta).

2. Por otro lado, en el caso de los estudios desarrollados se ha utilizado información o datos provenientes de estudios de terceros como, por ejemplo, la disposición a pagar (*WTP*) de los consumidores y ciudadanos por productos o materiales ecológicos (energía producida a partir de residuos, envases reciclados y muebles fabricados a partir del conglomerado de astillas). Una futura vía de investigación es determinar la disposición a pagar de los ciudadanos de Barcelona por productos ecológicos, a través del método de valoración contingente o el experimento de elección, que se basa principalmente en el desarrollo de encuestas a ciudadanos.

3. Evaluar los impactos debido a la afectación a la salud y a la calidad de vida de los hogares cercanos a la PVE de Barcelona, ya que actualmente existe gran oposición por parte de los ciudadanos debido a la emisión de dioxinas y a los posibles impactos ocasionados por esta instalación. En el análisis realizado se consideró el estudio de Agència de Salut Pública de Barcelona (2018) donde se señala que no hay una asociación significativa entre la mortalidad y la proximidad a la PVE. Sin embargo, sería necesario analizar los costes ocasionados por los daños a la salud publica teniendo en cuenta el estudio de Domingo et al. (2017). Donde se señala que los residentes de la zona cercana a la PVE tienen entre 3 y 4 veces más probabilidades de desarrollar cáncer a lo largo de su vida (debido a la exposición a PCDD/Fs) que los residentes de ciudades como Girona, Mataró y Tarragona, donde también hay incineradoras en funcionamiento. En este caso, otro análisis a realizar es el impacto ocasionado en los precios de la vivienda debido a la proximidad de la PVE mediante el método de precios hedónicos.

4. Analizar otros tipos de instalaciones de tratamiento como vertederos, plantas de compostaje, entre otras. O analizar los sistemas de gestión de otros países, como el caso de los países de Latinoamérica, donde se observa una gran presencia del sector informal de residuos. Para determinar el impacto económico positivo que se podría obtener de la formalización de este sector. Por otra parte, analizar el impacto de la conversión de vertederos a cielo abierto (todavía presentes en gran medida en Latinoamérica) a sistemas de relleno sanitario o incluso valorar otros tipos de sistemas de gestión de RSU.

5. Analizar mediante la metodología presentada los impactos de dos sistemas de recogida diferentes, como podría ser el caso de la recogida puerta a puerta y la recogida por contenedores, para determinar cuál es el sistema más rentable y favorable desde el punto de vista económico, social y ambiental.

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# Anexo A: Estadísticas de generación y tratamiento de RSU en la Unión Europea.

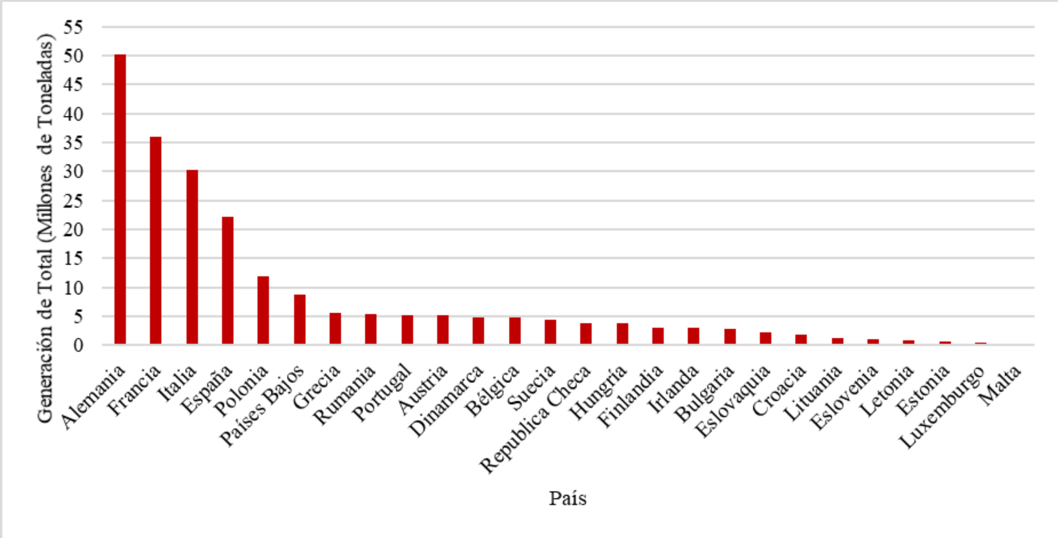


Figura 1. Generación Total de Residuos Sólidos Urbanos en millones de Toneladas de los países de la Unión Europea en 2018. Elaboración propia a partir de Eurostat (2020)

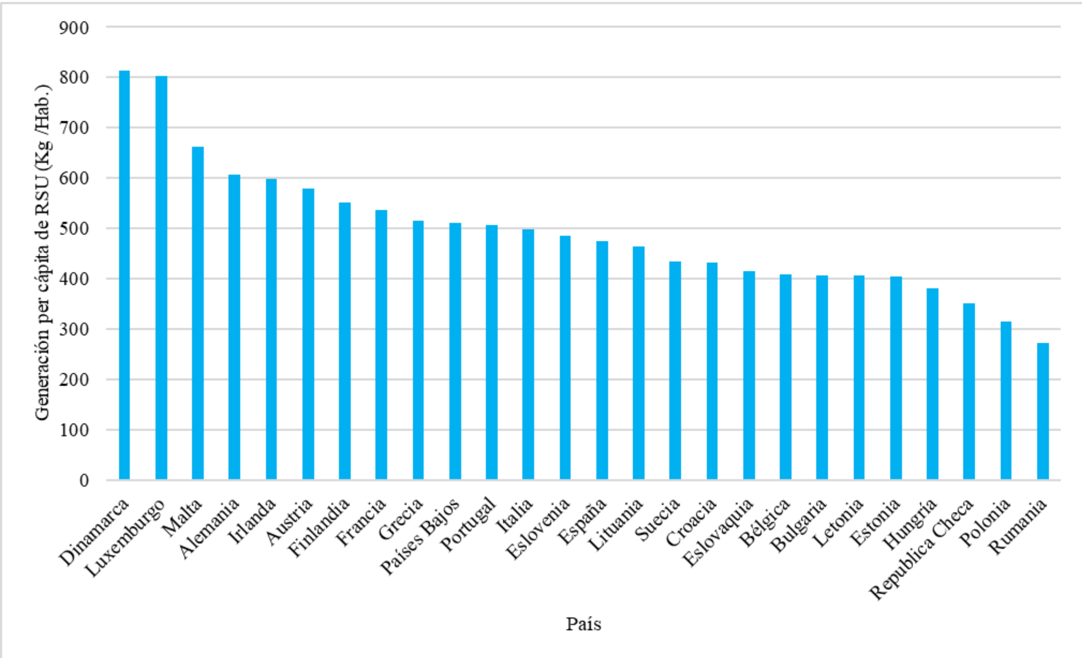


Figura 2. Generación per cápita de Residuos Sólidos Urbanos en Kg/hab. De los países de la Unión Europea en 2018. Elaboración propia a partir de Eurostat (2020)

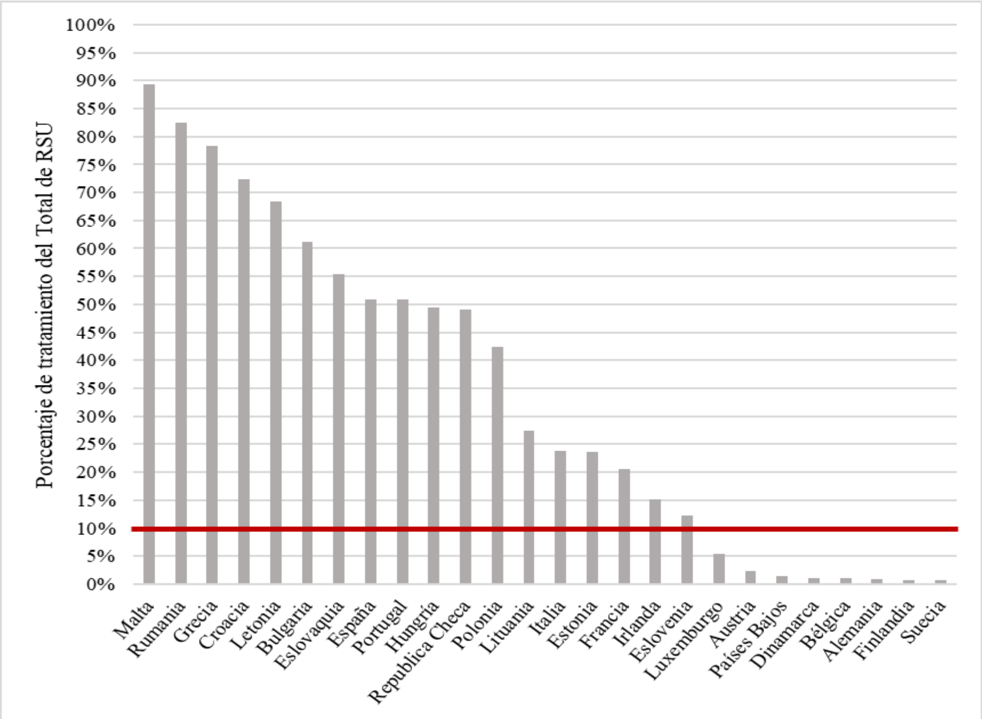


Figura 3. Porcentaje del total de residuos enviados a vertederos de los países de la Unión Europea en 2018. La línea roja representa el objetivo del límite del 10% de RSU enviados a vertederos para 2030. Elaboración propia a partir de Eurostat (2020)

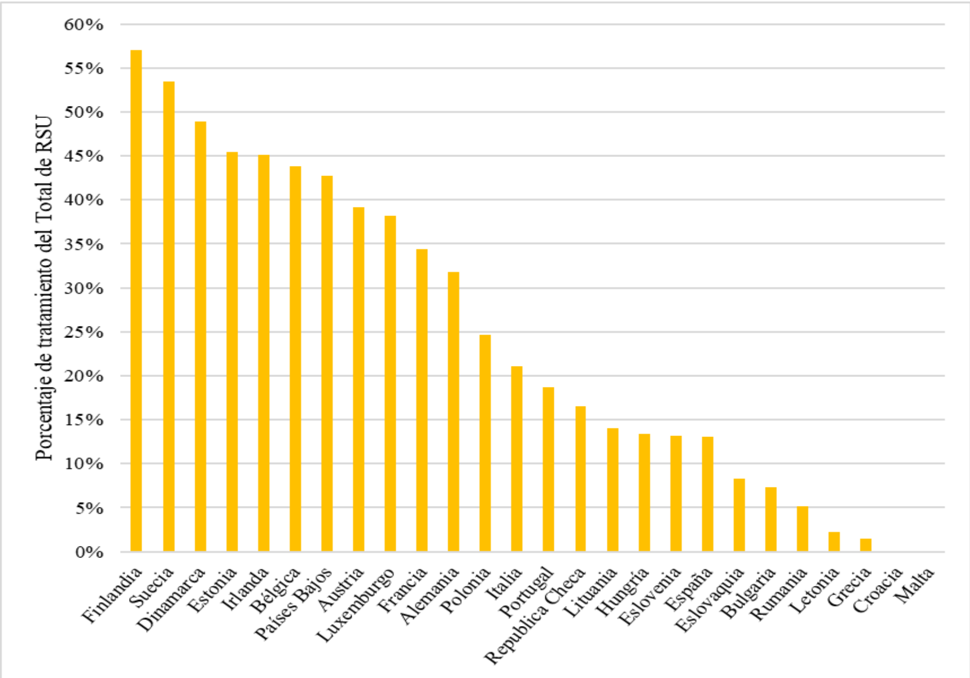


Figura 4. Porcentaje del total de residuos que son tratados en incineradoras de los países de la Unión Europea en 2018. Elaboración propia a partir de Eurostat (2020)

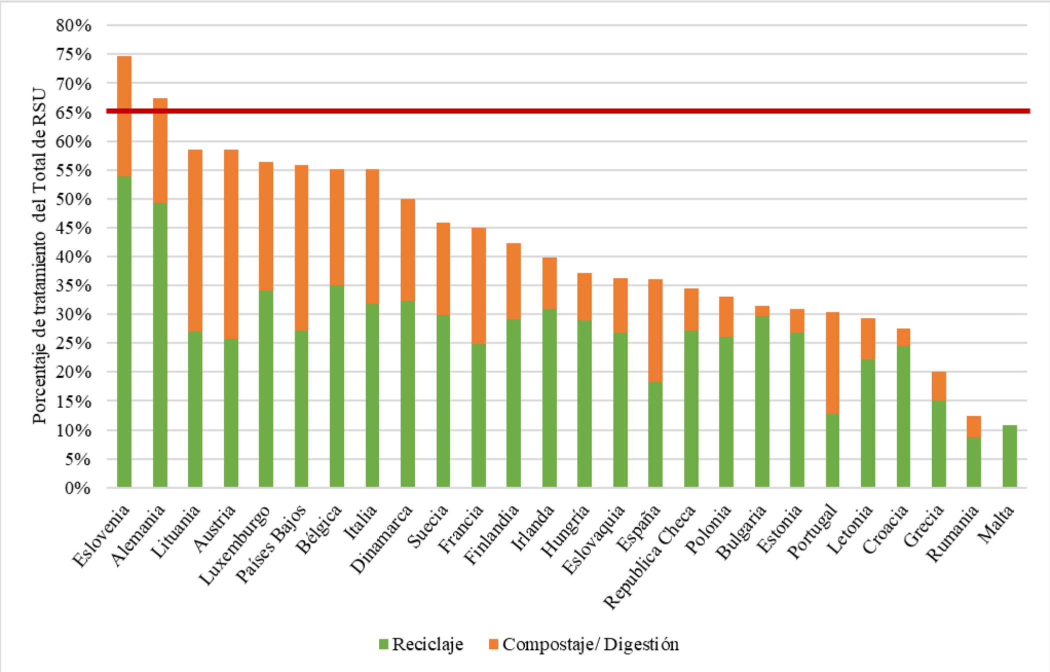


Figura 5. Porcentaje del total de residuos que son reciclados (reciclaje material + compostaje/ digestión) de los países de la Unión Europea en 2018. La línea roja representa el objetivo del 65% de preparación para la reutilización y el reciclaje de residuos municipales para 2030. Elaboración propia a partir de Eurostat (2020)

Tabla 1. Ranking según los porcentajes de los tipos de tratamiento de los países de la Unión Europea en 2018. Elaboración propia a partir de Eurostat (2020).

| **Incineración** | | | **Vertedero** | | | **Reciclaje** | | | **Compostaje/ Digestión** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **1** | Finlandia | 57.0% | **1** | Malta | 89.3% | **1** | Eslovenia | 53.9% | **1** | Austria | 32.7% |
| **2** | Suecia | 53.5% | **2** | Rumania | 82.5% | **2** | Alemania | 49.3% | **2** | Lituania | 31.6% |
| **3** | Dinamarca | 48.9% | **3** | Grecia | 78.4% | **3** | Bélgica | 34.9% | **3** | Países Bajos | 28.7% |
| **4** | Estonia | 45.5% | **4** | Croacia | 72.3% | **4** | Luxemburgo | 34.2% | **4** | Italia | 23.2% |
| **5** | Irlanda | 45.1% | **5** | Letonia | 68.4% | **5** | Dinamarca | 32.4% | **5** | Luxemburgo | 22.2% |
| **6** | Bélgica | 43.9% | **6** | Bulgaria | 61.2% | **6** | Italia | 31.8% | **6** | Eslovenia | 20.7% |
| **7** | Países Bajos | 42.7% | **7** | Eslovaquia | 55.4% | **7** | Irlanda | 30.9% | **7** | Bélgica | 20.2% |
| **8** | Austria | 39.2% | **8** | España | 51.0% | **8** | Suecia | 29.9% | **8** | Francia | 20.2% |
| **9** | Luxemburgo | 38.2% | **9** | Portugal | 50.8% | **9** | Bulgaria | 29.7% | **9** | Alemania | 18.0% |
| **10** | Francia | 34.4% | **10** | Hungría | 49.4% | **10** | Finlandia | 29.1% | **10** | España | 17.7% |

Tabla 2. Ranking según la cantidad (en millones de toneladas) de RSU tratados por tipo de tratamiento en los países de la Unión Europea en 2018. Elaboración propia a partir de Eurostat (2020).

| **Cantidad de RSU según el tipo de tratamiento (millones de toneladas)** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Incineración** | | | **Vertedero** | | | **Reciclaje** | | | **Compostaje/ Digestión** | | |
| **1** | Alemania | 15.936 | **1** | España | 11.325 | **1** | Alemania | 24.704 | **1** | Alemania | 9.019 |
| **2** | Francia | 12.370 | **2** | Francia | 7.382 | **2** | Francia | 8.909 | **2** | Francia | 7.259 |
| **3** | Italia | 5.756 | **3** | Italia | 6.486 | **3** | Italia | 8.675 | **3** | Italia | 6.334 |
| **4** | Países Bajos | 3.762 | **4** | Polonia | 5.191 | **4** | España | 4.057 | **4** | España | 3.942 |
| **5** | Polonia | 3.013 | **5** | Grecia | 4.330 | **5** | Polonia | 3.199 | **5** | Países Bajos | 2.527 |
| **6** | España | 2.898 | **6** | Rumania | 3.893 | **6** | Países Bajos | 2.395 | **6** | Austria | 1.651 |
| **7** | Suecia | 2.362 | **7** | Portugal | 2.539 | **7** | Bélgica | 1.611 | **7** | Bélgica | 0.932 |
| **8** | Dinamarca | 2.302 | **8** | Hungría | 1.851 | **8** | Dinamarca | 1.525 | **8** | Portugal | 0.881 |
| **9** | Bélgica | 2.022 | **9** | Republica Checa | 1.828 | **9** | Suecia | 1.320 | **9** | Polonia | 0.848 |
| **10** | Austria | 1.977 | **10** | Bulgaria | 1.750 | **10** | Austria | 1.301 | **10** | Dinamarca | 0.827 |

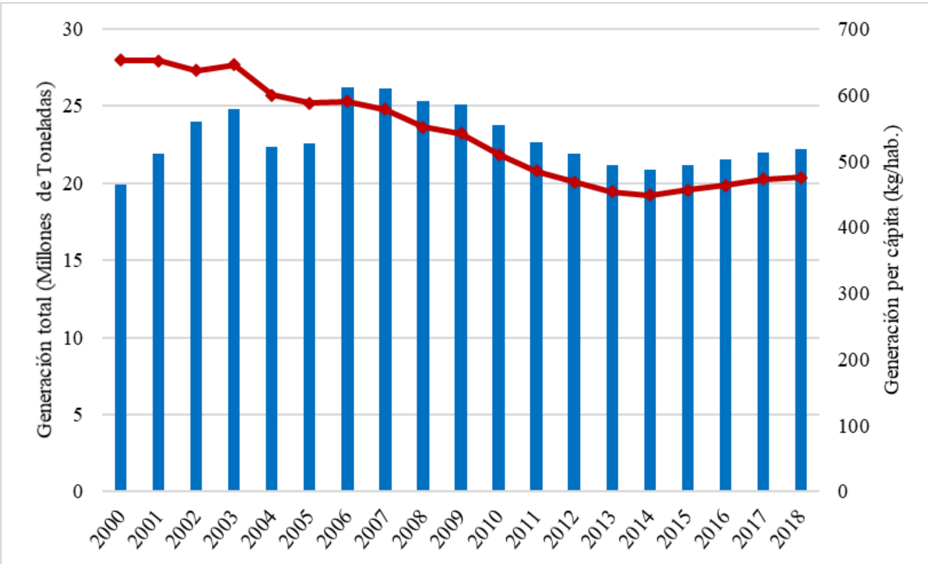


Figura 6. Generación total y per cápita de Residuos Sólidos Urbanos en España de 2000 a 2018. Línea roja representa la generación per cápita; Barras azules representa la generación total. Elaboración propia a partir de Eurostat (2020)

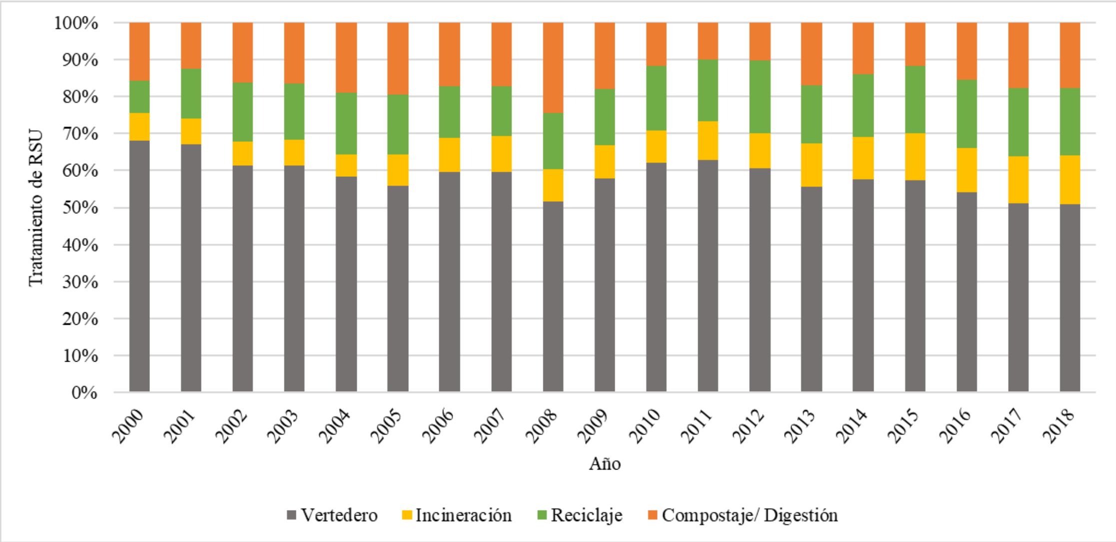


Figura 7. Tratamiento y eliminación de Residuos Sólidos Urbanos en España de 2000 a 2018. Elaboración propia a partir de Eurostat (2020)

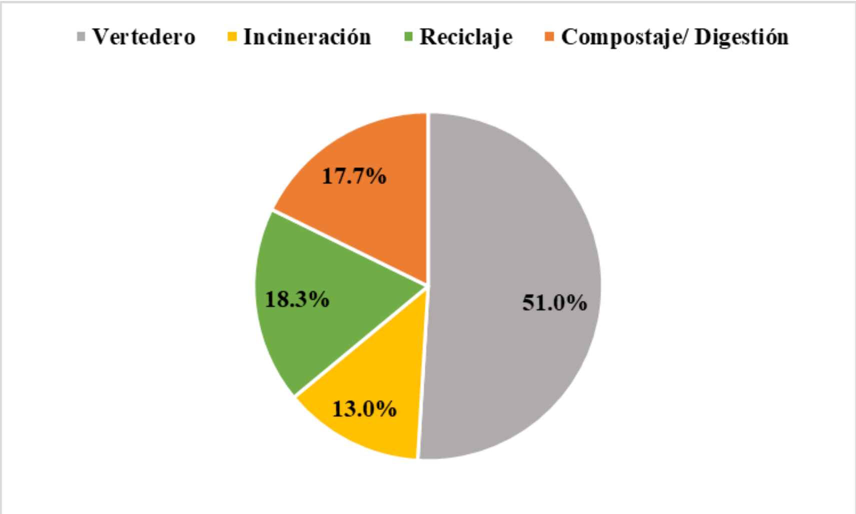


Figura 8. Tratamiento y eliminación de residuos en España en 2018. Elaboración propia a partir de Eurostat (2020)

# Anexo B: Artículos publicados o aceptados en revistas incluidas en el índice JCR

**Artículos publicados o aceptados en revistas incluidas en el índice JCR**


1. Medina-Mijangos, R., Seguí-Amórtegui, L., 2020. Research trends in the economic analysis of municipal solid waste management systems: A bibliometric analysis from 1980 to 2019. Sustain. 12, 1–20. https://doi.org/10.3390/su12208509

2. Medina-Mijangos, R., De Andrés, A., Guerrero-Garcia-Rojas, H., & Seguí-Amórtegui, L. (2021). A methodology for the technical-economic analysis of municipal solid waste systems based on social cost-benefit analysis with a valuation of externalities. Environmental Science and Pollution Research, 28 (15), 18807–18825. https://doi.org/10.1007/s11356-020-09606-2

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# Research Trends in the Economic Analysis of Municipal Solid Waste Management Systems: A Bibliometric Analysis from 1980 to 2019

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**Abstract:** This article analyzes state-of the art studies that focus on the economic aspects (EA) of municipal solid waste (MSW) management systems, including an analysis of articles that have developed methodologies for economic analysis (MEA), as well as those which study the economic analysis of the externalities or external impacts related to these systems. The aim of this study was to determine the trends in research and critical points based on the literature available in the Web of Science database from 1980 to 2019. First, we present the statistics and general trends, then perform an in-depth bibliometric study using the VOSviewer software, which allows the results to be grouped according to references, authors, institutions, countries, and journals. The study showed that 563 articles about the economic aspects have been published, 229 about methodology development, and only 21 considered the methodologies for analyzing externalities generated by the MSW management systems. In general, there is great interest in the economic analysis of the systems and technologies that deal with transforming waste into energy.

**Keywords:** economic assessment; municipal solid waste; externalities; methods; bibliometric analysis; Web of Science (WoS)

## 1. Introduction

Currently, countries face a serious problem due to the generation and management of greater quantities of waste caused by economic growth and new economic models based on encouraging ever-greater consumption rates in society [1,2]. The large-scale production of waste has led to the development of several operations (i.e., collection, transport, treatment, and elimination) for its management [3]. Specifically, when waste management is centered on the management of domestic waste, or waste of similar characteristics, it is known as municipal solid waste (MSW) management. Depending on the city or country, the complexities and characteristics of these operations may vary; for example, in developed countries, the processes and systems are more complex and use more sophisticated technologies and infrastructures. On the other hand, in developing countries, the processes are generally simpler and the informal waste sector has a notable presence [4,5].

When an MSW management system is implemented it can generate different impacts or consequences, which may be reflected as revenues or costs depending on whether the parties involved are affected positively or negatively. A distinction is usually made between internal and external impacts. In general, the economic-financial analysis of MSW management systems focusses only on studying the internal or private impacts, costs, and revenues related to OPEX (operational and maintenance costs) and CAPEX (capital costs). The internal or private impacts are those directly related to the MSW treatment process and its later reuse. These costs and incomes are incurred by the project investor or developer [6,7]. In contrast, the external impacts or externalities are those impacts or consequences resulting directly or indirectly from the operation of the MSW management system but whose effects are generally assumed by a party who is neither the owner nor the operator [7,8]. The externalities are generally connected with the social and environmental impacts (for example, effects on third-parties, control of contamination, increase in resources available, or guarantee of service, among others). Although the external impacts are more difficult to calculate, they are nonetheless important, as the impact of these characteristics can cause censorship of the project or its economic viability; therefore, they should be considered in the economic analysis [9–13].

MSW management is an area of increasing interest and concern, as evidenced by the increase in the amount of research carried out in recent years [14]. These studies generally focus on the environmental, social, and economic aspects, individually or combined [14]. Specifically, the economic aspect has acquired great importance due to it being a fundamental aspect in both governmental and national decision making [15], as the majority of decisions relating to the implementation of MSW management systems and technologies in modern society are affected by economic restrictions [9]. Therefore, the development of methods or models that allow the economic valuation of MSW management systems is essential, above all those that facilitate the economic assessment of the possible impacts or externalities (positive or negative) of MSW management systems on society and the environment [16].

To demonstrate the increasing interest in the economic analysis of MSW management systems, a bibliometric analysis was carried out, in which mathematical and statistical methods were applied in order to evaluate the performance of the authors, institutions, or countries, as well as to discover the principal areas of interest and show the future investigative trends [17,18]. The principal aim of this article was to analyze the worldwide dynamics regarding economic studies of MSW management. As such, we sought to: (1) evaluate the performance of authors, institutions, or countries; (2) discover the collaboration networks between journals, authors, and keywords in this field; and (3) discover the main areas of interest and show future investigative trends.

Several authors have carried out bibliometric studies in the field of waste. Among them is a study that examined the research trends in solid waste between 1993 and 2008 [19]. Some studies have focused on specific types of treatment, such as analysis of the reuse and recycling of solid waste between 1992 and 2016 [20], or the study of characteristics and trends of research into the incineration of waste and its conversion to energy [21]. Chen et al. (2017) [22] presented research into a specific type of waste, i.e., the studies of food waste between 1997 and 2014. Finally, some articles have concentrated on analyzing research trends in a specific journal, as in the case of the study into the characteristics and development of the journal *Resources, Conservation, and Recycling*, between 1988 and 2017 [18]. It should be noted that no bibliometric analysis focusing on the economic aspects of MSW management systems has been found.

The present study carried out a bibliometric analysis of the publications that dealt with the economic aspects of MSW management. Next, we conducted a review of the articles that developed methodologies for the economic analysis of MSW management systems. Finally, we analyzed articles that evaluated the possible external impacts (consequences) or externalities caused by the implementation of MSW management systems in economic terms. This study used publications and data obtained from the Web of Science (WoS), using the VOSviewer software to map the data graphically, using tools for co-occurrence of keywords, citations, bibliographic connections, and co- authorship.

The rest of the document is structured as follows: the next section describes the methodology and the data used. Then the bibliometric analysis is presented in Section 3, showing the general trends before viewing and discussing the collaborative networks. Finally, Section 4 contains the conclusions and further areas of research.

## 2. Materials and Methods

The data was obtained from the Core Collection of the Web of Science (WoS), a tool developed by Thomson Reuters and integrated in the ISI Web of Knowledge. The WoS is one of the most widely-used databases, providing graphics and statistics for the analysis of data about different areas of research, authors, document types, timelines, countries, universities, and institutions, among others. It also permits downloading the complete register of publications in txt format, which is generally used by mapping and data analysis software such as VOSviewer. The database used also included the following indexes: Science Citation Index Expanded (SCI-EXPANDED), Social Sciences Citation Index (SSCI), Arts and Humanities Citation Index (A&HCI), Conference Proceedings Citation Index – Science (CPCI-S), Conference Proceedings Citation Index – Social Science & Humanities (CPCI- SSH), Emerging Sources Citation Index (ESCI), Current Chemical Reactions (CCR-EXPANDED), and Index Chemicus (IC).

One of the most challenging aspects of bibliometric studies is the delimitation of the field of research under study. To obtain a broader view of the publications dealing with the economic aspects of MSW management systems, searches were carried out at three different levels, starting with a general search and becoming more specific. The results were obtained on February 29, 2020. The first search was carried out using the following keywords: Title: (Economic OR Cost OR Valuation) AND Topic: (MSW OR “Municipal Waste” OR “Municipal Solid Waste” OR “Urban Waste” OR “Household Waste”) NOT Topic: (Waste-Water OR “Waste Activated Sludge”), limiting the search to the period 1980 to 2019. It was decided to limit the search for terms related to the economic question to the Title field and to refine the results and obtain only those publications that were closely related to this field of research. When the topic field was selected, the search was carried out in the title, abstract, author keywords, and keywords plus. The aim of this search was to determine which articles studied the economic aspects of MSW system management; a total of 563 results were obtained and identified as economic aspects (EA). The second search added other terms to those of the first, such as Topic: (Methodology OR Model) to determine which articles had developed or presented a method or model for the economic analysis of MSW management systems. It obtained 229 results, in this case classified as methodologies for economic analysis (MEA). Finally, the third search added further limits to those of the first and second, such as Topic: (Externality OR External Cost) to determine which articles developed or presented a methodology to evaluate economically the externalities related to the MSW management systems, obtaining only 21 results. The complete register (composed mainly of the authors, titles, sources, and abstracts of the publications), as well as the references quoted, were downloaded in txt format for mapping and network analysis. In Figure 1, the methodology used to search and obtain data and data treatment is presented.

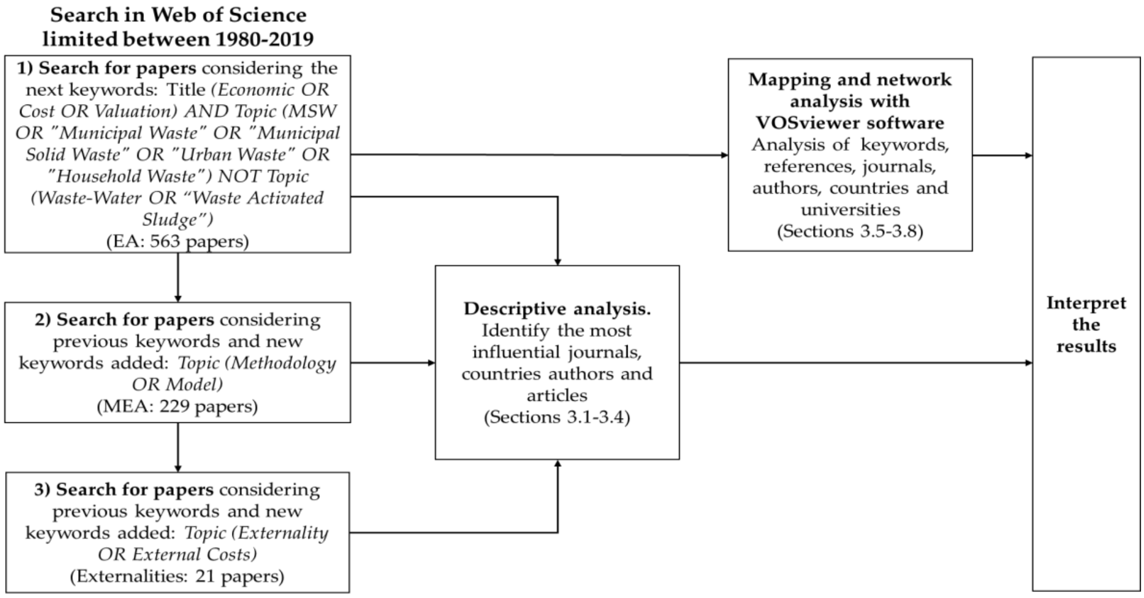



**Figure 1.** Methodology flowchart for search and analysis of data about economic aspects of Municipal Solid Waste (MSW) systems. Source: Own elaboration. EA: economic aspects; MEA: methodologies for economic analysis.

A descriptive analysis was used to investigate and identify the most influential journals, countries, authors, and articles of review database. Taking Seguí-Amortegui et al. (2019) [23] as a reference, this study used bibliometric indicators such as: (1) productivity, based on the number of publications [24]; (2) influence or impact, based on the number of citations [24]; (3) the Hirsch, or H- index, an indicator that shows that at least N publications have been cited at least N times (we aimed to show both the productivity and impact in just one number) [24,25]; (4) impact factor, a measure applied to the journals that represent the average number of citations of the articles published by this source over a period of two years [24].

This research used the VOSviewer software (developed by the University of Leiden) for the mapping and analysis of scientific publication networks, scientific journals, researchers, research organizations, countries, and keywords [26]. The analysis of the networks can be used to create a graphic map of the relationships between the data [18]. The articles in these networks can be connected by authorship, co-occurrence, citations, bibliographic connections, or links to co-citations, allowing maps to be seen and explored [26].

The VOSviewer software uses items (nodes) to represent the objects of interest (publications, researchers, journals, or keywords); the bigger the node, the bigger the weight or importance of the item. A link is the connection or relation between two items, representing the number of articles in which one specific item appears next to another. The thickest lines of the links show a more regular co-occurrence, in other words, greater intensity of cooperation [23,26]. This co-occurrence between nodes is also reflected in the distance between them. The color of the elements represents a group of items connected by their affinity to the subjects of research, elements of the same color being known as clusters [26].

## 3. Results

First, we present the general trends in research, which includes the number of publications per year, the number of citations per field and document, the countries with the most publications, and the most representative authors [23]. Then, we analyzed the current situation and the development of research into the economic aspects (EA) of the MSW management systems, which consisted of 563 articles; in addition, we provided information about the articles that contain methodologies for the economic analysis (MEA) of MSW management systems, which consisted of 229 articles. The second part of this section concentrates on the most cited documents regarding the economic analysis of MSW management systems (referring to the themes of EA and MEA). The third analyzes the most representative journals in the field. Next, we give information about the articles that have developed methods for the economic analysis of the external impacts or externalities (this search contained only 21 articles). The fifth part studies the analysis of the coincidence of authors' keywords regarding the economic analysis (EA) of the MSW management systems. Then the article explores the co-citation of references, journals, and authors on the subject of EA. Finally, we studied the co-authorship networks of countries and institutions involved in the research of EA.

### 3.1 General Trends

The first document about EA appeared in the WoS in 1980. From this year onward there was an intermittent flow of documents, which were not published every year. However, after 1988, documents appeared every year, staring with 1 article in 1988 and rising to 75 in 2019. The annual publications about the economic aspects of MSW management systems are shown in Figure 2, where it can be seen that interest in the research of the subject has grown. Although the search for the economic aspects of the MSW systems only generated 563 results, calculating the increase in the last 10 years (2010 to 2019) shows a rise of more than 294.74%.

In the case of the documents relating to MEA, the first article appeared in 1991, since when there has been an intermittent generation of articles. However, after 2003 more documents appeared every year, starting with 3 in 2003 and reaching a total of 40 in 2019. Although the search for the development of methods for the economic analysis of the MSW systems generated only 229 results, calculating the increase of the last 10 years shows that there has been a rise of more than 471.43%.

As can be seen in Figure 3, the countries with most publications dealing with EA are the USA with 87 publications, Italy with 59, and China with 44. These represent, respectively, 15.45%, 10.48%, and 7.81% of all publications on the subject. In addition, 80 countries have contributed to the development of the 563 publications. In the case of MEA, the countries with most publications are the USA with 31, Italy with 26, and China with 19. These represent, respectively, 13.53%, 11.35%, and 8.29% of all publications on the subject. It should be noted that the developed countries are to be found among the most representative, which reflects the developing countries' lack of interest in research into the economic aspects of MSW management.

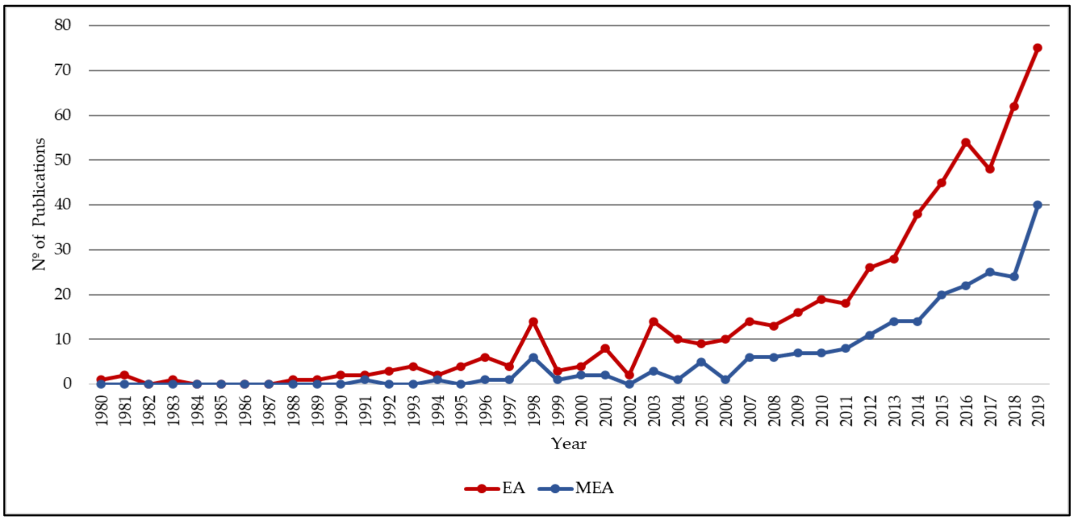
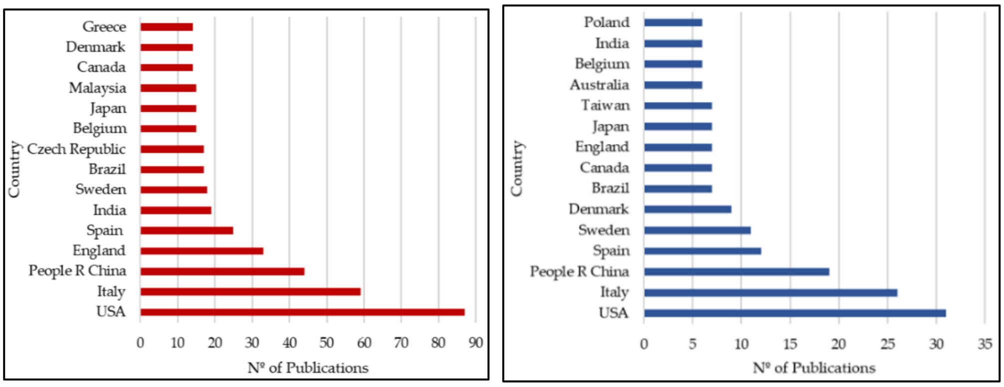



**Figure 2.** The annual number of publications about economic aspects (EA) and methodologies for economic analysis (MEA) of Municipal Solid Waste systems in Web of Science (WoS). Source: Own elaboration based on data from WoS 2020. The red line in the plot shows the number of publications per year in WoS on EA; the blue line indicates the annual number of research articles on MEA.

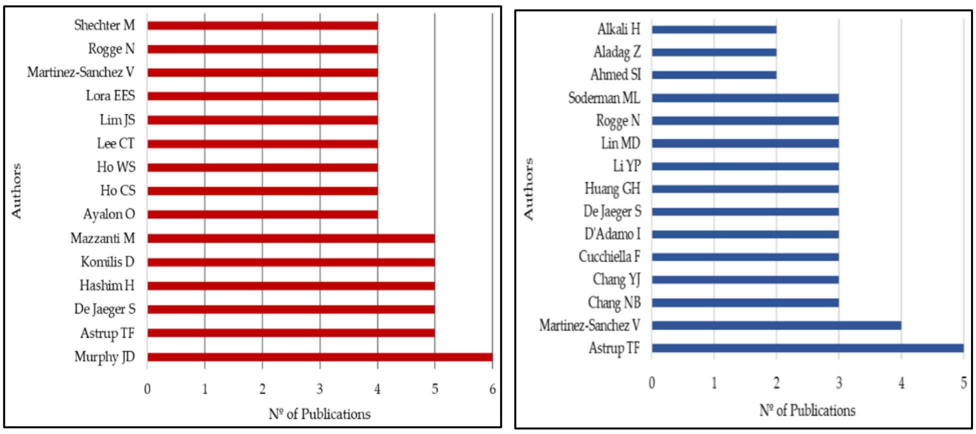
As shown in Figure 4, the authors with the most publications about EA are Murphy, J.D. with 6 publications (total articles in WoS: 151; h-index: 40), Astrup, T. with 5 publications (total articles in WoS: 385; h-index: 57), and Hashim, H. with 5 publications (total articles in WoS: 141; h-index: 28). These represent, respectively, 1.06%, 0.88%, and 0.88% of the 563 publications in this field. The authors with most articles about MEA are Astrup, T. with 5 publications, Martinez-Sanchez, V with 4 publications, and several authors with 3 publications, such as Chang, N.B., Chang, Y.J. and Cucchiella, F., among others.




(**a**) (**b**)

**Figure 3.** Publications in Web of Science (WoS) on economic aspects of Municipal Solid Waste systems, by country. Source: own elaboration based on data from WoS 2020. (**a**) The red bars show the number of publications about economic aspects (EA) research per country. (**b**) The blue bars show the number of publications about methodologies for economic analysis (MEA) per country.

The influence of the articles can also be measured by analyzing the number of citations. Table 1 shows the level of citations of all the articles published on EA, where it can be seen that only 7.11% (40) of the total (563) have more than 50 citations, 12.43% (70) have between 25 and 49 citations, 22.02% (124) have between 10 and 24 citations, and 58.44% (329) have less than 10 citations. The h- index of the articles about EA is 45 (i.e., 45 articles have at least 45 citations). In the case of articles about MEA, it can be seen that only 6.99% (16) of the total (229) have more than 50 citations, 8.73% (20) have between 25 and 49 citations, 24.89% (57) have between 10 and 24 citations and 59.40% (136) have less than 10 citations. The h-index of the articles related with MEA is 28.




(**a**) (**b**)

**Figure 4.** Publications in Web of Science (WoS) on economic aspects of Municipal Solid Waste systems, by author. Source: own elaboration based on data from WoS 2020. (**a**) The red bars show the number of publications about economic aspects (EA) research per author. (**b**) The blue bars show the number of publications about methodologies for economic analysis (MEA) per author.

**Table 1.** General citation structure in EA and MEA.

| Number of citations | No of articles | Accumulated no of articles | % Articles | % Accumulated articles |
|---|---|---|---|---|
| | | EA | | |
| ≥ 150 | 1 | 1 | 0.18% | 0.18% |
| ≥ 100 | 9 | 10 | 1.60% | 1.78% |
| ≥ 50 | 30 | 40 | 5.33% | 7.10% |
| ≥ 25 | 70 | 110 | 12.43% | 19.54% |
| ≥ 10 | 124 | 234 | 22.02% | 41.56% |
| < 10 | 215 | 449 | 38.19% | 79.75% |
| 0 | 114 | 563 | 20.25% | 100.00% |
| | | MEA | | |
| ≥ 100 | 5 | 5 | 2.18% | 2.18% |
| ≥ 50 | 11 | 16 | 4.80% | 6.99% |
| ≥ 25 | 20 | 36 | 8.73% | 15.72% |
| ≥ 10 | 57 | 93 | 24.89% | 40.61% |
| < 10 | 90 | 183 | 39.30% | 79.91% |
| 0 | 46 | 229 | 20.10% | 100.00% |

Source: Own elaboration based on WoS 2020.

### 3.2 Analysis of the Most-cited Articles Related to the Economic Aspects of MSW Management Systems

Table 2 shows the most-cited articles in the fields of EA and MEA, as well as some specific characteristics such as the journals where they were published, the total number of citations (NC), citations per year (CY), and the main results.

Regarding research into EA, 33.33% of the 15 most-cited articles were published in the journal *Waste Management* (Table 2). The 3 most-cited articles on this subject are Murphy and McKeogh, (2004) [27] with 176 citations, Consonni et al. (2005) [28] with 138 citations, and Douskova et al. (2009) [29] with 136 citations. In the case of research into MEA, the 3 most-cited articles are Reich (2005) [30] with 133 citations, Leme et al. (2014) [31] with 128 citations, and Johari et al. (2012) [32] with 114 citations. In both cases, these articles focus mainly on the economic analysis of technology and systems for generating energy from waste, waste collection costs, and the assessment of different recycling systems.

**Table 2.** General citation structure in MSW systems' Economic Assessment.

| Most Cited Papers on EA | | | | | |
|---|---|---|---|---|---|
| R | Reference | Journal | NC | CY | Main Results |
| 1 | Murphy and McKeogh (2004) [27] | RE | 176 | 10.35 | Four technologies which produce energy from MSW are researched. |
| 2 | Consonni et al. (2005) [28] | WM | 138 | 8.63 | Environmental and economic impacts of strategies for energy recovery are examined through LCA. |
| 3 | Douskova et al., (2009) [29] | AMB | 136 | 11.33 | Flue gas from a MSW incinerator was used as a source of $CO_2$ for the cultivation of the microalga Chlorella vulgaris to decrease the biomass production costs and to bioremediate $CO_2$. |
| 4 | Reich (2005) [30] | JCP | 133 | 8.31 | A methodology for economic assessment of MSW systems that consists of a financial LCC and an environmental LCC. |
| 5 | Leme et al. (2014) [31] | RCR | 128 | 18.29 | Different alternatives to energy recovery from MSW are compared from a techno-economic and environmental point of view. |
| 6 | Murphy et al. (2004) [33] | AE | 123 | 7.24 | Different scenarios of biogas use are analyzed from a technical, economic, and environmental point of view. |
| 7 | Johari et al. (2012) [32] | RSER | 114 | 12.67 | Methane emission from MSW disposed in landfills and its economic and environmental benefits are estimated. |
| 8 | Tan et al. (2015) [34] | ECM | 107 | 17.83 | Energy, economic and environmental impacts of WtE strategies for MSW management are evaluated. |
| 9 | Callan and Thomas (2001) [35] | LE | 107 | 5.35 | A multiple-output cost structure, which models the relationship between recycling and disposal activity. |
| 10 | Palmer et al. (1997) [36] | JEEM | 100 | 4.17 | Three price-based policies for MSW reduction and increased recycling are analyzed. |
| 11 | Bandara et al. (2007) [37] | EMA | 97 | 6.93 | MSW generation rate, waste composition, and related socio-economic factors are determined though field survey model. |
| 12 | Aye and Widjaya (2006) [38] | WM | 87 | 5.8 | Environmental and economic assessments to compare the options for traditional market waste disposal are performed through LCA and Cost-Benefit analysis. |
| 13 | Dijkgraaf and Gradus (2004) [39] | REE | 87 | 5.12 | Effects of unit-based pricing systems on waste collection are estimated. |
| 14 | Emery et al. (2007) [40] | RCR | 84 | 6 | Environmental and economic impacts of waste management scenarios are evaluated using a LCA computer model. |
| 15 | Kollikkathara et al. (2010) [41] | WM | 78 | 7.09 | A system dynamic approach that considers landfill capacity, environmental impacts, and financial expenditures. |

**Table 2.** General citation structure in MSW systems' Economic Assessment. (Cont.)

| Most Cited Papers on MEA | | | | | |
|---|---|---|---|---|---|
| R | Reference | Journal | NC | CY | Main Results |
| 1 | Reich (2005) [30] | JCP | 133 | 8.31 | A methodology for economic assessment that consists of a financial LCC and an environmental LCC. |
| 2 | Leme et al. (2014) [31] | RCR | 128 | 18.29 | Different alternatives to energy recovery from MSW are compared from a techno-economic and environmental point of view. |
| 3 | Johari et al. (2012) [32] | RSER | 114 | 12.67 | Methane emission from MSW disposed of in landfills and its economic and environmental benefits are estimated. |
| 4 | Callan and Thomas (2001) [35] | LE | 107 | 5.35 | A multiple-output cost structure, which models the relationship between recycling and disposal activity. |
| 5 | Palmer et al. (1997) [36] | JEEM | 100 | 4.17 | Three price-based policies for MSW reduction and increased recycling are analyzed. |
| 6 | Bandara et al. (2007) [37] | EMA | 97 | 6.93 | MSW generation rate, waste composition, and related socioeconomic factors are determined through field survey model. |
| 7 | Emery et al. (2007) [40] | RCR | 84 | 6 | A LCA computer model for evaluation of environmental and economic impacts of MSW management scenarios. |
| 8 | Kollikkathara et al. (2010) [41] | WM | 78 | 7.09 | A system dynamic approach that considers landfill capacity, environmental impacts, and financial expenditures. |
| 9 | Mazzanti and Zoboli (2009) [42] | ERR | 71 | 5.92 | A framework to analyze delinking for diverse waste related trends through a Waste Kuznets Curve. |
| 10 | Shmelev and Powell (2006) [43] | EE | 65 | 4.33 | A methodology for the regional MSW management modelling that considers spatial and temporal patterns, environmental, and economic impacts (such as public health and biodiversity). |

Source: Own elaboration based on data from WoS 2020. EA: economic aspects; MEA: methodologies for economic analysis; R: ranking; NC: total number of citations; CY: citations per year. RE: *Renewable Energy*; WM: *Waste Management*; AMB: *Applied Microbiology and Biotechnology*; JCP: *Journal of Cleaner Production*; RCR: *Resources Conservation and Recycling*; AE: *Applied Energy*; RSER: *Renewable and Sustainable Energy Reviews*; LE: *Land Economics*; JEEM: *Journal of Environmental Economics and Management*; EMA: *Environmental Monitoring and Assessment*; REE: *Resource and Energy Economics*; ECM: *Energy Conversion and Management*; EE: *Ecological Economics*; ERE: *Environmental and Resource Economics*; LCC: Life Cycle Costing; LCA: Life Cycle Assessment; MSW: Municipal Solid Waste; WtE: Waste to Energy.

### 3.3 Analysis of the Journals Related to Economic Aspects of MSW Management Systems

Table 3 shows a list of journals with the most articles published regarding the EA and MEA of MSW management systems. In the case of EA, 299 journals contained the 563 articles published on the subject. Of the sources that published articles about economic analysis, 78.59% have published only one article and just 7 journals have published 10 or more articles. In the case of MEA, 136 journals contained the 229 articles published on the subject. Of the sources that published articles about the subject, 78.67% have only published one article and just 4 journals have published 10 or more articles.

**Table 3.** The top 20 journals related to EA and top 15 journals related to MEA of MSW Systems.

| Journals related to EA | | | | | | | |
|---|---|---|---|---|---|---|---|
| R | Journals | AP | H-Index | TAP | AC | %AP | IF |
| 1 | WM | 74 | 25 | 6769 | 23.49 | 1.09% | 5.431 |
| 2 | RCR | 41 | 19 | 3619 | 24.27 | 1.13% | 7.044 |
| 3 | WMR | 35 | 12 | 2944 | 12.74 | 1.19% | 2.015 |
| 4 | JCP | 25 | 11 | 17314 | 17.04 | 0.14% | 6.395 |
| 5 | AE | 11 | 8 | 14429 | 32.09 | 0.08% | 8.426 |
| 6 | E | 10 | 5 | 17764 | 10.10 | 0.06% | 5.537 |
| 7 | ECM | 10 | 8 | 13050 | 28.80 | 0.08% | 7.181 |
| 8 | JEM | 9 | 7 | 10791 | 14.67 | 0.08% | 4.865 |
| 9 | EP | 8 | 5 | 21729 | 7.00 | 0.04% | - |
| 10 | RSER | 7 | 6 | 9339 | 40.29 | 0.07% | 10.556 |
| 11 | WBV | 7 | 4 | 1462 | 3.86 | 0.48% | 2.358 |
| 12 | BT | 6 | 6 | 22142 | 28.83 | 0.03% | 6.669 |
| 13 | S | 6 | 3 | 17777 | 6.33 | 0.03% | 2.592 |
| 14 | EE | 5 | 3 | 5872 | 17.60 | 0.09% | 4.281 |
| 15 | EST | 5 | 4 | 37941 | 22.00 | 0.01% | 7.149 |
| 16 | RE | 5 | 4 | 11689 | 53.00 | 0.04% | 5.439 |
| 17 | STE | 5 | 5 | 33352 | 23.8 | 0.01% | 5.589 |
| 18 | B | 4 | 2 | 6944 | 2.00 | 0.06% | 0.039 |
| 19 | CTEP | 4 | 3 | 1688 | 10.50 | 0.24% | 2.277 |
| 20 | EEMJ | 4 | 2 | 3375 | 3.75 | 0.12% | 1.186 |
| Journals related to MEA | | | | | | | |
| R | Journals | AP | H-Index | TAP | AC | %AP | IF |
| 1 | WM | 29 | 14 | 6769 | 21.00 | 0.43% | 5.431 |
| 2 | RCR | 20 | 13 | 3619 | 27.60 | 0.55% | 7.044 |
| 3 | WMR | 13 | 5 | 2944 | 10.62 | 0.44% | 2.015 |
| 4 | JCP | 11 | 7 | 17314 | 23.36 | 0.06% | 6.395 |
| 5 | AE | 5 | 3 | 14429 | 13.60 | 0.03% | 8.426 |
| 6 | EE | 5 | 3 | 5872 | 17.60 | 0.09% | 4.281 |
| 7 | E | 5 | 4 | 17764 | 8.40 | 0.03% | 5.537 |
| 8 | EP | 5 | 5 | 21729 | 9.20 | 0.02% | 4.865 |
| 9 | ECM | 4 | 4 | 13050 | 14.75 | 0.03% | 7.181 |
| 10 | S | 4 | 3 | 17777 | 5.50 | 0.02% | 2.592 |

Source: Own elaboration based on data from WoS 2020. EA: economic aspects; MEA: methodologies for economic analysis; R: ranking; AP: articles published about MSW economic analysis; H-index: the h-index in the area; TAP: total articles published; AC: average citations by article in the area. %AP: percentage of articles published (AP/TAP); IF: impact factor (2018). WM: *Waste Management*; RCR: *Resources Conservation and Recycling*; WMR: *Waste Management Research*; JCP: *Journal of Cleaner Production*; AE: *Applied Energy*; E: *Energy*; ECM: *Energy Conversion and Management*; JEM: *Journal of Environmental Management*; EP: *Energy Procedia*; RSER: *Renewable Sustainable Energy Reviews*; WBV: *Waste and Biomass Valorization*; BT: *Bioresource Technology*; S: *Sustainability*; EE: *Ecological Economics*; EST: *Environmental Science Technology*; RE: *Renewable Energy*; STE: *Science of the Total Environment*; B: *Biocycle*; CTEP: *Clean Technologies and Environmental Policy*; EEMJ: *Environmental Engineering and Management Journal*; EE: *Ecological Economics.*

The three main sources, according to the articles published on the subjects of EA and MEA are *Waste Management*, *Resources Conservation*, and *Recycling and Waste Management Research*. In addition, 49.91% of the total studies of EA (563) have been published in the top 20 journals. Of the total works on MEA (229), 44.10% have been published in the top 10 journals.

Research into EA represents just a small percentage of the total amount of research carried out in the top 20 journals (with coverage varying from 0.01% to 1.19%). In the case of MEA, the research carried out in the top 10 journals represents coverage of 0.02% to 0.55%.

Another measure of the journal's quality is the H index [26], which represents the number (H) of articles for which the author, journal, or institution have received at least H citations. The journal with the highest H-index for EA and MEA is *Waste Management* (25 and 29, respectively).

The journals with the highest average of citations per article published (AC) related to the subject of EA are *Renewable Energy* (53.00), *Renewable Sustainable Energy Reviews* (40.29) and *Applied Energy* (32.09). Regarding MEA, they are *Resources Conservation and Recycling* (27.60), *Journal of Cleaner Production* (23.36), and *Waste Management* (21.00).

The main categories of publications about EA are environmental sciences (54.35%), environmental engineering (42.51%), energy fuels (19.89%), green sustainable science technology (13.14%), economics (7.28%), and environmental studies (7.28%). Regarding MEA, the main categories are environmental sciences (57.20%), environmental engineering (41.48%), energy fuels (18.77%), and green sustainable science technology (14.41%).

### 3.4 Publications Related to Externalities

The search in WoS using the terms "Methodology" or "Model", as well as "Externality" or "External Costs", produced 21 publications, with 23.80% of the articles published in the journal *Waste Management*. Of all the articles, 23.80% were published before 2010, 38.10% appeared between 2010 and 2015, and 38.10% were published after 2015.

Table 4, shows the most-cited articles that considered external costs or benefits, where the most- cited was Massarutto et al. (2011) [44] with 59 citations. This work developed a model based on the principles of life cycle costing (LCC), which includes externalities such as air emissions (from incineration, landfills and collection vehicles), climate change ($CO_2$), and disamenities. Rabl et al. (2008) [45], with 55 citations, presented a methodology for evaluating external costs due to pollution from waste treatment is described, based on the ExternE project series of the European Commission. In this case, energy, material recovery, and possible differences in transport distance are considered. Martinez-Sanchez et al. (2015) [9] presented a costs model for the economic valuation of MSW management systems, had 40 citations. This model was based on the principles of LCC and considered the following external costs: environmental emissions and society's willingness to pay to prevent emissions or impacts of the MSW systems.

It must be pointed out that there are some articles that show an extensive review of the principal external impacts generated by MSW management systems [12,46]. They provide a general view of the external costs or externalities associated with several MSW management systems, such as disposal in a landfill and waste incineration, including different valuation methods. These articles are not included in the 21 obtained results because they do not provide methods for the economic valuation of the externalities that would allow them to be identified and their monetary value assessed.

**Table 4.** General citation structure related to externalities.

| Most Cited Papers related to Externalities or External Costs | | | | | |
|---|---|---|---|---|---|
| R | References | Journal | NC | CY | Main Results |
| 1 | Massarutto et al. (2011) [44] | WM | 59 | 5.9 | External costs and benefits implied by several alternative scenarios based on different combinations of energy and materials recovery. |
| 2 | Rabl et al. (2008) [45] | WMR | 55 | 4.23 | A methodology for evaluating the impacts and damage costs (‘external costs’) due to pollution from waste treatment. |
| 3 | Martinez-Sanchez et al. (2015) [9] | WM | 40 | 6.67 | A cost model that considers externality costs for the economic assessment of MSW management systems. |
| 4 | Woon and Lo (2016) [47] | RCR | 25 | 5 | Quantifies and compares the private and external costs of a landfill and an incineration facility. |
| 5 | Martinez-Sanchez et al. (2017) [48] | EST | 20 | 5 | Applicability of societal life-cycle costing to life-cycle optimization of MSW systems. |
| 6 | Mavrotas et al. (2015) [10] | RSER | 19 | 3.17 | A multi-objective mathematical programming model that considers external costs/benefits of WtE solutions. |
| 7 | Agar et al. (2007) [49] | JAWMA | 15 | 1.07 | A methodology to estimate heavy duty diesel vehicle emissions thought operational data from vehicle fleets monitored by a global positioning system (GPS). |
| 8 | Tonjes and Mallikarjun (2013) [50] | WM | 14 | 1.75 | An empirical systems model for recycling systems. |
| 9 | Maalouf and El-Fadel (2017) [51] | WM | 11 | 2.75 | A model that considers environmental externalities to integrate MSW and wastewater management for waste with high organic food content. |
| 10 | Panepinto and Genon (2012) [52] | WBV | 10 | 1.11 | A model to determine the optimal destination of MSW that considers monetary costs and environmental externalities. |

Own elaboration based on data from WoS 2020. R: ranking; NC: Total number of citations; CY: Citations per year. WM: *Waste Management*; WMR: *Waste Management and Research*; RCR: *Resources Conservation and Recycling*; EST: *Environmental Science and Technology*; RSER: *Renewable and Sustainable Energy Reviews*; JAWMA: *Journal Of The Air and Waste Management Association*; WBV: *Waste and Biomass Valorization*; MSW: Municipal Solid Waste; WtE: Waste to Energy.

### 3.5 Keyword Analysis

The keywords generally indicate the main content and subject of the article’s research, showing trends in research and the most important subjects in a specific area [23]. “When working with keywords, the occurrences attribute indicates the number of documents in which a keyword occurs” [26] (p. 36).

Examining the 563 articles about researching the EA of MSW management systems, the analysis reveals the existence of 1493 keywords. Figure 5 shows the principal keywords, organized in 9 clusters, where the most frequent keywords per cluster are as follows: recycling, circular economy (red cluster); MSW, costs (green cluster); MSW, renewable energy (dark blue cluster); biogas, economic analysis (yellow cluster); anaerobic digestion, gasification (purple cluster); MSW, techno- economic analysis (light blue cluster); waste management, waste-to-energy (orange cluster); life cycle assessment, incineration (brown cluster); and landfill, leachate (pink cluster).

It can be seen that among the top 20 keywords some, related to the transformation of waste into energy, stand out, such as incineration, waste to energy, renewable energy, and biogas. It can also be seen that the most common methods for the economic assessment of MSW systems are the life cycle costing and cost-benefit analysis.

There are also keywords related to some specific types of waste, such as "food waste" and "organic waste"; the importance of the research into these is due to the fact that they are the world's most widely-generated waste types [1,53]. The presence of the keyword "packaging waste" is also noticeable, its importance lying in the several negative impacts (environmental and economic) that can arise if it is not managed adequately, as in the case of "plastic packaging waste" [54,55]. The research and design of viable economic, social, and environmental technologies and MSW systems is essential, as is the development of techniques to improve the management and reduce generation of these wastes, which would lead to a reduction in possible negative impacts.

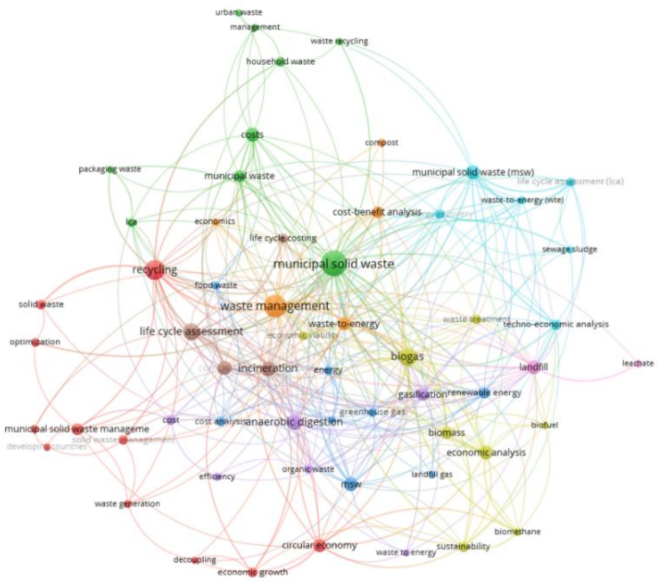



**Figure 5.** Co-occurrence network of author keywords in publications. The figure includes the 59 keywords with the most frequent occurrences of the 1493 total keywords that meet a minimum threshold of 5 occurrences.

Table 5 shows the top 20 keywords, as well as the occurrences (frequency) and co-occurrences link (total strength of link). Regarding occurrence, the most important keywords are municipal solid waste, biogas, and waste management; in the case of the co-occurrence link, the most important keywords are municipal solid waste, waste management, and recycling.

**Table 5.** The top keywords co-occurrence of publications.

| R | Keyword | Co | Oc |
|---|---|---|---|
| 1 | Municipal solid waste | 76 | 60 |
| 2 | Biogas | 57 | 29 |
| 3 | Waste management | 56 | 46 |
| 4 | Recycling | 44 | 36 |
| 5 | Incineration | 42 | 20 |
| 6 | Anaerobic digestion | 39 | 21 |
| 7 | Life cycle assessment | 36 | 26 |
| 8 | Municipal solid waste (MSW) | 33 | 18 |
| 9 | Gasification | 33 | 14 |
| 10 | Landfill | 31 | 18 |
| 11 | Composting | 30 | 18 |
| 12 | Economic analysis | 27 | 17 |
| 13 | Renewable anergy | 27 | 11 |
| 14 | MSW | 25 | 17 |
| 15 | Costs | 24 | 17 |
| 16 | Waste-to-energy | 24 | 15 |
| 17 | Circular economy | 22 | 16 |
| 18 | Waste-to-energy (wte) | 22 | 6 |
| 19 | Energy | 21 | 7 |
| 20 | Sustainability | 20 | 10 |

Source: Own elaboration based on WoS 2020. R: Rank; Co: keyword co-occurrences link; Oc: keyword occurrences.

### 3.6 Reference, Journal, and Author Co-Citation Analysis

This section analyzed co-citation (cited references, cited sources, and cited authors). Co-citation is defined as the frequency with which documents are cited together; when a third item cites two elements (author, reference, or journal) there is a co-citing relationship [56]. A co-citation link is a link between two elements cited by the same document, in this case the distance between two journals, authors or references shows the relationship of these items in terms of citation links. In general, the closer the nodes the stronger their relationship. The strongest co-citation links between nodes are also represented by lines [26].

First, an analysis was performed on the co-citation of cited references (Figure 6), obtaining three clusters where the most representative articles of each cluster are as follows. Leme et al. (2014) [31] (in red) with 24 citations and a total link strength of 52 (in first place for citations). This work compares different alternatives for generating energy from MSW in Brazil, from a techno-economic and environmental perspective. This cluster also included Murphy and McKeogh (2004) [27], Jamasb and Nepal (2010) [57], and others. Its main focus is the analysis of systems that transform waste to energy. Emery et al. (2007) [40] (in green) have 10 citations and a total link strength of 43, developing a model to examine the costs, employment, and recovery rates achieved using various waste recovery methods including recycling and incineration. This cluster also included: Reich (2005) [30]; Eshet et al. (2006) [46], among others. Its main focus is the analysis and comparison of different MSW management systems.

Dijkgraaf et al. (2003) [58] (in blue) have 15 citations and a total link strength of 85 (in first place for total link strength); this work focusses on collection systems in the Netherlands. It can be seen that the blue cluster is further away from the other two clusters, which shows a weaker relationship between the subjects under research. This cluster also included Callan and Thomas (2001) [35], Bel and Warner (2008) [59], and others. Its main focus is the cost analysis of MSW collection services.

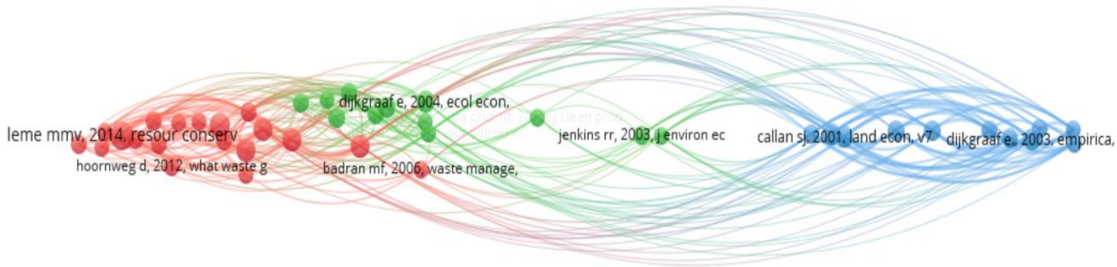



**Figure 6.** Co-citation of cited references on EA: 42 references of the 16089 cited references that meet the threshold of a minimum number of citations of a cited reference of 10.

Regarding the analysis of the journal co-citation network, there are 3 clusters (Figure 7). The green cluster includes *Waste Management*, the journal with most citations (1557) and the highest link strength (24215). This cluster is composed of journals on subjects related to environmental and sustainability issues, and specifically dealing with waste management (generation, characteristics, reduction, collection, separation, treatment, and elimination). The most representative journal of the red cluster (the most numerous) is *Bioresource Technology* (Citations: 440, Link Strength: 9665); this cluster is mostly made up of journals dealing with subjects such as energy and its generation, conversion, and use. Finally, the most representative journal of the blue cluster is the *Journal of Cleaner Production* (Citations: 492, Link Strength: 10108); this cluster contains interdisciplinary journals focusing on research into the environment and sustainability, as well as the use of resources, water, and energy. In this case, it can be seen that two of the clusters (blue and green) are closely linked, which shows that their subjects of research (waste management, environmental issues, and sustainability) are closer, whereas the red cluster is composed of journals whose principal subjects of research are connected with the generation of energy from waste.

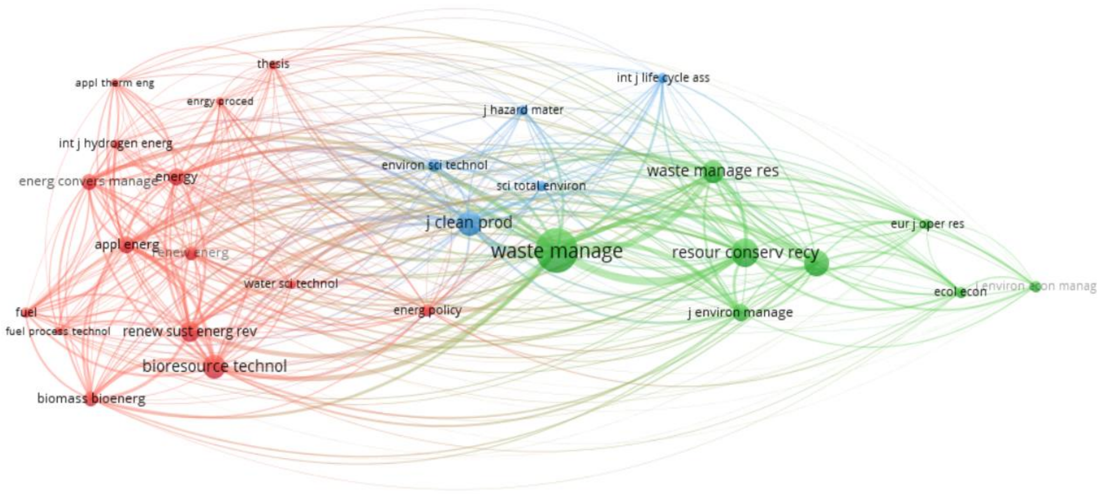



**Figure 7.** Journal co-citation network on EA: 28 main journals, of the 7542 cited sources, by the 563 documents that meet the threshold of a minimum number of citations of a cited source of 60.

The author co-citation network (Figure 8) shows four clusters: red (the most numerous), composed of 22 authors, among which is the European Commission (73 citations and link strength 326); other authors are Murphy, J.D. (55 citations and link strength 98) and Consonni, S. (35 citations and Link Strength 151) that focus on energy recovery.

The green cluster has 7 authors, of whom Bel, G. stands out (83 citations and link strength 406), having first place in terms of link strength and citations, with 91 documents in WoS about the economic policy of transport and public infrastructure; other authors are Dijkgraaf, E. (51 citations and link strength 361) and Simoes, P. (31 citations and link strength 201).

The blue cluster contains 6 authors, of whom Kinnaman, T.C. stands out (29 citations and link strength 154) with 17 documents in WoS about the economic impact of recycling and incineration. There are also Miranda, M.L. (24 citations and link strength 134) and Rabl, A. (23 citations and link strength 131).

The yellow cluster has 5 authors, where the most noticeably is Chang, N.B. (58 citations and link strength 268) with 355 documents in WoS about MSW management strategies and technologies.

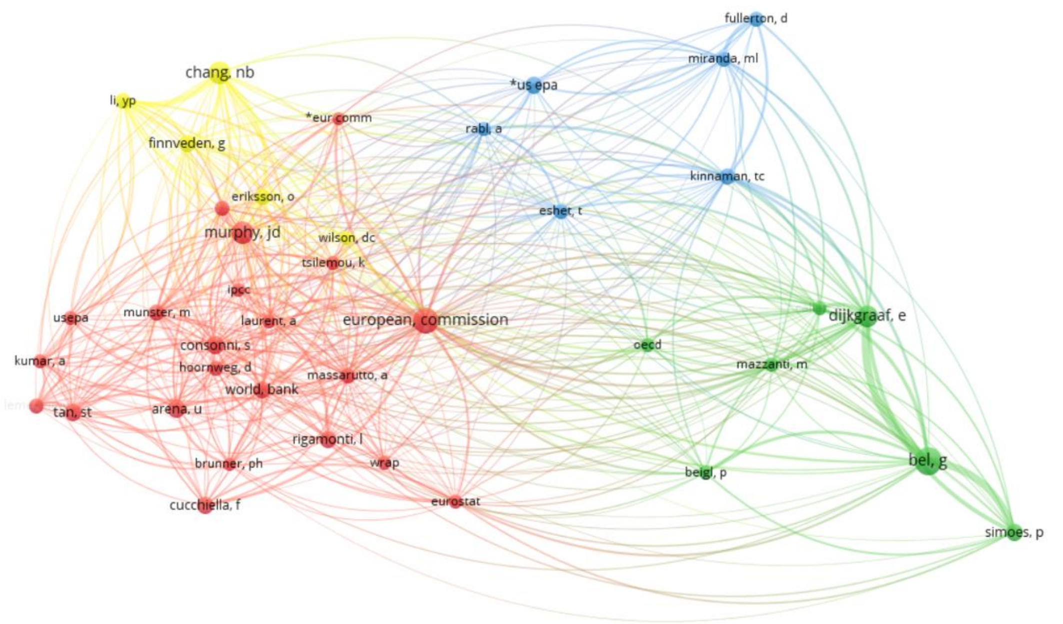



**Figure 8.** Author co-citation network on EA: 40 authors, of the 11608 cited authors, which meet the threshold of a minimum number of citations of a cited author of 20.

### 3.7 Bibliographic Coupling of Authors

The bibliographic coupling of authors analysis allowed us to see if authors A and B cite the articles of author C; in other words, two authors with common references are more closely related and have similar research interests [60].

The bibliographic coupling of authors (Figure 9) showed that there were eight clusters composed of 35 authors. Red is the main cluster, with 9 authors, the most representative being De Jaeger, S. Then, the green and dark blue clusters had 6 authors each, yellow had 5 authors, purple had 3, and light blue, brown, and orange clusters had 2 authors each.

The authors with most publications are as follows. De Jaeger, S. (5 publications) had a total of 20 publications in WoS about the optimization of transport routes for collecting waste and the recycling systems of packaging waste. Hashim, H. (5 publications) had a total of 141 publications in WoS, which focus on evaluating strategies for converting waste into energy and the use of biogas. Mazzanti, M. (5 publications) had a total of 78 publications in WoS, including research subjects such as the socioeconomic variables that influence waste generation, as well as political influence on the situation.

According to total link strength, the order of authors is Ho, W.S. (731), Silva Lora, E.E. (664), and Hashim, H. (643). For the number of citations, the order of authors is: Murphy, J.D. (329), Hashim, H. (238), and Silva Lora, E.E. (227).

Two clusters can be seen (light blue and brown) further away from the others, which represent recent subjects of research. On the one hand, the cluster formed by authors Ayalon, O. and Shechter, M., whose publications deal with themes regarding the economic valuation of the externalities of the MSW management systems. On the other hand, the cluster composed of Dennison, G.J. and Dodd, V.A., whose works on evaluating the costs of waste recycling focus on Dublin, Ireland.

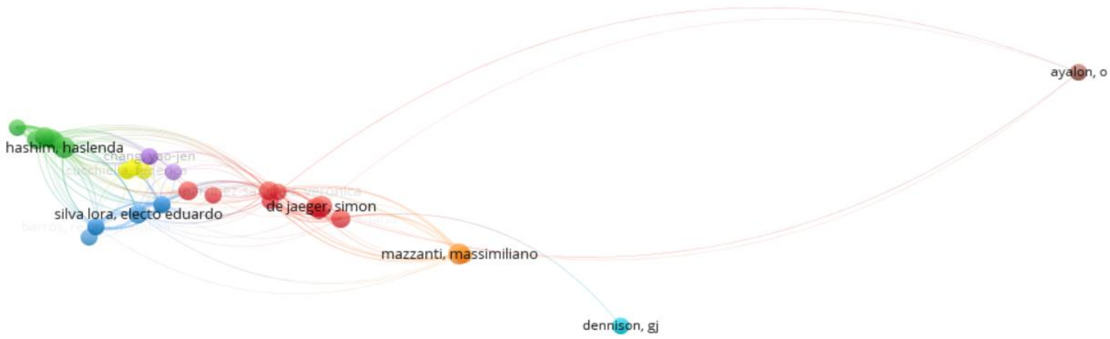



**Figure 9.** Bibliographic coupling of authors: 35 authors, of the 1702 authors, who meet the threshold of a minimum number of documents of an author of 3.

### 3.8 Country and University Co-Author Analysis

Finally, co-authorship between cities and universities was analyzed, where item size (nodes) reflects the relevance of the organizations or countries, and the distance reflects the degree of collaboration between them.

Analyzing the co-authorship relationships between countries provides us with a network composed of 19 countries spread over 5 clusters (Figure 10). The red cluster has 5 countries, the most representative being the USA (76 documents, 984 citations), Italy (59 documents, 1128 citations). and Spain (25 documents, 419 citations); the green cluster is made up of 5 countries, with the most representative being Sweden (17 documents, 450 citations) and Belgium (15 documents, 279 citations); the blue cluster has 4 countries, led by the Czech Republic (17 documents, 163 citations) and Malaysia (15 documents, 328 citations); the yellow cluster is composed of 3 countries, led by England (30 documents, 373 citations); the purple cluster includes China (44 documents, 564 citations) and Canada (13 documents, 277 citations). The countries that stand out for the number of publications and citations are the USA, Italy and China. It can also be seen that the different clusters are separated from each other, which indicates little collaboration between them. The presence of developed countries is noticeable, which reflects the low level of collaboration of the developing countries in this field.

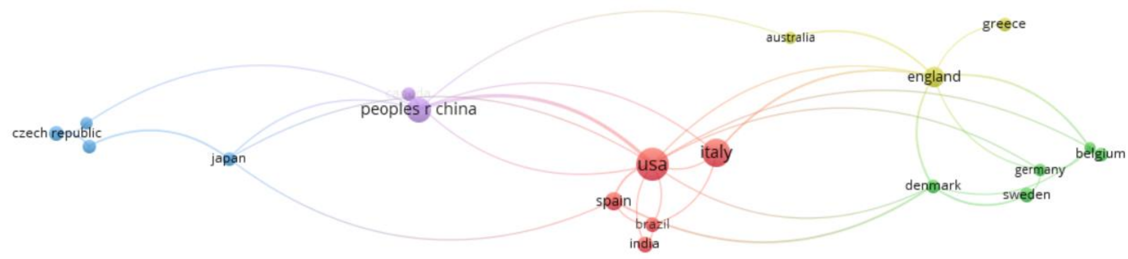



**Figure 10.** Countries' co-authorship network of EA: 19 countries, of the 80 nations, meet the threshold of a minimum number of papers of a country of 10.

Finally, from the institutions' co-authorship network (Figure 11) of universities or institutions that meet the threshold of at least 2 documents published, it can be seen that there is little collaboration between different universities. This is due to the fact that, of the 700 universities mentioned, the largest group is only 9, organized into three clusters as follows. The red cluster, composed of 4 universities: the IVL Swedish Environmental Research Institute, Sweden (2 documents, 34 citations), Chalmers, Sweden (2 documents, 66 citations), University of Gävle, Sweden (2 documents, 40 citations), and the KTH Royal Institute of Technology, Sweden (2 documents, 20 citations). The green cluster consists of 3 universities: University of Borås, Sweden (5 documents, 130 citations), Chalmers University of Technology, Sweden (3 documents, 50 citations), and RAM Lose Edb, Denmark (2 documents, 27 citations). The blue cluster has 2 universities: Technical University of Denmark (8 documents, 182 citations) and the Fundación ENT, Spain (2 documents, 32 citations). The importance of the Swedish universities is evident from their positions in all clusters.

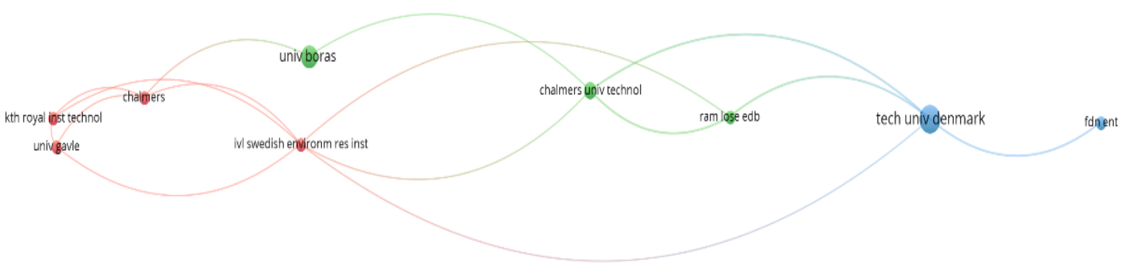



**Figure 11.** Institutions' co-authorship network of EA: 9 organizations, of 700, meet the threshold of a minimum number of documents of 2.

## 4. Discussion and Conclusions

Using the bibliometric analysis of the publications in WoS, this article shows the research trends in the economic analysis of MSW management systems, firstly from a general perspective by studying articles that analyze the economic aspects (EA), then more specifically by concentrating on those articles that present or develop a methodology for the economic analysis of these systems (MEA). The importance of this article lies in the fact that, up to now, there have been no bibliometric studies that have analyzed the economic aspects of MSW management systems. Another important point is the analysis of articles that present a methodology for analyzing the external impacts or externalities.

The bibliometric analysis shows the interest in the subjects of EA and MEA, which is evident from the increase in the number of publications. The United States, Italy, and China are the countries with the most publications in both areas. In the developing world, research into this field is scarce. Analysis of the MEA area shows that the LCC and CBA are the principal methods used to analyze the economic aspects, which were also the most representative keywords. The analysis of keywords also shows a greater emphasis on research into specific types of waste, such as “organic waste”, “food waste”, and “packaging waste”. The importance of research into these types of waste is because they represent the most typical waste generated worldwide, along with many possible negative impacts (economic, environmental and social) caused by incorrect management.

In general, an increase can be seen in the number of publications focusing on converting waste to energy. The energy recovery of waste in incineration plants provides an opportunity to reduce the amount of waste sent to landfill. Additionally, it can help reduce the dependency on energy generated by fossil fuels, which usually have to be imported [57]. However, the rise in publications is not in line with the hierarchy of waste, as established by organizations such as the European Parliament. This hierarchy prioritizes the adoption of methods to reduce the generation of waste, increase preparations for reuse and recycling, and discourages the use of incinerators and landfills, practices which are still common in parts of Europe and elsewhere. Analysis of the waste management systems (collection and treatment) is also important as they can reduce the generation of waste and increase the potential for reuse and recycling as opposed to incineration and landfills.

The economic aspect is of great importance, as it is a fundamental part of governmental and national decision making [15], but it is also important for the possible impacts (positive or negative) of MSW management systems, on society, and the environment, to be reflected in the costs and considered by decision-makers [61]. It can also be seen how this work does not consider an economic valuation of the impacts on society, nor the possible effects on public health, of the MSW management systems. Nevertheless, the effects on public health are a very important aspect of waste, as they are associated with every stage of the handling, treatment and elimination of waste, either directly or indirectly [62]. Therefore, the impacts on public health can be decisive factors in economically evaluating a MSW system.

This work can help researchers highlight different concepts and links between them, leading to further areas of research. In this case, this article reveals several trends in research. The first is the growing importance of the fields of EA and MEA, as shown by the increasing numbers of publications in the WoS. The second is the limited number of studies into developing methodologies for the economic analysis of externalities, which shows the need for more research in this field. In third place, the increasing interest in research into the use of waste to produce energy. The next emphasis is on the need for joint work by different universities (in different countries), as little collaboration has been observed. This collaboration would enable an exchange of knowledge and better management systems. Finally, more research is needed in this field from the developing countries.

Decision-makers will also find this work useful, as its results will help them to find the most economic systems and technologies, as well as the methodologies to evaluate these systems, thereby improving their decisions. Governments can develop policies, incentives, and regulations, based on the economic results of the different studies, to increase or discourage the use of certain technologies or management systems and thereby improve environmental, social or economic sustainability [63]. For the future, it is recommended that the search for articles is widened by the use of other well- known databases, such as Scopus [64]. Next, the search could be limited to a specific journal [18]. The third option would be to focus the bibliometric analysis of EA on treatment systems such as incineration, recycling and landfilling, among others. Finally, another interesting analysis would be to compare the number of results in terms of the three pillars of sustainability, the social, environmental, and/or economic areas.

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# A methodology for the technical-economic analysis of municipal solid waste systems based on social cost-benefit analysis with a valuation of externalities

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**Abstract:** Countries face a serious problem due to the generation and management of higher volumes of waste. Large-scale production of waste has promoted the establishment of various operations (collection, transport, treatment and disposal) for its management. When a MSW management system is implemented, it can generate different impacts or consequences (internal or external impacts). Generally, external impacts (social and environmental impacts) are not reflected in MSW economic analysis or taken into consideration in decision-making processes in regard to MSW management options. For this reason, the objective of this paper is present a methodology with which is viable to conduct the technical-economic analysis of Municipal Solid Waste management projects based on social Cost-Benefit analysis (sCBA) as it considers internal and external impacts. Its main objectives are to determine the total benefits (the

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difference between revenues and costs) generated by a project and to reduce uncertainty and risk of investing in particular MSW management system. Finally, a case study was carried out to verify the validity of the methodology through analysis and valuation of different impacts of a light packaging waste and bulky waste facility. Through the application of the methodology, it has been possible to visualize that this facility is viable operationally (BP = 42.94 €/ton) as economically (BT = 87.73 €/ton).

**Keywords:** Methodology; Economic analysis; social CBA; Municipal solid waste; Externalities; costs and revenues

## Abbreviation

| | |
|---|---|
| AB | Averting Behaviour Method |
| BTR | Benefit Transfer |
| CA | Complaint Assessment Method |
| CC | Control Cost Method (Abatement Cost) |
| CE | Choice Experiment or Choice Modelling Method |
| COI | Cost Of Illness |
| CUC | Clean-up Cost Method |
| CV | Contingent Valuation |
| DR | Dose Response Function |
| EAD | Experts' Assessment of Damage Costs |
| HP | Hedonic Price |
| HPF | Health Production Function |
| LCC | Life Cycle Costing |
| MSW | Municipal Solid Waste |
| MP | Market Price |
| OC | Opportunity Cost |
| PS | Substitute Price |
| PC | Productivity Change |
| RC | Replacement Cost Method |
| RP | Revealed Preference |
| sCBA | Social Cost-Benefit Analysis |
| SPR | Stated Preference |
| SP | Sale Price per Volume Unit |
| TC | Travel Cost Method |
| YOLL | Years of Life Lost |
| VSL | Value of a Statistical Life |
| WTP | Willingness to Pay |
| WTA | Willingness to Accept |

## Nomenclature

| | |
|---|---|
| AVW | Annual Volume of Waste Treated |
| $B_E$ | External Benefit |
| $B_P$ | Private Benefit |
| $B_T$ | Total Benefit |
| FC | Financial Costs |
| IC | Investment Costs |
| j | Impact index (j = 1, …, J) |
| J | Total Impacts |
| n | Project Year Index (n = 0, …, N) |
| N | Total Project Duration |
| NE | Negative Externalities |
| OC | Opportunity Cost |
| OMC | Operational and Maintenance Costs |
| PE | Positive Externalities |
| T | Taxes |

## 1. Introduction

Traditionally, the global economy operates through a linear model, where resources and raw materials are considered unlimited (Ellen MacArthur Foundation 2017). This traditional model generates significant waste as resources are used and discarded after minimal use and usually end up in open dumps or landfills. Due to the fact that the current amount of existing raw materials will not be enough to cover future demand and the vast amount of waste generated is managed incorrectly and unsustainably, a circular economy based on reuse, efficient recycling and recovery is fundamental along with a reduced reliance on primary raw materials in order to guarantee future demand (Ellen MacArthur Foundation 2017; European Commission 2015).

Countries face a serious problem due to the generation and management of greater volumes of waste caused by economic growth, industrialization and new economic models based on the idea of encouraging higher rates of consumption in society. According to Kaza et al. (2018), an estimated 2.01 billion tons of MSW were generated in 2016, and this number is expected to grow to 3.40 billion tons by 2050 under a business-as-usual scenario. The large scale production of waste has promoted the establishment of several operations (collection, transport, treatment and disposal) for its management (European Parliament 2008). When waste management is focusing on the management of household waste and waste similar in nature and composition to household waste, it is known as Municipal Solid Waste (MSW) management.

An aspect to consider in a MSW system is the collection system. According to González-Torre and Adenso-Díaz (2005), collection systems can be divided into curbside collection (door-to-door collection), neighbourhood collection (drop-off sites) and clean points (green points). Another system that is currently less used but that is gradually gaining importance is the pneumatic system. According to Teerioja et al. (2012), the pneumatic system is where waste collection points include one or several waste inlets, using a vacuum whereby waste is transported via underground pipelines to a waste terminal. MSW can be collected separately or mixed. In case of selective collection, waste is collected separately depending on the type of waste (organic, paper and cardboard, metal, glass, plastic and residual) to facilitate a specific treatment or disposal (European Parliament 2008; European Commission 2017). Another aspect to consider is the treatment system, this include recycling, composting or digestion (aerobic or anaerobic treatment of organic waste), incineration (thermal treatment with or without energy recovery, generally used for residual waste), landfilling and open dumping (Kaza et al. 2018; European Parliament 2000; European Commission 2017).

The MSW management systems can vary depending on the place or country where it is developed. In developed countries, the processes and systems are more complex and use more sophisticated tools and infrastructures. Generally, several types of waste collection and treatment systems can be observed depending on the waste type. In developing countries, the processes are generally simpler than developed countries, and a significant presence of an informal waste sector can be observed. In this case, MSW is usually disposed of in landfills or open dumps. According to Kaza et al. (2018), around the world, almost 40% of waste is disposed of in landfills. About 19% of materials are recovered through recycling and composting, and 11% of waste is treated through modern incineration. Although globally, 33% of waste is disposed of in open dumps, governments are increasingly recognizing the risks and costs of dumpsites and landfills.

The European Parliament (2017), emphasizes that it is necessary to develop MSW management and treatment capacities that are economically and environmentally viable. For this reason, it is necessary to develop a methodology that allows realizing an economic assessment of MSW systems, and that considers social and environmental impacts.  In this paper, we propose to adapt the methodology presented by Seguí et al. (2009) to realize a technical-economic analysis of MSW management systems. Seguí et al. (2009) present a methodology to realize a technical-economic analysis of wastewater regeneration and reutilization systems, where projects are analysed, considering private and external impacts. The objective of the methodology is to reduce uncertainty and risk of investing in certain MSW management system (Medina et al. 2019). This tool will allow decision-makers to analyse and compare different MSW management systems considering private revenues and costs and monetary valuation of externalities.

When a MSW management system is implemented, it can generate different impacts or consequences, that can be reflected as costs or revenues if stakeholders are affected negatively or positively. Generally, an economic-financial analysis of MSW management systems focuses on the study of internal or private impacts (costs and revenues related with OPEX and CAPEX), as in Al-Salem et al. (2014) and Aleluia and Ferrão (2017). According to Nahman (2011), when economic analysis is only focused in internal impacts, this can generate a bias against alternatives such as recycling (more expensive than landfills from a financial perspective, but preferable from an environmental and social perspective). External costs and revenues are usually more difficult to quantify in monetary terms and are not usually reflected in waste management costs and decisions. Despite this, external impacts are not of minor importance, since can practically cause censorship of the project or its economic viability.

Usually, only a few environmental or social impacts are considered in the literature, as in Woon and Lo (2016), where only opportunity cost of land, external environmental costs due to air pollution, and disamenity costs are considered. Despite this, there are some papers where an extensive review of the main impacts has been realized as in Eshet et al. (2006) where is provided with an overview of externalities costs associated with various types of pollution and disamenities related to landfill and incineration of MSW, including different valuation methods. In Weng and Fujiwara (2011) are presented potential impacts of MSW management. Meanwhile, some evaluation methods are suggested herein.

On the other hand, from a review of the literature, it is determined that there are not documents that collect and group, in a methodological way, the identification and description of the most relevant impacts to be considered when a project is implemented for MSW management. The most relevant studies, where methodologies for the economic analysis of the MSW management systems have been presented, are Martinez-Sanchez et al. (2015) and Mavrotas et al. (2015). In Martinez-Sanchez et al. (2015), a cost model for the economic assessment of MSW management systems is presented. This model is based on the principles of LCC and is only considered the following external costs: environmental emission and society's willingness to pay to avoid emissions or impacts of MSW systems. In Mavrotas et al. (2015), a multi-objective mathematical programming model is developed to determinate the optimal solutions for a MSW management system. In this model are considered the following external costs and revenues: atmospheric pollution impacts, impacts on soil and groundwater, impacts on quality of life, electricity use or displacement and fertilizer use reduction from compost (Mavrotas et al. 2015). Currently, most relevant impacts of MSW management systems have been documented in isolation, generally as a reflection of specific solutions for specific case studies as in Jamasb and Nepal (2010), Massarutto et al. (2011), Sasao (2004), Rabl et al. (2010) and Gaglias et al. (2016).

The methodology developed in this paper takes into account not only the private impacts (internal costs and revenues) but also the social and environmental impacts (external costs and revenues) of the MSW management projects. In this case, the proposed methodology is based on sCBA, that evaluates a project from the viewpoint of society as a whole where external costs caused by environmental and social impacts are considered (Hoogmartens et al. 2014). Social CBA has been chosen for methodology development due to its simplicity and easy understanding for any decision-maker. Besides, it will allow individual visualization of two types of impacts (private and external).

This paper is organized into four sections. Next presents the methodological approach. Section 3 includes a study case regarding light packaging waste and bulky waste treatment facility, which allows validating the methodology. Finally, discussion and conclusions are in Section 4.

## 2. Methodology Proposal

This section provides a description of the methodology developed for the technical-economic assessment of MSW management systems (Medina et al. 2019). The methodology is constituted by seven steps that should be fulfilled for its application (Medina et al. 2019), as shown in Fig. 1: 1) objective definition, 2) definition of the study scope, 3) project impacts, 4) identification of involved stakeholders, 5) study of financial necessities and possibilities, 6) aggregation of costs and revenues, and 7) sensitivity analysis.

The objective of the methodology is to reduce uncertainty and have a tool to determine if the infrastructure projects for waste management are economically, socially and environmentally viable. This methodology can be applied to different MSW management infrastructures (such as landfills, incineration plants and composting plants), collection systems (curbside collection, neighbourhood collection, clean points) and different types of waste stream. Based on sCBA principles, this paper aims at providing a consistent and comprehensive framework for the economic assessment of MSW management systems. One of the significant contributions of the present methodology is the recompilation and inventory of the impacts related to waste management systems. The purpose is to generate a tool that allows those responsible for decision making, in the field of MSW management, to issue a technologically and economically supported judgment to invest or not in certain management systems.

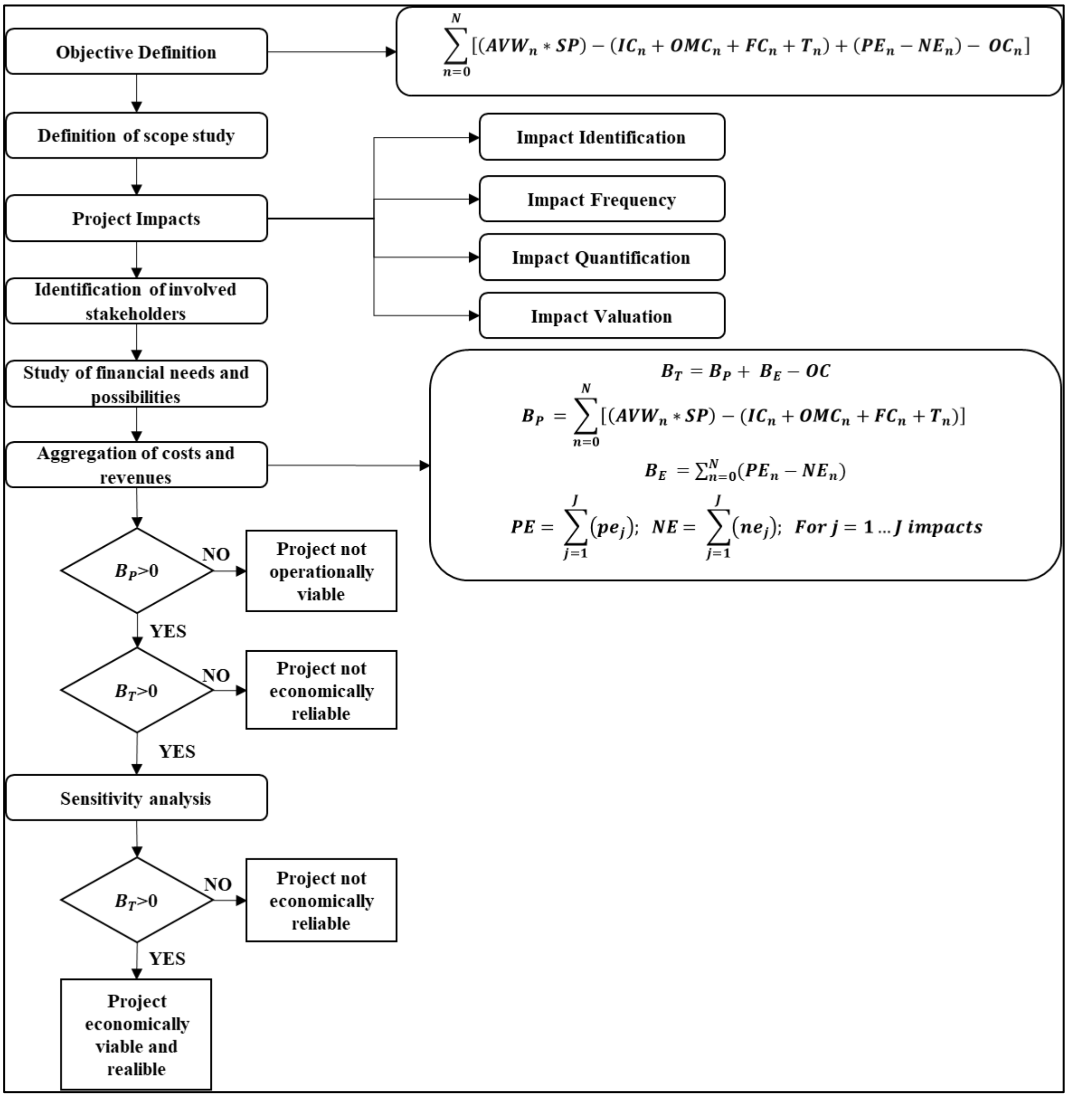


Fig. 1. Steps for technical-economic analysis to evaluate MSW management systems. Adapted from Seguí-Amórtegui et al. (2014).

## 2.1 Objective Definition

The objective of the technical-economic analysis is to evaluate MSW management systems, by obtaining Total Benefit (the difference between revenues and costs) of a specific stakeholders in determinate MSW management infrastructure (such as composting, recycling, incineration or landfill facilities) and/or determinate collection systems considering private and external impacts. The objective function to optimize is presented in Eq. (1):

$$\boldsymbol{B_T} = \sum_{n=0}^{N}[(AVW_n * SP) - (IC_n + OMC_n + FC_n + T_n) + (PE_n - NE_n) - OC_n] \quad (1)$$

## 2.2 Definition of the study scope

Definition of the study scope is the step that consists in determining and defining the area of analysis considering a specific geographic area, characteristics of MSW management system to be analysed (collection and/or treatment system, type of waste, among others) and boundaries of the system.

This step is fundamental to be able to delimit the influence of the project and thus be able to determine impacts that occur within this scope.

### 2.3 Project Impacts

Project impacts will be defined as any consequence of the implementation of a MSW management system, wanted or not, generally capable of being measurement, in a determined study scope. Private and external impacts will be distinguished (Seguí-Amórtegui et al. 2014).

The private or internal impacts are those directly related to the treatment process of MSW and later reuse. These are costs and revenues incurred by the investor or project developer. The negative private impacts pertain to the financial expenditures associated with investing (CAPEX) and operating (OPEX) of MSW management systems (Aleluia and Ferrão 2017). In positive private impacts are included revenues for the sale of recycled waste or energy generated from incinerator facilities.

On the other hand, external impacts or externalities (for example, the affectation to third parties, control of pollution, the increase in the availability of a resource or the guarantee in the supply, among others), refer to those that are directly or indirectly caused by the operation of the facility, but whose effects are generally borne by a party other than its owner or operator (Aleluia and Ferrão 2017). The externalities are generally related to social and environmental impacts.

#### *2.3.1 Impact Identification*

A compilation and inventory of the impacts of MSW management systems was carried out through a bibliographic review from specialized sources on waste, including public and scientific databases such as Science Direct, Web of Knowledge, Scopus, European Commission, World Bank and US Environmental Protection Agency where scientific articles and reports were obtained.

The objective of this section is to provide, for a person responsible for applying the methodology, a global vision of the most relevant impacts, covering the greatest number of them, in such a way that this methodology complies with a principle of generality and can be applied in any MSW management system. A summary of MSW System impacts is presented in Table 1, where seven impact groups are considered.

Table 1. Summary of MSW Systems Impacts.

| Impact group | Description of impacts |
|---|---|
| Infrastructure | Collection |
| | Transportation |
| | Pre-treatment and Treatment |
| | Final Disposal |
| Reuse, recycling and recovery of waste | Glass |
| | Plastic |
| | Paper and paperboard |
| | Organic material |
| | Energy (electricity or heat) |
| | Gate fees |
| Use of materials | Guarantee of supply |
| | Quality of materials |
| Public Health | Physical Risks |
| | Chemical Risks |
| | Biological Risks |
| Environment | Emissions to groundwater and surface water |
| | Emissions to air |
| | Emissions to soil |
| Education | Technique of workers |
| | Culture of reduction, reuse and recycling of waste |
| Quality of life | Disamenities: odour, dust, wind-blown litter, visual intrusion, noise |

**Infrastructure.** In this impact group are included private costs (capital expenditures, operational and maintenance expenditures) related to infrastructures for MSW management (such as bins, containers, collection and transportation vehicles, treatment facilities and disposal sites). These type of costs have been widely analysed in studies such as Aleluia and Ferrão (2017) and Jamasb and Nepal (2010).

In capital expenditures (CAPEX) are included costs associated with the construction, equipment and installation, land use and preparation and loan interest (Aleluia and Ferrão 2017). In Operational and Maintenance expenditures (OPEX) are included costs related to labour, equipment maintenance and repair, raw materials and inputs (energy, fuels, among others) and depreciation charges (Aleluia and Ferrão 2017). The impacts to be analysed within this group are:

a. <u>Collection infrastructure.</u> According to Debnath and Bose (2014), including the cost of labour, containers, vehicles and tools and the cost of other direct and indirect expenses to collect wastes from the source. Besides, this would also include the cost of cleanliness/hygiene of roads and drains in municipal wards (Debnath and Bose 2014).

b. <u>Transportation infrastructure.</u> According to Debnath and Bose (2014), including the cost of running motorized equipment and vehicles to transfer and transport wastes; also repairs and maintenance of vehicles, depreciation of vehicles and other equipment (Debnath and Bose 2014).

c. Pre-treatment and Treatment Infrastructures. Included the cost of equipment, labour, tools and inputs of MBT plants, biological treatment facilities such as composting and digestion plants, incineration facilities and materials recycling facilities (Debnath and Bose 2014). Besides, it is considered repairs and maintenance of equipment and depreciation charges.

d. Final Disposal infrastructures. This included the cost of landfilling, depreciation of sanitary landfills, waste handling and maintenance expenses of landfill sites (Debnath and Bose 2014).

In some countries or cities, a state government tax is imposed on all waste disposed to landfill or treated in an incineration plant. Consequently, this entails payment of a determined amount per ton of waste treated.

**Reuse, recycling and recovery of materials.** Included in this impact group are expected revenues from sales for reuse, recycling or recovery of materials in MSW treatment facilities. According to European Commission (2014), typical sources of revenues are: the application of charges to users (to households or to enterprises), either in the form of collection and disposal management fees or taxes; the sale of sub-products such as compost, recycled materials (plastic, glass, paper and cardboard), refuse-derived fuel or solid-recovered fuel or the sale of the energy recovered such as heat and electricity. In the case of recycled materials and energy recovered, there is a market for these goods and consequently, a sale price fixed by the market.

According to Eunomia Research & Consulting (2001), when MSW system is analysed from perspective of an entity that provides its services to a third party (such as a consortium or a government entity), it will receive a gate fee paid, that represents a unit payment (usually per ton) made by the local authority to the service provider to generate a revenue. According to European Commission (2014), the revenue is calculated based on the price paid for the waste processing service and not on the sales price of the materials.

On the other hand, when the system is analysed from perspective of an entity that manages all management processes, revenues from user fees paid for waste management services as well as from sale of recovered materials or energy generated will be received (European Commission 2014).

**Use of resources.** This impact group is related to needs that are satisfied, as well as benefits obtained, of waste used in several applications. For example, composted MSW can be beneficially used in a variety of applications from general landspreading for agronomic and silvicultural crop production to homeowner use (Shiralipour et al. 1992). On the other hand, use of MSW for energy generation can reduce dependence on energy generated from fossil sources, or use of recycled plastic can reduce dependence on fossil feedstocks. This group is determined by factors related to availability and supply guarantee and quality of recycled materials.

a. Guarantee of supply. This impact is related to the value that users place on the guarantee of raw materials or/and energy supply, in a resource scarcity context. A constant generation of waste could guarantee generation of energy from waste incineration and biomass and remanufacturing of recycled products. According to Risch (1978), for some countries seriously lacking primary natural resources, waste represents the most secure raw materials, which will enable them to reduce dependence on imported raw materials, to realize considerable energy savings and to contribute to environmental conservation. Consequently, an external benefit, due to reduction of costs generated for excavation of raw materials is obtained. On the other hand, in modern economies, energy used for productive activities is generated from fossil fuels, representing a cheap source. However, fossil fuels are non-renewable and therefore limited. As populations grow and economic development increases, the demand for energy rises. The energy recovered replaces the use of energy from alternative sources. Consequently, an external benefit is obtained due to the reduction of costs generated by the production of energy from fossil sources (Tong et al. 2018). For example, Lim et al. (2014) evaluate options to measure the external benefits of Waste to Energy facilities, considering four attributes or types of benefits: the improvement of energy security, reduction of GHG emissions, job creation, and extension of landfill life expectancy. In this case, energy security is related to as the uninterrupted availability of energy sources at an affordable price (Kim and Kim 2015).

b. Quality of materials. The recycled materials must be provided in sufficient quantities and acceptable quality which will not alter (or negatively effect) properties of products. Given these considerations, it is essential to provide manufacturers with a sufficient volume of high-quality recyclable materials at a price that is competitive with primary raw material. Not all uses require the same quality, so it is necessary to determine possible alternative uses for different qualities of waste. In some cases, buyers have incomplete information about the suitability of a given waste for a particular use. For example, in the case of recycled paper, which in the initial stages of market development was perceived to be of lower quality for numerous uses for which it was perfectly appropriate (Loughlin and Barlaz 2006). According to Milios et al. (2018), MSW compost generates of organic waste from MBT facilities can contain high levels of heavy metals and physical and biological contaminants. Although there is a risk that the application of MSW compost will increase the heavy metal content of agricultural soils, MSW compost has the potential to play an extremely beneficial role in the remediation and regeneration of a variety of contaminated and post-industrial sites. According to Loughlin and Barlaz (2006) another factor affecting the decision on whether to use recycled content is the appeal of recycled content to environmentally conscious consumers. Borchers et al. (2007), designs a choice experiment for estimating consumer preferences and willingness to pay (WTP) for voluntary participation in green energy electricity programs. The results show that there exists a positive WTP for green energy electricity.

**Public health.** According to Giusti (2009), "Health issues are associated with every step of the handling, treatment and disposal of waste, both directly (via recovery and recycling activities or other occupations in the waste management industry, by exposure to hazardous substances in the waste or to emissions from incinerators and landfill sites, vermin, odours and noise) or indirectly (e.g. via ingestion of contaminated water, soil and food)" (p. 2230). Therefore, public health impacts can be decisive factors when evaluated within a specific MSW system.

In this impact group are included damages to public health, and these can be evaluated from the point of view of workers, which can include the formal or informal sectors and populations living nearby MSW facilities. For example, in the case of developing countries, we can find informal collectors that collect recyclable materials in non-controlled landfills. These people work in environments of intensive work that are unregulated, poorly paid, unregistered and environmentally dangerous. Generally, informal recyclers experience various occupational health hazards, including stomach diseases, skin diseases, kidney and liver problems, back pain, cuts, burns, and fractured bones (Uddin and Gutberlet 2018). According to Zolnikov et al. (2018), the most common health effects are musculoskeletal diseases, injuries, and psychological disorders. In case of populations living nearby MSW facilities, for example, young children living in the landfill slum are more likely to develop diarrhoea and adverse health effects (e.g. infections and poisoning) than their general population counterparts (Shibata et al. 2015).

Human exposure to substances released at MSW management facilities can be 1) acute in case of a serious accident causing short term exposure to high levels of potentially hazardous substances and 2) chronic when it involves long-term exposure to low concentrations of these substances (Giusti 2009). According to Giusti (2009), the health and safety performance of the waste management industry is likely to vary significantly across the world, with major differences between developed and developing countries.

This impact group mainly considered: 1) physical risks, related to exposure to noise, ionizing radiation, and temperature; 2) chemical risks, related to exposure to gases, vapours, fumes, and chemicals and 3) biological, including exposure to viruses, bacteria, blood and blood products (Volquind et al. 2013). The human body can absorb these pollutants through different routes of exposure (inhalation, ingestion and dermal contact).

a. Physical risks. In landfills, the risks include surface, and underground fires and explosion hazard relate to biological decomposition processes (European Commission 2000). Landfill fires create a problem for landfill operators as these fires are mainly caused by spontaneous combustion, combustion due to high temperature in the absence of flame. Moqbel et al. (2010) investigate the effect of moisture content, oxygen concentration and leachate components on spontaneous ignition, combustion initiation, and self-heating of solid waste. On the other hand, Black et al. (2019) describe the health and occupational risks of informal waste collectors in Kathmandu Valley, Nepal; the results show that prevalent physical risks included injuries for glass cuts and metal cuts. The work was considered risky, but workers did not use Personal Protective Equipment.

b. Chemical risks. MSW facilities can emit several chemical pollutants such as dioxins, volatile organic compounds (VOCs), heavy metals, among others. Dioxins, such as PCDD/PCDFs, are present in incineration processes and can enter the body via inhalation, skin absorption and ingestion pathways. PCDD/PCDFs are environmental pollutants with potential carcinogenic effects (Domingo et al. 2017). According to the World Health Organization (2010), short-term exposure to high levels of dioxins and dioxin-like substances in occupational settings may cause skin lesions known as chloracne. Longer-term environmental exposure causes a range of toxicity, including immunotoxicity, developmental and neurodevelopmental effects, and effects on thyroid and steroid hormones and reproductive function. Several studies have evaluated the health risk of these pollutants including Zheng et al. (2008), J. Li et al. (2018), Domingo and Nadal (2009), Domingo et al. (2017), among others.

c. On the other hand, VOCs are present in landfill and composting processes and can cause adverse effects on health, in relation to both general toxicity and carcinogenicity. According to Domingo and Nadal (2009), "concerning adverse health effects of VOCs, an especial emphasis on the following compounds must be done: benzene and 1,3-butadiene, as potentially inductive agents of leukaemia; formaldehyde, as a nasal carcinogen potential; and certain Polycyclic aromatic hydrocarbons (PAHs) as compounds potentially inductive of cancer" (p. 384). According to Domingo and Nadal (2009), organic material contains a number of chemical and biological agents that can affect health of composting plant workers or consumers of vegetables grown in crops treated with compost. In the case of chemical risks, these are considered to be mainly ingestion of products cultivated in soils treated with compost and inhalation of toxic agents present in atmospheric dust of compost. Finally, according to Ma et al. (2018) a MSW Incinerator had a significant influence on human health risks mainly through heavy metals emissions (Pb and Ni). Heavy metals could pose high non-carcinogenic and carcinogenic risks. Vegetable ingestion and dermal absorption were the main exposure pathways to both non-carcinogenic risk and carcinogenic risk.

d. Biological risks. Biological risks are less known and analysed than chemical and physical risks. According to Van Tongeren et al. (1997), bioaerosol or organic dust can be defined broadly as dust of vegetable, animal, or microbiologic origin, and workers handling waste can be exposed to enteric viruses, infectious microorganisms, endotoxin-containing bacteria, allergenic fungi, and parasitic protozoa. Biological agents may act as infectious, allergenic, toxic, or carcinogenic agents in humans (Dutkiewicz et al. 1988). Health risks exist because bioaerosols can produce pulmonary inflammation (acute inflammation, hypersensitive pneumonitis), occupational asthma, and chronic bronchitis (Domingo and Nadal 2009). Specifically, health risks are indicated because bioaerosols have been reported to occur in workers involved in the waste industry including gastrointestinal symptoms, the ODTS (organic dust toxic syndrome), infections and irritation of eyes, ears, and skin, and occupational asthma (Van Tongeren et al. 1997).

**Environmental.** The use of certain MSW systems can have different consequences for the environment. Some MSW management options can propitiate a major emission of contaminants than others or save of primary energy. These emissions can affect agricultural performance, damage buildings and promote global warming. In this impact group are included: 1) Emissions to air, 2) Emissions to soil and 3) Emissions to groundwater and surface water. Table 2 shows the main contaminants present in the different MSW management systems.

a. Emissions to soil. Soil pollution is mainly due to the uncontrolled dumping of waste or leachate from landfills. The leachate represents a major environmental burden related mainly to landfill sites operation, with impacts in soil, groundwater and surface water pollution (Mavrotas et al. 2015). In Ma et al. (2018), eight elements, Chromium (Cr), Lead (Pb), Copper (Cu), Nickel (Ni), Zinc (Zn), Cadmium (Cd), Mercury (Hg), and Arsenic (As), in fly ash were identified through collection of soil samples from different functional areas and vegetables from areas surrounding the MSW Incinerator in China. The results showed that the soils around the MSW Incinerator were moderately polluted by Cu, Pb, Zn, and Hg, and heavily polluted by As and Cd. External benefits associated with compost includes calculation of avoided burdens from fertiliser and pesticides production and avoided nitrous oxide emissions from nitrate fertiliser application (Mavrotas et al. 2015).

b. Emissions to air. Impacts to air quality are caused mainly by greenhouse gases emissions, generally from landfills and other treatment facilities. Additionally, combustion gases emission with polluting compounds such as particulates, heavy metals, organic compounds, dioxins, among others, can cause damages to environmental. Contaminants typically found in the flue gas of incineration plants include particulates, dioxins, heavy metals and their compounds (especially Cd, Thallium (Tl) and Hg), acid gases (SO2, HCl, HF), nitrogen oxides (NOx), carbon dioxide (CO) and volatile organic (European Commission 2000). Effects on ecosystems and fauna arise from the same pollutants, especially those that bioaccumulate, such as dioxins, and heavy metals. Lower agricultural yield, forest die-back and damage to buildings can occur from emissions of acid gases and NOx, with particulates also causing damage to buildings (European Commission 2000). In landfill, trace gases are present, and over 100 different types of VOCs have been identified, such as benzene and vinyl chloride (European Commission 2000). The main components of landfill gas are methane (CH4) and carbon dioxide ($CO_2$); these are the main greenhouse gases. Composting plants generate VOCs; the characteristics of VOCs emitted from different units at a composting plant were investigated in Nie et al. (2018). A total of 44 VOCs (including alkanes, alkenes, aromatic compounds, halogenated compounds, oxygenated compounds, and sulfur-containing compounds) were identified and quantified. On the other hand, according to Massarutto et al. (2011) savings can be expected for materials recovery in terms of primary energy and $CO_2$, by the recycling of selected materials (such as glass, paper, plastics, metals and wood).

c. Emissions to groundwater and surface water. Emissions to water can result from the discharge of wastewater from incineration plants with wet flue gas cleaning systems, and this contains many pollutants including suspended solids (particulates), dioxins, and heavy metals (European Commission 2000). Currently, damages caused by waste in water bodies must be considered and evaluated. Ellen MacArthur Foundation (2017) estimated that there are over 150 million tons of plastics in the ocean today. In a business-as-usual scenario, the ocean is expected to contain 1 ton of plastic for every 3 tons of fish by 2025, and by 2050, more plastics than fish (by weight). According to W. C. Li et al. (2016), the oceans currently have a high accumulation of plastic waste, which can be macroplastic and microplastic, which represent a risk for organisms in the natural environment, for example, through ingestion or entanglement in plastic.

Table 2. Pollutant emissions of MSW transport and treatment.

| Environmental Impact | Treatment | | | | Transportation |
|---|---|---|---|---|---|
| | Incineration Plant | Landfill | Composting Plant | Recycling facility | |
| Emissions to surface water | Dioxins/ dibenzofurans (PCDD/PCDFs) | | | | |
| | | Leachate | | | |
| | Heavy metals | | | | |
| | Salts | | | | |
| Emissions to air | Particulates ($PM_{10}$) | | | | $PM_{10}$ |
| | NOx | | | | NOx |
| | $SO_2$ | | | | $SO_2$ |
| | CO | | | | |
| | $CO_2$ | $CO_2$ | $CO_2$ | $CO_2$ | $CO_2$ |
| | VOCs | VOCs | VOCs (2) | | |
| | HCl, HF (acid gases) | | | | |
| | Dioxins | Dioxins | | | |
| | Heavy metals | | | | |
| | $N_2O$ | | | | |
| | | | Bioaerosols | | |
| | | $CH_4$ | $CH_4$ | | |
| Emissions to soil | | Leachate | Leachate | | |
| | Heavy metals (1) | Heavy metals | | | |
| Avoided emissions | $CO_2$, $SO_2$, NOx, and other air pollutants emitted from electric power generation plants | | $N_2O$ by use of fertilizer | Primary energy and $CO_2$ by extraction of raw material | |

(1) Cr, Pb, Cu, Ni, Zn, Cd, Hg, and As (Ma et al. 2018)
(2) Alkanes, alkenes, aromatic compounds, halogenated compounds, oxygenated compounds, and sulfur-containing compounds (Nie et al. 2018)

**Education.** In this impact group are considered benefits due to change in the behaviour of workers or citizens through training or awareness programs. These programs would encourage improved processes of MSW management systems and be able to satisfy the needs and requirements of customers in terms of quality and quantity. In this impact group are included: Technique education, related to training programs that allow a human capital of first level and promotion of reduction, reuse and recycling culture, related to awareness programs for citizens focused on waste reduction, reuse and recycling.

a. Technique Education. A responsible and professionalized staff encourages a positive effect on productivity, a reduction of operating costs and maintenance of MSW facilities and positive repercussions in the environmental field. It should be noted that in order to achieve a change in the behaviour of workers, investments must be made in training courses. According to Mital et al. (1999), training leads to acquiring new skills and/or improvements in existing skills. These, in turn, lead to two economic benefits: 1) improvements in individual choices and earnings, and 2) cost savings for the organization. Economic benefits of training for organizations include significant improvements in productivity (through improvements in quality, reduction in scrap and waste, reduction in throughput time, greater flexibility to respond to needs, among others), and a competitive advantage to employers (Mital et al. 1999). In this impact group are included formalization activities for the informal waste sector. For this to occur, it is necessary to develop environmental education programs, skills development training, sorting and storage areas, social services and to provide adequate equipment (for example safety equipment, tools, uniforms). According to Ezeah et al. (2013), training programs can educate the workers to efficiently and effectively add value to the recovered materials (i.e. to clean, bale, crush or sort recovered materials). Uddin and Gutberlet (2018) recommend that public policies address the livelihood issues of these informal recyclers and further stimulate their organization, maybe into recycling groups, associations or co-operatives, for the purpose of collective empowerment. This can have positive benefits to reduce occupational health hazards and to conduct the work more effectively.

b. Culture of reduction, reuse and recycling. The implementation of environmental education programs for citizens can focus on waste reduction, recycling and recovery. Carrying out these programs will allow improvement of waste quality and the environment in general. It must be considered that in order to achieve a change in the behaviour of citizens, investments must be made in trained personnel for social and communication areas, dissemination expenses and program implementation. Some examples about this impact are presented in Xiao et al. (2017), where research and survey was conducted in Xiamen (China), a city that has been operating pilot waste separation programs since 2000. A model was used to identify the key factors that influence the willingness of citizens to participate in waste management, and this indicates that the factors of greatest influence are citizen knowledge, followed by social motivation, while institutional factors had the least positive effect. Several studies indicate that improving public participation can be achieved by providing better and more information, better means of communication, improving waste collection and disposal facilities, public advertising and community regulations. Consequently, this could improve the quality of the classification of household waste (Latinopoulos et al. 2018; Miliute-Plepiene et al. 2016; Xiao et al. 2017)

**Quality life.** Some MSW facilities (such as landfills and incinerators) are usually associated with disamenities (degrees, dust, visual intrusion, odour) that arise because of the mere existence of these facilities (Eshet et al. 2006). Generally, people are against the establishment of MSW facilities near their households due to the disamenities generated. The disamenities affect prices of local properties because welfare impacts experienced and can generate the NIMBY (not in my backyard) syndrome. The effectiveness of any MSW management system depends on its acceptance by the local community (Achillas et al. 2011). According to Hite et al. (2001), the greater the distance between MSW facilities and households, a higher level of welfare can be achieved, consequently is presented a higher property value due to higher levels of environmental quality.

According to Eshet et al. (2006), MSW facilities causes, in various degrees, dust, visual intrusion, odour, noise and traffic and landfills are also associated with disamenities as seagulls, vermin, and flies, and an incinerator is generally related to visual intrusion via the smokestack. The magnitude of the effects will depend on distance from the site, type of waste, type of site, topography and wind direction (Eshet et al. 2006). Several studies have analysed disamenities such in Sasao (2004), where public preferences were examined regarding a landfill site using a Choice Experiment. The results show that the NIMBY (not in my backyard) syndrome of the residents in the surrounding area of the landfill is observed to weaken at a decreasing rate, as the landfill is sited farther away. Hite et al. (2001) quantified the property-value impacts of change in environmental quality by using a hedonic price model, focusing on the impact of the presence of landfills on nearby residential real estate prices.

*2.3.2 Impact Frequency*

Each of the stakeholders involved in the project receives certain impacts that must be located throughout the life of the project. It is essential to consider the moment in which each impact occurs. A project can present impacts (internal or external) at the beginning of the project, during or after the life of the project (some facilities can present impacts after the close).

*2.3.3 Impact Quantification*

Some impacts can be quantified directly in monetary units. However, it will often be necessary to translate environmental and social aspects in monetary values, in order to work in homogeneous units, that allow the addition of total costs and revenues in MSW systems.

Consequently, it is necessary to define the units that these environmental and social aspects have for each of the impacts studied. These units will then be the basis for economic valuation. All these quantification units should be referenced to a set time in the frequency of impacts. In order to homogenize the results, it is proposed that everything is referenced per year.

*2.3.4 Impact Valuation*

As mentioned above, some impacts can be quantified directly in monetary units. However, defining external costs generally requires application of specific methods developed in environmental and resource economics (Dahlbo et al. 2007). According to OECD (2006), economists have developed a range of approaches to estimate the economic value of nonmarket or intangible impacts. There are several methods that share the common feature of using market information and behaviour to infer the economic value of external impact. These procedures are known as Valuation techniques.

Eshet et al. (2005) presented a classification of the methods and techniques, described briefly below. For more information about valuation methods applied in relation to waste management refers to Eshet et al. (2005) such as Averting Behaviour Method, Benefit Transfer, Complaint Assessment Method, Control Cost Method (/Abatement Cost), Cost Of Illness, among others. In Eshet et al. (2006)a is considered Value of Statistical Life (VSL) or Years of Life Lost (YOLL) for the assessment of external costs associated with human health.

### 2.4 Identification of involved stakeholders

After MSW system impacts have been identified, the stakeholders involved can be recognized. According to Littau et al. (2010) “Stakeholders are individuals, groups or institutions with interest in the project, and who can affect the outcome” (p. 22). For analysis of MSW management systems, the following will be considered as stakeholders: 1) Government entities (municipalities or utilities), 2) Consortia for materials recycling or recovery (glass, plastic, among others), 3) Waste management private companies and 4) Citizens. In addition to identification of stakeholders, it is important to define the stakeholder for which evaluation is done since it will depend on the treatment given to the information and impacts that will be considered.

### 2.5 Study of financial needs and possibilities

It is necessary to determine financial needs required for implementation, operation and maintenance of projects. Determining financing sources and conditions is an important aspect to consider before realizing the next step (aggregation of costs and revenues). On the other hand, financing conditions are an important point to consider in the sensitivity analysis.

### 2.6 Aggregation of costs and revenues

The aggregation of costs and revenues will allow a decision to be made about whether or not to invest in certain MSW management systems. In this methodology, it is proposed to express the costs and revenues in monetary units per ton of waste or monetary units per year. According to D. Pearce et al. (2006), revenues are defined as increases in human wellbeing and costs are defined as reductions in human wellbeing. For a project or policy to qualify on cost-benefit grounds, its social benefits must exceed its social costs.

The main objectives of the methodology are determined total benefits of a project and to visualize two situations separately. First, that the MSW management system is economically and financially viable for its operation, which is defined by the determination of private benefit (a situation that normally interests the technicians and politicians); and second, that the MSW management system is economically, financially, socially and environmentally viable (which interests economists and society).

*2.6.1 Total Benefit*

The main objective of the economic analysis of MSW systems is to find the Total Benefit ($B_T$). This is obtained from the sum of Private Benefit ($B_P$) and External Benefit ($B_E$) and subtraction of Opportunity Cost (*OC*). The objective function is presented in Eq. (2):

$$B_T = B_P + B_E - OC \tag{2}$$

*2.6.2 Private Benefit*

The Private Benefit ($B_P$) is obtained by subtracting Private Costs (*PC*) from Private Revenues (*PR*). This private revenue is the result of the product of the Sale Price of recovered products (*SP*) (e.g. plastic, glass, paper, cardboard, compost or energy) per Annual Volume of Waste treated or energy generated (*AVW*). On the other hand, the private costs are assembled from the sum of the Investment Costs (*IC*), Operational and Maintenance Costs (*OMC*), Financial Costs (*FC*) and Taxes (*T*). The taxes considered here refer to the payment of tax lien according to the tax base corresponding to a private company that provides the service of MSW management. For the calculation of taxes, it is necessary to consider the amortization or depreciation of the invested capital. The function is presented in Eq. (3)

$$B_P = \sum_{n=0}^{N} [(AVW_n * SP) - (IC_n + OMC_n + FC_n + T_n)] \tag{3}$$

When the Private Benefit ($B_P$) obtained is bigger than zero, it will guarantee that the MSW project is operational economically and financially from the private point of view.

*2.6.3 External Benefit*

The externalities are obtained from positive and/or negative impacts that generate with the implementation and exploitation of MSW project. These impacts have been described in a detailed way in section 2.3 (Project Impacts), which must be located throughout the life of the project, quantified and valued in monetary units. Thus, the benefit of externalities ($B_E$) would be given by Eq. (4) where is subtracting Negative externalities (*NE*) from Positive externalities (*PE*).

In the case of $PE$ is given by sum of external revenues and $NE$ is given by sum of external costs. The functions of $PE$ and $NE$ are presented in Eq. (4a) and Eq. (4b), respectively.

$$B_E = \sum_{n=0}^{N} (PE_n - NE_n) \quad (4)$$

$$PE = \sum_{j=1}^{J} (pe_j); \; For\ j = 1, \ldots, J\ impacts \quad (4a)$$

$$NE = \sum_{j=1}^{J} (ne_j); \; For\ j = 1, \ldots, J\ impacts \quad (4b)$$

*2.6.4 Opportunity Cost*

According to David W. Pearce (1992), "Opportunity cost can only arise in a world where resources available to meet wants are limited so that all wants cannot be satisfied. If resources were limitless no action would be at the expense of any other - all could be undertaken - and opportunity cost of any single action, the value of the "next best" alternative, would be zero. Clearly, in a real-world of scarcity, opportunity cost is positive" (p. 315).

The concept of opportunity cost applied to MSW systems can be explained from two main conditions. First, when there are several alternatives for the use of waste, opportunity cost will be given by the use that provides best economic performance; as long as, these yields are higher than those of financial instrument. Second, when there are no alternative uses, opportunity cost comes from the performance that provides some financial instrument, when investment, exploitation and maintenance costs are invested in this one. According to the United Nations (2015), Sustainable Development is defined as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. For sustainable development to be achieved, it is crucial to harmonize three core elements: economic growth, social inclusion and environmental protection. These elements are interconnected, and all are crucial for the well-being of individuals and societies. It is considered that sustainable development has three pillars: environment, assurance of continued integrity of natural resources; society, assurance of continued human health and well-being; and economy, assurance of continued economic prosperity (Fiksel et al. 2012). Traditionally, an opportunity cost is only considerate of maximizing profits. However, under the concept of Sustainable Development and its three pillars, the best alternative will be one that not only provides the best economic performance, but also best social and environmental performance.

## 2.7 Sensitivity analysis

Sensitivity analysis is a tool for studying the robustness of results and their sensitivity to uncertainty factors. According to European Commission (2014), sensitivity analysis is carried out by varying one variable at a time and determining the effect of that change. The sensitivity analysis evaluates the robustness of the project to possible changes in economic variables. The main variables to perform a sensitivity analysis are 1) discount rate, 2) financing conditions, 3) opportunity cost, 4) sale price of waste treated, 5) energy costs, among others.

Once the variables have been modified, and the final benefit remains positive, we can conclude that the project has confidence in its implementation and exploitation, since it could be shown that despite possible pessimistic scenarios, the project continues to be profitable.

## 3. Case of Study: Light packaging waste and bulky waste treatment facility

Considering the need to validate the methodology, this section is dedicated, through a study case, to apply social Cost-Benefit analysis (sCBA) into a light packaging waste and bulky waste treatment facility. SEMESA, (by its name in Catalan Selectives Metropolitanes S.A.), it is a company that belongs to the TERSA group and the Barcelona City Council.

It is a public company that operates in the metropolitan area of Barcelona, Spain. Its main objectives are to manage environmental services related to the circular economy focused on recovering waste and the promotion of citizen commitment to sustainability. This company is dedicated to the public service of selection and treatment of light packaging waste (yellow container) and the treatment of bulky waste by selective collection from Barcelona and its metropolitan area. The facility is located in Gavà-Viladecans, Barcelona, Spain. It is mainly surrounded by land for industrial and agricultural use and protected natural areas. The seven steps of the methodology applied to the case study of SEMESA are presented below.

1) Objective definition: The objective of this case of study, it is to evaluate if the MSW management system is operationally viable, as well as economically viable, by means to determine the total benefits (the difference between revenues and costs).

2) Definition of study scope, this case study focuses only on the analysis of the treatment plant (without considering the collection process), ranging from the arrival of waste at the treatment facility to the sale to other intermediate agents in the value chain (recycling companies). Costs and revenues generated in 2017 are considered (Faura-Casas Auditors-Consultors 2017).

3) Project impacts, Table 4 presents the impacts that are considered in this study case; nevertheless, only ones are economically evaluated.

Infraestructure, in the case of private costs are considered costs related to infrastructure as labour expenses such as wages, salaries, social security, among others. Additionally, provision costs are considered, that include raw materials and inputs costs, besides the payment of service provided by other companies. The assets and facilities used by SEMESA for the development of its activity are the property of TERSA. In the contract signed between TERSA and SEMESA

(January 1, 2012), the session of its assets and facilities owned by TERSA was formalized, the fixed price is the equivalent to the economic amortization cost of the assets and leased facilities. These costs are directly calculated from OPEX (Bureau Van Dijk 2008). Included in these costs is the fee paid to TERSA for 15,141 tons of residual waste equivalent to 237,678 € (Faura-Casas Auditors-Consultors 2017).

Reuse, recycling and recovery of waste, SEMESA is an infrastructure capable of managing a large amount of waste produced by citizens of the Barcelona Metropolitan Area, due to its capacity, 15,838 tons of light packaging waste (plastic, iron, aluminium, cardboard, among others) are sold to recycling companies each year. Besides, 63,275 tons of bulky and wood waste separated at the facility are also sold to recycling companies. Finally, 15,141 tons of residual waste are sent to incineration. The sale of recycled materials is considered private revenue. On the other hand, revenue is obtained from fees of the provision of light packaging selection services and the treatment of bulky waste.

Use of materials, an added value of SEMESA is to provide the Barcelona metropolitan area with MSW treatment capacity since without its presence these waste would end up in landfill and therefore, the payment of the tax rate of 47.10 € per ton of municipal waste destined for controlled deposit (BOE 2017b). Reducing the amount of waste sent to landfills or incinerators should reduce soil, water and air pollution.

Environment, as external impacts related to the environment, the $CO_2$ emissions generated by the treatment plant are considered. The $CO_2$ emissions expressed as the sum of the energy and fuel that SEMESA consume are calculated to be 1,597 tons $CO_2$-eq. (SEMESA 2017). Besides, the emissions avoided using recycled material instead of primary material are considered. Various countries seriously lack primary natural resources, in this case, waste represents the safest raw materials, which will allow them to reduce dependence on imported raw materials, make considerable energy savings and contribute to the conservation of the environment (Da Cruz et al. 2012; Risch 1978). Consequently, a benefit is obtained due to the reduction of the costs generated by the excavation of raw materials. $CO_2$ emissions from industrial activities are taxed with an average estimated value of about 10 € per ton of $CO_2$-eq (BOE 2017a). It is important to note that it is also considered that by 2025 a value of 30 € per ton of $CO_2$-eq. should be reached. This facility is essential for the development of a circular economy and consequently, avoid to sent waste to landfill and the extraction of raw materials, processes that generate significant damage to the environment through the emission of pollutants to the air, soil and water.

Education, on the other hand, SEMESA mission is the promotion of citizen commitment to sustainability; for this reason, it has environmental education programs for citizens (schools, university students, older people and citizens in general) focus on waste reduction, recycling and recovery. The environmental education programs for citizens would mean an increase in total benefits since this would achieve a better separation of waste, less generation of residual waste as well as a better quality of waste.

4) Identification of involved stakeholders, from the analysis of impacts, the agents involved in the study scope are: a) SEMESA, b) TERSA Group, c) Barcelona City Council, d) recycling companies, e) Citizens of Barcelona metropolitan area. The analysis was carried out from the SEMESA point of view; this is a public company belonging to the Barcelona City Council (government entity).

5) Study of financial necessities and possibilities, SEMESA has its own funds. The study considers 100% financing with share capital, from shares, where its sole shareholder is TERSA.

6) Aggregation of costs and revenues, the Eq. 5 and 6 present the results obtained from the Private Benefit and the Total Benefit, respectively. These values are expressed in € per ton of waste treated. These equations present the values of revenues and costs for the year analyzed (2017).

Taxes (T) were calculated considering a corporation tax of 25% of the result of the exploitation. A 99% discount is applied to this value for the provision of local public services, obtaining a value of 1,299€ (BOE 2014). Financial Costs (FC) are considered zero since it has its own funds and does not have any type of debt.

In case of the opportunity cost, it is considered that there are no better alternative uses for waste or for land use (industrial land), for this reason, opportunity cost comes from the performance that provides some financial instrument when investment, exploitation and maintenance costs are invested in this one. The interest in financial instruments in the year 2017 is considered to be 3% (Banco de España 2019); therefore, the opportunity cost is 1.75€/ton.

$$B_P = \sum_{n=1}^{1}[(101.35) - (58.40 + 0 + 0.01)] = 42.94 \text{ €} \quad (5)$$

$$B_T = \sum_{n=1}^{1}[(101.35) - (58.40 + 0 + 0.01) + (47.10 - 0.56) - 1.75] = 87.73 \text{ €} \quad (6)$$

Once the total revenues and costs (internal and external) have been determined, it is possible to assess whether the project is operationally viable (BP> 0) and economically viable (BT> 0). In the analysis where only are taken into account SEMESA private revenues and costs, the results show a positive economic return (BP> 0); consequently, the project is operationally viable. Specifically, the net profit contributed by SEMESA is 42.94€/ton of waste.

The analysis that takes into account the internal and external revenues and costs of SEMESA are BT>0, giving a benefit of 87.73€/tonne of waste, resulting in an economically viable project.

7) Sensitivity analysis, the results obtained have been subjected to an analysis that allows evaluating the model's sensitivity to changes in some of critical variables involved in the treatment of waste. Table 3 presents the results of sensitivity analysis considering the opportunity cost as the critical variable. When the opportunity cost is approximately greater than 89.5 €/ton, the BT begins to be negative.

Table 3. Sensitivity Analysis with Opportunity Cost as critical variable.

| Opportunity Costs (€/ton) | Revenues (€/ton) | Cost (€/ton) | $B_T$ (€/ton) |
|---|---|---|---|
| 0 | 148.45 | 58.96 | 89.50 |
| 15 | 148.45 | 58.96 | 74.50 |
| 30 | 148.45 | 58.96 | 59.50 |
| 45 | 148.45 | 58.96 | 44.50 |
| 60 | 148.45 | 58.96 | 29.50 |
| 75 | 148.45 | 58.96 | 14.50 |
| 90 | 148.45 | 58.96 | -0.50 |
| 105 | 148.45 | 58.96 | -15.50 |
| 120 | 148.45 | 58.96 | -30.50 |
| 135 | 148.45 | 58.96 | -45.50 |
| 150 | 148.45 | 58.96 | -60.50 |

Fig. 2 offers the opportunity cost versus Total Benefit. Other variables that can be evaluated are the energy cost, the used capacity of treatment facility, the sale price of the recycled materials or treatment services fees.

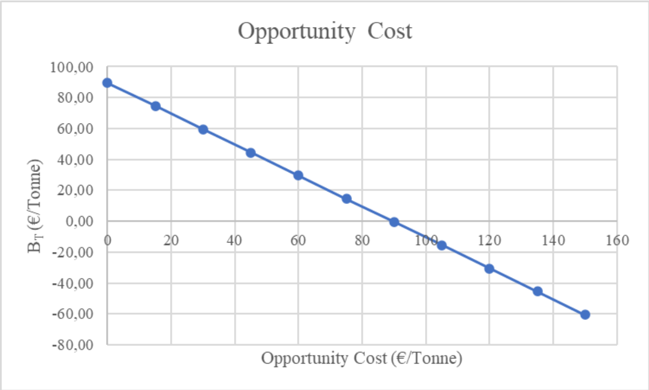


Fig. 2. Sensitivity Analysis: Opportunity Cost versus Total Benefit.

Table 4. Summary of MSW Systems Impacts considered for SEMESA.

| Type of impact | Impact group | Impact Identification | | Impact Frequency | Impact Quantification | Impact Valuation | | Impact Valuation | |
|---|---|---|---|---|---|---|---|---|---|
| | | Costs | Revenues | | | Costs (€/year) | Revenues (€/year) | Costs (€/ton) | Revenues (€/ton) |
| Internal | Infraestructure | Labour (wages, salaries, social security) | | During the life of the project | 86,081 tons of treated waste | 1,695,490 € | | 19.70 € | |
| | | Provision (raw materials and inputs) | | | 86,081 tons of treated waste | 3,331,582 € | | 38.70 € | |
| Internal | Reuse, recycling and recovery of waste | | Plastic, paper and others | | 15,838 tons of treated waste | | 15,652 € | | 0.18 € |
| | | | Wood | | 48,045 tons of treated waste | | 548,106 € | | 6.37 € |
| | | | Bulky material | | 5,174 tons of treated waste | | 274,711 € | | 3.19 € |
| | | | Fees for Service | | 86,081 tons of treated waste | | 7,886,134 € | | 91.61 € |
| External | Use of materials | | Avoided Material send to landfill | | 86,081 tons of treated waste | | 4,054,415 € | | 47.10 € |
| External | Environment | Emissions to air ($CO_2$) | | | 1,597 tons Eq. $CO_2$ | 47,880 € | | 0.56 € | |
| | | | Avoided Emissions to air ($CO_2$) | | Tons Eq. $CO_2$ | Not quantified | | | |
| External | Education | | Culture of reduction, reuse and recycling of waste | | Amount of People | Not quantified | | | |
| Total Internal Impacts | | | | | | 5,027,072 | 8,724,603 | 58.39 | 101.35 |
| Total Impacts | | | | | | 5,074,952 | 13,069,213 | 58.95 | 151.82 |

## 4. Discussion and Conclusions

Traditionally, an economic-financial analysis of MSW management systems focuses exclusively on the study of private costs and benefits (internal impacts). The methodology that is presented in this paper takes into account not only the private impacts but also social and environmental impacts (externalities) which could have relevance on the project. Generally, the most relevant impacts (positive and negative) of the MSW systems have been documented in isolation, usually as a reflection of specific solutions of case studies such as Jamasb and Nepal (2010), Massarutto et al. (2011), Sasao (2004), Rabl et al. (2010) and Gaglias et al. (2016). Although external impacts are more difficult to compute, are not of minor importance, since the impact of these characteristics can practically cause censorship of the project or its economic viability.

Based on sCBA principles, the methodology developed aims to provide a consistent and comprehensive framework for the technical-economic assessment of MSW management systems. The objective of the methodology is to reduce uncertainty and risk of investing in certain MSW management system. This tool will allow decision-makers to analyse and compare different MSW management systems taking into account private revenues and costs and monetary valuation of externalities. The methodology proposed is constituted by seven steps that should be fulfilled for its application: 1) objective definition, 2) definition of study scope, 3) project impacts, 4) identification of involved stakeholders, 5) study of financial necessities and possibilities, 6) aggregation of costs and revenues, and 7) sensitivity analysis. The key point in methodology is the identification, periodicity, quantification and monetary valuation of impacts (private and external) of any MSW project. In Table 5, a summary of the impacts of MSW management systems for the technical-economic analysis is presented.

The main objectives of the methodology are to determine the total benefits of the project and visualize two situations separately. First, that the MSW management system is economically and financially viable for its operation, which is defined by the determination of private benefit (a situation that usually interests the technicians and politicians) and second, that MSW management system is economically, financially, socially and environmentally viable (which interests economists and society).

By carrying out the case study, the methodology has been validated, representing a tool that allows to realize an economic analysis about MSW management systems, and determines its operational and economic viability. Related to the case study carried out (SEMESA), it can be concluded that the installation is operationally viable (BP = 42.94€/ton) as well as economically viable (BT = 87.73€/ton). Additionally, it can see that the most representative revenue is the payment for the provision of service for the selection and treatment of light packaging waste and bulky waste (91.61 €/ton). The most representative costs are related to infrastructure (58.39€/ton).

On the other hand, it is essential to point out that some external revenues have not been quantified as the promotion of the recycling culture and avoided emissions of $CO_2$ for the use of recycling material instead primary raw material. The monetary valuation of these external revenues could increase the total benefit of the analyzed facility. For this reason, in future studies, it is recommended to extend the economic valuation of the externalities of this MSW management system (SEMESA) and the analysis of all processes of this management system (considering collection, transportation and treatment of waste). Another critical factor is realizing an economic analysis about SEMESA processes in comparison to other management systems related to the waste hierarchy such as prevention, reuse, recycling, energy and elimination of waste (BOE 2017a).

In this study case, the opportunity cost is considered as the interest earned by the use of a financial instrument, because are not considered better alternatives for the use of waste or land where the facility is located but if better alternatives are considered in the future, they could convert the project not economically reliable if the opportunity cost is greater than 89.5 €/ton.

In order not to unnecessarily lengthen the paper, only one variable (opportunity cost) has been analyzed in the sensitivity analysis, so other variables such as energy cost, the used capacity of treatment facility, the sale price of the recycled materials or treatment services fees should be evaluated in future work.

In future works, another case studies will be carried out through analysis and evaluation of different MSW management systems, taking into consideration infrastructures such as incineration plants, landfills, composting plants and recycling facilities. These studies will be carried out in different countries or municipalities such as an incinerator in Sant Adrià del Besos, Barcelona, Spain; a composting Plant in Sant Pere de Ribes, Barcelona, Spain and an open dumpsite in Mexico.

Table 5. Summary of the impacts of MSW management systems for the technical-economic analysis.

<table>
<tr><th rowspan="2">Impacts group</th><th rowspan="2">Description of impacts</th><th rowspan="2">Frequency</th><th rowspan="2">Quantification</th><th colspan="2">Valuation method (Monetary Units/tons)</th><th rowspan="2">Authors</th><th rowspan="2">Type of Costs</th></tr>
<tr><th>Costs</th><th>Revenues</th></tr>
<tr><td rowspan="4">Infrastructure</td><td>Collection</td><td rowspan="4">Initial investment and during the life of the project</td><td rowspan="4">Tons of treated waste</td><td rowspan="4">OPEX, CAPEX</td><td rowspan="4"></td><td rowspan="4">Teerioja et al. (2012), Debnath and Bose (2014), Aleluia and Ferrão (2017), Jamasb and Nepal (2010)</td><td rowspan="4">Internal</td></tr>
<tr><td>Transportation</td></tr>
<tr><td>Pre-treatment and Treatment</td></tr>
<tr><td>Final Disposal</td></tr>
<tr><td rowspan="6">Reuse, recycling and recovery of waste</td><td>Glass</td><td rowspan="6">During the life of the project</td><td>Tons of treated waste</td><td rowspan="6"></td><td rowspan="6">MP</td><td rowspan="5">Massarutto et al. (2011), Jamasb and Nepal (2010)</td><td rowspan="6">Internal</td></tr>
<tr><td>Plastic</td><td>Tons of treated waste</td></tr>
<tr><td>Paper and paperboard</td><td>Tons of treated waste</td></tr>
<tr><td>Organic material</td><td>Tons of treated waste</td></tr>
<tr><td>Energy</td><td>Watts produced</td></tr>
<tr><td>Gate fees</td><td>Tons of treated waste</td><td>Al-Salem et al. (2014)</td></tr>
<tr><td rowspan="2">Use of materials</td><td>Guarantee of supply</td><td rowspan="2">During the life of the project</td><td>% of reliability</td><td rowspan="2">OC</td><td>PS, CV, CE, WTP (for recycled material)</td><td>Mesa-Jurado et al. (2012)</td><td rowspan="2">External</td></tr>
<tr><td>Quality of materials</td><td>% of purity</td><td>PS, CE, WTP (for recycled material)</td><td>Borchers et al. (2007)</td></tr>
<tr><td colspan="8">AB: Averting Behaviour Method; BTR: Benefit Transfer; CA: Complaint Assessment Method; CC: Control Cost Method (/Abatement Cost); CE: Choice Experiment Method; COI: Cost Of Illness; CUC: Clean-up Cost Method; CV: Contingent Valuation Method; DR: Dose Response Function; EAD: Experts' Assessment of Damage Costs; HP: Hedonic Price; HPF: Health Production Function; MP: Market Price; OC: Opportunity Cost; PS: Substitute Price; PC: Productivity Change; RC: Replacement Cost Method; RP: Revealed Preference; SPR: Stated Preference; TC: Travel Cost Method; YOLL: Years of Life Lost; VSL: Value of a Statistical Life; WTP: Willingness to Pay; WTA: Willingness to Accept</td></tr>
</table>

Table 5. ***Cont.***

| Impacts group | Identification | Frequency | Quantification | Valuation method (Monetary Units/tons) | | Authors | Type of Costs |
|---|---|---|---|---|---|---|---|
| | | | | Costs | Revenues | | |
| Public Health | Physical Risks<br>Biological Risks<br>Chemical risks | During the life of the project | People exposed | DR, COI, CV (WTP to avoid illness), VSL, YOLL | | Rabl et al. (2010), Navrud (2001) | External |
| Environment | Emissions to water | During the life of the project | Suspended particles | DR, BT, AB | | Mavrotas et al. (2015), Eshet et al. (2006)a | External |
| | Emissions to air | | Kilogram of pollutant | DR, BT, AB | | Mavrotas et al. (2015), Eshet et al. (2006)a | |
| | Emissions to soil | | Affected hectares | DR, BT, AB | | Mavrotas et al. (2015), Eshet et al. (2006)a | |
| Education | Technique of workers | During the life of the project | % productivity | Training | PC | Zwick (2006), Barrett and Connell (2001) | Internal/External |
| | Culture of waste reduction, reuse and recycling | | People | Investment | DR | Latinopoulos et al. (2018) | |
| Quality of life | Disamenities: odour, dust, wind-blown litter, visual intrusion, noise | During the life of the project | Km from site | CE, CV, HP | | Sasao (2004), Gaglias et al. (2016), Hite et al. (2001) | External |
| Total | | | | ∑ Costs | ∑ Revenues | | |

AB: Averting Behaviour Method; BTR: Benefit Transfer; CA: Complaint Assessment Method; CC: Control Cost Method (/Abatement Cost); CE: Choice Experiment Method; COI: Cost Of Illness; CUC: Clean-up Cost Method; CV: Contingent Valuation Method; DR: Dose Response Function; EAD: Experts' Assessment of Damage Costs; HP: Hedonic Price; HPF: Health Production Function; MP: Market Price; OC: Opportunity Cost; PS: Substitute Price; PC: Productivity Change; RC: Replacement Cost Method; RP: Revealed Preference; SPR: Stated Preference; TC: Travel Cost Method; YOLL: Years of Life Lost; VSL: Value of a Statistical Life; WTP: Willingness to Pay; WTA: Willingness to Accept

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# Technical-Economic Analysis of a Municipal Solid Waste Energy Recovery Facility in Spain: A case study.

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## Highlights

- Economic analysis of an Energy Recovery Facility in Spain is carried out.
- The Applied Methodology considers private impacts and externalities.
- The ERF is both operationally and economically profitable.
- Externalities increase the Total Benefit of this facility.
- The impacts presented can be used for the economic analysis of other MSW facilities.

**Abstract:** The aim of this work is to carry out a technical-economic analysis of an energy recovery facility (ERF) located in Sant Adrià de Besòs, Barcelona, Spain through a methodology based on social Cost-Benefit analysis, which considers the private impacts and externalities (social and environmental impacts) to determine the Total Benefit (the difference between revenues and costs) and decide if it is both operationally and economically profitable. The ERF plays an important role in Barcelona and its environs in generating energy, preventing the residual waste from being sent to landfills and therefore helping to comply with the objectives fixed by the European Commission. The key point of this work is the identification, frequency, quantification and monetary valuation of the impacts generated by the ERF, such as infrastructure costs, sale of energy, $CO_2$ emissions, the effects on public health, among others; providing a guide to future researchers and policymakers interested in the economic valuation

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of MSW management systems. Applying the methodology, it can be seen that the facility is both operationally ($B_P$ = 9.86 €/ton) and economically ($B_T$ = 23.97 €/ton) profitable. The results show that the ERF has high private costs, however, due to its high revenues from the sale of energy and services, the facility is operationally profitable, but with a low private benefit per ton treated. Externalities play an important role since they increase the Total Benefit and make the ERF more economic reliable.

**Keywords:** Economic assessment; Incineration; Municipal solid waste; Waste to energy; Externalities; social cost-benefit analysis

## Nomenclature

| | |
|---|---|
| AVW | Annual volume of waste treated |
| $B_E$ | External Benefit |
| $B_P$ | Private Benefit |
| $B_T$ | Total Benefit |
| FC | Financial costs |
| IC | Investment costs |
| J | Total impacts |
| j | Impact index (j = 1, …, J) |
| N | Total project duration |
| n | Project year index (n = 0, …, N) |
| NE | Negative externalities |
| OC | Opportunity Cost |
| OMC | Operational and maintenance costs |
| PE | Positive externalities |
| SP | Sale Price per Volume Unit |
| T | Taxes |

## 1. Introduction

The massive generation of waste is an increasingly worrying occurrence, for this reason the Directive 2008/98/CE of the European Parliament has established the following hierarchy of waste according to the priorities in legislation and policy regarding waste prevention and management: a) prevention; b) preparation for reuse; c) recycling; d) other forms of recovery and e) elimination (European Parliament, 2008). On the other hand, in the European Commission (2015) some main objectives regarding municipal solid waste (MSW) were presented, where one of the objectives established was the gradual limiting of municipal landfills to 10 percent by 2030.

Moreover, European Commission (2017) emphasises that generating energy from waste that cannot be recycled or reused can contribute to a circular economy and energy diversification. Energy recovery is a process that minimises the volume of waste by means of combustion, taking advantage of the energy generated by the process to generate steam and/or electricity (Scarlat et al., 2019; National Research Council, 2000).

Although the established objectives and hierarchy prioritise other waste treatment options and move towards the establishment of a circular economy, energy recovery plays an important role in preventing waste that can no longer be materially recovered from being sent to landfills and, therefore, helps in meeting the objectives in terms of waste materials. It can also reduce the dependence on energy generated by fossil fuels such as coal, petroleum, among others (Istrate et al., 2019).

## 1.1 MSW management and Energy Recovery in Spain

In several European countries and specifically in Spain, a large percentage of MSW is sent to landfills, which does not coincide with the hierarchy of waste and established objectives. In Spain, approximately 11,325 tons of the 22,222 tons of waste generated during 2018 (51% of the total) were sent to landfills; 4,057 tons (18.3%) were recycled; 3,942 tons (17.7%) were turned into compost, and 2,898 tons (13%) were incinerated to produce energy (Eurostat, 2020). In 2017, 116 landfills and 10 incineration plants had been registered in Spain (MITECO, 2017).

Furthermore, Spain has an enormous problem in terms of foreign energy dependency, as can be seen from the statistics. In 2017, for example, 73.9 percent of the fuel needed for generating primary non-renewable energy was obtained abroad of Algeria, Saudi Arabia, Nigeria, Mexico, Peru, among others (European Union, 2019; Cores, 2018; Cores, 2018b). More specifically, of that year’s fuel imports, 97.9 percent of the petroleum, 85.6 percent of the solid fuel and 101.3 percent of the natural gas were acquired on foreign markets (values over 100% indicate stock build up) (European Union, 2019).

In some Spanish cities and specifically in Barcelona city, different processes are carried out for MSW management, as can be seen in Fig 1. The MSW is collected by drop-off collection where 5 types of containers are used for the selective collection of waste: 1) yellow container for the collection of light packaging waste; 2) blue container for cardboard and paper waste; 3) green container for glass waste; 4) brown container for organic waste and 4) grey container for the residual fraction (waste that has not been selectively collected). Each waste fraction goes through different types of treatments.

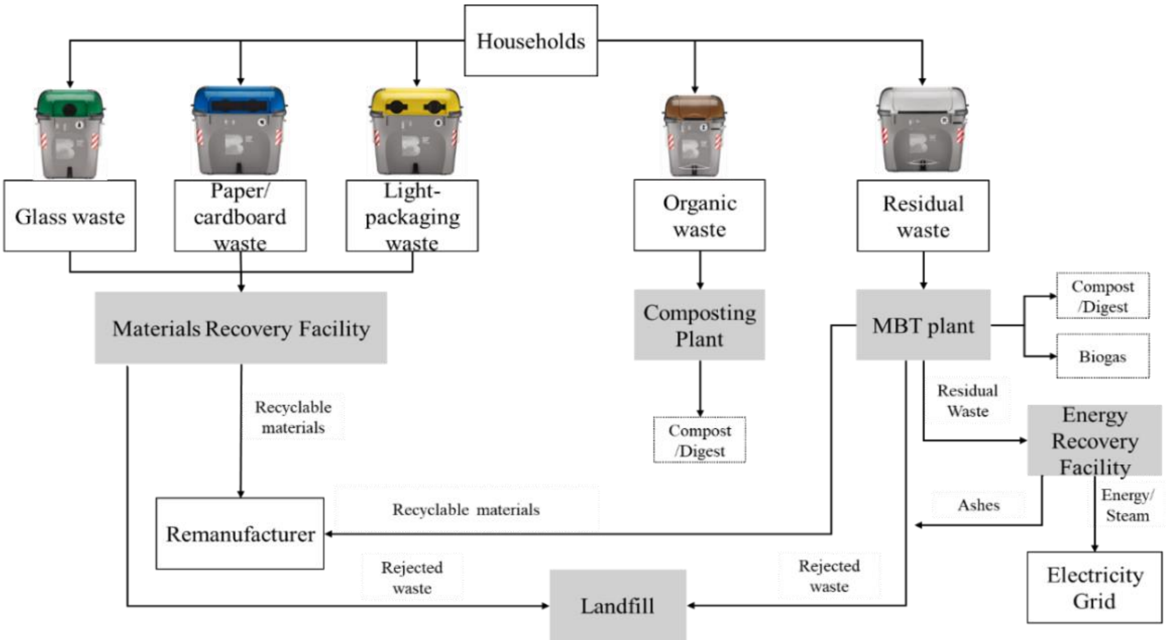


Fig 1. MSW management processes in Barcelona City. Source: AMB (2020).

In this case study, we focus on the energy recovery of the residual fraction (grey container), specifically in the one carried out in the Barcelona metropolitan area by the Energy Recovery Facility (ERF) which is part of the Integral Waste Recovery Facility (IWRF) of Sant Adrià de Besòs. The IWRF is also composed by a Mechanical-Biological Treatment Plant (MBT) where waste is pre-treated.

The ERF is responsible for the management, thermal treatment and elimination of the MSW coming mainly from the residual waste of three ecoparcs (Mechanical-Biological Treatment plants) located in Barcelona. The ERF started up in 1975 and was built on a site covering 10,044 m2 located in an industrial zone. Currently, it has three treatment lines with a total capacity of 360,000 tons of treated waste per year, which means the generation of 200,000 MWh of energy per year and the production of 150 ton/h of steam. In 2017, electricity production was approximately 535 kWh/ton treated, and the steam production was 0.259 tons/ton treated.

Therefore, the main focus of this case study is to determine the Total Benefit generated by the ERF of Sant Adrià de Besòs, Spain, taking into account private and external impacts, which will be identified, quantified and monetarily valuated. The rest of the document is structured in the following manner: the next section presents a review of the relevant literature related to the economic analysis of Waste to Energy facilities. Section 3 describes the methodology and the manner of obtaining and using the data. Then, the results of the case study are presented and discussed in Section 4. Finally, Section 5 contains the conclusions, in addition to future lines of research.

## 2. Literature review

The economic aspects are of great importance because most decisions related to the implementation of MSW management systems and technologies in modern society are affected by economic constraints (Martinez-Sanchez et al., 2015). When an MSW treatment system is set up, it may lead to different impacts or consequences, which can be reflected as costs or revenues depending on whether the interested parties are affected positively or negatively (Seguí-Amórtegui et al., 2014). These impacts can be classified as internal (private) or external (externalities). In general, an economic analysis of the MSW management systems focusses only on studying the internal impacts – the costs and revenues related to the investment, operation and maintenance of the treatment plants (Al-Salem et al., 2014). The external costs and revenues, (impacts related with environmental and social aspects) are usually more difficult to quantify in monetary terms and therefore are not usually reflected in the economic analyses or the MSW management decisions (Nahman, 2011). Nevertheless, the external impacts are not of minor importance, as they can signify the project's downfall or its economic viability (Medina-Mijangos et al., 2020).

Numerous studies have examined many aspects of incineration facilities, focusing especially on the economic analysis of energy recovery facilities for MSW management. Some have focussed only on the analysis of the private impacts, as in the case of Aleluia and Ferrão (2017) and Silva et al. (2019) where they mainly include Investment, Maintenance and Operation Costs, in addition to benefits from the sale of energy. Aleluia and Ferrão (2017) show that incineration plants are the most capital-intensive facilities and OPEX figures are the higher for incineration plants. Silva et al. (2019) show how incineration is advantageous from an energy generation perspective, but in economic terms, incineration does not yet yield good results due to the elevated installation costs, along with operational and maintenance costs.

Other authors have carried out an economic analysis of the external impacts generated by incineration plants, such as Rivas Casado et al. (2017) and Sun et al. (2017), where the Hedonic Pricing Method was used to analyse the disamenities caused by the incinerators to the nearby households. The results show that for every additional kilometre the property is away from WTE plants, the value of real estate increase.

Panepinto et al. (2016) performed an economic analysis of an incinerator in Italy centred on the environmental and economic convenience of the energy recovery (electric and/or thermal energy). The results highlight that currently, the environmental convenience corresponds to the cogenerative configuration; instead, the economic convenience corresponds to the only electric configuration.

Woon and Lo (2016) quantify and compare the private and external costs of a landfill and an advanced incineration facility in Hong Kong using life cycle costing methodology where the opportunity cost of land, disamenity cost, external environmental cost and benefit are considered as externalities. The results show that with the inclusion of private and external costs, the incinerator has a slightly lower life cycle cost. However, if only private costs are considered, the result is reversed, in which the landfill has a lower life cycle cost.

Other aspects analysed economically include the impacts on public health, the emission of pollutants (such as PCDD/Fs) and the reduction in coal use, among others (Jamasb & Nepal, 2010; Istrate et al., 2019; Rabl et al., 2008; Rabl et al., 2010).

Although several economic analyses have been performed on different incineration plants; generally, only focused on specific elements of waste to energy systems. In this case study, the methodology used allows researchers and decision-makers, in a simple way, to evaluate the operational and economic profitability of a specific treatment facilitiy considering the relevant impacts. The current paper attempts to determinate and analyse several private and external impacts (positive and negative), thus providing a guide to future researchers and policymakers interested in the economic valuation of any MSW management system.

## 3. Methodology and Data

The data to be used in this case study was obtained from publicly available information on the ERF company website (TERSA, 2019), containing documents such as auditor's reports, annual accounts, sustainability reports and production figures, as well as environmental studies performed by the ERF and other bodies. The SABI database was also used, which contains financial information about Spanish and Portuguese companies (Bureau Van Dijk, 2008). The case study looks at the costs and revenues generated in 2017.

In order to carry out the case study, the methodology presented in Medina-Mijangos et al. (2020) was applied. It presents a methodology for the technical-economic analysis of the MSW management systems based on the social Cost-Benefit Analysis (sCBA) because it evaluates projects from the viewpoint of society as a whole where private and external costs (caused by environmental and social impacts) are considered (Hoogmartens et al., 2014). CBA has been chosen for methodology development due to its simplicity and easy understanding for any decision-maker. In addition, the CBA has been widely used in the literature (Lavee et al., 2012; Lavee, 2012; Lavee, 2010).

Although the details presented in this document are specific to the Spanish context. The methodology used can be applied universally, since it determines and analyses several potential impacts resulting of the MSW treatment (internal and external), and can be extrapolated for the analysis of other treatment plants, allowing researchers to consider the same types of impacts described in this document, but adapted to specific contexts to reduce uncertainty for decision-makers.

It is important to mention the limitations of this study. Despite the fact that all the possible impacts to be considered in the analysis of the facilities have been included and described, the monetary valuation of some impacts related to the social concern has not been carried out, because each impact has its own methodology that must be presented and comprehensively developed in an individual context.

This methodology comprises seven steps that must be followed in its application, as seen in Fig 1: 1) definition of the objective, 2) definition of the scope of the study, 3) impacts of the project, 4) identification of the stakeholders, 5) financial needs and options study, 6) addition of costs and revenues, and 7) sensitivity analysis.

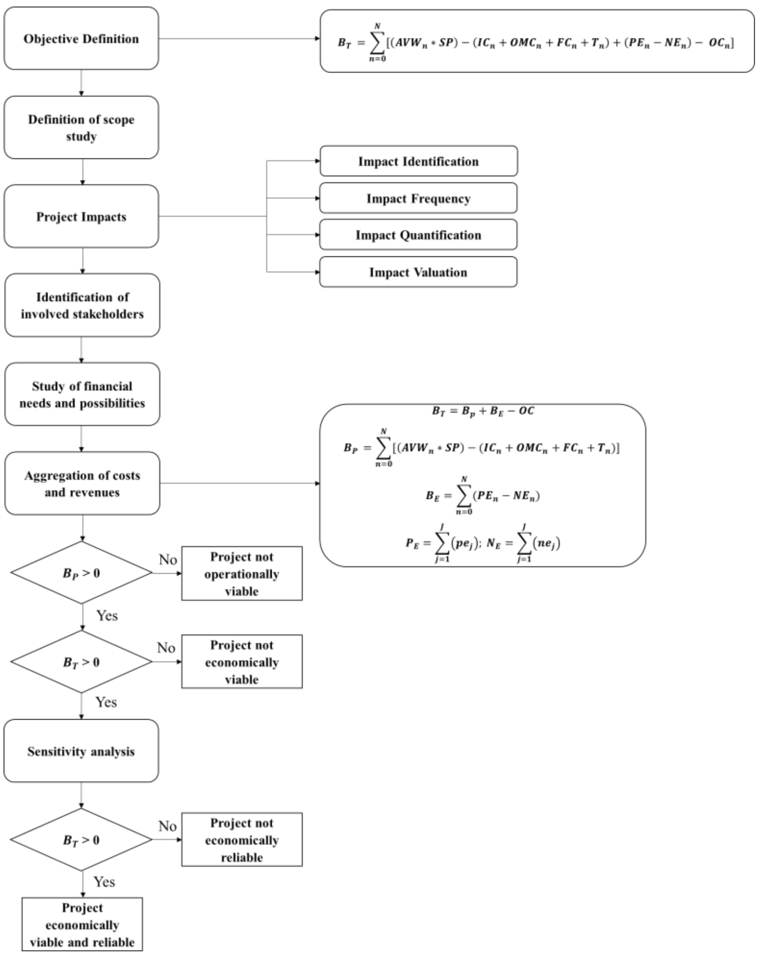


Fig 1. Steps for technical-economic analysis to evaluate MSW management facilities; Source: Source: Medina-Mijangos et al. (2020); Seguí-Amórtegui et al. (2014).

### 3.1 Definition of the objective

The objective of this case study is to determine whether the ERF of Sant Adrià de Besòs is both operationally and economically profitable, by means of establishing the Total Benefit (the difference between revenues and costs, whether internal or external). The objective function to be optimised is shown in Eq. (1) and (2):

$$\boldsymbol{B}_P = \sum_{\boldsymbol{n=0}}^{\boldsymbol{N}}[(AVW_n * SP) - (IC_n + OMC_n + FC_n + T_n)] \quad (1)$$

$$\boldsymbol{B_T} = \sum_{\boldsymbol{n=0}}^{\boldsymbol{N}}[(AVW_n * SP) - (IC_n + OMC_n + FC_n + T_n) + (PE_n - NE_n) - OC_n] \quad (2)$$

### 3.2 Definition of the scope of the study

The ERF is a Limited Liability Company, with its share capital spread between Barcelona de Serveis Municipals, S.A. (which has 58.64%) and AMB (holding 41.36%). Both companies belong to the Barcelona City Council, a governmental body. The main objective of this company is to provide a public management service, thermal treatment and elimination of MSW in the city of Barcelona and its metropolitan area.

This case study concentrates only on analysis of the MSW treatment of the ERF, without considering the Mechanical-Biological Treatment plant (MBT) or the waste collection process. Only the processes and impacts occurring from the arrival of the waste to the treatment facility (ERF) until the departure of the materials for sale to other agents in the value chain (energy, steam and materials management companies) are examined. In addition, only the costs and revenues generated in 2017 are considered (Faura-Casas Auditors Consultants, 2017). In 2017, a total of 368,791 tons of residual waste were treated (TERSA, 2017).

### 3.3 Impacts of the project

In this section, the key is the identification, frequency, quantification and monetary valuation of the impacts (private and external) of the ERF (Medina-Mijangos et al., 2020). In Table 1, a summary of the impacts of the ERF is presented, and the types of impacts are specified. The principal characteristics of each impact group analysed are detailed below.

Table 1. Summary of the ERF Impacts. Source: Source: authors elaboration based on Medina-Mijangos et al. (2020)

| Impact group | Description of impacts | Type of impact |
|---|---|---|
| Infrastructure | Treatment of waste | Negative/ Internal |
| Reuse, recycling and recovery of waste | Sale of Energy, steam and other materials | Positive/ Internal |
| | Gate fees | Positive/ Internal |
| Use of materials | Avoided Material sent to landfill | Positive/ External |
| | Guarantee of supply of energy | Positive/ External |
| | Districlima Dependence | Positive/ External |
| | Quality of energy | Positive/ External |
| Environment | Emissions to air | Negative/ External |
| | Avoided emission to air | Positive/ External |
| Public Health | Physical Risks | Negative/ External |
| | Chemical Risks (emission of dioxins) | Negative/ External |
| Education | Culture of reduction, reuse and recycling of waste | Positive/ External |
| | Technique of workers | Positive/ External |
| Quality of life | Disamenities: odour, dust, windblown litter, visual intrusion, noise | Negative/ External |

### *3.3.1 Infrastructure*

Treatment of waste. This impact group includes the private costs related to the infrastructure for managing MSW (Aleluia & Ferrão, 2017; Jamasb & Nepal, 2010). These costs can be classified as CAPEX (Capital expenditures) and OPEX (Operational expenditures) (Aleluia and Ferrão, 2017).

In this case study, only OPEX is considered because we focus on a specific operating year, and the capital costs are included in the values of the depreciation of fixed asset. Table 2 shows the costs related with infrastructure classified as: a) Labour cost: Costs such as salaries & wages, social security payments and training, among others are included; b) Equipment maintenance and repair c) Provision costs: The supply costs are considered, which include the cost of raw materials and supplies and the payment for services provided to the ERF by other companies; d) Depreciation of fixed assets: This is calculated according to the useful life of the goods, applying the linear method to the acquisition cost (Faura-Casas Auditors Consultants, 2017); d) Others cost: It is included a quantity corresponding to other operating expenses such as insurance, machinery rental, among others.

The annual costs related to the infrastructure (€/year) are directly obtained and calculated from annual accounts of the ERF (year 2017) (Faura-Casas Auditors Consultants, 2017). The values are divided between the total waste treated (368,781 tons), and it is obtained the cost per ton (€/ton). As can be seen in Table 2, the most representative costs are the costs related to the provision of services and other costs.

Table 2. Summary of Infrastructure costs. Source: authors elaboration based on Faura-Casas Auditors Consultants (2017)

| Concept | Annual Costs (€/year) | Cost per ton (€/ton) | Percentage (%) |
|---|---|---|---|
| a) Labour cost | | | |
| Salaries & Wages | 3,801,544 | 10.31 | 7.32 |
| Social Security | 1,134,432 | 3.08 | 2.19 |
| Other labour costs | 256,977 | 0.70 | 0.50 |
| b) Equipment repair and Maintenance costs | 4,901,799 | 13.29 | 9.44 |
| c) Provision costs | | | |
| Raw materials and inputs | 1,796,839 | 4.87 | 3.46 |
| Provision of services (Subcontracting) | 32,222,508 | 87.37 | 62.05 |
| d) Depreciation of fixed assets | 1,813,126 | 4.92 | 3.49 |
| e) Other Costs | 6,001,382 | 16.27 | 11.55 |
| Total | 51,928,607 | 140.81 | 100 |

### *3.3.2 Reuse, recycling and recovery of waste*

This impact group includes the expected private revenues from the sale of energy, steam and other materials generated from the waste, as well as other revenues obtained from the waste treatment process.

Table 3 shows the costs related to the revenues obtained. These revenues are classified as: a) Earnings from the sale of energy, steam and other materials obtained from waste; b) Gate fees that represent a unit payment (usually per ton) to the MSW service provider; c) Other revenues such as payment for services provided to other companies, equipment rental, among others. A total of 198,471 MWh of electrical energy was recovered from the waste, with 88.34% being sold to the electricity grid and 11.66% consumed internally. Additionally, 95,509 tons of steam (17,122 MWh) were sold to the Districlima company, to be used to supply heat and cooling for the network of buildings in Barcelona city. Finally, 74,127 tons of slag and 12,909 tons of ash were sold to authorised operators (TERSA, 2017). Also, it received the payment for services provided to other companies, as well as an MSW treatment fee and other revenues. As can be seen in Table 3, the most representative revenues are the revenues related to the provision of services and the MSW treatment fees.

Table 3. Summary of private revenues from the ERF. Source: Source: authors elaboration based on Faura-Casas Auditors Consultants (2017).

| Concept | Description | Quantity | Unit | €/Unit | Annual revenues (€/year) | Revenue per ton (€/ton) | Percentage (%) |
|---|---|---|---|---|---|---|---|
| Sales | Energy | 175,327 | MWh | 52.52 | 9,208,253 | 24.97 | 16.94 |
| | Steam | 95,509 | Tons | 6.96 | 664,628 | 1.80 | 1.22 |
| | Slags and ashes | 87,036 | Tons | 0.14 | 12,336 | 0.03 | 0.02 |
| | Water | 22,350 | $m^3$ | 1.01 | 22,657 | 0.06 | 0.04 |
| Gate fees | MSW treatment fee | 368,791 | Tons | 28.67 | 10,574,518 | 28.68 | 19.45 |
| Other revenues | Provision of services to other companies | | | | 25,459,459 | 69.03 | 46.83 |
| | Other | | | | 8,416,304 | 22.83 | 15.48 |
| | | | | Total | 54,358,155 | 147.40 | 100 |

### *3.3.3 Use of materials*

This impact group is related to the needs satisfied by the waste and the profits generated by using the waste in different applications. For example, the use of MSW to generate energy can reduce the dependency on fossil fuels, reduce the amount of waste sent to landfills and thereby meet the objectives of the European Commission to reduce landfill waste by 10 percent by the year 2030.

Avoided material sent to landfill. A benefit of the ERF is that it allows the thermal treatment of MSW, preventing that waste would end up in a landfill. To evaluate the profit obtained by not sending the waste to landfills, we consider the saving of the fee set by Catalonia Government of 47.10 € per ton of waste sent to controlled landfills; from this, we deduct the charge of 23.60 € per ton of waste sent to incinerators (BOE, 2017a). The main aim of these taxes is to achieve the objectives set by the European Commission. Therefore, there would be a saving of 23.50 €/ton. It is considered that 368,791 tons of waste were prevented from being sent to landfills.

Guarantee of supply of energy. Generally, the energy used in productive activities is generated by fossil fuels, a cheap source of energy. However, fossil fuels are not renewable and therefore are very limited. As the population grows and economic development increases, there is a rise in energy demand. The energy generated by MSW replaces that from other sources, such as fossil fuels (Tong et al., 2018; Lim et al., 2014; Kim & Kim, 2015). The contingent valuation method is used to evaluate the profits obtained by using waste-generated energy, to determine the consumers' views and their willingness to pay (WTP) for guaranteed, uninterrupted energy supply at a reasonable price (Kim and Kim, 2015). This impact is not evaluated in this study.

Districlima Dependence. Since 2004 the Districlima company has run the heating and cooling distribution network in Barcelona (in the commercial/cultural area and the technological district). This comprises a grid of 18 km with 100 connected buildings, as well, as two centres that use the steam produced by the ERF. Districlima has invested heavily in infrastructure, and its operation depends in great measure on the steam generated by the ERF, thereby obtaining an indirect profit from this resource (Districlima, 2020). This impact is not evaluated in this study.

Quality of energy. Another impact to be measured is the value that consumers give to the energy generated from waste, in terms of being green energy or renewable energy. Green energy is generated from renewable energy sources such as solar power, wind power, biomass power, among others (Guo et al., 2014). This type of energy has zero or minimum environmental impact because it decreases the greenhouses gases and emissions of fossil energy sources (Midilli et al., 2006). In this case, it would be necessary to design a choice experiment to calculate consumers' preferences and their willingness to pay (WTP) for voluntary participation in green electrical energy programmes, including that generated from waste (Borchers et al., 2007). Table 4 shows some recent studies in Europe, where WTP for green/renewable energy is calculated.

Table 4. Findings of studies on the WTP for green/renewable energy. Source: authors elaboration.

| Study | Sample | Country | Survey time | WTP over the current electricity bill by renewable energy | Collection Method |
|---|---|---|---|---|---|
| Kowalska-Pyzalska (2019) | 502 | Poland | November 2017 | 3.50 USD/month | CVM; Standardised telephone survey |
| Grilli et al. (2016) | 68 | Italy | 2016 | 5.20 €/month (100% of RES) | CVM; Face-to-face interview |
| Ntanos et al. (2018) | 400 | Greece | November-December 2016 | 8.83 €/month | CVM; Face-to-face interview |
| Gracia et al. (2012) | 400 | Spain | July 2010 | -1.24-1.24 €/month (Wind); 1.03-2.24 €/ month (Solar); -1.51 €/ month (Biomass) | CE; Face-to-face interview |
| Hanemann et al. (2011) | 233 | Spain | November-December 2009 | 29.91 €/month | CVM; Standardised telephone survey |
| Grösche and Schröder (2011) | 2,948 | Germany | 2008 | 2.03 Cents €/kWh | CE; Internet Survey |
| Zorić and Hrovatin (2012) | 450 | Slovenia | 2008 | 4.18 €/month | CVM; Internet and field interviews |
| Bigerna and Polinori (2014) | 1,019 | Italy | November 2007 | 2.31-4.02 €/month | CVM; Nationwide survey |
| Soliño et al. (2009) | 572 | Spain | January-February 2006 | 3.79-3.80 €/month (SB) 4.40-5.71 €/month (DB) (for biomass) | CVM; Face-to-face interview |
| Sundt and Rehdanz (2015) | 18 studies (85 WTP) | - | - | 13.13 USD/month | Meta-regression; values adjust to 2010 base year USD using PPP rates |
| Soon and Ahmad (2015) | 30 studies (137 WTP) | - | - | 7.16 USD/month | Meta-regression approach; values adjust to 2013 base year USD using CPI |

CVM: Contingent Valuation Method; CE: Choice Experiment; RES: Renewable Energy Supply; SB: Single bounded; DB: Double bounded; PPP: Purchasing Power Parity; CPI: Consumer Price Index

The summary WTP (USD2013 7.16) obtained by Soon and Ahmad (2015) was used for this case study. This WTP obtained was adjusted to the reference year (2017), and currency (EUR2017), applying the annual inflation rate (CPI) and the exchange rate between USD and EUR (OECD, 2020; World Bank Group, 2020). Finally, it was obtained a WTP of 6.67€; this value is the amount per month over the current electricity bill by renewable energy use. In Spain, approximately 238.05 kWh/month/household are consumed (INE, 2017), taking into account the average consumption, the WTP per kWh is 0.028 €/kWh. In 2017, the ERF produced 175,327 MWh of electricity, so it is considered a benefit of 4,909,156 €. According to TERSA (2017b), the energy produced in ERF is approximately 50 percent renewable; for this reason, we consider only the 50 percent of this impact benefit.

### *3.3.4 Environment*

The treatment of waste by the ERF may have different consequences for the environment, such as the emission of a greater amount of pollutants. These emissions can affect agricultural production, damage buildings and contribute to climate change. This impact group includes: 1) Emissions to the air, 2) Emissions to soil and 3) Emissions to groundwater and surface water. Appendix Annex I shows the principal pollutants generated by the incineration plants as well as the emissions avoided.

Emissions to air. $CO_2$ emissions are very important due to their effects on global warming. Table 5 shows the $CO_2$ emissions generated by the ERF in 2017, a total of 331,911.90 tons, where 63.6% is of anthropogenic origin and 36.4% from biogenic origin. The emissions of $CO_2$ eq. generated by the use of fossil fuels such as natural gas and diesel are also considered, as well as indirect emissions caused by the consumption of electricity obtained from the grid (Table 5). The values of $CO_2$ eq. obtained were calculated from the $CO_2$ emission factors determined by the Generalitat de Catalunya (2020), (Regional Government). On the other hand, the methodological decision was taken to exclude biogenic $CO_2$ (the $CO_2$ emissions associated with the natural degradation of organic matter) because biogenic carbon is a short term emission derived from the biosphere, completing a typical biological carbon cycle (Edwards et al., 2018). In this case, the emissions generated by the ERF (without considering the biogenic emissions) were 213,252.75 tons of $CO_2$ eq., or 0.578 tons of $CO_2$ eq./ ton treated.

Avoided emission to air. Table 5 shows the emissions of $CO_2$ eq. avoided by the generation of energy and steam from MSW. The energy generated by the ERF was sold to the electricity grid; as well as being used in the ERF (self-consumption). The steam generated was sold to Districlima company for the urban network of heating and cooling. It was used for central heating, air conditioning and hot sanitary water. The $CO_2$ eq. emission factor was considered, assuming that if the energy was not waste recovered from waste, it would have to come from the electricity grid, meaning an emission factor of 0.39 kg $CO_2$/MWh. This emission factor is calculated from the Spanish electricity production mix in 2017 (nuclear 22.4%, wind 19.1%, coal 17.1%, combined cycles 3.6%, hydraulic 7.4%, cogeneration 11.3% solar 5.4% and others 3.7%) (Generalitat de Catalunya, 2020). In this case, the emissions avoided by the ERF were 84,115.51 tons of $CO_2$ eq., or 0.228 tons of $CO_2$ eq./ton treated. Table 5 also shows the net emissions of $CO_2$ generated by the ERF (the difference between the emissions generated and the emissions avoided by the ERF) without considering the biogenic emissions, where it can be seen that the amount of net emissions is 129,137.24 tons of $CO_2$ eq, or 0.350 tons of $CO_2$ eq./ton treated.

Table 5. Emissions of $CO_2$ eq. generated and avoided by the ERF in 2017. Source: authors elaboration based on TERSA (2017b); Generalitat de Catalunya (2020).

| Type | Concept | MWh | Emission Factor (kg $CO_2$/MWh) | Tons of $CO_2$ eq. | Tons of $CO_2$ eq. /Ton Treated |
|---|---|---|---|---|---|
| Emissions Generated | Direct $CO_2$ emissions (anthropogenic origin) | - | 1 | 211,095.97 | 0.572 |
| | Direct $CO_2$ emissions (biogenic origin) | - | 1 | 120,815.93 | 0.328 |
| | Indirect emissions related to electricity consumption | 225.83 | 0.39 | 88.53 | 0.000 |
| | Natural gas consumption | 11,472.78 | 0.27 | 2,065.10 | 0.006 |
| | Diesel consumption | 11.67 | 0.18 | 3.15 | 0.000 |
| | Total (with $CO_2$ emissions of biogenic origin) | | | **334,068.68** | **0.906** |
| | Total (without $CO_2$ emissions of biogenic origin) | | | **213,252.75** | **0.578** |
| Avoided Emissions | Electric energy for self-consumption | 23,144.00 | 0.39 | 9,026.16 | 0.024 |
| | Electric energy sold to the grid | 175,327.00 | 0.39 | 68,377.53 | 0.186 |
| | Steam sold to Districlima | 17,122.00 | 0.39 | 6,711.82 | 0.018 |
| | Total | **215,593.00** | | **84,115.51** | **0.228** |
| | Net emissions (without $CO_2$ emissions of biogenic origin) | | | **129,137.24** | **0.350** |

The $CO_2$ emissions from industrial activities are taxed at an average rate of 10 €/ton of $CO_2$ eq. It should be considered that a value of 30 €/ton of $CO_2$ eq. will be charged from 2025 (BOE, 2017b). When calculating the economic impact of $CO_2$ emissions, the figure of 10 €/ton of $CO_2$ eq is used. To implement a $CO_2$ tax, governments generally determine the abatement/avoidance cost for a determinant pollutant. Eshet et al. (2006) point out that the highest required cost for abatement of a specific pollutant should be taken as the minimum value that society places on removing it.

### *3.3.5 Public Health*

This impact group includes the damage done to public health, which can be evaluated from the standpoint of the workers and/or the inhabitants of the area surrounding the MSW facilities. In the case of incineration plants, they are mainly associated with the emission of dangerous substances such as dioxins (Giusti, 2009). The impacts on public health can be decisive factors when evaluating a specific MSW system.

Physical Risks. Damages to the health of the ERF workers are mainly related to injuries caused by minor accidents and include dislocations, and sprains, superficial injuries and fractures. Table 6 presents the accident frequency index, incidence rate, as well as the average absenteeism rate, and information about the costs necessary to calculate the economic impact of the accidents that occurred in the ERF in 2016 and 2017. In order to avoid double-counting, only costs incurred by public or mutual entities are considered, since the salary payment, the social security fee, among others, have already been considered in the company's annual accounts as part OPEX. In this case, only the costs for medical care are considered, which corresponds to an average cost of 1,721.78 € due to fractures, sprains, and dislocations (Ministerio de Sanidad, 2014). Besides, 75% of salary during the sick leave period, which is approximately 1,010.32 € for the 16.94 days. That is, 2,732.20 €/accident, it must be considered that during 2017 there were five accidents with sick leave.

Table 6. Information about Accidents rates and costs. Source: authors elaboration based on TERSA (2017b); Faura-Casas Auditors Consultants (2017).

| Concept | Year 2016 | Year 2017 |
|---|---|---|
| Frequency Index [1] | 32.3 | 25.54 |
| Incidence Rate [2] | 5.81 | 4.6 |
| Absenteeism rate [3] | 2.55% | 2.69% |
| Accidents | 6 | 5 |
| Sick Leave per worker (Days) | 21.21 | 16.94 |
| Workers | 100 | 101 |
| Working Hours per worker (hour/year) | 1800 | |
| Risk prevention expense (€) | 3,893.66 | 3,344.11 |
| Average hourly wage (€/hour) | 15.51 | 16.13 |
| Average daily wage per worker (€/day) | 76.49 | 79.54 |

[1] accidents with sick leave/hours worked * 1,000,000

[2] accidents with sick leave/workers *100

[3] % of days lost due to professional contingency compared to the total number of calendar days

Chemical Risks (emission of dioxins). According to the results of García-Pérez et al. (2013), there is an excessive risk of lung and other cancers; in particular, there are notable increases in the risk of pulmonary and gall bladder tumours (in men) and stomach tumours (in women) in the case of workers and/or people living close to the incinerators. Domingo et al. (2015) and Domingo et al. (2017) determined the principal pollutants generated by the ERF, as well as indicating possible damage to health. According to the results, the concentration of PCDD/Fs in soil was 1.66 ng WHO-TEQ/kg in 2017 (average amount), higher quantities than those found near other waste management facilities in Catalonia. Similarly, the level of PCDD/Fs in the air was 0.044 pg WHO-TEQ/$m^3$ in 2017 (average amount), the highest amount recorded among similar facilities in Catalonia. The carcinogenic risks are shown in terms of the possibility of developing cancer due to life-long exposure (estimated as 70 years); more than $10^{-6}$ is considered negligible. The carcinogenic risks due to exposure to PCDD/Fs for the residents in areas close to the ERF were $2.5 \times 10^{-6}$ in 2017, which means that the residents in these areas had 3 to 4 times more probability of developing cancer than the residents of cities such as Girona, Mataró and Tarragona, where incinerators have also been operating for several years Domingo et al. (2017).

On the contrary to the articles mentioned previously, the Agència de Salut Pública de Cataluña (the Public Health Agency of Catalonia) carried out a study to determine if there was a connection between mortality from illnesses related to exposure to PCDD/F and proximity to the ERF. According to this study, the immediate surroundings of the ERF show no groupings with higher than average mortality when compared with the population of Barcelona in general. Nor has any significant link between mortality and proximity to the ERF been found Agència de Salut Pública de Barcelona (2018). This study is used as a reference when calculating the Total Benefit, considering that there is no cost associated with effects on public health.

### *3.3.6 Education*

This impact group considers the benefits due to changes in the workers' and citizens' behaviour as a result of training and awareness courses.

<u>Culture of reduction, reuse and recycling of waste.</u> The ERF is part of "Barcelona + Sostenible", a community-based education program where citizen entities, business and commercial organisations, educational centres, universities, professional associations and administrations promote sustainability measures, share good practices and develop projects for better waste management.

The education programmes allow to reduce improper sorting of waste by citizens and decrease processing expenditures, production errors and damages to equipment in waste facilities (Ibrahim, 2020b), generating economic benefits for the different treatment facilities. It should be emphasised that, in order to achieve a change in the public's behaviour, it is necessary to invest in skilled personnel in the social and communications sectors, as well as publicising and implementing the programme. This impact is not evaluated in this study because the economic benefits are mainly related to other treatment plants.

<u>Technique of workers.</u> Every year the company invests in training courses for its employees, which increases the responsibility and professionalism of its staff. The training courses provide the personnel with new skills and improvements in the existing ones, which in turn leads to economic benefits due to increased productivity, quality improvements, reduced waste, quicker production times and more flexible responses and a lower incidence of accidents in the workplace (Mital et al., 1999).

In this case, we evaluate the benefits of training considering two aspects: the increase in energy efficiency and the decrease in workplace accidents, taking as a reference the changes that occurred between 2016 and 2017, which we attribute to the training of workers.

In the first case, an increase in energy efficiency is observed from 526 kWh/ton to 538 kWh/ton (Table 7). In order to determine the economic benefit, two different scenarios are evaluated, on the one hand, what would be the revenues from the sale of electricity to the grid, if the production efficiency of 2017 had been the same as the previous year. The second scenario evaluates the revenues obtained, considering the energy efficiency of 2017.

In the second case, a decrease in workplace accidents (from 6 to 5) and sick leave (from 21.21 to 16.94) is observed (Table 7). In order to determine the economic benefit, the cost reduction due to a lower number of accidents and sick leave is calculated. The main assumptions are that each day off work per person is 79.54 €, and the average medical cost is 1,721.78 € due to fractures, sprains, and dislocations (Ministerio de Sanidad, 2014).

Table 7. Comparison of scenarios related to workers training benefit. Source: authors elaboration based on TERSA (2017b); Faura-Casas Auditors Consultants (2017).

| Benefits | Concept | Scenario 1 | Scenario 2 |
|---|---|---|---|
| Increase in energy efficiency | Energy efficiency (kWh/ton) | 526 | 538 |
| | Waste treated (ton) | 368,791 | 368,791 |
| | Total energy production (MWh) | 193,984.07 | 198,409.56 |
| | Energy sold to grid (MWh) | 171,365.52 | 175,275.00 |
| | Price Electricity (€/MWh) | 52.52 | |
| | Total Revenue (€) | 9,000,117.32 | 9,205,443.19 |
| | Benefit (€) | 205,325.87 | |
| Reduction of Workplace accidents | Accidents | 6.00 | 5.00 |
| | Salary by worker (€/day) | 79.54 | |
| | Sick leave by worker | 21.21 | 16.94 |
| | Total Medical Cost (€) | 10,330.68 | 8,608.90 |
| | Total Salary (€) | 10,120.59 | 6,735.45 |
| | Total Accidents Cost (€) | 20,451.27 | 15,344.35 |
| | Benefit (€) | 5,106.92 | |

### *3.3.7 Quality of life*

According to Eshet et al. (2006), both landfills and incinerators are associated with the conditions that arise as a result of their existence. Both installations cause, in varying degrees, smells, dust, windblown rubbish, visual intrusion, noise and traffic. The extent of the effects depends on the distance from the site, the type of waste, the type of site (existing, new or proposed), the topography and the direction of the prevailing wind.

Disamenities. To analyse the disamenities generated by the ERF it is necessary to perform a choice experiment to estimate the preferences of householders and their willingness to pay (WTP) in order to avoid having an incinerator close to their homes (Sasao, 2004) or to quantify by means of Hedonic Pricing Method (HPM) the impact on property values due to the issues caused and the change in environmental quality (Hite et al., 2001; Lavee and Bahar, 2017). Related with these disamenities, the neighbourhood associations (representing parts of Saint Adrià de Besòs, Barcelona and Badalona) created a coordinating body, Aire Net, to protest the high emissions of pollutants and bad odours coming from the TERSA incinerator (Agència de Salut Pública de Barcelona, 2018). Table 8 shows some of the most recent studies that have analysed the impact on housing prices due to the proximity of incinerators. In Jamasb and Nepal (2010) and European Commission (2000), 8 €/ton of waste are considered as disamenities cost. This cost is obtained using mainly U.S. study results because of the lack of European studies as can be seen in Eshet et al. (2006). In this case, we consider this disamenities cost (8 €/ton); however, it is recommended to perform an analysis to determine the specific disamenities cost for this ERF.

Table 8. Findings of studies on disamenities valuation related to incinerators. Source: authors elaboration.

| Study | Sample | Country | Time | Results | Method |
|---|---|---|---|---|---|
| Sun et al. (2017) | 2,119 real estate transaction data | Shenzhen city, China | 2013 to 2015 | For every additional km away from site, the mean price increase about 1.3%. If the distance is restricted to within 5 km, the effect rises to 8.6%. | HPM |
| Rivas Casado et al. (2017) | 55,000 transactions | England and Wales | 1983 to 2014 | Approximately 0.4% to 1.3% reduction in mean house price. | HPM |
| Zhao et al. (2016) | 2,258 transactions | Hangzhou, China | 2014 to 2015 | 25.4% reduction in house price within 1 km from incinerator and 14% reduction for 2-3 kms from site. | HPM |

HPM: Hedonic Price Method

### 3.4. Identification of the stakeholders involved

After MSW system impacts have been identified, the stakeholders involved can be recognised; furthermore, it is important to define the stakeholder for which evaluation is done since (Medina-Mijangos et al., 2020). It has been determined from the impact analysis that the agents involved in this study are: a) The ERF company (TERSA Group), b) The company that runs the Mechanical-Biological treatment plant, c) Barcelona City Council, d) The company that runs the urban heating, cooling and hot sanitary water network (Districlima), e) Citizens of the Barcelona Metropolitan area. The economic analysis was carried out from the standpoint of the ERF, a public company owned by the Barcelona City Council.

### 3.5 Financial needs study

In the case of the ERF, the company has its own funds. The study shows that almost all the financing is through share capital. This capital is divided between Barcelona de Serveis Municipals, S.A. (which has 58.64% of the shares) and AMB (which has 41.36%), both belonging to the Barcelona City Council, the governing body. However, two loans were taken (in 2010 and 2014) to bring the ERF into line with the new model of MSW management in Catalonia.

### 3.6 Addition of costs and revenues

Once the majority of the impacts has been quantified, it is possible to add the different costs and revenues, thereby obtaining the Total Benefit generated by the ERF by using the Eq. (1) and (2) shown in section 3.1. Consequently, two distinct situations can be observed. Firstly, the ERF is economically and financially profitable in its operations, which is defined by determining the Private Benefit (BP > 0); secondly, the ERF is economically, financially, socially and environmentally profitable, as defined by determining the Total Benefit (BT > 0). The Financial Costs (FC) are composed of the financial costs (equivalent to 32,713 €), as a result of the two loans with interest of 1.5% and 1.6% respectively, which is equivalent to 0.09 €/ton; the financial revenues were 1,925,084 €, equivalent to 5.22 €/ton, giving a net value of 5.13 €/ton. Taxes (T) were 689,652 €, or 1.86 €/ton, which corresponds to the company tax (BOE, 2014).

Regarding the Opportunity Cost (OC), this is the value of the foregone alternative action, under the concept of sustainable development and its three pillars, the best alternative will be one that provides not only the best economic performance but also the best social and environmental performance (Medina-Mijangos et al., 2020; Pearce, 1992). As no better alternatives have been found for the use of residual waste, it is determined that it comes as a result of the effects of financial instruments when the company's share capital and reserves (62,353,399 €) are invested in them. The interest from financial instruments in 2017 was 3% (Banco de España, 2019); therefore, the opportunity cost is 1,870,601.98 €, the equivalent of 5.07 €/ton.

### 3.7 Sensitivity analysis

The results obtained were subjected to analysis which allowed evaluating the sensitivity of the system to changes in some of the critical variables involved in waste treatment. The variables analysed were the energy costs, opportunity cost, capacity used in the treatment installations and treatment service charges, among others.

## 4. Results and Discussion

After applying the methodology described in the previous section, Table 9 shows the impacts considered in this case study, which were described in section 3.3. Primarily, the types of impacts generated by the ERF (internal or external) as well as the Impact Identification; these can have a positive or negative effect, being either a cost or revenue. There follows the Impact Frequency, which shows when each impact occurred. A project may show impacts at any stage of its life; in this case, all the impacts identified had effects during the project's useful life. In the case of Impact Quantification, the units that allow these impacts to be translated into monetary values have been defined. Finally, the Impact Valuation is presented, where the monetary value of some impacts was calculated. First of all, the costs and revenues in terms of 2017 are presented (€/year), then, taking as a reference the cost and revenue per waste unit treated in the ERF (€/ton), the united costs and revenues were calculated on the basis of 368,791 tons of waste treated.

Table 9. Summary of the Economic results of Impacts considered for the ERF per €/year and €/ton (year 2017). Source: authors elaboration.

| Type of impact | Impact group | Impact Identification | | Impact Frequency | Impact Quantification | Impact Valuation (€/year) | | Impact Valuation (€/ton) | |
|---|---|---|---|---|---|---|---|---|---|
| | | Costs | Revenues | | | Costs | Revenues | Costs | Revenues |
| Internal | Infrastructure | - Labour | | During the life of project | 368,791 tons | 5,192,953.00 | | 14.09 | |
| | | - Equipment repair and Maintenance costs | | | 368,791 tons | 4,901,799.00 | | 13.29 | |
| | | - Provision costs | | | 368,791 tons | 34,019,347.00 | | 92.24 | |
| | | - Depreciation of fixed assets | | | 368,791 tons | 1,813,126.00 | | 4.92 | |
| | | - Other Costs | | | 368,791 tons | 6,001,382.00 | | 16.27 | |
| Internal | Reuse, recycling and recovery of waste | | - Energy | During the life of project | 175,327 MWh | | 9,208,253.00 | | 24.97 |
| | | | - Steam | | 95,509 tons (17,122 MWh) | | 664,628.00 | | 1.80 |
| | | | - Ashes and slags | | 87,036 tons of slags and ashes | | 12,336.00 | | 0.03 |
| | | | - Water | | 22,350 $m^3$ of water | | 22,657.00 | | 0.06 |
| | | | - MSW treatment fee | | 368,791 tons | | 10,574,518.00 | | 28.68 |
| | | | - Services to other companies | | 368,791 tons | | 25,459,459.00 | | 69.03 |
| | | | - Other Revenues | | 368,791 tons | | 8,416,304.00 | | 22.83 |

Table 9. Summary of the Economic results of Impacts considered for the ERF per €/year and €/ton (year 2017). Cont. Source: authors elaboration.

| Type of impact | Impact group | Impact Identification | | Impact Frequency | Impact Quantification | Impact Valuation (€/year) | | Impact Valuation (€/ton) | |
|---|---|---|---|---|---|---|---|---|---|
| | | Costs | Revenues | | | Costs | Revenues | Costs | Revenues |
| External | Use of materials | | - Avoided Material send to landfill | During the life of project | 368,791 tons | | 8,666,588.50 | | 23.50 |
| | | | - Guarantee of supply of energy | | 175,327 MWh | Not quantified | | | |
| | | | - Quality of energy | | 175,327 MWh | | 2,454,578.00 | | 6.65 |
| | | | - Districlima Dependence | | 95,509 tons | Not quantified | | | |
| External | Environment | - Emissions to air ($CO_2$) | | During the life of project | 213,252.75 tons $CO_2$ eq. | 2,132,527.50 | | 5.78 | |
| | | | - Avoided Emissions to air ($CO_2$) | | 84,115.51 tons $CO_2$ eq. | | 841,155.10 | | 2.28 |
| External | Public Health | - Physical injuries | | During the life of project | 5 people | 13,660.50 | | 0.04 | |
| | | - Cancer Emission of PCDD/PCDFs | | | Amount of People Affected | 0 | | 0 | |
| External | Education | | - Culture of 3R for citizens | During the life of project | Amount of People | Not quantified | | | |
| | | | - Technique of workers | | % productivity | 210,432.79 | | | 0.57 |
| External | Quality Life | - Disamenities | | During the life of project | Price of households | 2,950,328.00 | | 8.00 | |
| | | | | | Total of Internal Impacts | 51,928,607.00 | 54,358,155.00 | 140.81 | 147.40 |
| | | | | | Total of External Impacts | 5,306,948.79 | 11,962,321.60 | 13.82 | 33.00 |
| | | | | | Total Impacts | 57,235,555.79 | 66,320,476.60 | 154.63 | 180.40 |

Eq. (2) and (3) show the results obtained from the Private Benefit and Total Benefit, respectively. These values are expressed in € per ton of waste treated.

$$B_P \ = \sum_{n=1}^{1}[(147.40) - (140.81 - 5.13 + 1.86)] \ = \ 9.86\text{ €} \quad (3)$$

$$B_T = \sum_{n=1}^{1}[(147.40) - (140.81 - 5.13 + 1.86) + (33.00 - 13.82) - 5.07] \ = \ 23.97\text{ €} \quad (4)$$

Once the total revenues and costs (internal and external) have been determined, it is possible to evaluate whether the ERF is operationally (BP > 0) and economically (BT > 0) profitable. In the analysis that only takes the ERF's private revenue and costs into account, the results show a positive economic return (BP > 0); therefore, the project is operationally profitable. Specifically, the net profit from the ERF is 9.86 €/ton of waste. The analysis that considers the internal and external costs and revenues of the ERF is BT > 0, which give a benefit of 23.97 €/ton of waste, which indicates an economically profitable project.

Regarding the impacts that have not been economically valuated, these are positive impacts (revenues) such as the value given by consumers to the guaranteed energy supply, the profits obtained by Districlima from the ERF (which cause a certain dependency) and the development of a culture of sustainability among consumers and citizens, all of which can increase the project benefit considerably. These impacts have not been monetarily valuated, as each has its own methodology, which must be presented and developed exhaustively in an individual context. In order to keep the article as concise as possible, each impact has been briefly presented and should be studied and monetarily valuated in future works. On the other hand, WTP for green energy and the impact of disamenities in households' prices were economically valuated considered the results of other studies. Despite the above, it is advisable to develop studies to evaluate these impacts in the study area.

In Fig 3, it can be seen that the internal impacts are the most representative impacts and with greater weight in the Total Benefit. Although external impacts have less weight in the Total Benefit, they play an important role, since they ensure that the ERF is economically profitable. It can be seen that the most important costs correspond to the impacts related to infrastructure, specifically with payments to other companies for services provided, which reach a value of 87.37 €/ton. The most important revenue derives from the impacts of waste recycling and recovery, specifically for services to other companies, with a value of 69.03 €/ton.

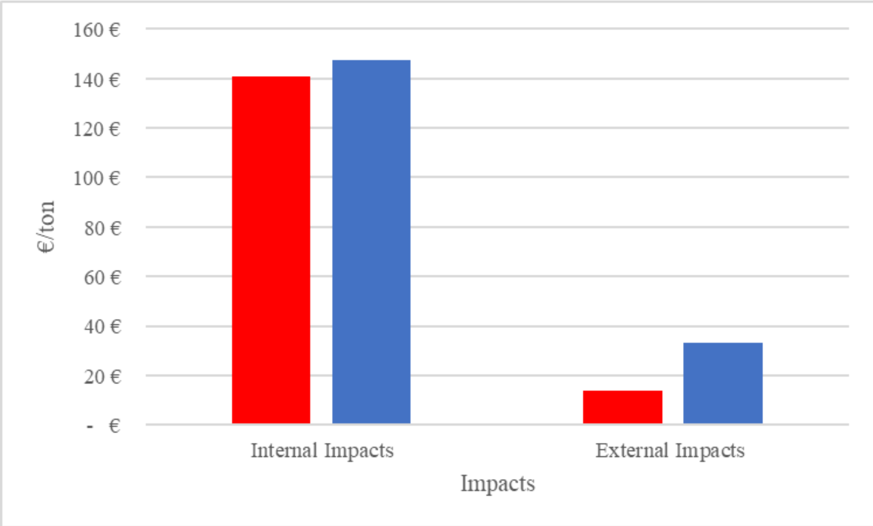


Fig 3. The ERF impact category. The red bars in the plot show the Costs generated by the ERF; the blue bars show the revenues generated by the ERF. Source: authors elaboration.

An important aspect of the applied methodology is that it permits the effects of externalities on the Total Benefit to be studied. In this case study, externalities increase the benefit of the treatment facility, making it more profitable and reliable. Finally, the applied methodology can be easily generalised.

According to Massarutto (2015), in European countries, the private costs range between 100 and 130 €/ton, that agrees with the results. In the case of Asian countries, the values are much lower, ranging between 13.5 and 22.5 €/ton (Aleluia and Ferrão, 2017). In comparison to landfills, that is the other option for the management of residual waste, landfills have lower private costs, as some authors demonstrated, such as Massarutto et al. (2011) where it is noted that private costs ranging between 34 and 44 €/ton. On the other hand, Jamasb and Nepal (2010) point out that private costs ranging between 7.7 and 9.12 €/ton.

Despite the above, Woon and Lo (2016) show that if externalities are considered, incinerators have better economic results than landfills.

### 4.1 Sensitivity Analysis

The sensitivity analysis was used to examine the robustness of the results of the technical-economic analysis. According to the European Commission (2014), the sensitivity analysis is carried out by varying one variable at a time and determining the effect of this change.

The first to be considered as a variable is the revenue received for services provided to other companies, which corresponds to the highest and most important revenue of the economic analysis, with a value of 69.03 €/ton. In this case, the project may become economically non-profitable if the revenue obtained from the companies who receive the waste management services falls below a value of 45.06 €/ton, where the BT begins to be negative and does not fulfil condition

BT > 0. This is unlikely because there is already a fixed fee per provision of services to other companies. In this case study, the Opportunity Cost is considered as the interest gained from the use of a financial instrument, as it is considered that there is no better alternative for the use of waste from the residual fraction. However, if other alternatives arise in the future, the project could become economically non-profitable if the opportunity cost exceeds 29.04 €/ton, where BT begins to be negative and does not fulfil the condition BT > 0. Under the current conditions, we can show that the ERF installation is both economically profitable and reliable.

## 5. Conclusions

The ERF provides an important service to the city of Barcelona and its environs, as the management of the residual waste prevents it being sent to landfills and avoids the possible damage to the environment and society that these installations cause. The ERF also generates energy from the waste, which helps guarantee a constant supply. However, there is still considerable opposition from the inhabitants due to the nuisances caused, above all the possible harm to public health and disamenities generated. The main objectives of this case study are to determine the Total Benefit of the ERF and view two situations separately. Firstly, the ERF should be economically and financially profitable in its running, which is defined by determining the private profit (a situation generally of interest to technicians and politicians); secondly, the MSW management system should be economically, financially, socially and environmentally profitable (of interest to economists and to society).

It can be concluded from this case study that the ERF is operationally (BP = 9.86 €/ton) and economically (BT = 23.97 €/ton) profitable. The case study has been subjected to a sensitivity analysis, evaluating the effects of two variables separately; first, the effects of the revenue from the ERF's services to other companies and later the opportunity cost. It can be concluded that, under the current conditions facing the ERF, the plant is both economically profitable and reliable. It is also important to point out that some external revenues have not been quantified, such as the promotion of a recycling culture and the value given by consumers to the guaranteed energy supply, among others. The monetary valuation of these external revenues may increase the Total Benefit of the facility analysed and make it less sensitive to critical variables. An important aspect of the applied methodology is that it permits the effects of externalities on the Total Benefit to be studied. The consideration and valuation of the externalities related to management systems are essential because they can cause the censorship of the treatment plant or its economic viability. In some projects, if only the private impacts are considered, the management systems can seem profitable; however, if the externalities are included, the system may prove to be unprofitable. In this case study, externalities increase the benefit of the treatment plant, making it more profitable and reliable.

For future studies, it would be recommendable to extend the economic valuation of the externalities generated by the ERF, as well as an analysis of all the processes in this management system (considering the collection, transport and treatment of waste). An important economic analysis is related to the changes generated by the MBT plant, as well as its effect on the costs and revenues of the ERF, comparing the positive and negative impacts generated since the plant was inaugurated in 2006. An in-depth economic analysis is also needed of the impacts on public health, assuming that in the case of the ERF the neighbours have 3 to 4 times more chance of developing cancer (due to exposure to PCDD/Fs) than residents of cities such as Girona, Mataró and Tarragona.

## Appendix A (Table 10)

Pollutant emissions of Incineration Plants. Source: Medina-Mijangos et al. (2020)

| Environmental Impact | Incineration Plant |
|---|---|
| Emissions to groundwater and surface water | Dioxins/ dibenzofurans (PCDD/PCDFs) |
| | Heavy metals |
| | Salts |
| Emissions to air | Particulates ($PM_{10}$) |
| | NOx |
| | $SO_2$ |
| | CO |
| | $CO_2$ |
| | VOCs |
| | HCl, HF (acid gases) |
| | PCDD/PCDFs |
| | Heavy metals |
| | $N_2O$ |
| Emissions to soil | Heavy metals [1] |
| Avoided emissions | $CO_2$, $SO_2$, NOx, and other air pollutants emitted from electric power generation plants |

[1] Cr, Pb, Cu, Ni, Zn, Cd, Hg, and As (Ma et al. 2018)

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# Anexo C: Artículo aceptado en revista incluida en el índice JCR

**ESEU-D-21-00077R1**

**The economic assessment of the environmental and social impacts generated by a light packaging and bulky waste sorting and treatment facility in Spain: A circular economy example**

Rubí Medina-Mijangos; Samer Ajour El Zein; Hilda Guerrero-García-Rojas; Luis Seguí-Amórtegui

Environmental Sciences Europe

Dear Mrs. Medina-Mijangos,

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# The economic assessment of the environmental and social impacts generated by a light packaging and bulky waste sorting and treatment facility in Spain: A circular economy example

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**Abstract:**

**Background:** The waste sorting and treatment facilities play an important role in the management of Municipal Solid Waste (MSW), as they permit the materials to be prepared for their later reuse and recycling. The aim of this work is to carry out a technical-economic analysis of a sorting and treatment facility (STF) of light packaging and bulky waste in Gavà-Viladecans, Barcelona, Spain, by means of a methodology based on a social Cost-Benefit analysis (sCBA), as it studies the private impacts and externalities (impacts related with environmental and social aspects) to determine the Total Benefit (the difference between revenues and costs) generated by the facility in order to decide whether it is operationally and economically profitable.

**Results:** The key point of the case study is the identification, frequency, quantification and monetary valuation of the impacts generated by the facility, as well as the sale of materials, the CO2 emissions and the increase in the availability of materials, among others. By applying the methodology, it has been possible to show that this facility is operationally (BP = 7.06 €/ton) as well as economically (BT = 55.72 €/ton) profitable.

**Conclusions:** The plant is highly profitable from a social and environmental perspective, as can be seen from the monetary valuation of the externalities. The STF fulfils a primordial function for the city of Barcelona and its environs, as it treats waste for later reuse and recycling, preventing waste from being sent to landfills and reducing the $CO_2$ emissions from the extraction of virgin raw materials, thereby helping to reach the objectives set by the European Commission. Finally, this paper provides a guide for future researchers and decision-makers interested in the economic analysis of MSW management systems.

**Keywords:** Economic assessment; Recycling; Municipal Solid Waste; Externalities; social cost-benefit analysis; Circular economy

## Nomenclature

| | |
|---|---|
| AMB | Metropolitan Area of Barcelona |
| AVW | Annual volume of waste treated |
| $B_E$ | External Benefit |
| $B_P$ | Private Benefit |
| $B_T$ | Total Benefit |
| FC | Financial Costs |
| IC | Investment Costs |
| J | Total impacts |
| j | Impact index (j = 1, …, J) |
| N | Total project duration |
| n | Project year index (n = 0, …, N) |
| NE | Negative Externalities |
| OC | Opportunity Cost |
| OMC | Operational and Maintenance Costs |
| PE | Positive Externalities |
| SP | Sale Price per Volume Unit |
| STF | Sorting and Treatment Facility |
| T | Taxes |

## 1. Introduction

The circular economy emerges as an alternative to the current linear economy model, where materials and products are used for a short time and then are discarded, generally ending up in landfills, generating negative impacts (environmental and social) [1]. The circular economy is a production and consumption model that seeks to ensure that materials remain in the economy longer, reducing the use of virgin raw materials and the generation of waste and consequently reducing damage to society and the environment [2]. The circular economy is based on the durable design, maintenance, repair, reuse, remanufacturing, restoration and recycling of products [3].

In general, recycling is considered beneficial for the environment and the economy [4]. It mitigates the lack of resources by reducing the consumption of raw materials, reducing the amount of waste sent to landfills, and extending their useful working life. Additionally, a decrease in the amount of waste sent to landfills and incinerators reduces ground, water and air pollution [5,6]. Some countries suffer from a serious lack of raw materials and, in their case, waste represents a sure supply of materials, which in turn reduces their dependence on imported materials, leads to substantial energy savings and contributes to conserving the environment [7]. On the other hand, recycling allows significant economic savings since it prevents that a large percentage of the value of the materials is lost to the economy after a short use, as in the case of plastic packaging materials, where it is estimated that approximately 95% of value is lost, that is, USD 80–120 billion annually because these materials are discarded after a short time [8]. In addition, recycling avoids costs due to the extraction and production of new raw materials and costs due to landfilling or incineration of waste (i.e., payment of gate fees, environmental and public health damage costs).

The waste sorting plants play an essential role in MSW management, as they allow the materials to be prepared for their later reuse and recycling. On the other hand, these facilities promote the circular economy, and they allow to keep the resources in use for as long as possible, the maximum value extracted from them while in use by recycling products into the same or similar quality application, and product recovery and regeneration at the end of life [8,9].

### 1.1 MSW management and Material Recovery in Barcelona

This article focusses on carrying out a Technical-Economic analysis of a waste sorting and treatment facility (STF), located in Gavà-Viladecans, Barcelona, Spain. The facility provides a waste management service to the metropolitan area of Barcelona (AMB) and promotes the circular economy. The AMB with an area of 636 km2 and more than 3.2 million inhabitants is one of the largest metropolitan areas in Europe [10]; it is composed of 36 municipalities, including Barcelona city, Badalona and Sant Adrià de Besòs. In 2017, 1,452,414 tons of MSW were generated by the AMB, corresponding to 1.22 kg/day per inhabitant. Specifically, 43,488 tons of light packaging waste were collected through the yellow containers and 71,469 tons of bulky waste were collected through the green points.

This facility analized is composed of two plants, one for light packaging waste treatment and the other for bulky waste treatment, as can be seen in Fig. 1. This facility is one of the three light packaging waste sorting and treatment facilities and the only bulky waste sorting and treatment facility in the AMB. This facility is managed by a public company belonging to the Ajuntament de Barcelona (Barcelona City Council), and it was established in 1992 and built on industrial-zoned land, with a surface area of 58,600 m2, and is surrounded by a mixture of industrial plants and agricultural areas [11].

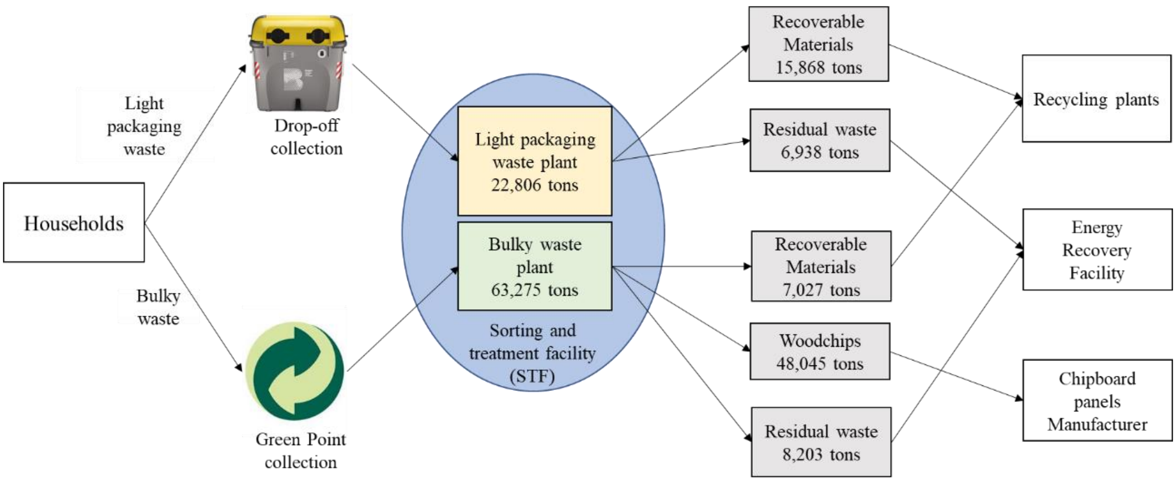


Fig 1. Flowchart of the MSW treated at the STF in 2017. Source: authors elaboration.

The light packaging waste plant carries out the sorting and treatment of light packaging waste obtained from the yellow containers, dealing with approximately 22,000 tons/year. This plant sorts different types of light packaging, such as plastic packaging (HDPE, PET, LDPE), metal packaging (aluminium and steel) and carton packaging for food and drink. These materials are then sold to authorised recycling companies for the later manufacture of new packaging and materials [12]. The bulky waste plant carries out the treatment of bulky waste and wood recovered from the green points around the AMB. This plant deals with approximately 60,000 tons/year, recovering and sorting different types of waste such as wood, scrap, mattresses, plastic furniture, pressurised cans, among others. The wood is triturated to obtain chips, used mainly in the manufacture of chipboard for the furniture industry. Once separated, the rest of the waste is sold to authorised companies, always prioritising its recovery. The waste that cannot be materially recovered is sent to the Energy Recovery Facility for energy generation [12]. Fig. 1 shows the amount of waste that was treated in 2017, as well as the amount of waste that was sold to different companies or sent to other facilities.

## 1.2 Literature Review

Generally, when waste management systems are evaluated, only the private or internal impacts such as costs and revenues related to the investment, operation and maintenance of the treatment plants are considered [13]. This may cause a bias against other options such as recycling, which from a purely financial point of view may be more expensive than dumping [14]. However, if we include the external costs and revenues or externalities (impacts related to environmental and social aspects) the results may change, favouring the adoption of options such as recycling, which has greater social and environmental advantages. Recycling waste means reducing the consumption of raw materials, leading to considerable energy savings and contributes to protecting the environment, as well as reducing the amount of waste sent to landfills, thereby increasing their useful life [6,7].

There are several studies that focus on the economic analysis of recycling systems, generally concentrating on comparing them with the landfills. Some studies carry out the analysis by focussing on the private costs, as in Tonjes & Mallikarjun (2013) [15], who present a model of systems to determine whether the recycling programmes are cost-effective. This paper considers primarily the private costs (personnel, financial and fuel costs, among others). Lavee (2007) [16] studies whether the recycling systems are economically efficient, considering the cost savings from reducing the amount of waste sent to landfills as well as the private costs associated with the adoption of recycling systems. The results show that, for 51% of municipalities, adopting recycling would be efficient, even without taking the externalities into account. Da Cruz et al. (2012) [6] present the costs and benefits of recycling packaging waste in Portugal, studying the profitability of the invested capital (debt and equity) with respect to the financing of the assets destined to the recycling process and the cost savings from redirecting waste from refuse collection activities and relying less on landfills. The unit cost of selective waste collection and sorting is calculated as 204 €/ton collected.

Gradus et al. (2017) [17] compare the cost-effectiveness of two different treatment options, recycling and incineration, for plastic waste in the Netherlands, focussing mainly on the environmental impact of the $CO_2$ emissions. They show that the main benefit of recycling plastic is that it avoids the $CO_2$ which would otherwise be produced during incineration and the production of the virgin plastic material. Craighill and Powell (1996) [5] compare the environmental impacts of a recycling system with a system for dumping in landfills using the Life Cycle Evaluation (a combination of the Life Cycle Assessment and economic evaluation) and considering the costs relating to gas emissions, traffic accidents and congested roads. The results show that the recycling system generally works better than the landfills in terms of contribution to climate change, the effects of acidification and the nutrition of surface water.

Although several economic analyses have been carried out regarding different recycling systems in terms of the collection and sorting of waste, generally, the focus is on economic valuation of one specific impact or only some impacts of those systems; for example, studying the costs relating to the environmental impact of the $CO_2$ emissions. Generally, these studies consider only private impacts or environmental impacts, without including social aspects such as the impact on quality of life, physical risks, and education. Furthermore, no previous studies have presented a model that considers and integrates various impacts generated by recycling systems.

The methodology used also allows researchers and decision-makers to evaluate, in a simple way, the operational and economic profitability of a specific treatment facility while considering the most relevant impacts related to economic, social, and environmental aspects of recycling systems, allowing the evaluation of MSW management systems considering the sustainability principles and their three pillars. In addition, have a more complete vision of these systems and their effects on society, environment, and economy. It is considered that the current economic system does not take into account environmental and social costs to maximise profits. Generally, while economic indicators such as investment or production are positive, environmental and social indicators are increasingly negative [18]. That is why it is important to change the traditional focus of profit-making companies and find a balance between economic, social and environmental aspects. Some authors note that environmental, social, and economic concerns must be integrated throughout decision-making processes to move towards development that is truly sustainable [19].

This article aims to determine and analyse several private and external impacts (positive and negative), thus providing a guide for future researchers and policy-makers interested in the economic analysis of any MSW management system. This article addresses the issue of costs and revenues involved in a MSW sorting facility, which is a highly debated issue in terms of environmental impact but has the difference of considering and quantifying social costs such as physical risks, education, and quality of life, which makes the work have a novel contribution, with the potential to constitute a consultation document to establish a standard methodology on this topic.

Previously, Medina-Mijangos et al. (2021) [20] presented a methodology for the economic analysis of any kind of MSW's management system, where several impacts were listed and described. Also, a case study was briefly presented to verify the applicability of the methodology; however, only a few impacts were valued monetarily. In the present paper, impacts related to environmental and social aspects are described in detail, quantified and valued monetarily for a specific context. The main aim of this case study is to determine the Total Benefit generated by the plant, taking several private and external impacts into account, which will then be identified, quantified and valuated monetarily; this will determine whether the plant is operationally and economically profitable.

The rest of the document is structured as follows: Section 2 describes the methodology and how the data has been obtained and used. Then the results of the case study are presented and discussed in Section 3. Finally, Section 4 contains the conclusions, as well as suggestions for future research.

## 2. Methods

The data used in this case study was obtained from public information available on the website of the company's group, which contains documents such as auditor's reports, annual accounts, sustainability reports and production data, as well as environmental studies carried out by the company and other bodies. The SABI database, which contains the financial information of Spanish and Portuguese companies, was also consulted (Bureau Van Dijk, 2008). The present case study focusses on the costs and revenues generated by the treatment facility in 2017.

The methodology conducted by Medina-Mijangos et al. (2021) was adopted in this study. This research followed a method for the technical-economic analysis of MSW management systems based on a social Cost-Benefit Analysis (sCBA), as it evaluated the waste management systems and plants from the perspective of society as a whole, where the private and external costs and revenues (caused by environmental and social impacts) were considered (Hoogmartens et al., 2014). The methodology is composed of seven steps which should be fulfilled, as shown in Fig 2: 1) Objective definition, 2) definition of scope study, 3) impacts of the project, 4) identification of the stakeholders, 5) study of the needs and financial possibilities, 6) aggregation of costs and revenues and 7) sensitivity analysis.

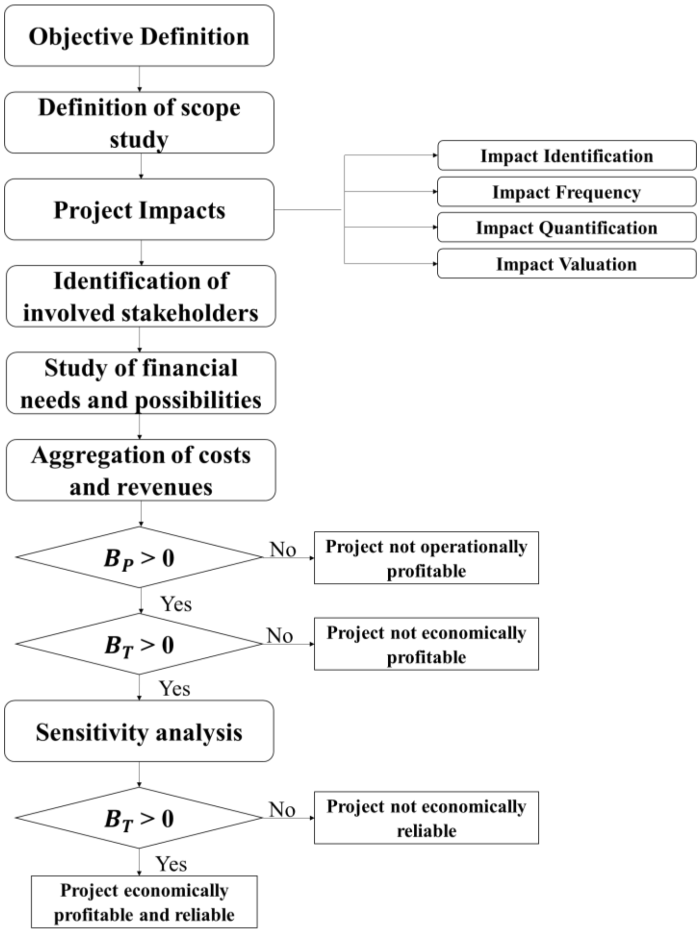


Fig 2. Steps for technical-economic analysis to evaluate the STF. Source:[20]; [23].

## 2.1 Objective Definition

The aim of this case study is to evaluate whether the STF is operationally and economically profitable, by determining if the Private Benefit (BP) and Total Benefit (BT) are greater than 0. The objective function to be optimised is shown in Eq. (1) and (2):

$$\boldsymbol{B}_P = \sum_{\boldsymbol{n=0}}^{\boldsymbol{N}}[(AVW_n * SP) - (IC_n + OMC_n + FC_n + T_n)] \quad (1)$$

$$\boldsymbol{B_T} = \sum_{\boldsymbol{n=0}}^{\boldsymbol{N}}[(AVW_n * SP) - (IC_n + OMC_n + FC_n + T_n) + (PE_n - NE_n) - OC_n] \quad (2)$$

Where AVW: Annual volume sold; FC: Financial Costs; IC: Investment Costs; N: Total project duration; n: Project year index (n = 0, …, N); NE: Negative Externalities; OC: Opportunity Cost; OMC: Operational and Maintenance Costs; PE: Positive Externalities; SP: Price of Sale per Volume Unit; T: Taxes. Definitions about the elements of equations can be found in the supplementary material (Additional file 1: Table S1).

## 2.2 Definition of scope study

The STF is a public company which is part of a group belonging to the Ajuntament de Barcelona [24]. Its main activity is the sorting and treatment of the MSW of the AMB. This case study focusses on analysing the treatment of MSW at the STF, taking both the light packaging and bulky waste treatment processes into account, without considering the collection and transport of the waste because these processes are realised by other companies. Only the processes and impacts occurring after the arrival of the waste at the treatment plant, until their sale to other intermediaries along the value chain (companies of reuse and recycling) are considered. The costs and revenues studied are from 2017 [24], that is N=1.

### 2.3 Impacts of the project

In this section the key points are the identification, frequency, quantification and monetary valuation of the impacts (private and external). The present case study has identified the majority of possible impacts; however, only some have been valued monetarily.

The impacts considered are related to the 3 pillars of sustainability: economic, social and environmental, and the sustainable development indicators established by international organisations such as the United Nations, the European Union, the U.S. Environmental Protection Agency (EPA). The key principle of sustainable development is integrating environmental, social, and economic concerns into decision making [19]. In Fig. 3, the essential aspects that must be promoted in the context of sustainability are included, which are related to impacts that have been considered and economically analysed in this case study.

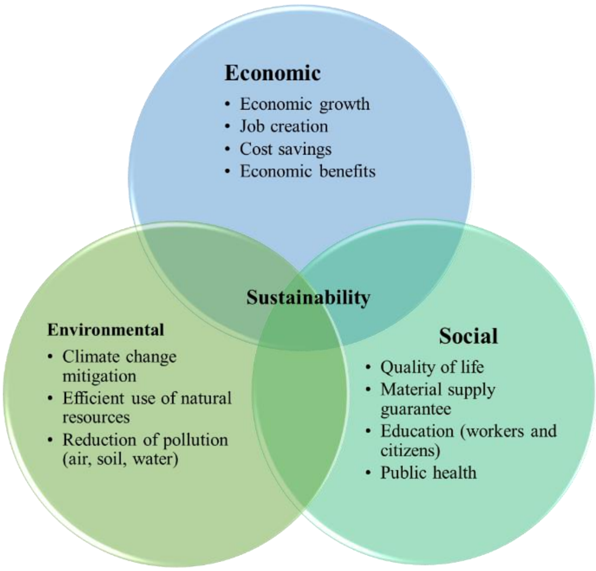


Fig 3. Impacts related to sustainability pillars. Source: [25].

Table 1 shows a list of the positive and negative impacts to be considered in this case study. The principal characteristics of each impact group analysed are detailed in the following sections.

Table 1. Summary of the STF Impacts. Source: authors' elaboration based on [20].

| Impact group | Description of impacts | Type of impact |
|---|---|---|
| Infrastructure | Treatment of waste | Negative/ Private |
| Reuse, recycling and recovery of waste | Sale of materials | Positive/ Private |
| | Gate fees | Positive/ Private |
| Use of materials | Avoided Material sent to landfill | Positive/ External |
| | Guarantee of supply of material | Positive/ External |
| | Quality of material | Positive/ External |
| Environment | Avoided emissions to air | Positive/ External |
| | Avoided emissions to water | Positive/ External |
| Public Health | Physical Risks | Negative/ External |
| | Chemical Risks | Negative/ External |
| Education | Culture of reduction, reuse and recycling of waste | Positive/ External |
| | Technique of workers (reduce of laboral accidents) | Positive/ External |
| Quality of life | Disamenities: odour, dust, windblown litter, visual intrusion, noise | Negative/ External |

### *2.3.1 Infrastructure*

Treatment of waste. This impact group includes the private expenditures (investment, operation and maintenance costs) relating to the infrastructure of MSW management [26,27]. These can be classified as CAPEX (Capital expenditures) and OPEX (Operational & Maintenance expenditures).

In this case study only OPEX is considered, as we are focussing on a specific operating year and the capital expenditures are included in the depreciation values. Table 2 shows the costs related to the infrastructure, classified as: a) Labour costs: this includes costs such as wages and salaries, social security payments and training costs, among others; b) Maintenance and repairs of equipment c) Supply costs, which include the cost of raw materials and supplies as well as payments for services rendered by other companies; d) Depreciation of fixed assets and equipment, the installations used by the plant in performing its tasks are owned by the parent group. The plant and the group signed a contract (1 January 2012) that formalises the transfer of the group's installations, with the fixed price being equivalent to the economic amortisation costs of the ceded plants [24]; d) Other expenses: this includes a quantity corresponding to other operative costs such as insurance, machinery rental and leasing, among others.

In 2017, a total of 22,806 tons of light packaging waste and 63,275 tons of bulky waste were treated in the plant [12]. The annual private costs are obtained directly from the 2017 annual accounts [24]. These annual values are divided by the total amount of waste treated (86,081 tons) to obtain the cost per ton (€/ton). As can be seen in Table 2, the most representative costs are those relating to other costs and the depreciation of the fixed assets.

Table 2. Summary of Infrastructure costs generated by the STF. Source: authors' elaboration based on [24].

| **Concept** | | **Annual Costs (€/year)** | **Cost per ton (€/ton)** | **Percentage (%)** |
|---|---|---|---|---|
| a) Labour cost | | | | |
| | Salaries & Wages | 1,290,339 | 15.00 | 15.60 |
| | Social Security | 354,864 | 4.12 | 4.28 |
| | Other labour costs | 50,287 | 0.58 | 0.60 |
| b) Equipment repair and Maintenance costs | | 1,165,892 | 13.54 | 14.08 |
| c) Supply costs | | | | |
| | Raw materials and inputs | 281,376 | 3.27 | 3.40 |
| | Provision of services (Subcontracting) | 1,412,751 | 16.41 | 17.06 |
| d) Depreciation of fixed assets | | 1,637,455 | 19.02 | 19.78 |
| e) Other expenses | | 2,086,242 | 24.24 | 25.20 |
| Total | | 8,279,207 | 96.18 | 100 |

### *2.3.2 Reuse, recycling and recovery of waste*

This impact group includes the private revenues obtained by the plant (Table 3), which can be classified as: a) Revenues from the sale of materials obtained from waste; b) Gate fees, which represent the payment to the provider of treatment services for each ton of waste treated; c) Other revenues, such as payment for services rendered to other companies and rental of equipment, among others [28]. Referring to the 2017 revenues, this includes the sale of treated light packaging waste, which recovered 15,868 tons of materials that were sent to recycling plants and 6,938 tons were sent to the energy recovery facility. Regarding the treated bulky waste, 7,027 tons of different materials such as cardboard, plastic and scrap metal, among others, were sold to authorised firms and 48,045 tons of woodchip were sold for the manufacture of chipboard panels. Finally, 8,203 tons were considered as residual waste and were sent to the energy recovery facility.

The annual revenues are obtained directly from the 2017 annual accounts [24]. The annual revenues result from multiplying the sale price by the quantity sold of the materials recovered in the treatment plant (AVW * SP). There is a market price for the different materials treated in the facility, such as scrap, paper, glass, plastic, and wood. In addition, the gate fees established (for light packaging and bulky waste) are multiplied by the amount of waste treated. These annual values are divided by the total amount of waste treated (86,081 tons) to obtain the revenue per ton (€/ton). As can be seen in Table 3, the most representative revenues are that relating to the provision of a waste management service, for both light packaging (49.89%) and bulky (38.83%) waste.

Table 3. Summary of private revenues generated by the STF. Source: authors' elaboration based on [24].

| Concept | Description | Quantity (ton) | Sale Price (€/ton) | Annual revenues (€/year) | Revenue per ton (€/ton) | Percentage (%) |
|---|---|---|---|---|---|---|
| Sales | Scrap | 3,374 | 81.08 | 273,548 | 3.18 | 3.08 |
| | Paper/ Carboard | 98 | 26.98 | 2,644 | 0.03 | 0.03 |
| | Glass | 93 | 11.86 | 1,103 | 0.01 | 0.01 |
| | Plastic | 12,243 | 1.06 | 13,008 | 0.15 | 0.15 |
| | Other materials | 7,087 | 0.05 | 378 | 0.00 | 0.00 |
| | Wood chips | 48,045 | 11.40 | 547,788 | 6.37 | 6.17 |
| Gate fees | Light-Packaging waste | 22,806 | 194.44 | 4,434,506 | 51.52 | 49.89 |
| | Bulky Waste | 63,275 | 54.55 | 3,451,628 | 40.10 | 38.83 |
| Other revenues | | - | - | 163,932 | 1.90 | 1.84 |
| | Total revenues (∑ revenues) | | | 8,888,535 | 103.26 | 100 |

### *2.3.3 Use of materials*

This impact group is related to the needs that the waste satisfies, as well as the benefits obtained from the waste used in different applications; for example, the use of recycled plastic can reduce the dependency on fossil fuels and reach the target fixed by the European Commission, increasing the percentage of preparation for municipal waste reuse and recycling to 65% for 2030.

<u>Avoided material sent to landfill.</u> One positive impact of the plant is that it allows the waste generated in Barcelona to be treated and sorted for recycling and reuse. Without this plant the waste would end up in landfills. To evaluate the benefits obtained by not sending the waste to landfill, consider the savings of the fixed rate, applied by the Generalitat de Cataluña, of 47.10 € per ton of waste sent to a controlled landfill [29]. The main objective of this fee is to discourage the use of landfills and reach the targets for waste management set by the European Commission. A total of 70,940 tons of materials have been recovered, instead of being sent to landfills, thereby producing a saving of 47.10 €/ton of recovered waste.

<u>Guarantee of supply of materials.</u> This impact group is related to the value that users give to a guaranteed supply of raw materials, in the context of a shortage of resources. Plastics made from fossil resources are a cheap but limited resource. To evaluate the benefits obtained from the use of materials generated from waste it is necessary to apply the contingent valuation method or a choice experiment to determine the consumers' opinions and their willingness to pay (WTP) for the guarantee of an uninterrupted supply of materials at a reasonable price.

<u>Quality of materials.</u> Another impact to be evaluated is the value that consumers give the products (packaging, furniture, etc) generated from waste in terms of their ecological and recycled status. In this case, it is necessary to design a choice experiment or a contingent valuation method to estimate the consumers' preferences and their willingness to pay (WTP) for these products or materials. The ecological or recycled status of products can be considered as a differentiating

factor that will allow companies to produce an added value and by communicating this extra value to customers obtain higher profits in the market [30].

In general, few studies have determined consumers' WTP for ecological products, such as the study performed by [31], which evaluated the consumers' WTP for different plastics used for water packaging. This study was realised in France, and 148 people were interviewed in February 2014. The results show that people are willing to pay an average premium of 0.79 €/pack of six 1.5 L bottles of recycled PET instead of PET bottles; this is a 21.94 % extra because the normal price for a pack of six PET bottles is 3.6 €.

Related to ecological furniture, [32] realised a structured questionnaire to examined consumer stated willingness to pay a price premium for eco-friendly children's furniture. This study was realised in Shanghai and Shenzhen (China), and 320 consumers were interviewed in 2013. Results indicate that 98% of respondents would be willing to pay a premium for such products. Of these respondents, 53% stated a WTP of no greater than 10%, while 45% stated a WTP of more than 10%. Moreover, [33] explored the influence of demographic factors on willingness to pay more for eco-friendly furniture. This study was realised in Czech Republic (Prague), and 195 consumers were interviewed between March and May 2017. The results show that the majority were willing to pay 557.69 USD higher than furniture's normal price for environmentally friendly ones.

A survey conducted in Europe and the United States with 1000 consumers was considered [34] to calculate the economic benefit related to the impact of ecological quality of materials recovered in the STF. This study indicates that 50% of consumers are willing to pay an additional 13% for ecological furniture and a 16% extra for green packaging. Therefore, an increase in sales revenues is considered (16% for packaging materials and 13% for wood). Currently, as in Table 4 is indicated, annual revenues of 16,755 € are received from the sale of packaging materials (paper, plastic and glass) and 547,788 € from the sale of wood, giving an additional profit of 2,681 €/year and 72,212 €/year, respectively.

Table 4. Summary of private revenues generated by the STF. Source: authors' elaboration based on [24].

| **Concept** | **Description** | **Quantity (ton)** | **Sale Price (€/ton)** | **Annual revenues (€/year)** | **Adittional WTP (%)** | **Adittional Revenues (€/year)** |
|---|---|---|---|---|---|---|
| Sales | Paper/ Carboard | 98 | 26.98 | 2,644 | 16% | 423.04 |
| | Glass | 93 | 11.86 | 1,103 | | 176.48 |
| | Plastic | 12,243 | 1.06 | 13,008 | | 2,081.28 |
| | Revenues from the sale of packaging materials | | | 16,755 | | 2, 680.80 |
| | Wood chips | 48,045 | 11.40 | 547,788 | 13% | 71,212.44 |
| | Revenues from the sale of material for ecological furniture | | | 547,788 | | 71,212.44 |
| | Total revenues (∑ revenues) | | | | | 73,893.24 |

*2.3.4 Environment*

The treatment of waste by the STF is principally related to the positive impact that the plant has, as it avoids several negative externalities such as the degradation of natural systems from leaks, greenhouse gas emissions and the impact on health and the environment of the substances contained in these materials (especially plastics).

Avoided emissions to air. The $CO_2$ emissions are very important due to their effect on global warming. Generally, the production of plastics uses fossil raw materials, which has a significant impact due to the $CO_2$ emissions generated during their extraction [8]. On the other hand, the use of recycled wood chips allows for a saving in the consumption of tons of virgin timber, as the wood treated in the plant is used for the production of chipboard panels, which reduces the $CO_2$ emissions.

Table 5 shows the amount of different types of materials recovered in the STF. Several studies have estimated the net $CO_2$ emissions obtained from the difference between the emissions from the primary production of the materials (with virgin raw materials) and those of the secondary production (using recycled materials), such as [35–37]. To calculate the total net $CO_2$ eq. emissions from the recycling of the different materials, the information about net emissions by material presented in [38,39] was used, where the mean and the standard deviation in terms of $CO_2$ eq. per ton of recycled material was determined. Finally, the mean in terms of net emissions of $CO_2$ eq. per ton of material was multiplied by the amount of each type of material recovered. In this case, the emission of 69,655 tons of $CO_2$ eq. were avoided.

The $CO_2$ emissions from industrial activities are taxed at an average estimated value of approximately 10 €/ton of $CO_2$ eq [41]. Generally, governments determine the abatement/avoidance cost of a specific contaminant in order to implement a $CO_2$ tax [42]. In 2025, this tax will reach a level of 30 €/ton of $CO_2$ eq. Therefore, when calculating the economic impact of avoided $CO_2$ emissions, the figure of 10 €/ton of $CO_2$ eq is used, and it is multiplicated by the total avoided $CO_2$ emissions.

Table 5. Net emissions of $CO_2$ eq. generated by the STF in 2017. Source: authors' elaboration based on [38–40].

| **Material** | **Amount of materials recovered (ton)** | **Net emissions by type of material (ton $CO_2$ eq./ton of recycled material)** | **Total net emissions by recovered material (ton $CO_2$ eq).** |
|---|---|---|---|
| Plastic HDPE | 1,451 | -1.530 | -2,220 |
| Plastic PET | 5,495 | -3.400 | -18,683 |
| Plastic LDPE | 2,700 | -2.900 | -7,830 |
| Plastic Mix | 2,597 | -0.788 | -2,047 |
| Glass | 93 | -0.280 | -26 |
| Steel | 2,822 | -0.940 | -2,653 |
| Aluminium | 552 | -11.640 | -6,425 |
| Cardboard | 98 | -0.320 | -31 |
| Wood | 48,045 | -0.619 | -29,740 |
| Total | | | -69,655 |

Avoided emissions to water. One of the principal impacts of plastic waste is the degradation of natural systems, especially in bodies of water such as oceans and rivers, as a result of breaks in the production and consumption chains. Worldwide, it is calculated that there are more than 150 million tons of plastic in the oceans [8]. Recycling plastics reduces the negative externalities generated, because although more waste is managed and treated correctly there is less probability of these wastes finding their way into natural ecosystems. In Europe the potential cost of cleaning coastlines and beaches may be as much as 630 million €/year. As well as the direct costs, there are possible adverse effects on human health and livelihoods, the food chain and other essential economic and social systems (tourist industry, fishing, maritime transport) [8].

It has been calculated that Barcelona is responsible for 1,787 ton/year of the plastic waste found in the Mediterranean Sea [43]. To calculate the benefits obtained through the correct management of this waste, the clean-up cost method [44,45] should be used, where the savings in the cost of cleaning the beaches of Barcelona and its metropolitan area are considered. It was determined that the approximate cost of cleaning 1 km of coastline is 53,416.40 €/year [46], with plastic waste responsible for 60% of this cost. Finally, it is considered that only 25% of this cost corresponds to the collection of waste from the beaches. The approximate quantity of plastic waste per km of coastline is 26.1 kg/day, or 9.53 ton/year [43].

According to this information the cost per ton of plastic waste is calculated as 841.11€. This value is close to that estimated by [47], who showed that the cost of collecting different types of waste from the beach varied from 980 to 2,610 €/ton, with an average value of 1,340 €/ton. Finally, it is assumed that the correct management and treatment of plastic waste in the sorting plant has prevented 1% of these materials (122.43 tons) from ending up on Barcelona's beaches, avoiding higher cleaning costs and producing a saving of 102,977 €.

*2.3.5 Public Health*

This impact group includes damage to public health, which can be evaluated from the perspective of the workers and/or the inhabitants of the areas surrounding the MSW treatment plants.

Physical Risks. Damage to health in the STF is mainly connected with physical risks, such as injuries and cuts from metal or glass. These injuries were caused by minor accidents and consist mainly of dislocations, sprains and strains, as well as superficial injuries and fractures.

According to the methodology for the economic evaluation of work accidents in Spain, presented by [48], the following variables should be considered: 1) Cost of time lost (the injured worker and others who have stopped work due to the accident); 2) Material costs of machinery, plant or material; 3) Costs due to losses, which could be the profits unobtained by the company as a result of the accident and the consequent temporary, partial or complete stoppage of the production system, or an increase in the costs of measures to keep production at the same level (overtime, employing a replacement, subcontracting the task, etc.); 4) General expenses, the costs of the accident (transporting the injured, fines, professional and medical costs, etc.). They also include the Social Security costs, such as compensation for the worker on sick leave (usually 25% of the salary is paid by the company and the 75% by Social Security) and the company's payments to the system for the injured worker during this period; 5) The time spent on the accident by the other workers, for example in investigating the causes.

Table 6 shows the index of accident frequency, the index of incidents and the absenteeism index. Also, it provides information about the costs needed to calculate the economic impact of accidents occurring in the STF, in both 2016 and 2017, to observe the changes in the different indices. In 2017, there were 56 employees and 6 accidents requiring sick leave. It can be seen that the number of accidents in 2017 was considerably lower than in 2016, while spending on accident prevention increased. To prevent double accounting of the costs, only those incurred by public bodies are considered because salaries, social security quotas and other concepts have already been included in the company's annual accounts as part of the operating and maintenance cost (OMC). As shown in Table 6, only the medical expenses due to fractures, sprains and dislocations are considered, at an average cost of 1,721.78 €/accident [49]. In 2017, it is considered that the daily salary per worker is 63.13 €, and there were approximately 27.67 days of sick leave by accident, the total payment of the salary to injured workers was 1,746.81 €/accident; therefore, the social security payment (75% of the salary) was 1,310.10 €/accident. In 2017, there were 6 accidents with sick leave, with a total cost by accident of 3,031.88 €. Finally, the total cost for physical injuries was 18,191.28 €.

Table 6. Information about Accident rates and costs generated by the STF. Source: authors' elaboration based on [12,24,50].

| Concept | Year 2016 | Year 2017 |
|---|---|---|
| Frequency Index [1] | 132.85 | 59.1 |
| Incidence Rate [2] | 23.91 | 10.64 |
| Absenteeism rate [3] | 5.64% | 7.58% |
| Workers | 54 | 56 |
| Working Hours per worker (hour/year) | 1800 | |
| Risk prevention expense (€) | 56.91 | 2,278.43 |
| Accidents | 13 | 6 |
| Sick Leave per worker (Days) | 20.59 | 27.67 |
| Average daily wage per worker (€/day) | 62.86 | 63.13 |
| Medical expenses (€/accident) | 1,721.78 | |

[1] accidents with sick leave/hours worked * 1,000,000

[2] accidents with sick leave/workers *100

[3] % of days lost due to professional contingency compared to the total number of calendar days

Chemical Risks. Another risk present in the waste treatment plants is that of fires which, due to the presence of wood, increases above all in the bulky waste treatment plants. Waste fires have a high risk of spreading towards urban areas (in other words they carry the risk of structural fires), as well as forested areas (with the risk of forest fires) [51]. These fires may produce costs for the waste management company (related to the loss of materials and damage to buildings, among others), environmental costs due to air, land and water pollution, costs to society (such as health care and insurance compensation, among others) [52] and socioeconomic costs (such as emotional stress caused by public fears) [53]. In the case of the STF, there were no fires in 2017, so the cost associated with fire damage was considered 0 €.

*2.3.6 Education*

This impact group considers the benefits due to the change in behaviour of the workers and/or citizens due to awareness and training programmes.

Culture of reduction, reuse and recycling of waste. The STF runs awareness programmes with the aim of educating and raising awareness regarding the environment, by means of activities relating to climate change, energy, the cycle of materials and waste. This involves communications activities and environmental training, such as guided tours of the plants for schools, university students of related fields and technicians from public and private companies [54]. These programmes lead to better separation of waste by the citizens, thereby preventing improper waste which does not belong to the light packaging fraction from ending up in the yellow container. In order to achieve a change in the public's behaviour it is necessary to invest in staff trained in communications and social media, publications and the programme's implementation [55]. Fig. 4 shows the improper waste from the light packaging fraction in Catalonia obtained from statistics databases [56] and the percentage of rejected light packaging waste in the STF [12]. It can be observed that the improper waste rate in Catalonia is minor than the improper waste rate in the STF. In addition, it can be seen that the percentage of rejected waste of the STF decreased from 35.2% to 30.4% in 2017.

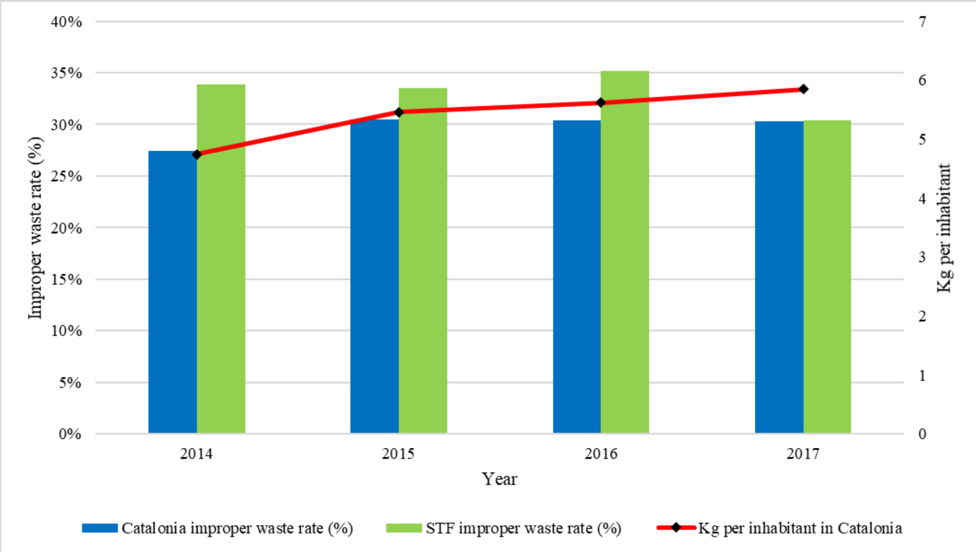


Fig. 4 Improper waste from light packaging waste fraction in Catalonia and the STF. Source: authors' elaboration based on [12,56].

Taking the changes between 2016 and 2017 as a reference, in this case, we can evaluate the benefits of awareness programs for citizens by considering the reduction of improper waste in the STF (Table 7). To determine the economic benefits, it is necessary to calculate the reduction of costs due to the payment of gate fees for improper waste. Therefore, two different scenarios are evaluated. First, scenario 1 assesses the costs due to the payment of gate fees for improper waste treated at the plant in 2016 (i.e., 35.24%). Second, scenario 2 evaluates the cost considering the percentage of improper waste in 2017 (i.e., 30.42%). In total, it was avoided that 872 tons of improper waste were treated, thereby avoiding the payment of 51.52 €/ton for the gate fees.

Table 7. Comparison of scenarios related to the reduction of improper waste in the STF. Source: authors' elaboration based on [12,56].

| **Impact** | **Concept** | **Scenario 1 (year 2016)** | **Scenario 2 (year 2017)** |
|---|---|---|---|
| Reduction of improper waste in the STF | Total light packaging waste treated (Ton) | 22,157 | 22,806 |
| | % Rejected waste | 35.24% | 30.42% |
| | Amount of improper waste (tons) | 7,810 | 6,938 |
| | Gate fee (€/ton) | 51.52 | |
| | Total payment of gate fees for improper waste (€) | 402,371.20 | 357,445.76 |
| | Benefit (€) | | 44,925.44 |

An increase in processing costs, errors in production and damage to equipment in the treatment plants are the additional costs engendered by the incorrect sorting of waste, as well as accidents and even fires during the storage phase [57].

For their part, the awareness programmes may affect the quantity of waste that is left on the beaches, reducing the amount of waste that has to be collected and consequently the cost of cleaning the beaches. According to the Ajuntament de Barcelona, the cleaning costs could be reduced by 25% if the public did not leave its rubbish on the beach. This amount is not included in the economic analysis because a more in-depth study is needed of the quantity of waste left on the beaches and its year-by-year reduction.

Technique of workers. Every year, the STF invests in training courses for its workers, which means a responsible and professional workforce. Personnel training leads to the acquisition of new skills and improvements in existing ones, providing economic benefits from significant improvements in productivity and quality, a decrease in rejected waste, reductions in production times, more flexibility in meeting demands and even a lower accident rate in the workplace [58].

Taking the changes between 2016 and 2017 as a reference, in this case we can evaluate the benefits of training by considering only the reduction in work accidents, which can be attributed to the workers' training. In 2017, the company invested 19,917.12 € in training schemes. A fall in the accident rate can be observed (from 13 to 6) but there was an increase in the number of days lost to sick leave per employee (from 20.59 to 27.67) (Table 8).

To determine the economic benefits, it is necessary to calculate the reduction of costs due to the decrease in accidents. The main assumptions are that each day of sick leave due to fractures, strains and dislocations costs 63.13 € and the average medical cost is 1,721.78 € [49].

Table 8. Comparison of scenarios related to workers training benefit of the STF. Source: authors' elaboration based on [12,24].

| **Impact** | **Concept** | **Scenario 1 (year 2016)** | **Scenario 2 (year 2017)** |
|---|---|---|---|
| Reduction of Workplace accidents | Accidents | 13 | 6 |
| | Salary by worker (€/day) | 63.13 | 63.13 |
| | Sick leave by worker (days) | 20.59 | 27.67 |
| | Medical Cost by accident (€) | 1,721.78 | 1,721.78 |
| | Total Medical Cost (€) | 22,383.14 | 10,330.68 |
| | Total Salary (€) | 16,898.00 | 10,480.84 |
| | Total Accidents Cost (€) | 39,281.14 | 20,811.52 |
| | Benefit (€) | | 18,469.62 |

### *2.3.7 Quality of Life*

Some MSW treatment plants may disturb the nearby households, as their very existence may cause bad odours, dust, windborne rubbish, visual intrusion, noise and traffic [42].

Disamenities. In STF's case, the plant is located in an industrial and farming zone, so there is no housing in the vicinity; consequently, this impact does not affect the STF and generates no costs. On the contrary, if there were houses nearby, it would be necessary to perform a choice experiment to estimate the owners' preferences and their willingness to pay (WTP) in order to avoid having an incinerator near them, or to use the Hedonic Pricing Method to quantify the impact on house prices due to the problems caused and the change in environmental quality [59,60].

Other types of facilities generate costs due to the negative effects on environmental quality. In the case of incinerators, a value of 8 € per ton of waste treated is estimated; this is a value slightly lower than the impacts caused by the landfill disamenities, that is, 10 €/ton [61].

### 2.4 Identification of the stakeholders

Stakeholders are individuals, groups or institutions who have an interest in or a relationship with the company, such as workers, investors, consumers, among others, and that can be affected by the impacts that the organisation's activities and operations have in the social, work, environmental, and economic arenas [62].

Once the impacts of the MSW system have been determined, the stakeholders can be identified. It is also important to decide from which stakeholder's perspective the economic analysis should be performed, as this will determine the impacts to be considered. It was determined from the impact analysis that the stakeholders in this case study are: a) The STF b) the parent group (TERSA), c) Ajuntament de Barcelona, d) managers of recoverable materials, e) citizens of the Barcelona metropolitan area. The economic analysis was carried out from the STF's perspective, which is a public company part of the TERSA group (Government body).

### 2.5 Study of the needs and financial possibilities

Determining the sources and conditions of financing is an important aspect to be considered before conducting cost-benefit analysis [63]. The STF will count on its own funds; thus, the study considers all financing sources from social capital shareholders in line with substancial number of firms in this industry who opt for equity financing [64] seeking no short term overhead expenses with debt financing and assuming the low opportunity cost determinants [65] that arises from bootstrap financing that arises in this case with self-financing [66].

### 2.6 Aggregation of costs and revenues

Once the impacts have been quantified and valuated monetarily, by using Eq. (1) and (2), it is possible to add the different costs and revenues to obtain the Total Benefit generated by the STF. Consequently, the situations can be determined and viewed separately. First of all, whether the STF is economically and financially profitable in its functions, which is defined by determining the Private Benefit ($BP > 0$); secondly, whether the STF is economically, financially, socially and environmentally profitable, which is defined by determining the Total Benefit (BT > 0).

The Financial Costs (FC) are considered as zero, as the company has its own funds and no debts. Taxes (T) are calculated considering that company taxes are 25% of the exploitation results. A discount of 99% is applied to this value for providing a local public service, obtaining a value of 1,299 €, or 0.015 €/ton [67].

Regarding the Opportunity Cost (OC), this is the value of the rejected alternative actions; within the concept of sustainable development and its three pillars, the best alternative provides not only the best economic impulse but also the best social and environmental development [20,68]. The concept of opportunity cost applied to MSW systems can be explained from two main conditions. First, when there are several alternatives for the use of waste, opportunity cost will be given by the use that provides the best economic performance, as long as these yields are higher than those of financial instrument. Second, when there are no alternative uses, opportunity cost comes from the performance that provides some financial instrument when investment costs are invested in this one [20].

In terms of the Opportunity Cost, it is considered that there is no better use for the waste treated because another alternative for the treatment of waste (light packaging waste and bulky waste) would be sending it to incinerators or landfills, consequently, not respecting the waste management hierarchy established by the European Parliament, where recycling is prioritised over energy valorisation and the deposit in landfills.

Therefore, the Opportunity Cost is considered to have come from the revenue provided by some financial instrument when the social capital and the reserves are invested in it. This facility has a total capital and reserves equal to 2,366,212.52 € and the interest on financial instruments was estimated as 3% in 2017 [69]; therefore, the Opportunity Cost is 70,986.37 €, the equivalent of 0.82 €/ton.

## 3. Results and Discussion

After applying the presented methodology, Table 9 shows the impacts considered in this case study; it should be pointed out that only some of them have been monetarily valued. Additionally, several elements have been presented, such as the identification, frequency, quantification and monetary valuation of the impacts (private and external) of the STF, a key point in the methodology used. Table 9 shows the main types of impacts (private or external) generated by the STF. These may have a positive or negative effect, either as costs or revenues. Regarding the Impact Frequency, in the current project all of the identified impacts have effects during the project’s useful life. In the case of the Impact Quantification, the units that allow these impacts to be translated into monetary values have been defined. Finally, the Impact Valuation is shown, where the monetary value of some impacts was calculated. First of all, the costs and revenues referring to 2017 (€/year) are presented, then the costs and revenues per unit of waste treated (€/ton), with 86,081 tons of waste receiving the full treatment.

It should be mentioned that some impacts have not been valuated economically, such as the positive impact related to the value that consumers give to a guaranteed supply of raw materials; other impacts have been calculated from secondary studies or have considered only some of the aspects relating to the analysed impacts. For example, in the case of the workers' training schemes, only the reduction of accidents has been considered; however, this impact is linked to improved productivity, quicker production time and greater flexibility in responding to demands, among others. These impacts have been included and described to have a more complete view of the impacts generated by the facility, allowing policy-makers to consider these impacts in future economic analyses of other projects or waste management systems. These impacts or aspects have not been monetarily valued, as each one has its own methodology, which should be presented and developed individually and exhaustively. To keep this article as concise as possible, it was decided to briefly present these impacts, which should then be studied and monetarily valued in future works.

In Table 9, private costs and revenues related to the operation and maintenance of the STF are presented. The most significant costs correspond to the impacts concerning infrastructure, where they reach a total value of 96.18 €/ton; of these, the costs related to the insurance, maintenance and leasing of machinery are the most significant (37.78 €/ton). On the other hand, the most important revenues are related to the recycling and recovery of waste, reaching a total value of 103.26 €/ton; here, the revenue derived from the light packaging sorting service is the most significant (51.52 €/ton), followed by revenues from the bulky waste treatment service (40.10 €/ton). In this case, the provision of the service generates more profit than the sale of materials. Also, in Table 9, external revenues and costs related to environmental and social aspects are presented. In the case of external costs and revenues, the most representative revenues correspond to economic savings since the sending of waste to landfills has been avoided and therefore the payment of gate fees to these facilities, giving revenues of 38.82 €/ton. This facility only generates external costs due to physical damages that correspond to 0.21 €/ton.

Table 9 allows to visualise the relative weight of each type and group of impacts generated by the STF. Being able to observe that, in the case of costs, 99.78% corresponds to private impacts. On the other hand, in terms of revenues, 67.51% corresponds to private impacts and 32.49% to external impacts. The relationship between private revenues and costs (R/C) indicates a ratio of 1.07, which shows that revenues are greater than costs. On the other hand, the relationship between total revenues and costs (R/C) presents a ratio of 1.58, which indicates that the STF becomes a more profitable project due to externalities.

Using Eq. (1) and (2), the Private Benefit (BP) and Total Benefit (BT) for this facility are calculated. AVW*SP corresponds to the sum of the private revenues and it is equal to 103.26 €/ton. Operational and Maintenance Costs (OMC) correspond to the sum of private costs, and it is equal to 96.18 €/ton. In this case study, only OMC is considered, as we are focussing on a specific operating year, and the Investment Costs (IC) are included in the depreciation values; consequently, IC is 0. As described in the section "Aggregation of costs and revenues", FC is equal to 0 because the company does not have any debt; T corresponds to the company's taxes minus the discounts applied, and it is equal to 0.015 €/ton. PE corresponds to the sum of the revenues due to the positive external impacts (Table 9), and it is equal to 49.69 €/ton. NE corresponds to the sum of the costs due to the negative external impacts (Table 9); it is equal to 0.21 €/ton. Finally, OC corresponds to the revenue from the investment of capital and reserves in a financial instrument, and it is equal to 0.82 €/ton.

The Eq. (3) and (4) show the results obtained from the Private Benefit and the Total Benefit, respectively. The values are expressed in € per ton of waste treated.

$$B_P = \sum_{n=1}^{N}[(103.26) - (0 + 96.18 + 0 + 0.015)] = 7.06\,€ \quad (3)$$

$$B_T = \sum_{n=1}^{N}[(103.26) - (0 + 96.18 + 0 + 0.015) + (49.69 - 0.21) - 0.82] = 55.72\,€ \quad (4)$$

Once the total revenues and costs (private and external) have been determined, it is possible to evaluate whether the treatment plant is operationally (BP > 0) and economically (BT > 0) profitable. In the analysis that takes only the private revenues and costs of the STF into account, the results show a positive economic return (BP > 0); consequently, the project is operationally profitable, with the Private Benefit being 7.06 €/ton. The analysis that takes the private and external revenues and costs of the STF into account is BT > 0, which gives a Total Benefit of 55.72 € /ton of waste, which means the project is economically profitable.

Although the private costs and revenues have the greatest weight in this case study, the Total Benefit increases considerably because the monetary valuation of the externalities. One important aspect of the applied methodology is that it allows the effects of the externalities on the Total Benefit to be seen. In this case, the plant could easily become operationally unprofitable, as the Private Benefit (BP) only reaches a value of 7.06 €/ton; however, the externalities raise the Total Benefit (BT) of the treatment plant, making it more profitable and reliable.

The STF fulfils an important function for the city of Barcelona and its environs, as its waste management service of light packaging and bulky waste prevents waste from being sent to landfills, thereby reducing the possible environmental and societal damage caused by these installations. Another important aspect is that it prevents damage to natural systems due to breaks in the production and consumption chain. The impact of plastic is so serious that it has been calculated that in 2050 the oceans will contain more plastic than fish [8]. All these positive impacts (environmental and social) are reflected in the company's Total Benefit. This plant is highly advantageous from an environmental and social perspective, with few negative externalities. All the impacts that have not been valued monetarily are positive ones; therefore, the Total Benefit will be higher.

If the results are compared with the landfills, these have lower private costs, as shown in [70], where it can be seen that private costs vary from 37 to 44 €/ton. However, due to their possible impact on society and the environment, they have greater external costs, which are between 16.27 and 21.01 €/ton [27]. These values show that the private costs of the STF are higher than those of the landfills; however, the STF is highly profitable due to both its private and external revenues. On the other hand, if the results are compared with another facility that provides waste treatment in the AMB, we can see that the Energy Recovery Facility (ERF) has a Private Benefit (BP) of 9.86 €/ton and a Total Benefit (BT) of 23.97 €/ton [28]. This shows that the STF is more advantageous from an environmental and social point of view, consistent with the current hierarchy of priorities established by the European Parliament [71].

### 3.1 Sensitivity Analysis

The sensitivity analysis is used to test the robustness of the results of the technical-economic analysis. The sensitivity analysis changes one variable at a time and then determines the effect of this change [72]. The variables that can be analysed are the opportunity cost, the used capacity of the treatment plant and the treatment service fees, among others.

The first variable to consider is the revenue received from the light packaging sorting service and the treatment of bulky waste, which corresponds to the highest revenue of the treatment plant, with a total value of 91.62 €/ton treated. In this case, the project could become unprofitable if the revenue obtained from the waste management services fell below 35.89 €/ton treated, where BT becomes negative and does not fulfil the condition BT > 0. This is unlikely, however, as there is a fixed fee for the waste treatment and sorting services, and the plant treats a constant amount of waste every year.

The second variable to consider is the opportunity cost. In this case study, it is considered as the interest earned from the use of a financial instrument, as there is no better alternative use for waste. However, should better alternatives arise in the future the project might become economically unprofitable if the opportunity cost exceeds 56.54 €/ton treated, where BT becomes negative and does not fulfill the condition BT >0.

Therefore, the sensitivity analysis shows that under current conditions, the plant is economically profitable and reliable.

Table 9. Summary of the Economic results of Impacts considered for the STF per €/year and €/ton (year 2017). Source: authors elaboration.

| Type of impact | Impact group | Impact Identification | | Impact Frequency | Impact Quantification | Impact Valuation (€/year) | | Impact Valuation (€/ton) | | Percentage (%) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Costs | Revenues | | | Costs | Revenues | Costs | Revenues | Costs | Revenues |
| Private | Infrastructure | - Labour Costs | | During the life of project | 86,081 tons of waste | 1,695,490 | | 19.70 | | 20.44% | |
| | | - Equipment repair and Maintenance costs | | | 86,081 tons of waste | 1,165,892 | | 13.54 | | 14.05% | |
| | | - Provision costs | | | 86,081 tons of waste | 1,694,127 | | 19.68 | | 20.42% | |
| | | - Depreciation of fixed assets | | | 86,081 tons of waste | 1,637,455 | | 19.02 | | 19.73% | |
| | | - Other Costs | | | 86,081 tons of waste | 2,086,242 | | 24.24 | | 25.15% | |
| Private | Reuse, recycling and recovery of waste | | - Scrap | During the life of project | 3,374 tons of waste | | 273,548 | | 3.18 | | 2.08% |
| | | | - Plastic, Paper/ cardboard, glass and others | | 19,521 tons of waste | | 17,133 | | 0.19 | | 0.12% |
| | | | - Wood chips | | 48,045 tons of waste | | 547,788 | | 6.37 | | 4.16% |
| | | | - Fees for Light Packaging sorting Service | | 22,806 tons of waste | | 4,434,506 | | 51.52 | | 33.68% |
| | | | - Fees for Bulky treatment service | | 63,275 tons of waste | | 3,451,628 | | 40.10 | | 26.22% |
| | | | - Other revenues | | 86,081 tons of waste | | 163,932 | | 1.90 | | 1.24% |

Table 9. Summary of the Economic results of Impacts considered for the STF per €/year and €/ton (year 2017). Source: authors elaboration.

| Type of impact | Impact group | Impact Identification | | Impact Frequency | Impact Quantification | Impact Valuation (€/ year) | | Impact Valuation (€/ton) | | Percentage (%) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Costs | Revenues | | | Costs | Revenues | Costs | Revenues | Costs | Revenues |
| External | Use of materials | | - Avoided Material send to landfill | During the life of project | 70,940 tons of waste | | 3,341,274 | | 38.82 | | 25.38% |
| | | | - Quality of materials | | 60,479 tons of waste | | 73,893 | | 0.86 | | 0.56% |
| External | Environment | | - Avoided Emissions to air ($CO_2$) | During the life of project | 69,655 tons $CO_2$ eq. | | 696,550 | | 8.09 | | 5.29% |
| | | | - Avoided Emission to water | | 122.43 tons of plastic waste | | 102,977 | | 1.20 | | 0.78% |
| External | Public Health | - Accidents (injuries) | | During the life of project | 6 People affected | 18,191 | | 0.21 | | 0.22% | |
| | | - Fires | | | 0 People affected | 0 | | 0 | | 0% | |
| External | Education | | - Culture of 3R for citizens | During the life of project | Amount of People | | 44,925 | | 0.52 | | 0.34% |
| | | | - Technique of workers | | % productivity | | 18,470 | | 0.21 | | 0.14% |
| External | Quality Life | - Disamenities | | During the life of project | Price of households or WTP to avoid | 0 | | 0 | | 0% | |
| Total Private Costs and Revenues (∑ Private Impacts) | | | | | | 8,279,206 | 8,888,535 | 96.18 | 103.26 | 99.78% | 67.51% |
| Total External Costs and Revenues (∑ External Impacts) | | | | | | 18,191 | 4,277,089 | 0.21 | 49.69 | 0.22% | 32.49% |
| Total Impacts (Private Impacts + External Impacts) | | | | | | 8,297,397 | 13,165,624 | 96.39 | 152.95 | 100.00% | 100.00% |

## 4. Conclusions

The main aims of this case study are to determine the Total Benefit of a light packaging and bulky waste sorting and treatment facility, looking at the two situations separately. First of all, the treatment plant is economically and financially profitable in its operations, as defined by determining the Private Benefit (a situation generally of interest to technicians and politicians); secondly, the treatment system is economically, financially, socially and environmentally profitable (of interest to economists and society). Although the details in this document are specific to a Spanish context, the methodology used is of universal application, as it can determine and analyse different potential impacts (private and external) arising from the MSW treatment. It can also be extrapolated to the analysis of other treatment plants, allowing the researchers to consider the same types of impacts described in this work but adapted to specific contexts in order to reduce decision-makers' uncertainty.

The STF fulfils a primordial function for the city of Barcelona and its environs, as it treats waste for later reuse and recycling, preventing waste from being sent to landfills and reducing the CO2 emissions from the extraction of virgin raw materials, thereby helping to reach the objectives set by the European Commission, among others. All these impacts can be reflected as costs or revenues that determine whether the STF is profitable or not. From the findings of the present case study, it can be concluded that the STF is both operationally (BP = 7.06 €/ton) and economically (BT = 55.72 €/ton) profitable. However, it should be noted that some external (positive) impacts have not been quantified, such as the value that consumers give to a guaranteed supply of materials. Additionally, others have been valued, considering only some aspects related to the analysed impacts. A monetary valuation of these externalities would increase the Total Benefit of the plant, making it more profitable and reliable.

An essential aspect of the research conducted allows the effect of the externalities on the Total Benefit to be highlghted. The valuation study of the externalities related to the waste management systems is essential, and help decide on the economic viability of the treatment plant [73]. If only the private impacts are evaluated, the management system may look unprofitable and therefore be rejected [73]. However, if the externalities are evaluated and added, the system may become profitable.

It is recommended that future research should analyse the externalities that have not been valued monetarily, broadening the analysis of some aspects related to these externalities. In addition, an analysis of the other processes of the management system (waste collection and transport) for light packaging waste and bulky waste is needed [74], taking into consideration the different companies involved to determine the impacts generated depending on various factors such as types of transport (electric, hybrid or diesel), collection systems (door-to-door, green point, drop-off system) and percentage of waste separation from citizens.

It is also important to extend the current study into the impacts of emissions to water (oceans and rivers), considering all the possible effects that could be avoided by correct waste management [75]. Furthermore, there is a need to focus on obtaining specific data about the willingness of the citizens of Barcelona to pay for ecological products [76] and, thus, the outcomes of this paper raises awareness of its importance and opens the line for a future research.

## Abbreviations

AMB: Metropolitan Area of Barcelona; AVW: Annual volume of waste treated; BP: Private Benefit; BT: Total Benefit; FC: Financial Costs; IC: Investment Costs; N: Total project duration; n: Project year index (n = 0, …, N); NE: Negative Externalities; OC: Opportunity Cost; OMC: Operational and Maintenance Costs; PE: Positive Externalities; SP: Sale Price per Volume Unit; STF: Sorting and Treatment Facility; T: Taxes.

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**Additional File 1**

**Table 1.** Definitions about the elements of equations used.

| Abbreviations | Concepts | Definition |
|---|---|---|
| *BP* | Private Benefit | It corresponds to the difference between private revenues and costs. If it is greater than 0, it indicates that the facility is profitable from a private point of view. |
| *BT* | Total Benefit | It corresponds to the difference between total revenues and costs (private and external). If it is greater than 0, it indicates that the installation is profitable from an economic, social, and environmental point of view. |
| *AVW* | Annual volume sold | Corresponds to the quantity sold to the managers of recovered materials for recycling. |
| *FC* | Financial Costs | Financial costs and revenues are included. The revenues are related to the benefits due to the investment in financial instruments and the costs due to debts with third parties. |
| *IC* | Investment Costs | Private costs related to costs of construction, acquisition of equipment and facilities, preparation and use of the land. |
| *NE* | Negative externalities | Sum of costs due to negative external impacts, that is, damage to the environment and society. |
| *OC* | Opportunity Cost | It is considered as the value of the waived alternative share. Under the concept of sustainable development and its three pillars, the best alternative is the one that provides not only the best economic performance but also the best social and environmental performance. |
| *OMC* | Operational and Maintenance costs | Private costs related to operational and maintenance costs including labour costs, equipment maintenance and repair costs, provision costs, depreciation of fixed assets and other costs. |
| *PE* | Positive externalities | Sum of revenues due to positive external impacts, that is, benefits and savings from avoiding damage to society and the environment. |
| *SP* | Sale price per Volume Unit | Corresponds to the market price for recovered materials. |
| *T* | Taxes | Related to the taxes set by the public administrations to the treatment facilities. |

# Anexo D: Capítulo de libro

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**ACCEPTANCE OF ABSTRACT**

**Title:** Waste-to-Energy: Recent developments and future perspectives towards circular economy"

**Editors:** Abd El-Fatah ABOMOHRA, Qingyuan WANG, Jin HUANG
School of Architecture and Civil Engineering, Chengdu University, Chengdu 610106, China.

**Dear Authors,**

Regards from Chengdu University, China. We are happy to inform you about the acceptance of your abstract in the upcoming book "**Waste-to-Energy: Recent developments and future perspectives towards circular economy**" that will be published by **SpringerNature**.

Attached is the revised Abstract with minor suggestions and/or comments. We are looking forward to receive the Full Chapter on or before 15th May 2021 in a single WORD file to the e-mail address **wte@cdu.edu.cn** for review. Please read the following sections carefully;

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## MAIN REQUIRMENTS FOR THE CHAPTER

- Length of chapter: Approx. 40 pages (A4 pages, 1-inch margins, font size 12 Times New Romans, 1.5-line space).
- Abstract (150-200 words) followed by 5 keywords.
- Figures: up to 6: Follow normal Figures numbering (Figure 1, Figure 2,..etc)
- Tables: up to 4: Follow normal Tables numbering (Table 1, Table 2,..etc)

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Editors,
Chengdu, 26th Feb. 2021

# Chapter

# Waste-to-energy plant in Spain: a case study using a Techno-economic analysis.

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**Abstract:** The population growth and the new consumption models contribute significantly to a greater generation of waste, which is generally incorrectly managed because a large percentage of the waste generated is sent to landfills. Waste to energy (WtE) plants play a fundamental role in managing and treating municipal waste because they reduce the amount of waste sent to landfills and reduce dependence on imported fossil fuels; however, these facilities can also cause negative impacts. This case study evaluates the technical-economic feasibility of an incineration plant by using a social Cost-Benefit Analysis, which considers economic, social, and environmental impacts. The WtE facility is in Barcelona (Spain) and produces energy from municipal solid waste (MSW) with a total capacity of more than 350,000 tons of waste treated per year, which means the generation of more than 180,000 MWh of electricity and 110,000 tons of steam per year. The positive and negative impacts generated by this facility are identified, discussed, and monetarily valued to carry out this economic analysis. Some of the impacts considered are the sale of energy, the decrease of waste disposal in landfills, the reduction of greenhouse gas (GHG) emissions, and the generation of dioxin emissions. The results show that the facility is profitable from a private point of view (*BP = 15.97*) and an economic, environmental, and social perspective (*BT = 37.48*).

**Keywords:** Technical-economic analysis, MSW, Social impacts, Environmental impacts, waste to energy, Case study

## 1. Waste to energy facilities in Spain

The energy recovery from Municipal Solid Waste (MSW) in incineration plants represents an opportunity to reduce the amount of waste that is sent to landfills and, therefore, to be able to meet the objectives set by the European Commission on waste, which indicates that the share of Municipal Solid Waste (MSW) deposited in landfills will be limited to 10% by 2035 (Medina-Mijangos and Seguí-Amórtegui 2021).

Furthermore, it is an alternative to reduce dependence on energy generated from fossil fuels, which are generally imported (Jamasb and Nepal 2010). Waste to energy (WtE) has several positive effects since this process avoids methane ($CH_4$) emissions from landfills and carbon dioxide ($CO_2$) emissions from fossil fuels (Scarlat et al. 2019). Moreover, Lim et al. (2014) identify four benefits related to WtE plants, such as the improvement of energy security (uninterrupted availability of energy at an affordable price), the reduction of GHG emissions, the creation of employment and the extension of life expectancy from landfills.

However, WtE facilities can also cause negative impacts due to the emissions of pollutants such as particulates ($PM_{10}$), nitrogen oxides (NOx), acid gases (SO2, HF, HC1), carbon dioxide ($CO_2$), volatile organic compounds (VOCs), dioxins (PDDC/PFs), heavy metal (Cr, Pb, Cu, Ni, Zn, Cd, Hg and As). These pollutants can have undesirable effects on public health, agriculture, buildings, ecosystems and promote climatic change (European Commission 2000). In addition, these facilities can affect the price of houses located near due to the disamenities generated and the "Not In My Back Yard" syndrome.

The European Parliament establishes a waste hierarchy for legislation and policy on the prevention and management of waste (European Parliament 2008), where prevention, reuse, and recycling are prioritised over other types of recovery (including energy recovery) and deposit in landfills. However, other options that deviate from the hierarchy may be considered, as long as it is justified by reasons of technical viability, economic viability and environmental protection.

In the case of Spain, in 2019, 22,438 thousand tons of MSW were generated, of which 54% was sent to landfills, 11.29% was converted into energy, and the remaining percentage was recycled or treated biologically to obtain compost. In 2018, 122 landfills were registered where 11,917,233 tons were deposited (MITERD 2018). Additionally, Spain has ten incineration plants that treat an average of 2,527,000 tons/year, as shown in Table 1.

In Spain, the incineration plants are responsible for the management and thermal treatment of non-hazardous municipal waste. Specifically, the residual waste from the non-selective collection of the grey container. This fraction is previously sent to mechanical-biological treatment (MBT) facilities where the waste is subjected to different physical and biological processes to recover materials (organic matter, plastic, cardboard, steel, among others). Waste that can no longer be materially recovered (rejected waste) are sent to incineration plants for energy recovery, obtaining electricity and steam.

Table 1. Waste to energy facilities located in Spain. Source: Adapted from MITERD (2018).

| Facility | ID | Opening year | Location | Nº of furnaces | Nominal capacity (ton/year) |
|---|---|---|---|---|---|
| Energy Recovery Facility of Meruelo | TIRCANTABRIA | 2006 | Cantabria | 1 | 120,500 |
| Energy Recovery Facility of Sant Adrià de Besòs | TERSA | 1975 | Barcelona | 3 | 360,000 |
| Mataró incinerator | TRM | 1994 | Barcelona | 2 | 160,000 |
| Girona incinerator | TRARGISA | 1984 | Girona | 2 | 35,000 |
| Tarragona incinerator | SIRUSA | 1991 | Tarragona | 2 | 140,000 |
| Cerceda Thermoelectric Plant | SOGAMA | 2000 | La Coruña | 2 | 360,000 |
| Energy Recovery Facility of Mallorca | TIRME | 1997 | Balearic Islands | 4 | 730,000 |
| Las Lomas Energy Recovery Plant | MADRID | 1993 | Madrid | 3 | 328,500 |
| Energy Recovery Facility of Melilla | REMESA | 1994 | Melilla | 1 | 47,000 |
| Zabalgarbi facility | ZABALGARBI | 2005 | Vizkaia | 1 | 246,000 |
| | | | Total | 21 | 2,527,000 |

On the one hand, Spain shows a significant dependence on energy generated from fossil fuels. In 2018, 44% of primary energy consumption came from oil and petroleum products and 20.75% from natural gas (INE 2020). On the other hand, Spain presents a critical problem with foreign energy dependence since 73.3% of primary energy was acquired outside the country. Specifically, a 78% dependence on imports of solid fossil fuels and 99% of oil and petroleum products is shown (European Commission 2020).

## 2. Methodology and data

The data were obtained from public documents (such as annual accounts, environmental and technical studies, production data, among others), available on the company's website. Additionally, studies published in indexed journals about the analysed facility and studies about environmental and social impacts of other MSW treatment facilities are used.

The methodology presented in Medina-Mijangos et al. (2021) was used to carry out the technical-economic analysis. It considers the private and external impacts (revenues and costs) generated by the MSW management projects. Additionally, several of the impacts described in this paper are contemplated in this case study.

This methodology is based on cost-benefit analysis and considers that the systems or projects evaluated must comply with sustainability principles and its three pillars; therefore, the methodology used considers the project's economic, social, and environmental dimension, as shown in Figure 1. In addition, it is implied that the best option is the one that meets the needs of society, and it is environmentally and economically viable, socially and environmentally bearable, as well as economically and socially equitable (Mensah 2019).

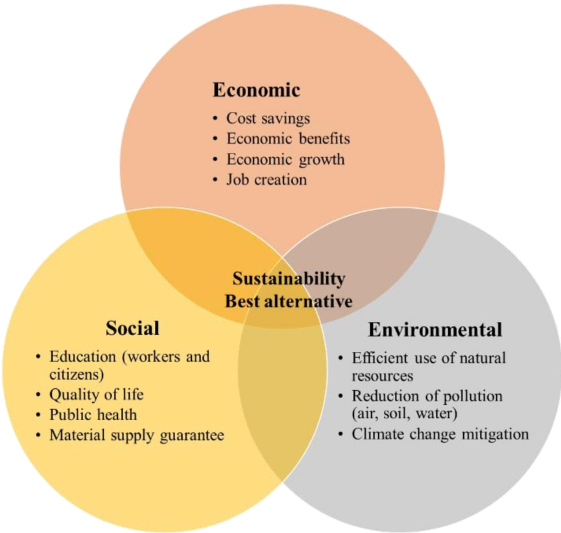


Figure 1. Evaluation of MSW management systems considering pillars of sustainability. Source: Adapted from Fiksel et al. (2012).

## 3. Objective definition

The aim of this study is to determine the Private Benefit (*BP*) and the Total Benefit (*BT*) using Eq. 1 and 2, based on the determination of both private and external revenues and costs generated by the Energy Recovery Facility (in this case study, it is identified as ERF). Therefore, the results are expressed in € per ton, where it is necessary to divide the annual results by the total waste treated.

$$\boldsymbol{B}_P = \sum_{\boldsymbol{n=0}}^{\boldsymbol{N}}[(AV_n * SP) - (IC_n + OMC_n + FC_n + T_n)] \quad (1)$$

$$\boldsymbol{B}_T = \sum_{\boldsymbol{n=0}}^{\boldsymbol{N}}[(AV_n * SP) - (IC_n + OMC_n + FC_n + T_n) + (PE - NE) - OC] \quad (2)$$

Where *AV*: Annual volume sold; *FC*: Financial Costs; *IC*: Investment Costs; *N*: Total project duration; *n*: Project year index (n = 0, …, N); *NE*: Negative Externalities; *OC*: Opportunity Cost; *OMC*: Operational and Maintenance Costs; *PE*: Positive Externalities; *SP*: Price of Sale; *T*: Taxes

In this way, it can be concluded whether the facility is profitable from a private point of view (if *BP* is greater than 0) and profitable from an economic, environmental, and social perspective (if *BT* is greater than 0).

## 4. Description of the scope of the study

In this case study, the Sant Adrià de Besòs Energy Recovery Facility (ERF) located in Barcelona (Spain) is analysed. This facility is managed by TERSA (by its Catalan name Tractament i Selecció de Residus S.A.) and was inaugurated in 1975, being the oldest incinerator in Spain. This facility performs the process of minimising the volume of waste through combustion, taking advantage of the energy generated by this process to produce steam and electricity (Medina-Mijangos and Seguí-Amórtegui 2021). The ERF manages the waste generated in the Barcelona Metropolitan Area (AMB), an area made up of 36 municipalities such as Barcelona City, Badalona, Sant Adrià de Besòs, among others, with approximately 3.24 million inhabitants (AMB 2021). Additionally, the ERF and the mechanical-biological treatment plant known as Ecoparc 3 (managed by the Ecoparc del Mediterrani S.A.) are part of the Integral Waste Recovery Plant.

The costs and revenues generated by this ERF are evaluated, considering only one year, 2019. Considering only the processes carried out by the ERF, without considering the impacts generated during the previous processes as in the case of the collection, transport or treatment carried out in the mechanical-biological treatment plant. Previously, this facility was economically analysed in Medina-Mijangos and Seguí-Amórtegui (2021) but considering the year 2017. This case study also includes other impacts that had not been analysed.

This facility receives rejected waste from Ecoparc 3, as well as other waste classification and treatment facilities. Through the thermal process, energy is obtained for self-consumption and sale to the electricity grid. On the other hand, steam is also obtained that is sold for the city's hot and cold network (Figure 2). Finally, the slags are sold to authorised managers to produce ecological concrete, and the ashes are sent to controlled landfills.

Specifically, in 2019, 351,308 tons of rejected waste from Ecoparc 3 and other treatment facilities were treated, obtaining 197,733 MWh of energy, of which 23,560 MWh were used for self-consumption, and 171,173 was sold to the electric power grid. Additionally, 23,560 tons of steam generated was sold to Districlima (the company in charge of managing the urban heat and cold distribution network of Barcelona city). Finally, 69,163 tons of slag were sold to authorised managers and 12,357 tons of ash were sent to landfills.

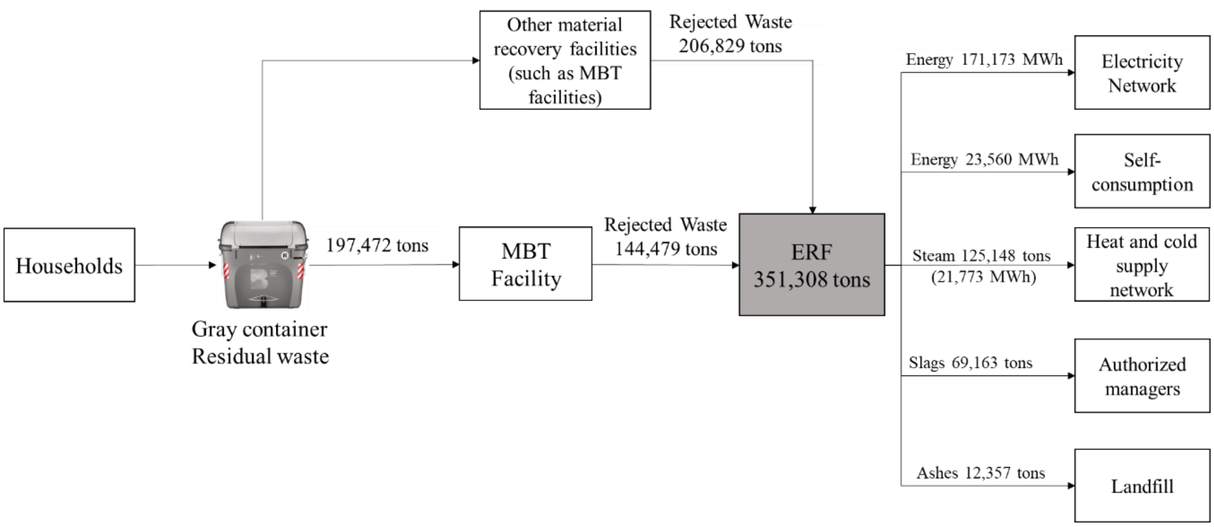


Figure 2. Waste management processes of the ERF in 2019. Source: Authors elaboration. MBT: Mechanical-Biological Treatment; ERF: Energy Recovery Facility.

### 4.1 Waste to Energy technology

The ERF incorporates heat recovery and power generation. Moreover, this facility has implemented advanced process controls and exhaust gas cleaning measures to ensure meet the legal limits established by regulatory bodies (European Commission and the Spanish legislation).

Figure 3 shows the different equipment and technologies used in the incineration process. The technology used for the thermal treatment of waste in the ERF is described below.

Waste reception: The rejected waste from Ecoparc 3 is transported through an underground conveyor that directly discharges the waste into the pit. The rest of the facilities transport waste using trucks, which are weighed before accessing the facilities. Once in the pit, the waste treatment furnaces are fed through an overhead crane.

Energy generation. The rejected waste is burned in the furnace. Combustion is carried out in a controlled manner in three combustion grates with a nominal capacity of 15 tons/h per furnace. The gases produced are conducted through a boiler, where water is heated to steam. The steam produced moves two turbines, responsible for producing electricity. The equipment present in energy generation is described in detail below.

- Furnace. A feed hopper introduces the waste into one of the three furnaces from the top. Inside the furnaces, three groups of fixed and movable grates lower the waste at a controlled speed to burn it. Air is injected to maintain the fire. Above the combustion grates, there is a natural gas burner, which automatically ignites if the temperature of the gases drops below 850 ºC. Next, to neutralise the nitrogen oxides that appear as a result of combustion, urea is injected.
- Tubular boiler. The water in the boiler is heated to steam with the hot gases from the furnace. The gases emitted by the furnace at 850 ºC are conductive around a circuit filled with water. As it passes the circuit, the heat is transmitted to the water, which is heated to 400ºC generating superheated steam.
- Turbines. The steam from the water boiler is conducted through the turbine. As it passes, it spins the rotor blades. This movement is transmitted through the shaft to an alternator, which in turn rotates magnets along with electrical cables. This movement of the magnets generates a variable magnetic field around the cables, and with it, an electric current.
- Condensers. Water vapour passes through a tank filled with cold seawater through a circuit. It transmits heat to seawater and cools down to a liquid state.

Flue gas cleaning system. After combustion, the incineration gases are scrubbed to avoid emitting pollutants into the atmosphere. The treatment process allows the removal of solid particles, acid gases, dioxins, heavy metals, and fine particles to reach levels well below the legal limits. The ERF has a continuous measurement system to guarantee the quality of the treatment, which continuously controls the levels of these and other substances. The equipment present in flue gas treatment is described below.

- Electrofilter. The combustion gases in the furnace horizontally pass through a chamber with vertical electrodes, which electrically charge the solid particles in suspension. Next to the electrodes, there are flat metal plates that attract the particles and retain them. Periodically, the metal plates are shaken, and with the resulting vibration. Consequently, the particles fall from the plates into a hopper at the bottom of the chamber.
- Atomizer and gas absorber. The gases emitted from the electrofilter are sprayed with hydrated lime. Hydrochloric and hydrofluoric acids react with lime, resulting in a mixture of water and salts.
- Selective Catalytic Reduction system. The ERF has a Selective Catalytic Reduction (SCR) system based on ammonia injection as a reducing agent for combustion gases such as nitrous oxides (NOx). The catalyst requires a working temperature between 220-340 ºC to be effective. The SCR is located at the outlet of the flue gas cleaning system to treat acid gases and their particles present in the combustion gases.
- Activated carbon injection. At the outlet of the absorber, solid activated carbon is injected into the gas flow. Carbon absorbs dioxins and heavy metals.
- Bag filter. It removes fine particles, including combustion particles, micronised lime and micronised activated carbon. The air passes through bag filters, which retain fine particles.
- Stack. It expels the gases produced by incineration under the conditions required by law, that is, without exceeding the required concentration thresholds. Then, it releases the purified gases. This technology has a continuous measurement system that allows always knowing the levels of pollutants.

<u>Slag separation.</u> The solid materials (residues) that come out of the furnace are collected, cooled, and separated to be recycled (metals) or used as a basis for roads and other civil works. The ashes are disposed of at landfills.

- Slag extractor. It collects residues that fall from the furnace or reach the end of the grates without being burned (such as metals). Then, it transports them to the slag and ash separator. The slag extractor is a conduit with water, where the burned residues fall. It carries water to extinguish objects that are still incandescent, and because this way, the finest materials dissolve in it and do not disperse during transport. Finally, there is a conveyor that ejects the largest objects from the extractor.
- Slag and ash Separator. It separates residues into metallic and non-metallic. The residues collected by the slag and ash extractor are dropped into a pit. A worker loads them with a crane onto a conveyor. With the movement, the conveyor separates the largest metal objects. An electromagnet then separates the rest of the metal objects.

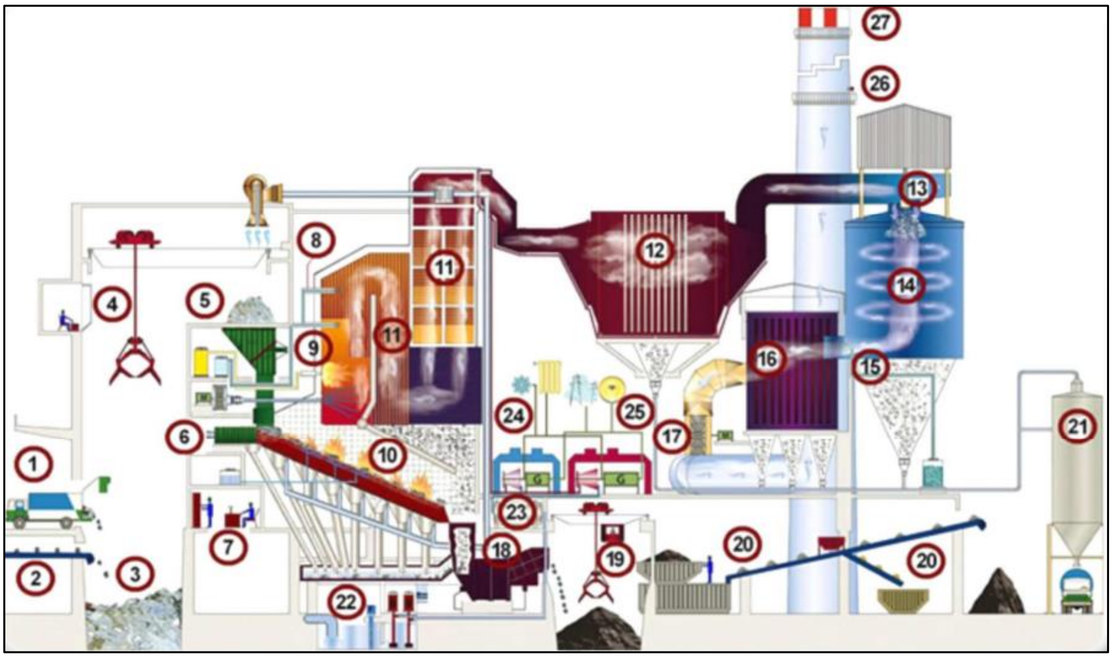

Figure 3. Waste management technology used in the ERF. Source: TERSA (2020a). 1. Reception Hall; 2. Transfer of waste rejection from the Ecoparc; 3. Waste pit; 4. Overhead crane; 5. Feed Hopper; 6. Ram feeder; 7. Control and command room; 8. Urea injectors in the combustión chamber; 9. Natural gas burner; 10. Combustión grates; 11. Furnace zone – Boiler; 12. Electrostatic particle filter; 13. Lime dissolving atomiser; 14. Acid gas absorber; 15. Activated carbon injection; 16. Bag filter; 17. Induced draft fan; 18. Slag and ash extractor; 19. Slag pit and crane; 20. Slag and ash separator; 21. Fly ash container; 22. Seawater for cooling; 23. Condenser; 24. KKK Turbine; 25. Alstom Turbine; 26. Control of atmospheric emissions; 27: Stack

## 5. Stakeholders involved

Waste treatment facilities generally involve different stakeholders with different (sometimes opposite) points of views and interests. The stakeholders can positively or negatively support the facilities, depending on the negative or positive impact generated by the installation. The technical and economic analysis was performed from the viewpoint of the ERF, a public company owned by the Barcelona City Council. The ERF stakeholders are listed below.

- Shareholders/ investors
- Workers
- European/national/local government
- Health authorities (i.e. Agència de Salut Pública de Catalunya)
- Environmental authorities (i.e. Miteco, Agència de Residus de Catalunya)
- Nongovernmental organisations (NGOs)
- Community Groups (*Aire Net*)
- Spanish electrical network
- Other treatment facilities (i.e. Ecoparc 3)

- Authorised slag managers
- District cooling and heating company (Districlima)
- Power/energy consumers
- Population living near the facility
- Barcelona citizens

A sustainable waste management system can only be achieved by involving all stakeholders. According to Contreras et al. (2008), the role of stakeholders has transformed over time from being merely receivers of impacts to playing an essential function in the design, implementation and promotion of MSW management systems.

## 6. Analysis of private revenues and costs

Internal or private impacts refer to the revenues and costs associated with the investment, operation and maintenance of waste treatment facilities (Jamasb and Nepal 2010). These are costs incurred by the investor or the project developer (public or private entity) and, therefore, are restricted to the spatial boundary of a waste treatment facility (Aleluia and Ferrão 2017). Waste-to-energy facilities require highly complex and advanced technologies, which implies significant investments and high operating and maintenance costs.

The ERF private costs and revenues were calculated directly from the information provided in the annual accounts. Table 2 presents the private costs related to operational and maintenance costs (OMC), including labour costs, equipment maintenance and repair costs, provision costs, depreciation of fixed assets and other costs. Total private costs are 144.09 €/ton, considering that 351,308 tons of waste were treated in 2019.

Table 2. Summary of the ERF private costs in 2019. Source: Authors elaboration based on Faura-Casas Auditors Consultors (2019).

| Concept | Annual Costs (€/year) | Cost per ton (€/ton) |
|---|---|---|
| Labour cost | | |
| Salaries & Wages | 4,867,153 | 13.85 |
| Social Security | 1,401,801 | 3.99 |
| Other labour costs | 473,957 | 1.35 |
| Equipment repair and Maintenance costs | 2,326,893 | 6.62 |
| Provision costs | | |
| Raw materials and inputs | 1,507,621 | 4.29 |
| Provision of services (Subcontracting) | 30,046,827 | 85.53 |
| Depreciation of fixed assets | 2,036,141 | 5.80 |
| Other Costs | 7,960,717 | 22.66 |
| Total | 50,621,110 | 144.09 |

In Table 3, private revenues are presented, related to the sale of energy and steam generated by the ERF and the sale of other materials such as slag. Also, revenues are obtained due to the gate fees, which correspond to the amount paid by local authorities for each ton of waste received for treatment in a specific facility. Also, other revenues are taken into account.

The amount of energy, steam, slag, and water sold (*AV*) is multiplied by the sale price (*SP*), which corresponds to the market price for these goods. On the other hand, the revenues due to gate fees are obtained by multiplying the total amount of waste treated at the facility by the rate set per ton. As a result, total private revenues are equivalent to 156.60 €/ton.

Table 3. Summary of the ERF private revenues in 2019. Source: Authors elaboration based on Faura-Casas Auditors Consultors (2019).

| **Concept** | **Description** | **Quantity** | **Unit** | **Unitary Price €/tons** | **Annual revenues (€/year)** | **Revenues per ton (€/ton)** |
|---|---|---|---|---|---|---|
| Sales | Energy | 171,173 | MWh | 50.54 | 8,650,424 | 24.62 |
| | Steam | 125,148 | Tons | 7.60 | 951,271 | 2.71 |
| | Water | 15,300 | $m^3$ | 1.02 | 15,606 | 0.04 |
| | Ashes and slags | 81,520 | Tons | 0.15 | 12,228 | 0.03 |
| Gate fees | MSW treatment fee | 351,308 | Tons | 29.00 | 10,186,748 | 29.00 |
| Other Revenues | Provision of services | | | | 30,059,537 | 85.56 |
| | Other Revenues | | | | 5,137,887 | 14.64 |
| | Total | | | | 55,013,701 | 156.60 |

The sale of energy is the revenue that shows the most significant variability as shown in Figure 4, since the Spanish electricity market regulates the price, showing its lowest level in 2016 where the price was 41.02 €/MWh, and the highest level was in 2018 where the price was 60.28 €/MWh.

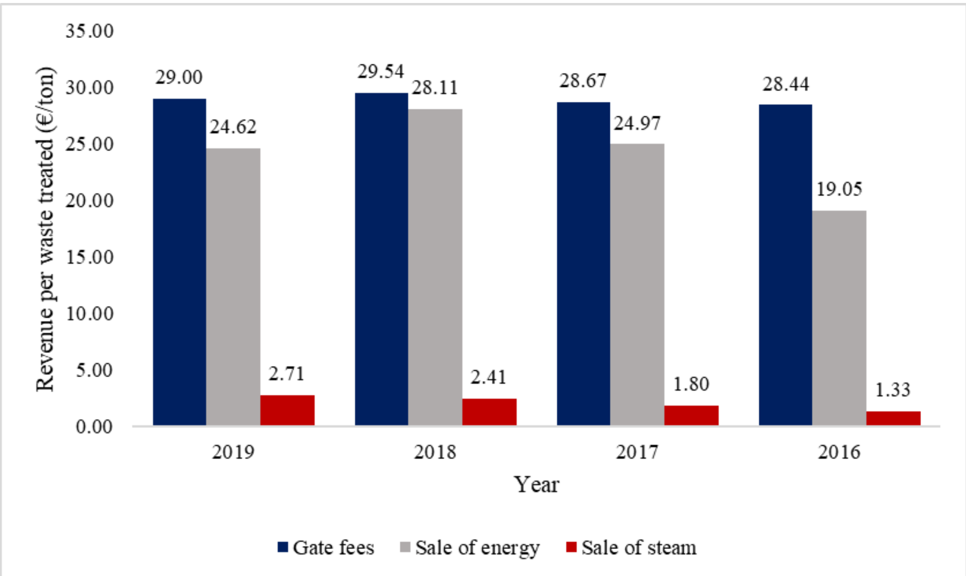


Figure 4. Comparison of private revenues related to the sale of energy and steam and the gate fees. Source: Authors elaboration.

From the results obtained, the Private Benefit (BP) is calculated through Eq. 1. The ERF is economically analysed, considering a specific year (2019); therefore, N is equal to 1. Investment costs (IC) are equal to 0 because they are included in the depreciation values of the fixed asset.

In the case of FC, both financial costs and revenues are considered. Therefore, according to the company's annual accounts, it has revenues due to the investment in financial instruments and costs due to third-party debts, having total financial revenues of 2,077,236 €/year, that is, 5.91 €/ton.

In the case of T, the 25% corporate tax is considered, minus the bonuses received for the provision of local public services (BOE 2014), obtaining a tax value of 862,307 €/year, that is, 2.45 €/ton.

Finally, a BP of 15.97 €/ton is obtained (Eq. 3), which means that the facility is profitable from a private perspective. This result is slightly higher than that presented in Medina-Mijangos and Seguí-Amórtegui (2021), where a BP of 9.86 €/ton was obtained.

$$B_P = \sum_{n=1}^{N}[(156.60) - (0 + 144.09 - 5.91 + 2.45)] = 15.97\ €/ton \quad (3)$$

Considering only Private Benefit can bias against alternatives such as recycling and even incineration, which may be more expensive than landfills from a purely private (financial) perspective, but preferable from an economic, social and environmental point of view (Nahman 2011). Therefore, it is advisable to evaluate projects and facilities considering their private and external impacts.

## 7. Overview of environmental and social impacts of the ERF

External revenues and costs or externalities refer to those impacts caused directly or indirectly by the operation of a treatment plant but whose effects are assumed by a party other than its operator or owner (Aleluia and Ferrão 2017). These revenues and costs are essentially related to social and environmental impacts.

This section describes and discusses the main external impacts generated by the ERF. Impacts associated with the use of waste, environment, public health, quality of life, education and economic development are included.

### 7.3 Use of waste

This impact group is associated with the benefits obtained from the use of waste. For example, the reduction of the quantity of waste sent to landfills and, consequently, achieving the objectives set by the European Commission of limiting the deposit of waste in landfills to 10% (European Commission 2015) and reducing the environmental and social impacts generated by the landfills. Furthermore, the generation of renewable energy that allows increasing the participation of these sources in the Spanish electricity mix and reducing the use of fossil fuels ensures an uninterrupted supply by having a continuous generation of waste, reducing environmental impacts due to energy production from fossil sources.

### *7.1.1 Reduce waste sent to landfill*

The ERF is shown as a facility capable of managing a large amount of waste generated by the Metropolitan Area of Barcelona (AMB). Due to its capacity, each year, more than 350,000 tons of municipal waste are incinerated. Consequently, an added value of the ERF is to provide the AMB with waste treatment capacity since, without its presence, this waste would end up in the landfill (Medina-Mijangos et al. 2021).

Landfills can cause various impacts due to the risk of air, water and soil contamination through the emission of leachate, landfill gases and other pollutants such as methane ($CH_4$), carbon dioxide ($CO_2$), nitrogen oxides (NOx), sulphur dioxide ($SO_2$), volatile organic compounds (VOCs) and particulates ($PM_{10}$) that have the potential to cause environmental damage (Nahman 2011). Furthermore, these facilities are related to social impacts such as the depreciation of the adjacent property (due to odours, dust, windblown trash, vermin, noise, traffic/congestion, visual intrusion), and the opportunity costs of the land where the landfill is located (Hirshfeld et al. 1992). According to Jamasb and Nepal (2010), the cost of landfilling waste is likely to increase due to land scarcity, further thus making energy recovery from waste even more cost-effective. In addition to health damage due to the risk of fires and explosions and the emissions of contaminants.

The economical amount saved per canon paid per ton of waste sent to landfills is considered to quantify the benefit obtained by this facility. It is important to note that this value must be subtracted from the canon paid per ton of waste sent to incineration, which has already been included in the private costs. The tax rate of 47.10 € per ton of municipal waste destined for controlled deposit is set, and a tax of 23.60 € per ton of municipal waste incinerated (BOE 2017a). Consequently, a saving of 23.50 €/ton of waste is considered. In 2019, 351,308 tons of waste had been treated, preventing 338,951 tons of waste from being sent to landfills; finally, only 12,357 tons of ash were sent to controlled landfills.

The ERF is shown as a facility capable of managing a large amount of waste generated by the Metropolitan Area of Barcelona (AMB). Due to its capacity, each year, more than 350,000 tons of municipal waste are incinerated. Consequently, an added value of the ERF is to provide the AMB with waste treatment capacity since, without its presence, this waste would end up in the landfill (Medina-Mijangos et al. 2021).

### *7.1.2 Willingness to pay for renewable energy*

Renewable electricity, also called green electricity, is generated from renewable energy sources (solar, hydro, biomass, wind, geothermal) (Guo et al. 2014). Green electricity has significant environmental benefits and can reduce greenhouse gas emissions while meeting energy needs and decreasing dependence on fossil fuels (Midilli et al. 2006).

Several studies show that there is a Willingness To Pay (WTP) a premium for renewable energy. For example, in Soliño et al. (2009), the WTP for biomass energy in Spain was calculated using the contingent valuation method. The results show that the WTP vary from 3.79 to 5.71 €/household/month depending on whether it is a single bounded or a double bounded dichotomous format and the periodicity of the payment (annual or bimonthly). The authors highlighted that society would experience a positive change in welfare if a renewable energy program were implemented.

Hanemann et al. (2011) conducted a study using the contingent valuation method, showing that Spanish households strongly favour applying green electricity programs that make electricity more expensive to reduce carbon dioxide emissions. The average willingness to pay per month and household is 29.91 € over the current electricity bill. The results also show that people living in the Mediterranean area are more likely to pay for green electricity programs and are willing to pay higher electricity prices to prevent climate change effects.

Gracia et al. (2012) identify the WTP through the choice experiment where the findings suggest that in Spain, most consumers are not willing to pay a premium for increases in the share of renewable energies in the electricity mix. In the case of energy from biomass, a discount of 1.51 €/month would be necessary.

Because the results of individual studies are often inconclusive or even contradictory, with considerable variations in the magnitude, sign, and importance of their WTP estimates, Soon and Ahmad (2015) made a summary estimate of the WTP from numerous studies using a meta-analytic approach, where a WTP of 7.16 USD was obtained.

The summary WTP obtained (7.16 $USD_{2013}$) was adjusted to the reference year (2019) and currency ($EUR_{2019}$), applying the annual inflation rate (CPI) and the exchange rate between USD and EUR (World Bank Group, 2021, OECD, 2021).

It was obtained a WTP of 7.02 €/month over the current electricity bill by renewable energy use. In Spain, approximately 235.88 kWh was consumed per month and household in 2019 (INE 2021), resulting in a WTP per kWh de 0.02976 €/kWh. In 2019, the ERF sold 171,173 MWh of energy electricity, but it is considered that only 50% of the energy produced by the ERF is renewable, that is, 85,586.5 MWh, giving a benefit of 2,547,054.24 €/year.

*7.1.3 Dependence of other companies*

The Districlima company in charge of managing the urban heat and cold distribution network of the Barcelona city depends on the supply of steam generated by the ERF for heating, air conditioning and sanitary hot water of more than 100 buildings connected to the network, made up of hotels, offices, homes, schools, shopping centres, among others (Figure 5).

The investments made in total exceed €64.7 million in a network that has more than 68 km of pipes, which run, for the most part, through the subsoil of the city —providing the company with direct economic benefits of approximately 2,615,000 € per year. In addition to other environmental, economic and social advantages such as reduction of $CO_2$ emissions, mitigation of the "heat island" effect (managing to lower the ambient temperature between 1ºC and 2ºC, thanks to the replacement of hundreds of air conditioning units), the continuous guarantee of supply, savings in the user's energy bill, aesthetic effects, among others (Districlima 2020).

Districlima depends mainly on the ERF since its activity depends entirely on the supply of the steam generated, and therefore the closure of the ERF would affect Districlima and the citizens and consumers of Barcelona.

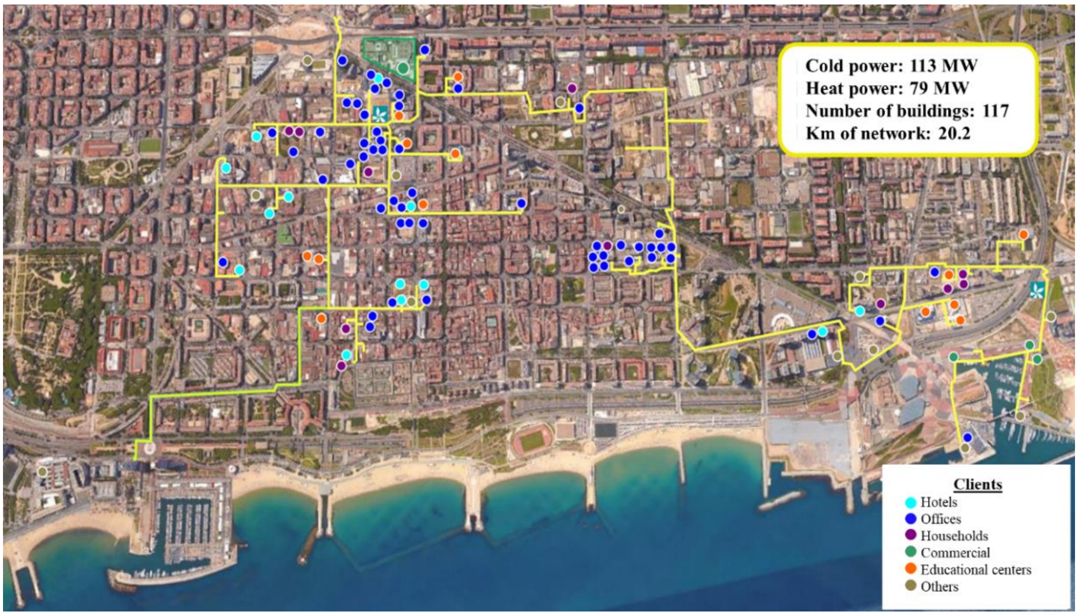


Figure 5. Network of cooling and heating in Barcelona city in 2019. Source: Adapted from Districlima (2020).

As there is no financial information for the 2019 year, to calculate the revenue generated per ton of steam sold, the average of the last three years available is taken. Considering that, in 2019, the ERF sold 125,148 tons of steam to Districlima, a net profit of € 2,978,423 is obtained (Table 4).

According to Vlachokostas et al. (2020), WtE facilities can be economically viable when they are located close to domestic or industrial consumers to benefit from energy and steam production, as is the case of the ERF.

Table 4. Summary about the activity of Districlima. Source: Adapted from Districlima (2020).

| Concept | Information year | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **2019** | **2018** | **2017** | **2016** | **2015** | **2014** | **2013** | **2012** | **2011** | **2010** |
| Steam sold (tons) | 125,148 | 111,674 | 95,509 | 78,012 | 75,822 | 75,102 | 78,611 | 68,042 | 68,263 | 66,382 |
| Operating income (thousands of €) | - | 15,044 | 13,527 | 11,276 | 10,286 | 10,086 | 9,186 | 8,651 | 8,361 | 6,985 |
| Annual net profit (thousands of €) | 2,978 [1] | 2,615 | 2,423 | 1,764 | 1,239 | 1,118 | 786 | 629 | 730 | 1,306 |
| Nº of consumers | 117 | 109 | 104 | 95 | 89 | 84 | 81 | 78 | 67 | 59 |
| Km of network | 20.2 | 19.5 | 18.6 | 16.8 | 15.6 | 15 | 15 | 14.4 | 13.4 | 13.1 |

[1] calculated from the net profit per ton of steam sold in the last three years

## 7.2 Environmental

This impact group is associated with the negative effects on the environment caused by the waste facilities due to pollutants emitted into the air, water, and soil. Furthermore, the emission of contaminants avoided due to the production of steam and electricity are included. Table 5 shows the main pollutants emitted by the waste to energy facilities.

Table 5. Main pollutants emitted by the waste to energy facilities. Source: Adapted from Medina-Mijangos et al. (2021).

| Impact | Pollutants |
|---|---|
| Air emissions | Particulates ($PM_{10}$) |
| | NOx |
| | $SO_2$ |
| | $CO_2$ |
| | CO |
| | VOCs |
| | HCl, HF (acid gases) |
| | PCDD/Fs |
| | Heavy metals |
| | $N_2O$ |
| Water emissions | Dioxins/dibenzofurans (PCDD/Fs) |
| | Heavy metals |
| | Salts |
| Soil emissions | Heavy metals (Cr, Ni, Pb, Zn, Cu, Cd, As and Hg) |
| Avoided emissions | $CO_2$, $SO_2$, NOx (emitted by electric power generation plants) |

### *7.2.1 Climate change*

According to the Intergovernmental Panel on Climate Change (IPCC), climate change and its most visible manifestation, global warming, is fundamentally anthropic and is essentially caused by greenhouse gas (GHG) emissions by using fossil fuels. Therefore, $CO_2$ emissions eq. are an essential element to consider when analysing external impacts from the ERF.

First, direct $CO_2$ emissions generated by the energy recovery process and by the consumption of fossil fuels (natural gas and diesel) are considered to determine $CO_2$ eq. emissions. It is calculated that

34.37% of the total direct emissions are of biogenic origin, from organic matter, and the remaining 65.63% are of anthropogenic origin, from other materials present in municipal waste. Second, indirect emissions related to the consumption of electrical energy from the electrical network are considered.

Electrical energy is used mainly for the operation of the plant. This energy usually comes from self-consumption, less in periods of shutdown due to maintenance or breakdown in which electricity from the grid is used. Natural gas is used as an auxiliary fuel for combustion and as a fuel for emergency engines. Diesel is consumed in trucks, as well as in generator sets and fire pumps.

Figure 6 shows the electricity, diesel and natural gas consumption made between 2017 and 2019. In 2018, the increase in electricity and natural gas consumption had been caused by various plant shutdowns/starts. Consequently, no maintenance shutdowns have been made at the ERF in 2019, which has led to the normalisation of consumptions.

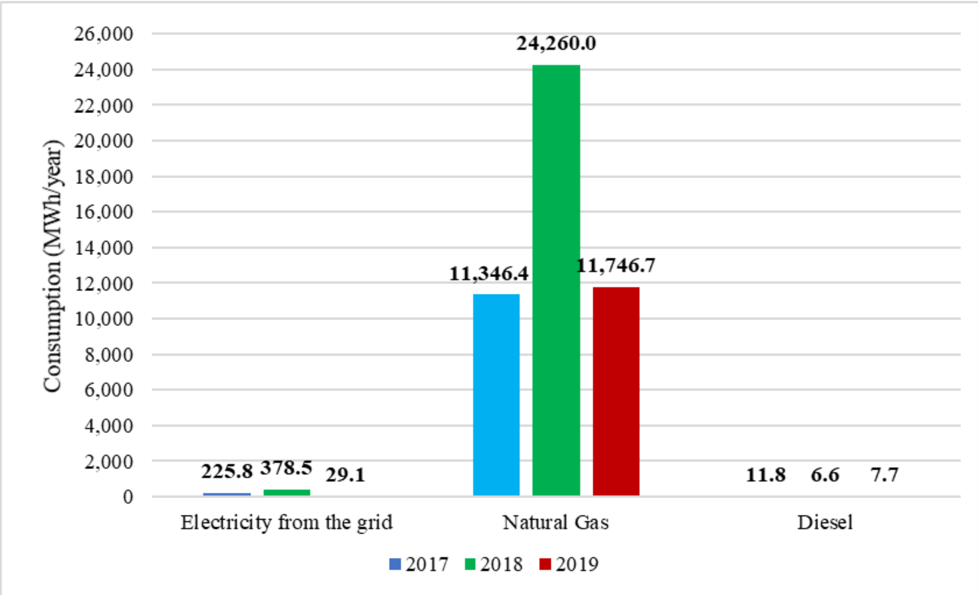


Figure 6. Comparison of consumption of the ERF. Source: Adapted from TERSA (2020a).

Table 6 shows the emissions generated in 2019 by the ERF, where a distinction is made between $CO_2$ eq. of biogenic and anthropogenic origin. Biogenic $CO_2$ ($CO_2$ emissions associated with the natural degradation of organic matter) was excluded because biogenic carbon is a short-term emission derived from the biosphere, completing a typical biological carbon cycle (Edwards et al. 2018, Medina-Mijangos and Seguí-Amórtegui 2021). In this case, the emissions generated by the ERF were 208,931.49 tons of $CO_2$ eq., or 0.595 tons of $CO_2$ eq./ton treated.

Table 6. Emissions of $CO_2$ eq. generated by the ERF in 2019. Source: Adapted from TERSA (2020a), Generalitat de Catalunya (2020).

| Concept | Consumption (MWh) | Emission factor (kg $CO_2$/MWh) | Emissions of $CO_2$ eq. (tons) | Waste treated (tons) | Emission of $CO_2$ eq. per ton of waste (ton/ton treated) |
|---|---|---|---|---|---|
| Direct $CO_2$ emissions (anthropogenic origin) | - | 1 | 206,781.00 | 351,308 | 0.589 |
| Direct $CO_2$ emissions (biogenic origin) | - | 1 | 109,397.00 | | 0.311 |
| Natural gas consumption | 11,746.7 | 0.180 | 2,141.42 | | 0.006 |
| Diesel consumption | 7.7 | 0.270 | 2.05 | | 0.000 |
| Indirect emissions related to electricity consumption | 29.1 | 0.241 | 7.01 | | 0.000 |
| **Total (with $CO_2$ emissions of biogenic origin)** | | | **318,328.49** | | **0.906** |
| **Total (without $CO_2$ emissions of biogenic origin)** | | | **208,931.49** | | **0.595** |

Table 7 shows the emissions of $CO_2$ eq. avoided by the generation of steam and energy from waste. The energy generated by the ERF was sold to the electricity grid and used in the ERF (self-consumption). The steam generated was sold to Districlima for the urban network of cooling and heating. It was used for air conditioning, central heating and hot sanitary water (Medina-Mijangos and Seguí-Amórtegui 2021). The $CO_2$ eq. emission factor was considered, assuming that if the energy generated from waste, it would have to come from the electricity grid, meaning an emission factor of 0.241 kg $CO_2$/MWh (Generalitat de Catalunya 2020). In this case, the emissions avoided by the ERF were 52,358.21 tons of $CO_2$ eq., or 0.149 tons of $CO_2$ eq./ton treated.

Table 7. Avoided Emissions of $CO_2$ eq. by the ERF in 2019. Source: Adapted fromTERSA (2020a), Generalitat de Catalunya (2020).

| Concept | Energy production (MWh) | Emission Factor (kg $CO_2$/kWh) | Emissions of $CO_2$ eq. (tons) | Waste treated (tons) | Emission of $CO_2$ eq. per ton of waste (ton /ton treated) |
|---|---|---|---|---|---|
| Electric energy for self-consumption | 23,560 | 0.241 | 5,677.96 | 351,308 | 0.016 |
| Electric energy sold to the grid | 171,921 | 0.241 | 4,1432.961 | | 0.118 |
| Steam sold to Districlima | 21,773 | 0.241 | 5,247.293 | | 0.015 |
| **Total** | **217,254** | | **52,358.21** | | **0.149** |

The tax set by Catalan legislation on emissions from various industrial activities is considered to calculate the cost due to $CO_2$ emissions. According to its industrial activity, the ERF is classified as a municipal waste incineration facility with a capacity greater than 3 tons per hour. The $CO_2$ eq. emission price has been set at an average value of about 10 €/ton of $CO_2$ eq., which should increase to a value of about 30 €/ton $CO_2$ eq. in 2025 (BOE 2017b).

The objective of these taxes is that the damage caused by greenhouse gas emissions falls on those who generate them and therefore reduce the emissions through new technologies and innovation. Therefore, emitters have an incentive to reduce emissions as long as it is cheaper than paying the price per ton of $CO_2$ emitted. 30 €/ton is considered a minimum estimate of the damage currently caused by carbon emissions. Pricing emissions above 30 €/ton does not guarantee that polluters pay for the total damage they cause or that prices are high enough to decarbonise economies (OECD 2018). However, a price below 30 €/ton means that polluters do not directly face the cost of emissions and possible damage to society and that the incentives for a profitable reduction are too weak. According to OECD (2018), it is considered that carbon prices should amount to at least USD 40-80 (35-70 €) per ton of $CO_2$ by 2020, and USD 50-100 (44-88 €) per ton of $CO_2$ by 2030.

### *7.2.2 Air emissions*

Regarding atmospheric emissions, several strategic projects have been carried out to reduce emissions, setting limits much lower than those established in the current regulations at a European level.

The ERF has different filter systems and smoke and gas catalysis to avoid the local deterioration of air quality. Initially, in 2004, the ERF installed NOx and HCl emission reduction systems and later in 2018 upgraded the NOx emission reduction system with a catalytic filter, which reduces NOx emissions to 50 mg/Nm$^3$, representing an investment of €14.5 million.

These projects represent investment costs, although they produce a profit for the ERF, avoiding damage to both the environment and public health. Table 8 shows the results of the 2019 checks, where the mean values are lower than the legal limits.

Table 8. Atmospheric emissions of the ERF in 2019. Source: Adapted on TERSA (2020a).

| **Contaminants** | **Mean values** | | | **Legal Limits** |
|---|---|---|---|---|
| | **2017** | **2018** | **2019** | |
| Particulates (mg/Nm³) | 3.23 | 3.02 | 3.17 | 10 |
| CO (mg/Nm³) | 19.84 | 29.32 | 26.47 | 50 |
| HCl (mg/Nm³) | 5.15 | 4.20 | 5.10 | 10 |
| SO2 (mg/Nm³) | 12.82 | 10.20 | 10.58 | 50 |
| HF (mg/Nm³) | 0.07 | 0.08 | 0.098 | 1 |
| NOx (mg/Nm³) | 125.16 | 100.48 | 109.39 | 200 |
| TOC (mg/Nm³) | 1.74 | 1.90 | 1.17 | 10 |
| Hg (µg/Nm³) | 1.15 | 0.600 | 0.324 | 50 |
| Various (Sb + Cr + Co + Cu + Mn + Ni + V+ As + Pb) (mg/Nm³) | 0.0345 | 0.0465 | 0.0240 | 0.5 |
| Cd + Tl (mg/Nm³) | 0.0020 | 0.0042 | 0.00300 | 0.05 |
| PCDD/PCDFs (nmg/Nm³) | 0.0288 | 0.0171 | 0.0174 | 0.1 |

### *7.2.3 Emissions to water*

The ERF performs two different releases. On the one hand, the sanitary water and rainwater (without treatment) are released directly into the municipal sewers; on the other, the cooling water, which is taken from the sea and, after passing through the thermal process, is returned to the sea with the only variation being a slight increase in temperature. The ERF carries out three-monthly checks on the two emission points.

Table 9 shows the results of the 2019 checks, where the mean values are below the legal limits; therefore, only the costs associated with the periodic checks, which have already been included in the operating costs, are considered.

Table 9. Emissions to water by the ERF in 2019. Source: Adapted from TERSA (2020a).

| Concept | Mean Values | Legal Limits |
|---|---|---|
| pH | 7.63 | Between 6 and 10 |
| Chemical oxygen demand (mg/l) | 279.17 | 1,500 |
| Chlorides (mg/l) | 208.33 | 2,500 |
| Soluble Salts (mg/l) | 1516.67 | 6,000 |
| Suspended matter (mg/l) | 36.90 | 750 |
| Inhibitory Matter (equitox/m3) | 22.20 | 25 |
| Total phosphorus (mg/l) | 5.22 | 50 |
| Nitrogen (mg/l) | 45.62 | 90 |

## 7.3 Public Health

This group of impacts includes damage to the health of the ERF workers or the population living near the facility due to pollutant emissions. Also, physical accidents to workers caused by activities carried out in the ERF are considered.

### *7.3.1 Chemical Risks*

In the MSW incineration process, fumes are produced because of combustion. These fumes are mixtures of oxides, heavy metals, carbon particles, dioxins and furans (PCDD/Fs), among other elements that generate serious danger to human health. The results of García-Pérez et al. (2013) show that there is an excess risk for all cancers combined and for lung cancer, in particular, there are marked increases in the risk of tumours of pleura and gallbladder (in men) and tumours of the stomach (in women) for people around incinerators.

Specifically, PCDD/Fs constitute a group of persistent organic chemical compounds. PCDD/Fs can enter the body via ingestion, skin absorption and inhalation pathways. The possible health effects of dioxin emission are detailed below.

- Short-term exposure to high levels of PCDD/Fs may cause skin lesions known as chloracne, which is persistent (World Health Organization 2010).
- Longer-term exposure may cause a range of toxicity, including immunotoxicity, developmental and neurodevelopmental effects, and effects on thyroid and steroid hormones and reproductive function; the most sensitive life stage is considered to be the neonate or fetus (World Health Organization 2010).
- PCDD/Fs are environmental pollutants that have raised considerable concern, especially due to the potential carcinogenic effects (Domingo et al. 2017).

In Domingo et al. (2017), air and soil samples were collected in locations near the ERF to determine the levels of PCDD/Fs and the possible risks to human health. It was determined that the main route of human exposure to PCDD/Fs in the study area is air inhalation. The hazardous quotient (HQ) is used to evaluate the non-carcinogenic effects of exposure to a specific contaminant. HQ values below unity are considered safe. The HQ for the area was 0.01, indicating that there are no significant non-cancer risks due to human exposure to PCDD/Fs in the vicinity of the ERF (Domingo et al. 2017).

On the other hand, Agència de Salut Pública de Barcelona (2018) has carried out a study that explores the risk of mortality due to causes associated with the exposure of PCDD/Fs in the area of Barcelona city for the period from 1991 to 2015. They have included diseases with an origin related to dioxin exposure such as malignant neoplasia of the liver, malignant neoplasm of the trachea, bronchi and lungs, neoplasia of connective tissue and other soft tissues, Non-Hodgkin's lymphoma, leukaemia and diseases of the circulatory system. This study aims to analyse if the proximity to the incinerator could lead to increased exposure to PCDD/Fs in the air. This environmental exposure could lead to an increased risk of suffering from certain cancers and diseases of the circulatory system that would be reflected in higher mortality from these causes.

Next, the study results are shown according to the Standardised Mortality ratio map —SMR (Figure 6) and the Probability map of exceeding the Barcelona city's mean mortality —PEM (Figure 7) depending on the proximity to the plant. SMR is the ratio of the observed number of deaths (or incidents) to the number of deaths (or incidents) that would be expected in a reference population or area (Kelsey and Gold 2017). SMR for the entire city is 100, and values above 100 indicate higher mortality than in Barcelona city.

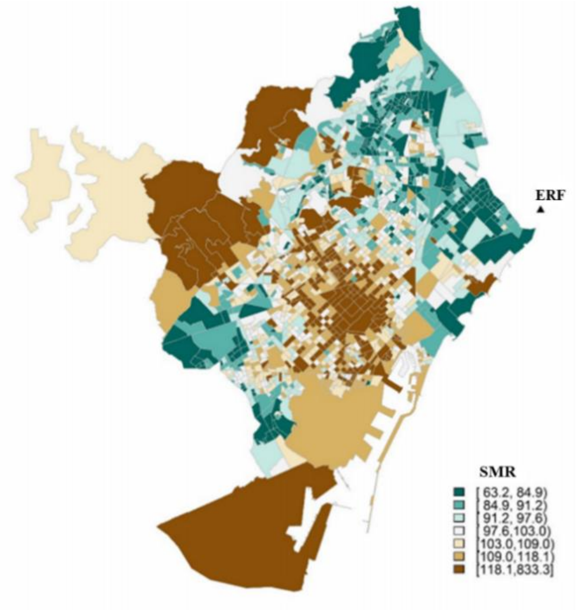


Figure 7. Map of the areas of Barcelona city according to the Standardised Mortality Ratio (SMR) for all mortality causes. Source: Agència de Salut Pública de Barcelona (2018).

These descriptive maps show that the areas closest to the incineration plant do not have a higher mortality ratio than the Barcelona average. In both cases, in the vicinity of the ERF, good results are observed compared to other areas of the city (brown and red colours of the maps). Therefore, it can be concluded that no groupings of areas have been detected in the vicinity of the incineration plant with a mortality rate above the city average. Furthermore, no significant association has been found between proximity and mortality to the incineration plant (Agència de Salut Pública de Barcelona 2018).

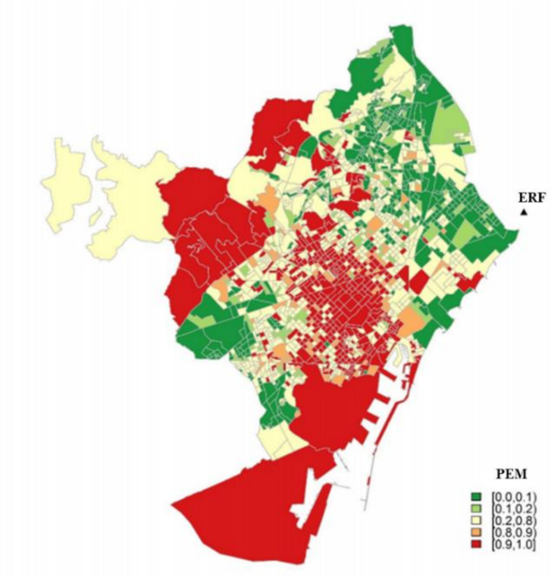


Figure 8. Map of the areas of Barcelona city according to the probability of exceeding Barcelona mean mortality (PEM) for all causes of mortality. Source: Agència de Salut Pública de Barcelona (2018).

The study considers a period of time in the past in which the environmental levels of dioxins were higher than those of today since, in recent years, a series of catalysts and particulate filters have been installed and renewed to prevent the emission of substantial amounts of toxic fumes. These improvements and innovations are reflected in the investment costs (included in the private impacts) and avoid the costs generated by damage to health. In this case, it can be concluded that the cost due to impacts on public health caused by chemical pollutants is equal to 0 €.

*7.3.2 Physical risks*

Damages to the health of the ERF workers are mainly associated with injuries caused by minor accidents and include dislocations and sprains, fractures and superficial injuries (TERSA 2020b, Medina-Mijangos and Seguí-Amórtegui 2021).

According to Gil Fisa & Pujol Senovilla (2009), these work accidents would cause various costs such as 1) Cost of time lost during the accident; 2) Costs for material damage; 3) Costs due to production losses; 4) General and medical expenses; 5) Time spent investigating the accident by other company personnel. Only the expenses incurred by mutual or public entities are considered to avoid double-counting since the salary payment, the social security fee, among others, have already been considered in the company's annual accounts as part of the labour costs (Medina-Mijangos and Seguí-Amórtegui 2021). In this case, only the medical care costs and the worker salary paid by the public administration in the period of sick leave are considered (generally, in Spain, 25% of the worker salary is paid by the company and 75% by Social Security). According to Medina-Mijangos and Seguí-Amórtegui (2021), in 2017, there were six accidents in the ERF and the cost for physical risks was 13,660.50 €. However, in 2019, no accidents were recorded in the treatment facility, which means that there is no cost related to physical damage, more than the costs incurred for risk prevention, which in 2019 were 12,837.96 € compared to 2018, which were 1,236.79 €, these costs are included in the annual accounts.

### 7.4 Quality Life

Generally, treatment facilities generate various disamenities such as dust, odours, visual intrusion (smokestack) and noise. In the case of incinerators, they can generate changes in environmental quality associated with the emissions of pollutants.

In order to assess the economic impacts due to the disamenities generated, several authors have carried out studies to analyse the effects on the quality of life of the households that live in the vicinity of incinerators and their negative effect on house prices. For example, in the case of Sun et al. (2017), a study was carried out in Shenzhen city, China using the hedonic price method, where it is concluded that for each additional kilometre that the property moves away from the WTE plants, the value of the properties can increase by 1.30%. On the other hand, Rivas Casado et al. (2017) point out that the impact of incinerators on local UK house prices ranges between approximately 0.4% and 1.3%.

Many projects were significantly delayed or even abandoned, mainly due to opposition from the local community and the "Not In My Back Yard" (NIMBY) syndrome, which is often exacerbated when facilities are located near dense urban areas (Vlachokostas et al. 2020). In the case of the ERF, the Aire Net platform (by its name in Catalan) was created, made up of numerous entities and associations from the municipalities of Barcelona, Sant Adrià de Besòs and Badalona, to inform citizens about environmental pollution that cause industries and service infrastructures. In this case study, the figure of 8 € per ton of waste treated was used to monetary value the disamenities generated by incinerators; this is a value slightly lower than the impacts caused by the landfill disamenities, that is, 10 €/ton (European Commission 2000).

### 7.5 Education

This impact group refers to the change of behaviour of citizens and workers through training and awareness programs to obtain benefits related to the improvement of the processes of the treatment facilities.

Waste incorrectly classified by citizens (before waste collection processes) increases the risk of spontaneous fires, higher processing costs, production errors, and possible damage to equipment

(Ibrahim 2020), in addition to increase workplace accidents. Therefore, in this study, it is considered that the incorrect classification of waste by citizens does not affect the ERF. Despite this, the ERF makes annual investments in developing environmental education programs aimed at citizens that could benefit other treatment facilities.

On the other hand, it is considered that the training programs for workers allow improving the skills of the workforce with which it is possible to achieve greater effectiveness and efficiency of the manufacturing process and the quality of the goods produced. According to Mital et al. (1999), the economic benefits of worker training include significant productivity improvements through reduction of waste, reduction of production time, improvements in quality, greater flexibility to respond to needs, and an advantage competitive for employers and countries as a whole. However, these training programs require investments, which are reflected in the annual accounts. In 2019, 101,925.24 € was invested for the training of workers, compared to the 52,732.1 € registered in 2018.

In this case study, the increase in energy efficiency is evaluated (Table 10) due to greater investment in the training of workers. In 2018, there was an energy efficiency of 526 kWh/ton treated, compared to 554 kWh/ton in 2019. Therefore, two different scenarios are analysed to compare the benefits obtained. Firstly, considering the revenues obtained if the efficiency had remained the same as in 2018 (i.e., 526 kWh/ton). The second scenario considers the revenues obtained in 2019 due to the increase in electrical efficiency (i.e., 554 kWh/ton). In both cases, the sale price of energy corresponds to 50.54 €/MWh, and it is considered that 23,560 MWh of the total energy production was used for self-consumption, and the remaining was sold to the electricity grid.

Table 10. Information about the benefits due to increased energy efficiency. Source: Adapted from TERSA (2020b).

| **Increase in energy efficiency** | | |
|---|---|---|
| **Concept** | **Scenario 1** | **Scenario 2** |
| Energy efficiency (kWh/ton) | 526 | 554 |
| Waste treated (ton) | 351,308 | 351,308 |
| Total production (MWh) | 184,959 | 194,740 |
| Energy sold to grid (MWh) | 161,399 | 171,180 |
| Price Electricity (€/MWh) | 50.54 | |
| Total Revenue (€) | 8,157,129.56 | 8,651,437.20 |
| Benefit (€) | 494,307.64 | |

Comparing the energy efficiency of the ERF with other recovery plants located in Spain (Table 11), we can see that there are facilities with better results than the ERF analysed, so it is necessary for this facility to improve its processes to achieve greater energy efficiency and therefore better economic and environmental results.

Table 11.1 Energy efficiency of TERSA, TIRME, SIRUSA and MADRID energy recovery facilities in 2019.

| Facility | Year | Waste treated (ton) | Energy produced (MWh) | Energy efficiency (MWh/ton) |
|---|---|---|---|---|
| TERSA | 2019 | 351,308 | 194,740 | 0.554 |
| TIRME | 2018 [1] | 573,788 | 326,804 | 0.570 |
| SIRUSA | 2019 | 129,815 | 49,649 | 0.382 |
| MADRID | 2019 | 331,955 | 228,263 | 0.687 |

[1] information about 2019 activity is not available

### 7.6 Economic development of the area

It is important to note that two vastly different ecosystems coexist in the vicinity of the ERF. On the one hand, the ERF is located in a highly industrialised area that provides urban services to the Catalan capital, such as waste treatment, electricity production, heat production and wastewater treatment. On the other hand, the industrial area (where the ERF is located) is surrounded by an urban area with good quality public transportation services, a new university campus, shopping malls, along with other services.

Despite the benefits obtained from the ERF related to the management of MSW, it avoids urbanisation and the growth of the tourism, financial and real estate sector, having a "conflict of interest" between the land of industrial use and the land of urban use where industrial investments are losing ground to urban development and its associated investments.

## 8. Monetary valuation of externalities

In Table 12, the results obtained from the different external impacts are presented, where the results are expressed in annual costs and revenues (€/year) and costs and revenues per ton of waste treated (€/ton). As 351,308 tons have been treated, it is obtained a total external cost of 13.95 €/ton and total external revenue of 41.30 €/ton.

As can be seen, this facility generates several positive impacts. The most representative positive impact (revenue) is related to reducing waste that is sent to landfills. In contrast, the negative impact (cost) with the most significant effect is related to the disamenities generated by the ERF. The results show no costs related to health damage due to chemical risks; however, it is essential to closely monitor dioxin emissions to detect abnormal situations and continue investing in innovative projects and advanced technology.

Table 12. Economic analysis of external impacts related to the ERF in 2019. Source: Authors elaboration.

| Impact group | Impact Identification | | Impact Quantification | Impact Valuation (€/year) | | Impact Valuation (€/ton) | |
|---|---|---|---|---|---|---|---|
| | **Costs** | **Revenues** | | **Costs** | **Revenues** | **Costs** | **Revenues** |
| Use of waste | | Reduce waste sent to landfill | 338,951 tons of waste | | 7,965,348.50 | | 22.67 |
| | | Quality of energy (renewable energy) | 85,586.5 MWh of energy | | 2,547,054.24 | | 7.25 |
| | | Districlima dependence | 125,148 tons of steam | | 2,978,423.00 | | 8.48 |
| Environment | Emissions to air ($CO_2$) | | 208,931.49 tons $CO_2$ eq. | 2,089,314.90 | | 5.95 | |
| | | Avoided emissions to air ($CO_2$) | 52,358.21 tons $CO_2$ eq. | | 523,582.10 | | 1.49 |
| Public Health | Physical injuries | | 0 people affected | 0 | | 0 | |
| | Chemical risk (Cancer by emission of PCDD/Fs) | | 0 people affected | 0 | | 0 | |
| Education | | Technique of workers (increase in energy efficiency) | % productivity (change 526 to 554 kWh/ton) | 494,307.64 | | | 1.41 |
| Quality Life | Disamenities | | Price of households | 2,810,464.00 | | 8 | |
| | | | Total external impacts | 4,899,778.90 | 14,508,715.48 | 13.95 | 41.30 |

Once the impacts described above have been monetarily valued, it is possible to add the costs and revenues to obtain the Total Benefit through Eq. 2. In the case of opportunity cost, it is considered as the value of the waived alternative share. Under the concept of sustainable development and its three pillars, the best alternative is the one that provides not only the best economic performance but also the best environmental and social performance (Medina-Mijangos and Seguí-Amórtegui 2021).

As it is not considered that there is a better alternative for the treatment and use of rejected waste, because the alternative treatment would be the disposal in landfills, facilities that entail various negative environmental and social impacts; it is determined that the opportunity cost is that provided by a financial instrument when the company's capital and reserves are invested in them (68,336,034 €). The interest on financial instruments in 2019 was 3% (Banco de España, 2019); therefore, the opportunity cost is 2,050,081 €, the equivalent of 5.84 €/ton. Finally, the Total Benefit of 37.48 €/ton is obtained, as shown in Eq. 4.

$$B_T = \sum_{n=1}^{N} [(156.60) - (0 + 144.09 - 5.91 + 2.45) + (41.30 - 13.95) - 5.84] = 37.48\ €/ton \quad (4)$$

Therefore, it can be concluded that the ERF is profitable from a private point of view ($BP$ = 15.97) and an economic, environmental, and social point of view ($BT$ = 37.48).

## 9. Sensitivity analysis

This section analyses the robustness of the management system by considering and evaluating different scenarios and variables such as $CO_2$ emissions, the impacts of dioxins on public health and the opportunity cost of the land where the ERF is located.

### 9.1 $CO_2$ emissions

An important factor is related to emissions of biogenic origin (basically due to the organic matter contained in the waste), with the entry into operation of the previous selection of waste, through Ecoparc 3, and the consequent decrease in organic matter reaching the ERF, there is generally a tendency in recent years for the percentage values of biogenic $CO_2$ to decrease. Some studies consider biogenic emissions as a critical sensitivity factor, noting that whether or not biogenic carbon is included as an externality can make a significant difference in the total cost of the project (Edwards et al., 2018).

In this case study, if emissions of biogenic origin are considered, the total emissions of $CO_2$ eq. It would be 0.906 ton $CO_2$ eq./ton of waste instead of 0.595 ton $CO_2$ eq./ton of waste. This value becomes more important if we consider that the payment imposed in Catalonia per ton of $CO_2$ eq., in 2025, it will be 30 € instead of 10 €.

When considering biogenic emissions, the Total Benefit decreases, reaching its lowest level when the tax reaches 30 €/ton $CO_2$ eq. as shown in Table 13. Including biogenic emissions can incentivise the ERF and other waste management companies to reduce total $CO_2$ emissions through innovative projects and advanced technology.

Table 13. Effect of biogenic emissions and the increase in the $CO_2$ emission tax on the Total Benefit of the ERF. Source: Authors elaboration.

| Concept | Emission of $CO_2$ per ton treated (ton $CO_2$/ton) | Cost per ton treated with a tax of 10 € (€/ton) | Cost per ton treated with a tax of 30 € (€/ton) | Total Benefit with a tax of 10 € (€/ton) | Total Benefit with a tax of 30 € (€/ton) |
|---|---|---|---|---|---|
| Without emissions of Biogenic origin | 0.595 | 5.95 | 17.85 | 37.34 | 28.42 |
| With emissions of biogenic origin | 0.906 | 9.06 | 27.18 | 34.23 | 19.09 |

## 9.2 Public health

Another sensitivity factor is related to the possible damage to health from the emissions of pollutants, specifically from the emission of PCDD/Fs.

Carcinogenic risks are expressed in terms of the probability of developing cancer due to exposure throughout life (estimated at 70 years); the carcinogenic risk of < 10−6 is considered significant (Domingo et al., 2017). The carcinogenic risks due to exposure to PCDD/Fs for residents in the vicinity of the ERF were 2.3 × 10−6 in 2017, exceeding the threshold of 10-6, which is why it is considered a significant risk. The results indicate that residents living in the vicinity of the ERF are 3-4 times more likely to develop cancer throughout their lives (due to exposure to PCDD/Fs) than residents of cities such as Girona, Mataró and Tarragona (Figure 9), where there are also other incineration plants operating (Domingo et al., 2017).

These results have caused great concern among the population. However, the authors note that the most critical limitation of the current study is the small number of air and soil samples. Consequently, the results should be viewed with caution.

Although the previous economic results did not reflect costs related to the impacts on public health, because the study presented by the Agència de Salut Pública de Barcelona (2018) was taken as a reference; if the results of Domingo et al. (2017) are considered, the results of the economic analysis could vary.

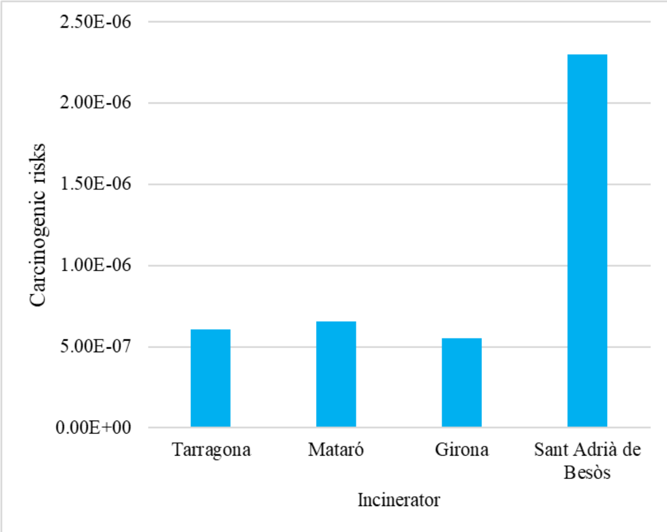


Figure 9. Carcinogenic risks due to PCDD/Fs exposure for residents living near Catalan incinerators. Source: Adapted from Domingo et al. (2017).

For the calculation of the total costs of cancer in Spain, the costs presented by Badia & Tort (2015) were taken as reference, where a) direct costs composed of hospital costs, costs of the consumption of antineoplastic drugs and the primary care costs; b) indirect costs made up of premature mortality costs and disability costs (both temporary and permanent), and c) informal care costs. Thus, obtaining a total cost of €12,216 million through the human capital method that supposes that when a worker leaves the labour market, his productivity is lost until he returns to work and a total cost of €7,168 million according to the friction method that supposes that when a worker leaves the labour market, his productivity is lost until he is replaced.

A most recent study realised by Wyman (2020) considers a) direct medical costs composed of treatment cost, follow-up cost, pharmacy cost paid by the patient, palliative care; b) direct non-medical costs consisting of transportation, accommodation and subsistence paid by the patient, equipment and works, formal and informal care; transport to radiation therapy subsidised by the State, c) indirect costs composed of loss of income after cancer and demand for productivity due to premature death. It is estimated that cancer costs for Spanish society around €19.3 billion for the total people diagnosed each year, equivalent to 1.6% of Spanish GDP.

The incidence (new cancer cases) was considered to calculate the total number of patients in Spain in 2019, which were 275,617 people (Observatorio AECC 2021); this would mean an approximate cost of 70,024.71 €/patient. These results coincide with a study carried out in France where it is established that the total cost of cancer in France is 10 billion €/year for treatment and 15 billion €/year, including lost productivity. Therefore, the cancer incidence is considered to be 240,000 new cases per year in France, which implies a cost per case of approximately 42,000 €/cancer per treatment and 63,000 €/cancer including lost productivity (Rabl et al. 2010).

In Table 14, the incidence of cancer in different geographical areas is presented among the populations where incinerators are located (Tarragona, Girona and Barcelona). First, we can see that the incidence rate (per 100,000 inhabitants) is below the national average. Based on the Barcelona incidence, the incidence by type of cancer in Sant Adrià de Besòs has been calculated considering only diseases with an origin related to dioxin exposure such as malignant neoplasia of the liver, malignant neoplasia of the trachea, bronchi and lungs, connective tissue and other soft tissue neoplasia, Non-Hodgkin's lymphoma, leukaemia. If we assume that all the incidents of these five types of cancers (58 patients) are due to the presence of the incinerator, the total cost for cancer in the area would be 4,061,433.18 €/year, that is, 11.56 €/ton. In this case, the Total Benefit obtained by the system is 25.92 €/ton treated, showing that the system continues to be economically profitable because the condition of BT > 0 is met.

On the other hand, if it is considered that in the city of Sant Adrià de Besòs there are 3 to 4 times more likely to develop cancer than residents of cities such as Girona, Mataró and Tarragona for the five types of cancer considered, we would have an incidence of 174 people considering the probability of 3 times more than in the other communities. This represents a public health expenditure for cancer of 12,184,299.54 €, that is, 34.68 €/ton of waste treated. This would mean that the Total Benefit of the system, considering the data presented by Domingo et al. (2017), would be 2.80 €/ton treated, showing that the system continues to be economically profitable because the condition of BT > 0 is met.

Table 14. Cancer incidence in geographical areas of Spain where incinerators are located. Source: Adapted from Observatorio AECC (2021).

| **Geographic area** | **Tarragona** | **Girona** | **Barcelona** | **Spain** | **Sant Adrià de Besòs** |
|---|---|---|---|---|---|
| Incidence | 4,644 | 4,291 | 32,164 | 275,617 | 211 |
| Population | 804,664 | 771,044 | 5,664,579 | 47,105,358 | 37,097 |
| Incidence rate [1] | 577 | 557 | 568 | 586 | 568 |
| Neoplasms of the liver | 115 | 106 | 785 | 6,768 | 5 |
| Neoplasm of trachea, bronchus and lung | 476 | 438 | 3,230 | 27,945 | 21 |
| Connective and soft tissue neoplasm | 455 | 416 | 3,184 | 27,197 | 21 |
| Non-Hodgkin's Lymphoma | 134 | 124 | 934 | 7,947 | 6 |
| Leukaemia | 100 | 93 | 698 | 5,941 | 5 |

[1] incidence per 100,000 inhabitants.

The economic results obtained are preliminary and with a global vision because this analysis has been carried out with secondary data from public statistics, and there are no specific data on the areas where the incinerators are located.

### 9.3 Opportunity cost of land

The ERF is located in industrial land, but if it is considered for other uses the land where the ERF is located, such as urban development in the area, the Total Benefit obtained from the system would considerably change.

It is necessary to consider the available land where the ERF is located as urban land instead of industrial land to calculate the cost associated with this impact. It is estimated that in 2019, the average price of urban land in the municipality of Sant Adrià del Besòs is equivalent to 2,735 €/m2 (Idealista 2021). Finally, according to the AMB, the price of industrial land is 730 €/m2 (AMB 2019). Therefore, given the existence of the alternative in land use, a cost of 2,005 €/m2 is established. The total area of the ERF is 10,044 m2, obtaining an opportunity cost of 20,138,220€, that is, 57.32 €/ton treated.

In this case, the Total Benefit obtained by the system is -14.00 €/ton treated, showing that the system becomes economically unprofitable because the condition of BT > 0 is not met. However, this industrial zone is essential for the proper functioning of the AMB; therefore, the change from industrial to urban land is not viable since not only the ERF limits this change but also other facilities.

## 10. Conclusions and Recommendations

Waste to energy facilities emerge as an alternative to landfilling of rejected waste (waste that can no longer be materially recovered), reducing the environmental and social impacts that the landfills generate. Although the European Parliament establishes a waste hierarchy for legislation and policy on the prevention and management of waste, where prevention, reuse, and recycling are prioritised over other types of recovery (including energy recovery) and deposit in landfills. It is considered that rejected waste can only be managed through incineration or landfilling, therefore in Spain, incineration is prioritised, complying with the established waste hierarchy principle. Consequently, the ERF fulfils a fundamental function for the AMB because it allows the energy recovery of more than 360,000 tons of rejected waste, which would otherwise end up in landfills.

Besides, there is a strong dependence on other companies such as Districlima, which has made significant investments in the heating and cooling network, and whose activity is based on the supply of steam generated by the ERF.

It is essential to include externalities in the technical-economic analysis of waste treatment facilities because sometimes if an analysis is carried out from a purely financial perspective, infrastructures such as landfills may seem less expensive than incinerators; however, by including externalities, the results are reversed, demonstrating that incineration plants are profitable from an environmental and social perspective.

In the present case study, the infrastructure is profitable from a private and external point of view, and we can even observe that externalities make this infrastructure more profitable and reliable since even in pessimistic scenarios, the infrastructure continues to generate economic benefits, as shown by the sensitivity analysis, except in the case of the assessment of the opportunity cost of land, where the result becomes negative ($BT < 0$). Although the ERF limits investment, it weighs down the local attractiveness, preventing urbanisation and the growth of the tourism, financial and real estate sectors. The ERF is located in a highly industrialised area that provides urban services to the Catalan capital, such as waste treatment, electricity production, heat production and wastewater treatment. This industrial zone is essential for the proper functioning of the AMB; therefore, the change from industrial to urban land is not viable since not only the ERF limits this change but also other facilities.

As mentioned previously, the results of Domingo et al. (2017) should be taken with care due to the small number of samples taken, also because there may be other sources of pollutant emissions in the area (other industrial facilities or even traffic). Moreover, other studies have shown that no groupings of areas in the vicinity of the incineration plant with mortality above the city average have been detected. Despite this, it is essential to make investments in strategic projects that allow the reduction of pollutant emissions through new technologies and innovation, which has already been done for several years, such as the implementation of a catalytic NOx reduction system, which allow reducing NOx emissions to 50 mg/Nm$^3$, representing an investment of €14.5 million. Furthermore, periodic measurements of contaminants are also crucial to ensure that the legal maximums are met. Additionally, to detect abnormal situations and that there are no risks to public health.

Researchers and policymakers should be interested in the economic values of externalities to allow the internalisation of external costs related to incineration through instruments such as regulations, taxes, subsidies, compensations, and negotiable emission permits to avoid direct damages to society. Spanish legislation by including gate fees to landfills and incinerators aims to incorporate externalities into private costs. Additionally, a $CO_2$ emission tax has been set in Spain, which corresponds to a tax of 10 €/ton of $CO_2$ and will reach a value of 30 €/ton of $CO_2$ by 2025. Despite this, this value may prove to be insufficient to motivate the decarbonisation of economies. According to the OECD (2018), the carbon prices should amount to at least 35-70 €/ton of $CO_2$ by 2020 and 44-88 €/ton of $CO_2$ by 2030. Therefore, policymakers should set taxes and fees that ensure the minimum cost of the damage that carbon emissions currently cause.

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# Anexo D: Participación en Congresos Internacionales y Simposios

**Participación en Congresos Internacionales y Simposios**

1. Medina-Mijangos, R., 2019. Metodología para el análisis técnico-económico de los sistemas de gestión de residuos mediante el análisis Coste-Beneficio, in: 8 Simposio Becarios CONACYT En Europa. Estrasburgo, Francia, p. 100.
2. Medina, R., De Andrés, A., Seguí-Amórtegui, L., 2019. Methodology for Technical-Economic Analysis of Municipal Solid Waste Management Systems, in: 5th International Congress on Water, Waste and Energy Management. Paris, France, pp. 72–73.
3. Medina-Mijangos, R., Seguí-Amórtegui, L., 2021a. Economic analysis of a mechanical-biological treatment plant in Spain: A case study, in: 4th Doctoral Congress in Engineering: Symposium on Environmental Engineering. FEUP Edições, Porto, Portugal, pp. 74–77.
4. Medina-Mijangos, R., Seguí-Amórtegui, L., 2021b. Sustainability in the evaluation of Municipal Solid Waste management projects, in: 4th Doctoral Congress in Engineering: Symposium on Environmental Engineering. FEUP Edições, Porto, Portugal, pp. 128.

# Metodología para el análisis técnico-económico de los sistemas de gestión de residuos mediante el análisis Coste-Beneficio

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**Eje temático:** Agroalimentación y medio ambiente
**Presentación individual**

*Palabras clave: Residuos Sólidos Municipales, Sistemas de gestión de residuos, Externalidades, Análisis Coste-Beneficio*

La economía global opera tradicionalmente a través de un modelo lineal, donde los recursos se consideran ilimitados y son desechados después de un corto uso, terminando generalmente en vertederos. De acuerdo a Kaza et al. (2018), aunque a nivel mundial, el 33 por ciento de los desechos aún se vuelcan en vertederos abiertos, los gobiernos están reconociendo cada vez más los riesgos y costes de estos. Hollins et al. (2017), enfatizan que es necesario desarrollar sistemas de gestión de residuos, económica y ambientalmente viables.

Al analizar económicamente los sistemas de gestión de residuos pueden considerarse dos tipos de costes e ingresos: privados y externos. Algunos estudios solo centran su atención en los costes e ingresos privados, los cuales son gastos financieros asociados con la inversión y la operación. De acuerdo con Nahman (2011), esto resulta en un sesgo en contra de alternativas como el reciclaje, que puede ser más caro que los vertederos desde una perspectiva puramente financiera, pero preferible desde un punto de vista ambiental y social. Lo ideal, es analizar las opciones de gestión de residuos considerando también las externalidades, costes relacionados con impactos sociales y ambientales. Sin embargo, a diferencia de los costes financieros, las externalidades son a menudo intangibles y difíciles de cuantificar en términos monetarios, por lo tanto, no se reflejan generalmente en los costes de gestión ni se toman en cuenta en la toma de decisiones.

Esta investigación propone una metodología que permita analizar técnica y económicamente los sistemas de gestión de residuos. Que permitirá a los tomadores de decisiones, analizar y comparar diferentes sistemas de gestión de residuos teniendo en cuenta costes e ingresos privados y la valoración monetaria de las externalidades. Por otro lado, se demostrará su validez mediante la realización de estudios de caso en diferentes localidades de México y España.

# Methodology for Technical-Economic Analysis of Municipal Solid Waste Management Systems

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**1. Introduction** – The main objective of the paper is present a methodology for technical-economic analysis of Municipal Solid Waste (MSW) management systems that consider private and external impacts. An impact is defined as any outcome that results from MSW system implementation, wished or not, promoted or accidental, generally susceptible of measurement, in a specific study area. It is distinguished between private and external impacts. The internal or private impacts are those directly tied to the treatment process of MSW and its later reuse. [1]. These are costs and incomes that are incurred by the investor or project developer [2]. The negative private impacts pertain to the financial expenditures associated with investing (CAPEX) and operating (OPEX) waste treatment systems [2]. In positive private impacts are included revenues for sale of recycled waste or energy generate from incinerators facilities. On the other hand, external impacts or externalities (for example, the affectation to third parties, control of pollution, the increase in the availability of resource or the guarantee in the supply), refer to those that are directly or indirectly caused by the operation of the plant, but whose effects are borne by a party other than its owner or operator [2]. The externalities are generally related to social and environmental impacts. Traditionally, an economic-financial analysis of waste management systems focuses exclusively on the study of private costs and benefits (internal impacts). The methodology that is presented in this paper takes into account not only the private impacts but also social and environmental impacts (externalities) which could have relevance on the project. Generally, the most relevant impacts (positive and negative) of the MSW systems have been documented in isolation, usually as a reflection of specific solutions of case studies as [3], [4], [5], [6], [7], among others.

In this paper, we propose to adapt the methodology presented by Seguí-Amórtegui et. al. [8] to realize a technical-economic analysis of MSW management systems. In Seguí-Amórtegui et. al. [8] is presented a methodology to realize a Technical-Economic Analysis of Wastewater Regeneration and Reutilization Systems, where are analysed projects considering private and external impacts. This methodology is based in social Cost-Benefit analysis (CBA), this is an analytical tool for judging the economic advantages or disadvantages of an investment decision by assessing its costs and benefits in order to assess the welfare change attributable to it [9]. The essential theoretical foundations of CBA are that benefits are defined as increases in human wellbeing (utility) and costs are defined as reductions in human wellbeing. For a project or policy to qualify on cost-benefit grounds, its social benefits must exceed its social costs [10].

**2. Results and Discussion** - The methodology presented in this paper is constituted by seven steps that should be fulfilled for its application: (1) objective definition, (2) definition of study scope, (3) project impacts, (4) identification of involved stakeholders, (5) study of financial necessities and possibilities, (6) adding of costs and revenues, and (7) sensitivity analysis.

Externalities are not generally reflected in waste management charges or taken into account in decision making regarding waste management options. This results in a bias against alternatives such as recycling, which may be more expensive than landfilling from a purely financial perspective, but preferable from an environmental and social perspective. There is therefore a need to quantify externalities in monetary terms, so that different treatment and disposal options can be compared on the basis of their overall costs to society (private costs and incomes plus external costs and benefits) [11]. For this reason, a key point in the methodology is the identification, periodicity, quantification and valuation of impacts of the project. The impacts identified and discussed are: (1) MSW infrastructures, (2) Reuse, recycling and recovery of waste, (3) Resource use, (4) Public Health, (5) Environment, (6) Education and (7) Quality life.

**3. Conclusions -** Based on CBA principles, the methodology developed aims to provide a consistent and comprehensive framework for the economic assessment of MSW management systems. The aim objective of the methodology is to reduce uncertainty and risk of investing in certain MSW management system. This tool will allow decision makers to analyse and compare different MSW management systems taking into account private benefits and costs and monetary valuation of externalities. The main objectives of the methodology is determinate the maximization of benefits of the project and visualize two situations separately: 1) that the MSW management system is economically and financially viable and for its operation, which is defined by the determination of private benefit (situation that normally interests the technicians and politicians); and 2) that MSW management system is economically, financially, socially and environmentally viable (which interests economists and society).

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# Economic analysis of a mechanical-biological treatment plant in Spain: A case study

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## Abstract

Mechanical-biological treatment plants play an essential role in managing municipal solid waste (MSW) in Spain because they allow the separation of the materials still present in the residual fraction and carry out their subsequent material and energy recovery through recycling of waste, generation of compost and energy. Furthermore, these plants generate various impacts (economic, social and environmental), which can be translated as revenues or costs. This work aims to determine the private and external impacts generated by a mechanical-biological treatment plant in Barcelona (Spain) to determine if this plant is profitable from an economic, social, and environmental perspective. The results have allowed visualising that this treatment plant is profitable from the private and external perspective and is beneficial for the environment and society.

**Keywords:** Mechanical-biological treatment, Municipal solid waste, Revenues and costs, Externalities.

## 1. Introduction

Mechanical-biological treatment (MBT) plants combine the mechanical separation of different types of waste contained in municipal solid waste (MSW) with the biological stabilisation of organic matter through processes such as anaerobic digestion or composting (Fei et al. 2018). MBT plants have positive externalities, such as reducing the amount of waste sent to incinerators and/or landfills, reducing leachate, landfill gas emissions and odours generated by organic matter (Di Lonardo, Lombardi, and Gavasci 2012). Also, the circular economy is promoting by allowing the reuse and recycling of recoverable materials and organic matter still present in the residual fraction. Ecoparc 3 is an MBT plant located in Sant Adrià de Besòs, Barcelona (Spain), that treats the residual fraction (waste that has not been selectively collected) from Barcelona city and its metropolitan area. It has a capacity of 200,000 tons/year. The general waste management process is presented in Figure 1.

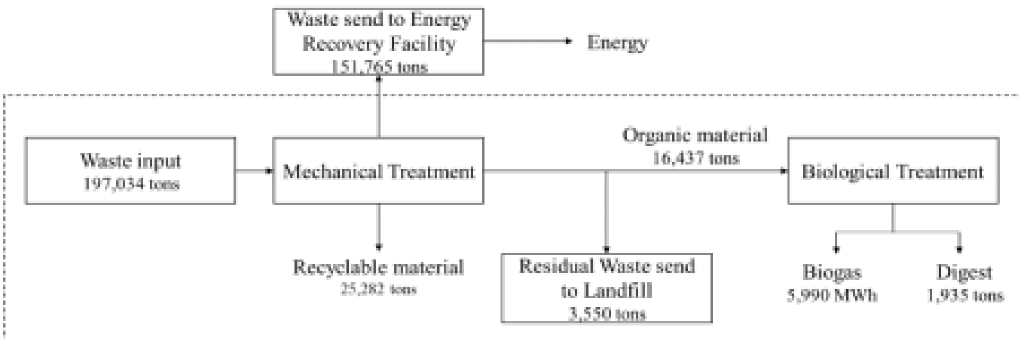


**Figure 1:** Waste management process of the Ecoparc 3 in 2017. The dotted line represents the scope of the study

In the mechanical treatment, the selection of recyclable materials such as paper, cardboard, glass, PET, HDPE, ferrous metals, non-ferrous metals, plastic film is made, and organic matter is separated. Subsequently, through the biological treatment, the organic matter obtained from the selection process is subjected to pre-treatment. Later, it is introduced into two digesters where the fermentation reactions take place by wet means. As a result of this process, biogas and digestate are generated. Finally, energy is produced through cogeneration engines; it is used for self-consumption and exported to the electricity grid.

## 2. Materials and Methods

The data was obtained from public information available on the MBT plant website (Ecoparc 3) and TERSA website (the company that manages the Energy Recovery Facility); documents such as annual accounts, sustainability reports, production data and environmental studies can be founded. In addition, the SABI database was used, which contains financial information about Spanish and Portuguese companies (Bureau Van Dijk 2008). For this case study, the costs and revenues generated in 2017 are considered. The methodology presented in Medina-Mijangos et al. (2021) is used. This is based on the principles of cost-benefit analysis, and the authors consider that the projects evaluated must comply with the principles of sustainability and its three pillars. Therefore, the methodology used considers the possible economic, social and environmental impacts generated by the project. The objective of the case study is to determine the private benefit, as well as the total benefit, from the determination of both private and external impacts generated by the MBT Plant, which will be identified, described, quantified and monetary valuated. In this way, it can be concluded whether the facility is profitable from a private point of view (if BP is greater than 0) and profitable from an economic, environmental, and social perspective (if BT is greater than 0). The objective function to be optimised is shown in Formula 1 and Formula 2, where, AVW: Annual volume sold; BP: Private Benefit; BT: Total Benefit; FC: Financial costs; IC: Investment costs; N: Total project duration; n: Project year index (n = 0, ..., N); NE: Negative Externalities; OMC: Operational and maintenance costs; PE: Positive externalities; SP: Price of sale; T: Taxes.

$$\mathbf{B_P} = \sum_{n=0}^{N}[(AVW_n * SP) - (IC_n + OMC_n + FC_n + T_n)] \quad \textbf{(1)}$$

$$\mathbf{B_T} = \sum_{n=0}^{N}[(AVW_n * SP) - (IC_n + OMC_n + FC_n + T_n) + (PE_n - NE_n)] \quad \textbf{(2)}$$

Private impacts refer to the costs and revenues associated with the investment, operation and maintenance of waste treatment facilities (Jamasb and Nepal 2010). These are costs incurred by the investor or the project developer (private or public entity) and are restricted to the spatial limitations of a waste treatment facility (Aleluia and Ferrão 2017). These impacts are obtained directly from the company's annual accounts. On the other hand, external costs or externalities refer to those impacts caused directly or indirectly by the operation of a treatment plant but whose effects are assumed by a party other than its owner or operator (Aleluia and Ferrão 2017). These costs and revenues are essentially related to social and environmental impacts. Some externalities related to the MBT are listed below.

Reduction of waste sent to incineration. An added value of the MBT is to provide the Barcelona metropolitan area with waste treatment capacity since, without its presence, it would be sent directly to incineration. Therefore, the economical amount saved per canon paid per ton of waste sent to incineration is considered to quantify the benefit obtained by this facility.

$CO_2$ emissions. Climate change and its most visible manifestation, global warming, is essentially caused by greenhouse gas (GHG) emissions produced by fossil fuels. Therefore, $CO_2$ emissions are an essential element to consider when analysing external impacts from the MBT plant. To calculate total $CO_2$ eq. emissions, the direct $CO_2$ emissions generated by the plant and by the consumption of fossil fuels (diesel and natural gas) are considered. Also, indirect emissions related to the consumption of electrical energy from the electrical network are considered.

Avoided $CO_2$ emissions. The MBT allows the recovery of recoverable materials such as plastic, cardboard, glass present in the residual fraction for their subsequent recycling. For the calculation of net $CO_2$ eq. emissions for the recycling of different materials (difference between the emissions from the primary production of materials made with virgin raw materials and the emissions from the secondary production made with recycled raw materials), the information provided in Brogaard et al. (2014) and Turner et al. (2015) was used, where the mean and standard deviation in terms of $CO_2$ eq. per ton of recycled material is presented. Also, the energy generated by the MBT is sold to the electricity grid and used for self-consumption. The $CO_2$ eq. emission factor was considered, assuming that if the energy were not waste recovered from waste, it would have to come from the electricity grid, meaning an emission factor of 0.392 kg $CO_2$/MWh. In 2017, 5,990 MWh of energy was produced.

In this case, the MBT is economically analysed considering a specific year, that is, 2017; therefore, N is equal to 1. To calculate FC, both financial costs and revenues are considered. According to the company's annual accounts, it has revenues due to the investment in financial instruments and costs due to third party debts, having total financial revenues of 39,897 €/year, that is, 0.20 €/ton. To calculate T, a corporate tax of 25% less the bonuses received for the provision of local public services (BOE 2014) are considered, obtaining a tax value of 685,643 €/year, that is, 3.48 €/ton.

## 3. Discussion

Once the impacts are identified, quantified and valued monetarily, it is possible to determine the costs and revenues generated by the MBT due to both private and external impacts, obtaining the results presented in Table 1. It is considered that 197,034 tons of waste were treated in 2017.

**Table 1:** Economic Analysis of Impacts considered for Ecoparc 3.

| Type of impact | Impact Identification | | Impact Quantification | Impact Valuation (€/year) | | Impact Valuation (€/ton) | |
|---|---|---|---|---|---|---|---|
| | Costs | Revenues | | Costs | Revenues | Costs | Revenues |
| Private | | Revenues related to material and energy sold | 197,034 tons of waste | | 14,035,879 | | 71.24 |
| Private | Cost related to infrastructure | | 197,034 tons of waste | 11,455,483 | | 58.14 | |
| External | | Avoided material send to incineration | 41,719 tons of waste | | 984,568 | | 5.00 |
| External | Emissions to air ($CO_2$) | | 4,529 tons $CO_2$ eq. | 45,290 | | 0.23 | |
| External | | Avoided emissions to air ($CO_2$) | 30,937.46 tons $CO_2$ eq. | | 309,375 | | 1.57 |
| | Total private impacts | | | 11,455,483 | 14,035,879 | 58.14 | 71.24 |
| | Total external impacts | | | 45,290 | 1,293,943 | 0.23 | 6.57 |

By using Formula 1 and Formula 2, it is determined that the MBT plant is profitable from the private point of view because it is obtained a BP of 9.82 €/ton, on the other hand, it also conclude that it is profitable from the external point of view since a BT of 16.16 €/ton was obtained.

## 4. Conclusions

The MBT plant fulfils a fundamental function for the Barcelona city because it allows the recovery of recyclable materials present in the residual fraction (waste that is not selectively collected); otherwise, it would be sent directly to incineration. In addition, the MBT plant allows reducing the use of virgin raw materials since the circular economy is promoted. The results obtained demonstrated that this facility is profitable from a private and external perspective because it represents economic and environmental advantages; however, the results should be taken with caution because only a few impacts have been analyzed. Furthermore, the study focuses on a specific year. Nonetheless, the impacts that have not been analyzed are only positive, such as consumers' willingness to pay (WTP) for ecological or recycled products, use of compost or digestate instead of inorganic fertilizers, among others. Future studies will expand the study of externalities to include social impacts related to education, quality of life, public health and use of waste.

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# Sustainability in the evaluation of Municipal Solid Waste management projects

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## Abstract

Industrialization and population growth have generated negative consequences for the environment and society, so various international organizations, such as the UN and the European Parliament, call for sustainable development that allows economic growth but guarantees social inclusion and environmental protection. Sustainable development is considered to have three pillars: environment, society and economy (Fiksel, Eason, and Frederickson 2012). To achieve sustainability, economic, environmental, and social factors must be balanced in equal harmony. These elements are interconnected and are crucial for the prosperity and well-being of societies.

In the case of municipal solid waste (MSW), management projects should be chosen as long as they are justified for reasons of technical viability, economic viability, protection of the environment and continuous guarantee of health and human well-being (European Parliament 2008). Waste policies and projects should seek to minimize the negative effects of waste generation and management on human health and the environment and reduce the use of resources.

This paper aims to present the main impacts and principles to consider when evaluating management projects by including private impacts related to investment, operation and maintenance costs and revenues, and external impacts related to environmental and social aspects. In this way, it is possible to make a decision that ensures that the projects are viable from an economic, environmental and social perspective, ensuring sustainability (Medina-Mijangos et al. 2021). The determination of the main impacts related to MSW management systems has been carried out by analyzing the state of the art.

**Keywords:** Sustainability, Municipal solid waste, Projects, Private and external impacts

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