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Sustainability in Maritime Sector: Waste Management Alternatives Evaluated in a Circular Carbon Economy Perspective

Michela Gallo [1], Luca Moreschi [1], Michela Mazzoccoli [1], Veronica Marotta [1] and Adriana Del Borghi [1,*]

Department of Civil, Chemical and Environmental Engineering (DICCA), University of Genoa, Via all'Opera Pia 15–16,145 Genova, Italy; michela.gallo@unige.it (M.G.); luca.moreschi@edu.unige.it (L.M.); michela.mazzoccoli@unige.it (M.M.); veronica.marotta@edu.unige.it (V.M.)

* Correspondence: adriana.delborghi@unige.it; Tel.: +39-010-3352918; Fax: +39-010-3356596

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Abstract: Sustainability and waste management on board are key issues that need to be addressed by the maritime sector also in terms of greenhouse gas emissions (GHG). With the aim of evaluating waste management alternatives in a circular economy perspective, the study examines a combined system for the optimisation of ship waste management and assesses its possible use for energy purposes. Different systems are analysed in relation to their GHG emission reduction potential regardless of routes and ports of destination. A SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis was carried out on waste management alternatives in order to preliminary identify their potential in terms of GHG emissions reduction, cost, environmental sustainability, methodological coherence, feasibility and replicability. Following this analysis, two case studies of particular interest were identified: (1) the thermo-chemical treatment of waste oils and sludge to obtain fuel oils; (2) the installation of a waste-to-energy plant and subsequent energy recovery on board. UNFCCC (United Nations Framework Convention on Climate Change) methodologies were applied to these two case studies to calculate GHG emission reduction resulting from their implementation. The obtained results are presented with the aim of supporting sustainable waste management strategies on board in a circular carbon economy perspective.

Keywords: maritime sector; waste management; greenhouse gases; circular carbon economy; waste-to-energy; SWOT

1. Introduction

Climate change and greenhouse gas (GHG) emissions reduction represent the main challenges for the sustainability of any action and sector. The awareness of the issue—which over the past 30 years has been strengthening in converging opinions within the scientific community—is now moving towards the public decision makers, influencing the future leanings of the global economy and subsequently the individual behaviours. As regards the emissions of greenhouse gases, the European Union has defined a series of goals to reduce them by 2050 through the Climate and Energy 20-20-20 Package [1] and the 2030 Climate and Energy framework [2]. In particular, by 2030, GHG emissions must be reduced by at least 40% compared to 1990. The maritime transport sector is also involved in achieving these goals and the GHG emissions generated by this sector are progressively integrated into the Commission's strategy and in the policy of the Union. It has been evaluated that the International maritime shipping has emitted 870 million tons of CO_{2e} in 2007 alone, which corresponds to about 2.7% of the global GHG emissions [3]. Although the percentage contribution may still appear to be low, by the progressive containment of GHG emissions in other civil (e.g., air transport sector) and industrial sectors (e.g., steelworks, chemical industry) the international maritime industry is expected in future to weigh about 19% of global emissions in case of not taking appropriate reduction measures. For this reason, the contribution of the naval sector to the reduction in GHG emissions is nowadays greatly taken into account, as highlighted in several international offices. In this context, EU Regulation 2015/757 [4] was issued on monitoring, reporting and verification of carbon dioxide emissions generated by maritime transport (known as EU MRV Regulation). The MRV Regulation is a mandatory system of monitoring, reporting and verification established by the European Commission for ships over 5000 gross tonnages travelling one or more commercial routes—both freight and passenger transport—to and from European Union ports, regardless of their flag. Subsequently, during the Conference of the Parties (COP) of the United Nations Framework Convention on Climate Change (UNFCCC) held in 2016 in Marrakech (COP22), the International Maritime Organization (IMO) presented its mitigation actions to support the Sustainable Development Goals of the United Nations. In the same year, in the context of 70th session of the Marine Environment Protection Commission (MEPC 70) a mandatory system of data collection on the fuel consumption of ships was adopted and the roadmap for the development of an "IMO global strategy on the reduction in greenhouse gases emissions from ships" was defined. During the subsequent COP23 held in Bonn in November 2017, which consolidates the targets and the ambitions of the Paris agreement, an action plan for the decarbonisation of the maritime sector was created. At the summit, it was agreed that the international maritime industry has the technological tools needed for the decarbonisation of the sector itself, through the application of different strategies including: cruise speed reduction, further technological development to increase energy efficiency in the design phase, the use of renewable energy sources (e.g., wind), the use of alternative fuels. With these premises, the IMO published in 2018 an initial plan for reducing GHG emissions and it was planned to agree on a definitive strategy by 2023 [5]. Recently at the European level, the Parliament and the Council reached an agreement on the CO_2 emissions of ships, in order to align any EU action with the targets set by the IMO, with the support of the European Sea Ports Organization (ESPO) [6]. Otherwise, if the IMO negotiations on a strategy for CO_2 reduction measures have not achieved sufficient progress, the naval sector will be included in the application of EU Directive 2003/87 [7] on the Emissions Trading System (ETS) from 2023.

In addition to the GHG emissions due to fuel consumption for propulsion, the assessment of GHG emissions due to onboard waste management systems could be of great importance [8].

Management and production of waste in the context of the naval sector is indeed an issue of interesting relevance: a cruise ship, with its capacity to host about 5000 people, a length often in excess of 300 metres, and a gross tonnage of over 100000 tons, is like a small floating city which, also considering the logistical and management peculiarities, can produce a huge quantity of waste—about 70 times more than a typical cargo ship. Ship cruises represent less than 1% of the global merchant fleet, but it has been estimated that they are responsible for 25% of all the waste produced by the entirety of merchant ships [9]. Onboard waste is distinguished in two main categories: "garbage", that is the kind of waste listed and regulated in the International Marpol Convention (e.g., paper and cardboard, plastic, food, ashes of incinerator, metals, glass); and "not Marpol" or "special" (as defined in Italian laws applicable to this kind of waste) which can be—depending on their features—hazardous or non-hazardous. Waste must be differentiated on board by type and unloaded separately in order to join the recovery and recycling programs in the ports that carry out this activity. More specifically, waste can be divided as follows: oil—ballast water; oil—oily bilge water; black water (sewage); grey water (wastewater generated in households or office buildings from streams without faecal contamination); solid waste (garbage); hazardous waste. An interesting aspect to explore could be the evaluation of the criteria to be met to access the possibility of converting potential GHG emission reductions—generated by the strategies and methods of waste management implemented—in negotiable carbon credits that can be subjected to the subsequent certification and registration process [10].

The proposed study analyses different waste management systems and strategies that can be implemented onboard, in relation to their potential to reduce GHG emissions. The goal of this study is to identify, among the different methods of waste management, either those for which the reduction in GHG emissions is significant or those for which waste becomes a resource, according to a model of circular economy, which overcomes the concept of end of life for waste, in accordance with the guidelines of the European Union.

2. Materials and Methods

With the aim of evaluating waste management alternatives in a circular economy perspective, the study examines a combined system for the optimisation of ship waste management and assesses its possible use for energy purposes [11]. Different systems are analysed in relation to their GHG emission reduction potential regardless of routes and ports of destination. A SWOT analysis was carried out on these waste management alternatives and key aspects, such as the potential for reducing GHG emissions, costs, environmental sustainability, methodological coherence, feasibility and replicability were assessed. Following this analysis, two case studies of particular interest were identified: (1) the thermo-chemical treatment of waste oils and sludge to obtain fuel oils; (2) the installation of a waste-to-energy plant and subsequent energy recovery on board. UNFCCC methodologies [12] were applied to these two case studies to calculate GHG emission reduction resulting from the implementation of the identified alternatives [13]. The obtained results are presented with the aim of supporting sustainable waste management strategies on board in a circular carbon economy perspective.

2.1. Identification of the Measures

Table 1 summarises the implementable waste management measures preliminary identified. Some strategies were supported by bibliographical research in order to analyse the aspects considered interesting in terms of potential GHG emission reduction. Other measures were selected according to common best practices in waste management systems within a circular economy perspective.

Table 1. Waste management measures preliminarily identified.

ID	Waste	Description	Measure
1	Organic	Characterisation of substrates deriving from food scrap and organic waste	Pre-treatment
2	Organic	Thermo-chemical treatment of materials with high organic content for syngas production.	Treatment
3	Waste oils and sludge	Thermo-chemical treatment of waste oils and sludge for the obtaining of fuel oils [14].	Treatment
4	Oily water	Separation system for oily water through a cyclone separator, recycling of waste oils and use in engines and subsequent treatment of separated water, with possible reuse onboard or unloading into sea.	Treatment
5	Organic	Systems of anaerobic conversion with thermophilic bacteria for organic matrices of various types [15].	Treatment
6	Waste vegetable oils	Cleaning and characterisation of the combustion properties of syngas/biogas derived from waste. Optimised energy conversion of syngas/biogas derived from waste in internal combustion engines (gas turbine/alternative engine) also with supply of waste vegetable oils [16].	Treatment
7	Waste Heat	Waste Heat Recovery. The measure consists in the adoption of Organic Rankine Cycles (ORC), which have a good operating flexibility, high safety due to low operating pressures and would allow the heat recovery of waste heat from other systems.	Treatment
8	CO_2	Carbon capture and storage (CCS) onboard through adsorption due to solid substances—such as calcium hydroxide and potassium hydroxide—as sorbent directly to the unloading and the next CO_2 recycling through calcination. Possibility of combination with methanation and/or union to another syngas [17,18].	Treatment

Table 1. *Cont.*

ID	Waste	Description	Measure
9	Grey/black water	System of biologic treatment grey/black water through separation of solids, disinfection, drying [19].	Treatment
10	All waste	Installation of a waste-to-energy plant and next energy recovery [20].	Treatment
11	Garbage	Onboard separation of garbage with a dedicated space.	Pre-treatment
12	Plastic	Plastic grinding and treatment for possible use of 3D printer for gadgets and items production.	Best Practice
13	Paper	Decrease of paper use, through an increase of the digitalization [21].	Best Practice
14	Glass	Decrease of glass use through installation of dispenser and re-usable containers.	Best Practice
15	Packaging	Decrease of packaging on board.	Best Practice
16	All waste	Installation of a grinding and compaction system for multi-material treatments.	Treatment

These measures were first assessed in relation to their emission reduction potential. The SWOT analysis has been used to evaluate strengths and weaknesses, opportunities and threats of each measure using five evaluation criteria [22]:

1. GHG emissions reduction potential: assessment of a significant contribution of the measure to the reduction in GHG emissions;
2. cost: analysis of potential costs for installation and management of the measure;
3. feasibility/replicability: analysis of potential replicability in the maritime sector and evaluation of the possible difficulties in the implementation;
4. environmental sustainability: assessment of the environmental sustainability of the measure in terms of impacts different from the GHG emissions;
5. existence of an approved specific methodology: analysis of internationally recognized CO_{2e} calculation methodologies (e.g., UNFCCC, IMO).

For each criterion, the group to which it belongs (strength, weakness, opportunity and threat) was identified based on the binary composition of the evaluation factors of controllability and usefulness reported in Table 2.

Table 2. Usefulness and controllability related to Strength, Weakness, Opportunity and Threat.

Category	Usefulness	Controllability
Strength	Possible achievement of the goals of reduction in GHG emissions	Achievement of the goals depending on internal factors
Weakness	Difficulty in achieving the goals of reduction in GHG emissions	Achievement of the goals depending on internal factors
Opportunity	Possible achievement of the goals of reduction in GHG emissions	Achievement of the goals depending on external factors
Threat	Difficulty in achieving the goals of reduction in GHG emissions	Achievement of the goals depending on external factors

Usefulness is defined as the potential of GHG reduction. Therefore, an action is defined as "useful" if there is a reduction in GHG emissions after the implementation of the strategy considered. On the contrary, it is defined as "not useful" when the GHG emissions reduction is not checked or is not very significant.

Controllability is defined as the possibility to keep the achievement of the greenhouse gas reduction targets proposed under control of the entity that implements the measure. Therefore, an action is defined as "controllable" when the achievement of the reduction targets is dependent on the choices and operations performed. On the contrary, it is defined as "not controllable" when external factors (environmental, regulatory, etc.) can influence the achievement of the reduction target.

For the evaluation of usefulness and controllability, the following parameters were examined as external drivers: regulatory constraints; technical constraints; available technologies. To improve the applicability of the results, a qualitative evaluation was proposed, and a score was assigned for each category considered. The score is assigned based on the relevance of strength, weakness, opportunity and threat of each individual action. Table 3 shows the assigned scores related to strengths, weaknesses, opportunities and threats.

Table 3. Scoring criteria.

	Score			
	0	**1**	**2**	**3**
Strength	Not present	Low	Medium	High
Weakness	Not present	Low	Medium	High
Opportunity	Not present	Low	Medium	High
Threat	Not present	Low	Medium	High

The strategies are evaluated on the basis of the parameters of controllability and usefulness. Strategies that report strength values are always considered useful and controllable with different intensity, whereas those that report threat values are to be considered not useful and not controllable with different intensity.

SWOT analysis results, with the identification of the most significant measures in terms of GHG emission reduction applicable to onboard waste management, are shown in Figure 1.

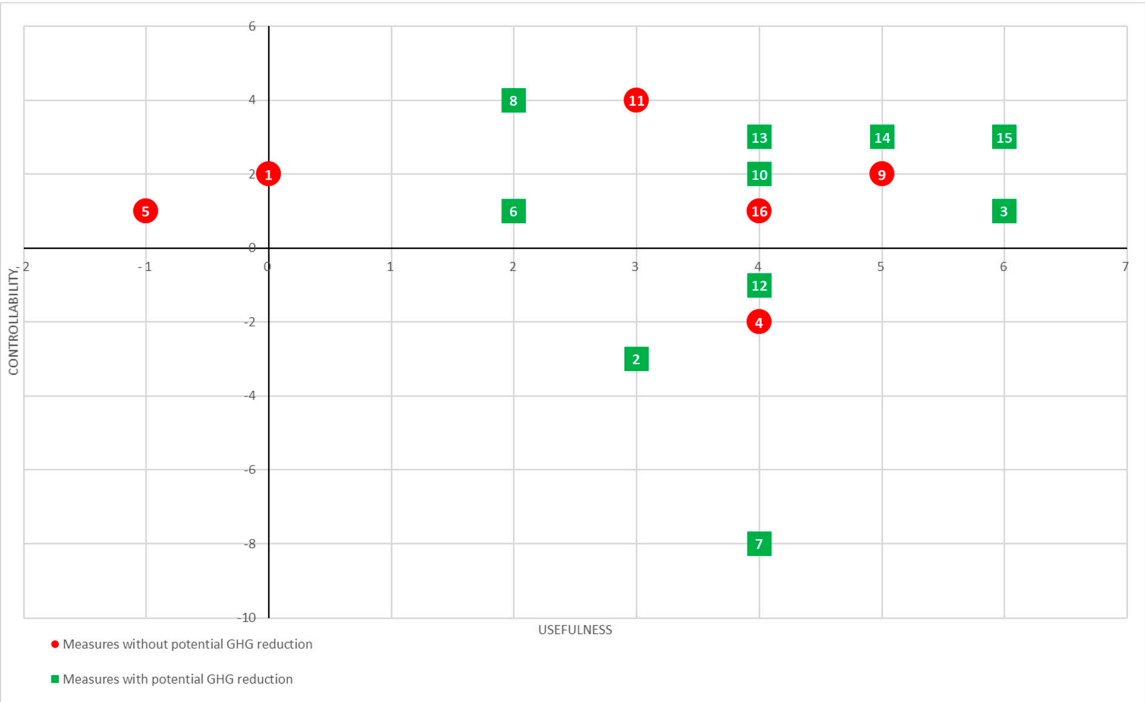

Figure 1. Scatter chart on the results of the SWOT analysis of the proposed measures.

The measures No.13, No.14 and No.15 related to the best practices on onboard waste reduction show good potential both in terms of usefulness and controllability. However, they are not considered in this study, mostly because of their difficult implementation in a luxury business such as cruises aim to be.

Therefore, based on the results, the following measures are chosen as case studies:

- Measure No.3.—Thermochemical treatment of waste oils and sludge for the obtaining of fuel oils;

- Measure No.10.—Installation of a waste-to-energy plant and next energy recovery on board.

2.2. GHG Emission Reduction Calculation

The calculation of GHG emission reduction resulting from the implementation of the selected case studies are performed according to the requirements of the specific UNFCCC methodology for the development of greenhouse gas reduction projects related to the waste sector [12].

Since there are no available methodologies for plants implemented on board, for the purpose of the study UNFCCC methodologies have been analysed for the determination of the reduction in GHG emissions, resulting from the implementation of specific small- and large-scale measures and projects in the waste sector.

2.2.1. Thermochemical Treatment

The thermochemical process consists of the pyrolysis treatment of the exhausted oils generated onboard. Oil wastes are mainly sludge resulting from the purification of fuels. Under a business-as-usual scenario, this type of waste is collected and delivered in ports. Pyrolysis, i.e., the thermal decomposition of organic materials that occurs in the absence of oxygen, can convert sludge into fuel oil, as well as gaseous and solid compounds. Pyrolysis oil can be used directly as fuel, gas can be fed to a boiler and solid to an incinerator.

The design data, reported in Table 4, have been provided taking into account different sources:

- A: Information about average sludge production on board from a private communication of the Carnival Maritime (Hamburg, Germany);
- B: Chemical analysis of a sludge sample kindly provided by Grandi Navi Veloci (GNV), an Italian Ro-Ro ferry company, made by the Research Centre for Alternative and Renewable Energy (Florence, Italy);
- C: Data from the literature [23];
- D: Calculated data from the current study.

Table 4. Pyrolysis process design data.

Parameter	Value	Source
Average quantity of oily sludge	1057 t/year	[A]
Water contained in oily sludge	63.4%	[B]
Process yield on secondary fuel oil	30%	[C]
Gas production	17%	[C]
Solid production	32%	[C]
Water production	21%	[C]
Quantity of settled oily sludge	390 t/year	[D]
Secondary fuel oil obtained by pyrolysis	118 t/year	[D]
Gaseous product obtained by pyrolysis	67 t/year	[D]
Solid product obtained by pyrolysis	125 t/year	[D]

According to the UNFCCC methodologies, the Emission Reduction (ER) resulting from a project is calculated using Equation (1):

$$ER_y = BE_y - PE_y \pm LE_y \quad (1)$$

where:

- ER_y: Emission reduction in the year y (tCO_{2e}/year);
- BE_y: Baseline emissions at year y (tCO_{2e}/year);
- PE_y: Project activity emissions in the year y (tCO_{2e}/year);
- LE_y: Leakage emissions in the year y (tCO_{2e}/year).

Baseline Emissions (BE) are mainly caused by the disposal of sludge, due to the current treatment system for oily residues. For the calculation, reference was made to ACM0022 "Alternative waste treatment processes" [24]. This methodology applies to project activities where fresh waste, originally intended for disposal in a solid waste disposal site (SWDS), is treated using any combination of the waste treatment options among the following: composting, anaerobic digestion, thermal treatment, mechanical treatment, incineration and gasification. The last one is a treatment very similar to pyrolysis process. The methodology includes the calculation of baseline emissions due to the disposal of waste in landfills where no alternative treatment is applied. Emissions are calculated using Equation (2) [25].

$$\begin{aligned} BE_{CH_4,y} = \; & \varphi \times \left(1 - f_y\right) \times GWP_{CH_4} \times (1 - OX) \times \tfrac{16}{12} \times F \times DOC_{f,y} \times MCF_y \\ & \times \sum_{x=1}^{y} \sum_{j} \left(W_{j,x} \times DOC_j \times e^{-k_j (y-x)} \times \left(1 - e^{-k_j}\right)\right) \end{aligned} \quad (2)$$

For the calculation of Project Emissions (PE), it should be considered that there is no specific methodology for calculating the emissions from pyrolysis plants of liquid substances, as pyrolysis process is not widely applied on an industrial level yet. Therefore, reference was made to the calculation of the emissions caused by a pyrolysis process for the treatment of waste that allows avoiding the production of methane from the waste itself [26]. According to this methodology, PE are calculated using Equation (3):

$$PE_{PIR} = PE_{COM,PIR} + PE_{FC,PIR} + PE_{TRASP,PIR} + PE_{EC,PIR} \quad (3)$$

where:

- $PE_{COM,PIR}$: Emissions from pyrolysis of non-biogenic carbon in the year y (tCO_{2e}/year);
- $PE_{FC,PIR}$: Emissions from the consumption of auxiliary fuel by the pyrolysis facility in the year y (tCO_{2e}/year);
- $PE_{TRAS,PIR}$: Emissions from fossil fuel consumption due to incremental transportation in the year y (tCO_{2e}/year);
- $PE_{EC,PIR}$: Emissions from electricity or diesel consumption in the year y (tCO_{2e}/year).

According to [26], $PE_{COM,PIR}$ are calculated with Equation (4):

$$PE_{COM,PIR} = \frac{Q_{m,nonbiogenic}}{Q_{m,total}} \times Q_{CO2,pyro} \quad (4)$$

where $Q_{m,nonbiogenic}$ and $Q_{m,total}$ are, respectively, the quantity of non-biogenic carbon and total carbon treated in the pyrolysis process. $Q_{CO2,\,pyro}$ is the CO_2 emitted by the pyrolysis process in the year including the pyrolysis or flaring if the gases and vapours originating from the waste (tCO_{2e}).

$PE_{EC,PIR}$ emissions are calculated using Equation (5), according to [27]:

$$PE_{EC,PIR} = EC \times \frac{FC \times NCV \times EF_{CO2}}{EG} \times (1 \pm TDL) \quad (5)$$

Leakage Emissions (LE) are negative emissions caused by the new system (i.e., emissions associated with the production of reagents) or positive emissions caused by the system to be replaced (i.e., emissions related to the avoided production of fossil). Since the pyrolysis process would allow the use of secondary fuel, indirectly avoided emissions from the lack of virgin fuel production were considered as leakage emissions.

LE are calculated with Equation (6) according to large scale consolidated methodology [28]:

$$LE_y = Q_{fuel} \times NCV_{fuel} \times EF_{CO2,up} \quad (6)$$

where Q_{fuel} is the quantity of fossil fuel avoided, NCV_{fuel} is the net calorific value of fuel oil and $EF_{CO2,up}$ is the emission factor for upstream emissions associated with consumption of fossil fuel.

2.2.2. Installation of a Waste-to-Energy Plant

The second case study involves the installation of a waste-to-energy plant [29] for energy use onboard for heating, air conditioning and refrigeration. The strategy consists in the installation of an incineration plant, within which there is a line dedicated to waste fuel oils. These have the task of feeding and maintaining a constant temperature inside the combustion chamber.

For the calculation of emission reductions, reference was made to the small-scale methodology AMS-III.Q [30].

On the basis of this methodology, BE are calculated as:

$$BE_{elec,y} = f_{cap} \times f_{wcm} \times \sum_{j} \sum_{i} EG_{i,j,y} \times EF_{Elec,i,j,y} \tag{7}$$

where:

- $BE_{elec,y}$: baseline annual emissions due to electrical energy transfer (t CO_2);
- fc_{ap}: ratio between the energy generated by the waste and the total energy used in the project activity to produce useful energy (in year y);
- f_{wcm}: ratio between the electricity generated by the project activity and the energy generated by the waste used to produce it;
- EG_i: amount of electricity supplied, which in the absence of project activity would have been purchased during the year y;
- EF_{Elec}: CO_2 emission factor for the energy source replaced by the project activity, during the year y, being:

$$EF_{Elec,i,j,y} = \frac{EF_{CO2,i,j}}{\eta_{Plant,j}} \tag{8}$$

where:

- $EF_{CO2,i,j}$: the CO_2 emission factor per unit of energy of the fossil fuel used in the baseline generation source i;
- $\eta_{Plant,\,j}$= the overall efficiency of the identified existing plant that would be used by j^{th} recipient in the absence of the project activity.

In the case study analysed, the use of exhaust gases from the incineration plant for cooling the refrigerating room, was considered in particular as a measure to reduce greenhouse gas emissions.

It based on the following parameters:

- $f_{cap} = 1$, because the amount of energy generated by waste for the project activity is the same as the energy that would have been necessary for the operation of the plant before the introduction of the project activity itself;
- $f_{wcm} = 1$, since the energy necessary for the operation of the refrigeration system is provided in total by the waste-to-energy plant.

Furthermore, the following system data were considered even though they have not been used for the calculation of GHG emissions:

- System working only during navigation outside 12 nautical miles;
- Use factors set equal to 25%, 50% and 75%;
- Daily operation of 11 h;

- COP (coefficient of performance) = 2.12, related to the equipment that would be replaced with the use of the ammonia-water absorption cycle;
- Use of ammonia steam generator with an assumed power of 900 kW supplied by exhaust gases;
- Consumption of fuel (diesel) in the primary engine = 200 g/kWh (data obtained from a previous study carried out on a cruise ship);
- Installed electric power of 195.5 kW relative to the plant dedicated to refrigeration of the cold room.

PE are defined according to Equation (9):

$$PE_y = PE_{AF,y} + PE_{EL,y} \tag{9}$$

where:

- $PE_{AF,y}$: combustion of auxiliary fuel to supplement waste gas/heat
- $PE_{EL,y}$: emissions due to consumption of electricity for gas cleaning before being used for generation of electricity or other supplementary electricity consumption by the project activity

In the absence of auxiliary fuel consumption, but in the presence of electricity consumption due to the circulation pumps of the various fluids involved and the control elements (estimated between 5% and 10% of the cooling capacity), $PE_{AF,y}$ is equal to zero, whereas PE_Y is equal to $PE_{EL,y}$.

Therefore, ER are calculated as:

$$ER_y = BE_y - PE_y - LE_y \tag{10}$$

3. Results

GHG emission reduction resulting from the implementation of the selected case studies is described in this paragraph. Calculations are performed according to the requirements of the specific UNFCCC methodology [12] presented in the paragraph "Materials and Methods".

3.1. GHG Emission Reduction for Termochemical Treatment

Taking into account the data shown in Table 5, the baseline emissions result equal to 6.4 tCO_{2e}/year.

Table 5. Parameters for calculating baseline emissions.

Parameter		Value	Annotation
φ_y	Model correction factor to account for model uncertainties for year y	0.85	Default value for wet conditions
f_y	Fraction of methane captured at the SWDS and flared, combusted or used in another manner that prevents the emissions of methane to the atmosphere in year y	0.7	Typical average value
$GWP_{,CH4}$	Global Warming Potential of methane	30	[31]
OX	Oxidation factor (reflecting the amount of methane from SWDS that is oxidised in the soil or other material covering the waste)	0.1	Default value
F	Fraction of methane in the SWDS gas (volume fraction)	0.5	Default value
$DOC_{f,y}$	Fraction of degradable organic carbon (DOC) that decomposes under specific conditions occurring in the SWSD for year y (weight fraction)	0.5	Default value
MCF_y	Methane correction factor for year y	0.5	Default value for semi-aerobic managed SWDS
j	Type of residual waste or types of waste in the municipal solid waste		Only oily sludge
$W_{j,x}$	Amount of solid waste type *j* disposed or prevented from disposal in the SWDS in the year *x* [t/year]	1057	See Table 4

Table 5. *Cont.*

Parameter		Value	Annotation
$DOC_{,j}$	Fraction of degradable organic carbon in the waste type j (weight fraction)	0.09	Default value for industrial sludge
k_j	Decay rate for the waste type *j* [1/year]	0.06	Default value for industrial sludge
x	Years in the time period in which waste is disposed at the SWDS, extending from the first year in the time period (x = 1) to year y (x = y)	1	To be precautionary and make a comparison relative to a year, only one year of production of sludge to be disposed is considered
y	Year of the crediting period for which methane emissions are calculated	1	

For the calculation of Project Emissions (PE), the following hypotheses were made:

- As the sludge consists mainly of hydrocarbons, all the sludge fed to the reactor downstream of the sedimentation are considered as non-biogenic carbon;
- Since there are few data available concerning pyrolysis processes, it is not easy to determine the value of $Q_{CO2,\ pyro}$ in Equation (4). In first approximation it was considered that all the gas produced by the process was CO_2: about 17% of the sludge fed (see Table 4);
- Emissions from the consumption of auxiliary fuel by the pyrolysis facility—$PE_{FC,PIR}$ in Equation (3)—were not considered since the heat recovery is done totally through sources already present on board the ship (incinerator);
- Emissions from fossil fuel consumption due to incremental transportation—$PE_{TRAS,PIR}$ in Equation (3)—were not considered as this type of transport is not foreseen;
- As regard emissions from electricity—$PE_{EC,PIR}$ in Equation (3)—, those related to agitators and pumps have been included.

Other assumptions and data to calculate $PE_{EC,PIR}$ are reported in Table 6.

Table 6. Parameters to calculate emissions from electricity consumption.

Parameter	Value	Annotation
Agitator power (kW)	0.7	0.3–1 kW/m^3: for agitated vessel [32]
Pump power (kW)	2	From data sheet of a pump similar to that needed in this case (www.dabpumps.com)
Working hours (h/year)	1400	4 h/day for 50 week/year
Fuel consumption (g/kWh)	171	From data sheet of Wartsila engine: type of engine usually installed on cruise ships (www.wartsila.com)
EC—Quantity of electricity consumed (MWh/year)	3.8	Calculated from the current study
FC—Quantity of fossil fuel fired in the plant to produce electricity (t_{comb}/year)	0.65	Calculated from the current study
NCV—Average net calorific value of fossil fuel used (GJ/t_{fuel})	41.08	For fuel oil [33]
EF_{CO2}—CO_2 emission factor of fossil fuel used [t_{CO2}/GJ]	0.0765	For fuel oil [33]
EG—Quantity of electricity generated in plant	3.8	Calculated from the current study
TDL—Average technical transmission and distribution losses for providing electricity to source	0	Assumed 0 as a simplification according to [27]

During pyrolysis process, solid residue is produced (125 t/year, see Table 4). It can be unloaded in port and disposed of or reused on board. In the second case, no further emissions have to be considered, while, in the first one, the emissions due to the disposal of solid in landfill must be calculated. The latter are determined based on Equation (1), which has already been used to calculate the baseline emissions, and are not very significant: 0.7 tCO_{2e}/year.

The total Project Emissions are 69 tCO_{2e}/year in the case where the pyrolysis residue is reused on board, and 70 tCO_{2e}/year in the other case (see Table 7).

Table 7. Project emissions.

Project Emissions	Disposal (tCO_{2e}/year)	Reuse (tCO_{2e}/year)
From pyrolysis process	67	67
From electricity consumption	2	2
From solid residue disposal	0.7	-
Total	70	69

Regarding the calculation of Leakage Emissions (Equation (6)), NCV_{fuel} is the net calorific value of fuel oil (see Table 6) and $EF_{CO2,up}$ is the emission factor for upstream emissions associated with consumption of heavy fuel oil (marine type) and is equal to 9.4 tCO_2/TJ [34]. Considering the possible replacement of 118 t/year of heavy fuel oil (Q_{fuel}), LE_y results equal to 46 tCO_{2e}/year.

According to the above hypothesis, Emission Reduction is negative: −17 tCO_{2e}/year in the case where the solid is reused on board, and −18 tCO_{2e}/year in the case of its disposal on ground.

Therefore, this new process shows a slight increase in CO_2 emissions compared to the current management system. However, when also considering waste transportation to the treatment plant in the baseline scenario, it is possible to evaluate the minimum distance for which the emission reduction for the analysed measure starts to be positive. Considering an emission factor equal to 0.166 kg CO_{2e}/tkm, in the case where solid residue produced by pyrolysis is reused on board (ER1), the emission reduction gets positive for transport distances above 94–95 km. In the second case, if the solid residue is disposed of in landfills (ER2)—and the distance to the plant is considered equal to that for the avoided transportation—the emission reduction gets positive for transport distances above 114–115 km. The different gradients of the lines are due to the different amounts of overall waste for which waste transport is avoided: 1057 tons in case of ER1; and 932 tons in the case of ER2, being 125 tons of solid residue from pyrolysis still transported to the landfill. ER variation according to waste transport is shown in Figure 2.

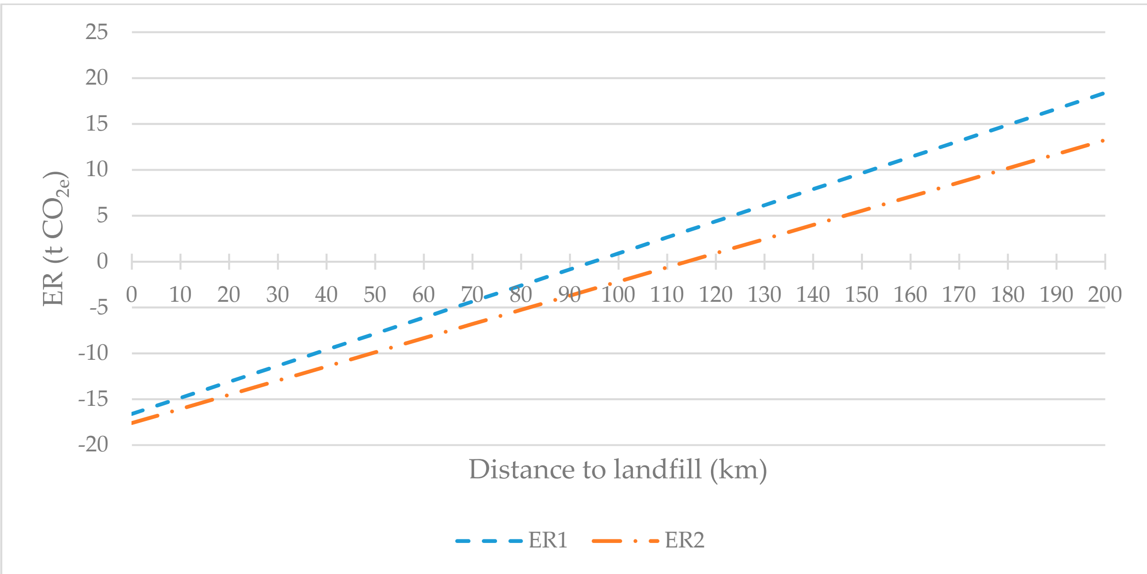

Figure 2. Emission reduction (ER) variation according to waste transport. ER1: case study where solid residue produced by pyrolysis is reused on board. ER2: case study where solid residue is disposed of in landfills.

3.2. GHG Emission Reduction for Waste-to-Energy Plant

Baseline, Project and Leakage emissions of the installation of a waste-to-energy plant have been calculated according to equations reported in Section 2.2.2.

Considering the assumptions and the data reported in Table 8, BE_{elec} = 3.842 t of CO_2 per day for 11 h of daily operation, whereas PE results are equal to 0.3842 t CO_2.

Table 8. Parameters for calculating emissions.

Parameter		Value	Annotation
f_{cap}	Ratio between the energy generated by the waste and the total energy used in the project activity to produce useful energy (in year y)	1	The amount of energy generated by waste for the project activity is the same as the energy that would have been necessary for the operation of the plant before the introduction of the project activity itself
f_{wcm}	Ratio between the electricity generated by the project activity and the energy generated by the waste used to produce it	1	The energy necessary for the operation of the refrigeration system is provided in total by the waste-to-energy plant
EG_i	Amount of electricity supplied	0.0191 TJ	In the absence of project activity would have been purchased during the year y
EF_{elec}	CO_2 emission factor for the energy source replaced	73.3 t CO_2/TJ	Energy source replaced by the project activity, during the year y
$\eta_{Plant,j}$	Overall efficiency of the identified existing plant	0.365	η diesel engine = 0.40 η mechanical transmission = 0.99 η electric generator = 0.97 η electric transmission = 0.99 η converter = 0.96

Based on plant configuration, LE are considered to be equal to zero.

ER_y = 3.842 − 0.384 − 0 = 3.458 t CO_2 (per day for 11 h of daily operation)

Assuming a daily use, the reduction on an annual basis is equal to 1262.1 t CO_2.

Considering the efficiency of the identified plant is based on hypothesised values, though reasonable, the trend for the emission reduction according to different overall efficiencies is shown in Figure 3 within a range between 0.2 and 0.6.

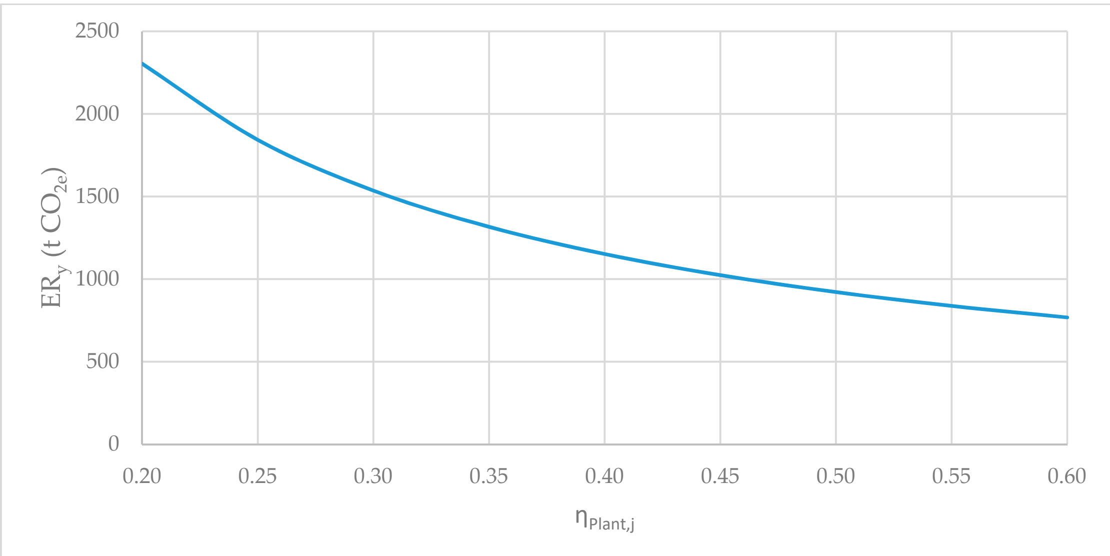

Figure 3. Emission reduction (ER) variation according to plant efficiency ($\eta_{Plant,j}$).

With respect to the previous measure, no waste transportation is considered or assumed in the baseline scenario, since the management of waste fuel oils is usually made on board by means of incineration. Therefore, different assumptions would be unrealistic for the analysed measure.

4. Discussion

Table 9 summarises the results of the two case studies described above.

Table 9. Results of the case studies.

Strategy	Reduction in GHG Emissions	Annotation
Thermo-chemical treatment of waste oils and sludge to obtain fuel oil and innovative oil waste management system (without waste transport)	−18 t CO_{2e}/year	There is no reduction in emissions on an annual basis, but there is a slight increase in CO_2 emissions
Installing a waste-to-energy plant and recovery energy	1262 t CO_{2e}/year	The reduction in GHG emissions is not particularly significant

The results showed that, on the one side, in the case of installing a waste-to-energy plant and recovering energy, the reduction in GHG emissions is not particularly significant, reaching 1262 t CO_{2e}/year. On the other hand, while no reduction in GHG emissions is present, there is a slight increase in the case of the thermo-chemical treatment of waste oils and sludge to obtain fuel oil and an innovative oil waste management system.

The restrained GHG emission reduction potential shown by the analysed measures for onboard waste management further highlights the need for the maritime sector to proceed as soon as possible to set specific targets linked to the effective use of fuel for propulsion, which is the most significant source of GHG emissions. In fact, the adoption of other measures onboard, even if they involve a lower use of the main fuel as in the two proposed case studies, could be not very significant in terms of reduction of GHG emissions.

Nevertheless, the case studies showed that sustainable waste management strategies onboard could support a circular carbon economy perspective. On the one hand, in the case of the thermo-chemical treatment of waste oils and sludge to obtain fuel oil and innovative oil waste management, the system allows the re-use of oil waste avoiding the disposal to landfill and reducing—even if only slightly—the consumption of virgin fuel according to a circular economy perspective. Reuse of waste and circular economy are issues of great interest to the European Union [35]; therefore, pyrolysis of sludge to obtain secondary fuel could be a good opportunity also in relation to European objectives related to sustainable development. On the other side, in the case of installing a waste-to-energy plant, the proposed strategy allows energy recovery of onboard waste—still valuable in terms of circular economy principles—in addition to a slight reduction in GHG emissions.

5. Conclusions

The proposed study analyses different waste management systems and strategies that can be implemented onboard. In particular, two case studies were identified, and the effective reduction in GHG emissions was calculated, applying the requirements and calculation rules defined by the corresponding UNFCCC methodologies.

Even though the case studies present no significant GHG emission reduction potential, it must be noted that for almost all the measures implemented onboard the ship and analysed in this study there is a lack of methodologies applicable to the maritime sector for the calculation of the reduction in GHG emissions. In particular, the UNFCCC methodologies—created ad hoc for the waste sector—are actually calibrated for stationary plants and therefore do not consider the peculiarities and critical aspects of the plant design and management methods onboard the ship. Therefore, assuming a potential future obtaining of carbon credits from such measures, firstly it would be necessary to partially modify existing calculation methodologies or to propose new specific methodologies for the maritime sector in the UNFCCC.

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References

1. EU. Directive 2009/29/EC of the European Parliament and of the Council of 23 April 2009 (Amending Directive 2003/87/EC so as to Improve and Extend the Greenhouse Gas Emission Allowance Trading Scheme of the Community). 2009. Available online: https://ec.europa.eu/clima/policies/strategies/2020 (accessed on 3 April 2020).
2. EU. COM (2014) 15—Communication: A Policy Framework for Climate and Energy in the Period from 2020 to 2030. 2014. Available online: https://ec.europa.eu/clima/policies/strategies/2030 (accessed on 3 April 2020).
3. IMO. Second IMO GHG Study 2009. International Maritime Organization, 2009. Available online: http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/SecondIMOGHGStudy2009.pdf (accessed on 3 April 2020).
4. EU. Regulation (EU) 2015/757 of the European Parliament and of the Council of 29 April 2015 on the Monitoring, Reporting and Verification of Carbon Dioxide Emissions from Maritime Transport, and Amending Directive 2009/16/EC. 2015. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32015R0757&from=EN (accessed on 3 April 2020).
5. IMO. IMO Action to Reduce Greenhouse Gas Emissions from International Shipping. 2019. Available online: http://www.imo.org/en/MediaCentre/HotTopics/Documents/IMO%20ACTION%20TO%20REDUCE%20GHG%20EMISSIONS%20FROM%20INTERNATIONAL%20SHIPPING.pdf (accessed on 3 April 2020).
6. EU. 72nd Session of the Marine Environment Protection Committee (MEPC 70) at the International Maritime Organization (IMO). 2018. Available online: https://ec.europa.eu/clima/sites/clima/files/news/20180413_memo_en.pdf (accessed on 3 April 2020).
7. EU. Directive 2003/87/EC of the European Parliament and of the Council of 13 October 2003 Establishing a Scheme for Greenhouse Gas Emission Allowance Trading within the Community and Amending COUNCIL Directive 96/61/EC. 2003. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32003L0087&from=EN (accessed on 3 April 2020).
8. Gallo, M.; Marotta, V.; Magrassi, F.; Taramasso, A.C.; Del Borghi, A. University campus waste prevention and reduction: A circular-economy approach. *Econ. POLICY ENERGY Environ.* **2017**, 235–252. [CrossRef]
9. Butt, N. The impact of cruise ship generated waste on home ports and ports of call: A study of Southampton. *Mar. Policy* **2007**, *31*, 591–598. [CrossRef]
10. Gallo, M.; Del Borghi, A.; Strazza, C.; Parodi, L.; Arcioni, L.; Proietti, S. Opportunities and criticisms of voluntary emission reduction projects developed by Public Administrations: Analysis of 143 case studies implemented in Italy. *Appl. Energy* **2016**, *179*, 1269–1282. [CrossRef]
11. Magrassi, F.; Del Borghi, A.; Gallo, M.; Strazza, C.; Robba, M. Optimal Planning of Sustainable Buildings: Integration of Life Cycle Assessment and Optimization in a Decision Support System (DSS). *Energies* **2016**, *9*, 490. [CrossRef]
12. UNFCCC Methodologies. Available online: https://cdm.unfccc.int/methodologies/methodologiesAccrv6/index.html (accessed on 3 April 2020).
13. Gallo, M.; Del Borghi, A.; Strazza, C. Analysis of potential GHG emissions reductions from methane recovery in livestock farming. *Int. J. Glob. Warm.* **2015**, *8*, 516. [CrossRef]
14. Bhargavi, G.; Nageswara Rao, P.; Renganathan, S. Review on the Extraction Methods of Crude oil from all Generation Biofuels in last few Decades. *IOP Conf. Ser. Mater. Sci. Eng.* **2018**, *330*, 012024. [CrossRef]
15. Kuo, J.; Dow, J. Biogas production from anaerobic digestion of food waste and relevant air quality implications. *J. Air Waste Manag. Assoc.* **2017**, *67*, 1000–1011. [CrossRef] [PubMed]

16. Giwa, A.S.; Xu, H.; Wu, J.; Li, Y.; Chang, F.; Zhang, X.; Jin, Z.; Huang, B.; Wang, K. Sustainable recycling of residues from the food waste (FW) composting plant via pyrolysis: Thermal characterization and kinetic studies. *J. Clean. Prod.* **2018**, *180*, 43–49. [CrossRef]
17. Strazza, C.; Del Borghi, A.; Gallo, M. Development of Specific Rules for the Application of Life Cycle Assessment to Carbon Capture and Storage. *Energies* **2013**, *6*, 1250–1265. [CrossRef]
18. Boubenia, A.; Hafaifa, A.; Kouzou, A.; Mohammedi, K.; Becherif, M. Carbone dioxide capture and utilization in gas turbine plants via the integration of power to gas. *Petroleum* **2017**, *3*, 127–137. [CrossRef]
19. Del Borghi, A.; Gaggero, P.L.; Gallo, M.; Strazza, C. Development of PCR for WWTP based on a case study. *Int. J. Life Cycle Assess.* **2008**, *13*, 512–521. [CrossRef]
20. Block, C.; Van Caneghem, J.; Van Brecht, A.; Wauters, G.; Vandecasteele, C. Incineration of Hazardous Waste: A Sustainable Process? *Waste Biomass Valorization* **2015**, *6*, 137–145. [CrossRef]
21. Strazza, C.; Del Borghi, A.; Gallo, M.; Manariti, R.; Missanelli, E. Investigation of green practices for paper use reduction onboard a cruise ship—a life cycle approach. *Int. J. Life Cycle Assess.* **2015**, *20*, 982–993. [CrossRef]
22. SWOT Analysis: Discover New Opportunities, Manage and Eliminate Threats. Available online: https://www.mindtools.com/pages/article/newTMC_05.htm (accessed on 3 April 2020).
23. Wang, Z.; Guo, Q.; Liu, X.; Cao, C. Low Temperature Pyrolysis Characteristics of Oil Sludge under Various Heating Conditions. *Energy Fuels* **2007**, *21*, 957–962. [CrossRef]
24. UNFCCC. ACM0022: Alternative Waste Treatment Processes—Version 2.0. 2014. Available online: https://cdm.unfccc.int/methodologies/DB/YINQ0W7SUYOO2S6GU8E5DYVP2ZC2N3 (accessed on 3 April 2020).
25. UNFCCC. Methodological Tool: Emissions from Solid Waste Disposal Site—Version 07.0. 2015. Available online: https://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-04-v7.pdf (accessed on 3 April 2020).
26. UNFCCC/CCNUCC. Indicative Simplified Baseline and Monitoring Methodologies for Selected Small-Scale CDM Project Activity Categories. Available online: https://cdm.unfccc.int/EB/031/eb31_repan17.pdf (accessed on 3 April 2020).
27. UNFCCC/CCNUCC. Methodological Tool: Baseline, project and/or leakage emissions from electricity consumption and monitoring of electricity generation (Version 03.0). 2017. Available online: https://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-05-v3.0.pdf (accessed on 3 April 2020).
28. UNFCCC. Large-scale Consolidated Methodology Production of biofuel (version 03.1). 2017, p. 35. Available online: https://cdm.unfccc.int/methodologies/DB/ZNCG27VU8E0ABXO6GHGKTR75U0MIWL (accessed on 3 April 2020).
29. Makarichi, L.; Jutidamrongphan, W.; Techato, K. The evolution of waste-to-energy incineration: A review. *Renew. Sustain. Energy Rev.* **2018**, *91*, 812–821. [CrossRef]
30. UNFCCC. AMS-III.Q.: Waste Energy Recovery—Version 6.1. 2015. Available online: https://cdm.unfccc.int/methodologies/DB/RGPW18XV4FJH1FTTGS2LSD3BWNKNAA (accessed on 3 April 2020).
31. IPCC. *Climate Change 2013—The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Intergovernmental Panel on Climate Change, Ed.; Cambridge University Press: Cambridge, UK, 2014; ISBN 978-1-107-41532-4.
32. Perry, R.; Green, D. *Perry's Chemical Engineers' Handbook*, 7th ed.; McGraw-Hill Professional: New York, NY, USA, 2007.
33. MATTM. *Tabella Parametri Standard Nazionali*; MATTM: Rome, Italy, 2015; Available online: https://www.minambiente.it/sites/default/files/archivio/allegati/emission_trading/tabella_coefficienti_standard_nazionali_2012_2014_v1.pdf (accessed on 3 April 2020).
34. UNFCCC. Methodological Tool: Upstream Leakage Emissions Associated with Fossil Fuel Use—Version 02.0. 2014. Available online: https://cdm.unfccc.int/methodologies/PAmethodologies/tools/am-tool-15-v2.0.pdf (accessed on 3 April 2020).
35. EU. COM(2014) 398 final "Towards a circular economy: A zero waste programme for Europe". Brussels, 2.7.2014. Available online: https://ec.europa.eu/environment/circular-economy/pdf/circular-economy-communication.pdf (accessed on 3 April 2020).