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# Analysing the Sustainability of the Production of Solid Recovered Fuel from Screening Waste

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**Abstract:** The development in wastewater management has caused a shift towards a circular model that prioritises energy generation and waste reduction. Traditional unitary processes in wastewater treatment, such as screening, only allow for landfill disposal without energy recovery. However, producing solid recovered fuel (*SRF*) from waste screening may be a possibility. The economic and environmental viability of this alternative, as a fundamental requirement for its implementation at industrial level, was assessed through a multi-scenario analysis using Monte Carlo simulation. The cost and benefit streams were determined based on the financial net present value ($NPV_f$) and the social net present value ($NPV_s$), including monetised $CO_2$ emissions generated. The results showed that waste drying costs were found to be the most significant ones, with thermal drying being more financially advantageous than solar drying. The densification of *SRF* raises the costs by 7.88 to 8.48%, but its use as fuel would likely be profitable due to the economic benefits it provides. Current landfill disposal practices, which have an $NPV_s$ of −1052.60 EUR/t, are not a feasible, particularly when compared to the other *SRF* production scenarios, with maximum $NPV_s$ of −53.91 EUR/t. *SRF* production without densification using solar drying is the most acceptable scenario with the lowest $NPV_s$ (38.39 EUR/t).

**Keywords:** screening waste; solid recovered fuel; pelletisation; NPV; economic analysis; Monte Carlo simulation; $CO_2$ emission; wastewater



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## 1. Introduction

For decades, wastewater management has been developing toward sustainability and a circular economy through energy self-sufficiency and zero waste [1]. The different physical, chemical and biological processes in municipal wastewater treatment plants (WWTPs) generate waste of different natures [2]. Screening is a waste with a high moisture content and is described as a solid mixture of organic matter, sanitary textiles, paper and plastics [3]. It generally has no energy recovery within the circular economy guidelines [4] and is mainly disposed of in landfills, generating economic and environmental problems [5]. In Europe, landfill is bound to disappear since, with the new restrictions raised in Directive 850/2018 in 2035, the amount by weight of municipal waste deposited in landfill will have to be reduced to a maximum of 10% of the total [6]. The search for a second life for screening waste is therefore an absolute priority for achieving zero waste in WWTPs [7].

Based on the above considerations, the scientific publications in the literature analyse alternatives to landfill disposal of screening waste, focusing mainly on anaerobic digestion treatments [8]. As an alternative to these studies and to avoid landfill disposal, an analysis of screening waste from a WWTP in Granada (Spain) concluded that the properties of the waste were suitable for transformation into solid recovered fuel (*SRF*) [9]. This statement is in accordance with the ISO 21640:2021 standard [10], which considers "solid waste from urban wastewater treatment" as a possible source for *SRF* production. This biofuel has been recognised as a viable alternative to fossil fuels and can be used in different industrial sectors, such as power plants [11] or cement plants [12]. Although the production of *SRF* does not follow a specific preparation technology [13,14], the process generally includes the stages of shredding, removal of unsuitable fractions (e.g., metals or inerts), drying and conditioning of the product [15]. Drying is relevant for the screening treatment, as moisture levels of up to 84.4% [16] would have to be lowered to achieve optimal values concerning the calorific energy of the fuel obtained. Solar drying is generally carried out in a greenhouse containing a scarification roller and an air movement system and can be applied to dry sludge from WWTPs [17]. Another more established alternative is thermal drying [18]. The shredding of the dry screening is a complicated task due to the high percentage of sanitary textiles and their resistance to grinding [19]. On a technical level, *SRF* densification improves boiler feed for combustion [20], and processes such as gasification [21] are more suited for densified fuel. From an economic point of view, and motivated by the decrease in volume, the transport phase is a much more efficient process [22].

Solutions for screening waste management must be environmentally viable and acceptable in social and economic terms [23]. At this point, the techno-economic analysis of *SRF* production should be a focus of research. Most studies in this area analyse the economic feasibility of using *SRF* as a substitute for fossil fuels; however, *SRF* production chain has yet to be studied in economic terms. The co-firing of *SRF* with biomass and coal was subjected to a cost impact study in cement plants [24]. In Metro Vancouver (Canada), using a cost/benefit analysis, four scenarios involving the use of a fuel produced from municipal solid waste (MSW) were compared [25]. As an alternative to the use of *SRF*, gasification was analysed in terms of economic viability, considering the initial and operating costs of a plant with a capacity of 5000 tons/year [26].

Based on the results obtained in the study mentioned above, *SRF* was produced without densification and densified from this waste [9]. Thus, this perspective for managing screening waste is an innovative solution for future wastewater treatment. Economic and environmental feasibility is a requirement for the potential implementation of this process at the industrial level, thus defining the objective of this research. In this study, the *SRF* production process, which includes the drying, shredding and densification stages, has been analysed from an economic and environmental point of view. The tool used for the detailed calculations was the net present value, which was combined with Monte Carlo (MC) analysis, providing conclusive results on the comparison between *SRF* production scenarios and the current landfill disposal of waste.

## 2. Materials and Methods

The feasibility analysis was carried out based on four *SRF* production scenarios. This section presents the economic and environmental evaluation methods. In addition, MC simulation was proposed as a risk analysis.

### *2.1. Description of Scenarios*

- The proposed scenarios are shown in Figure 1 and described below.
- Scenario 0. Disposal in landfill: the current elimination of waste in the landfill of will be considered.
- Scenario 1. Production of non-densified *SRF* with solar drying: greenhouse drying will be considered and a shredded fuel with homogeneous particle size will be obtained.
- Scenario 2. Production of non-densified *SRF* with thermal drying: for this scenario, drying will be conventional by means of thermal heating, obtaining the same fuel after shredding as in the previous scenario.
- Scenario 3. Production of densified *SRF* with solar drying: as a continuation of scenario 1 and as a post-treatment to improve *SRF* characteristics, in this case, the fuel obtained will be in the form of pellets.

- Scenario 4. Production of densified *SRF* with thermal drying: Scenario 2 will be complemented with the densification stage to obtain pellets as *SRF*.

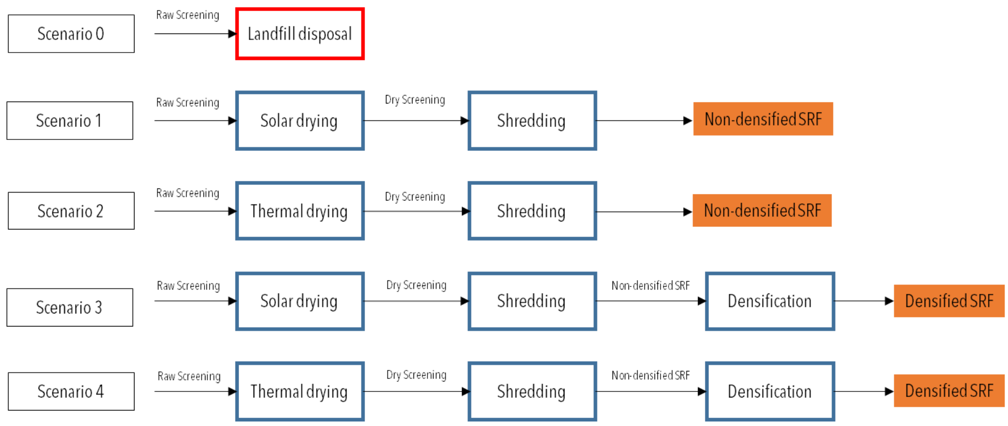


**Figure 1.** Proposed scenarios, landfill and production of solid recovered fuel (*SRF*), for screening waste treatment.

### 2.2. Cost/Benefit Assessment

Costs and benefits were identified to facilitate an economic evaluation for the treatment of screening waste. The main costs studied were assigned to two macro-categories: investment costs required to start a new business, representing a one-time cost, and operating and maintenance costs (OMCs), which incur periodically, usually yearly.

The proceeds from the potential sale of the final *SRF* would constitute a specific revenue stream for the company. According to the alternative scenarios, there are two output products, the non-densified and the densified *SRF*. Although the production of *SRF* is on an increasing trend [27], the market selling price is still a variable to be established, as it depends on a wide range of factors, such as the cost of production, the environmental impact and the quality of the *SRF* [28]. Furthermore, depending on the WWTP, the *SRF* produced could be valorised energetically through gasification, pyrolysis or gasification processes within the WWTP itself [29], without the need for sale.

In addition, the costs derived from the $CO_2$ emissions generated in the *SRF* production process are also analysed. These costs are attributable to all the phases established in the four alternative scenarios and will also be accounted for in the landfill disposal scenario. Although $CO_2$ emissions do not present specific monetised costs for the company, they offer a broader view of the social and environmental cost of the processes developed [30]. The amount of $CO_2$ was measured economically using SendeCO$_2$ (https://www.sendeco2.com/es/precios-co2, accessed on 20 March 2023), a European $CO_2$ trading system. An average conversion factor of EUR 80.87/t of $CO_2$ was established for 2022, which will be used for this study, assuming it to be stable throughout the defined lifetime project.

### 2.3. Economical Analysis; Financial Net Present Value ($NPV_f$)

There are several methods to evaluate the economic efficiency of the implementation of a process [31]. Of these, the $NPV_f$ study was utilised for this study, which has already been used in decision making in the field of energy recovery [32]. The economic return and profitability of the potential investments of the company producing the waste were studied for a payback period, after which, a neutral $NPV_f$ should be obtained from the cost–benefit ratio. The $NPV_f$, which is presented in Equation (1), is the result of cash flows that contain the annual revenues (*RE*) obtained from selling the *SRF*, the initial investment costs ($I_0$), the operation and maintenance costs (*OMC*) and the industrial benefit (*BE*). In this analysis, the starting point was an $NPV_f$ equal to zero over a project lifetime (*N*) of 10 years, where each cash flow ($n = 0, \ldots, N$) is discounted from its time n to the present time ($n = 0$) by the discount rate ($r$) of 12% [33]. The Industrial Benefit considered was 6%, according to Spanish Royal Decree 1098/2001 [34].

$$NPV_f = -I_0 + \sum_{n=1}^{N} \frac{1}{(1+r)^n}(RE - BE - OMC) \quad (1)$$

The volume of *SRF* obtained, considering the yields of all production phases, is 37.7% with respect to the input residue, the raw screening waste, mainly due to drying. In addition, a 5% loss of *SRF* is considered during the production process to obtain the potential *SRF* to be sold (95% of dry screening). These two percentages are included in the term, "*SRF*relation". Based on the assumption of $NPV_f$ being equal to zero and considering the cash flow, the final simulated sale price (*SP*) is obtained from Equation (2).

$$SP = \frac{\frac{I_0}{\sum_{n=1}^{N} \frac{1}{(1+r)^n}} + OMC}{SRF\ relation * (1 - BE)} \quad (2)$$

### 2.4. Environmental Analysis: Social NPV

The social *NPV* ($NPV_s$) is the financial tool that considers all costs difficult to quantify in monetary terms because they do not constitute an annual cash flow. The $NPV_s$ includes all economic elements that make up the $NPV_f$ and assumes the social cost resulting from the $CO_2$ emissions generated during the proposed scenarios. The $NPV_s$ is calculated using Equation (3), which presents the value of the $NPV_f$, as from Equation (1). From this, the economic cost of the $CO_2$ emissions generated is subtracted and calculated for an $r$ = 12% and a 10-year project lifetime.

$$NPV_s = -I_0 + \sum_{n=1}^{N} \frac{1}{(1+r)^n}(RE - BE - OMC - CO_2) = NPV_F - \sum_{n=1}^{N} \frac{CO_2}{(1+r)^n} \quad (3)$$

### 2.5. Monte Carlo Simulation

The MC risk analysis technique, applied in quantitative studies in a wide range of areas, including project management, energy, engineering, research and development [35], was performed to determine the trend, variability and performance under uncertainty. The simulation, performed over a period of 10 years and using the costs and benefits found in the literature, determined a simulated sale price of the *SRF* for an $NPV_f$ equal to zero. The methodology was applied to 5000 iterations among the different variables, guided by random items of costs and benefits as inputs. The same procedure was also used to determine the $NPV_s$.

## 3. Results and Discussion

### 3.1. Economic Analysis

A literature review was carried out with the aim of obtaining a global view of *SRF* production and a broad spectrum of costs for each scenario. The unit of reference for comparing the different studies analysed was EUR/t. The initial as well as operation and maintenance costs are presented for each of the phases present in the scenarios. Table 1 shows the minimum and maximum values found in the literature reviewed. The wide range corresponds to the variability of the studies analysed regarding the process, location, types of materials or the volume treated.

**Table 1.** Value ranges for the initial cost as well as operation and maintenance cost (*OMC*) of solar and thermal drying, shredding and pelletising.

| Process | Initial Cost (EUR/t) | | *OMC* (EUR/t) | |
|---|---|---|---|---|
| | Min | Max | Min | Max |
| Solar drying | 116.26 | 230.33 | 0.97 | 38.23 |
| Thermal drying | 2.45 | 22.93 | 9.54 | 61.45 |
| Shredding | 0.74 | 3.56 | 2.30 | 5.07 |
| Pelletising | 1.58 | 18.74 | 3.63 | 13.00 |

#### 3.1.1. Initial Costs

Solar drying is becoming an alternative to the established thermal drying methods for processes applicable to municipal and agricultural waste [36], using renewable energy and applicable in many parts of the world [37]. In the field of wastewater, greenhouses for sludge drying are already being established [17,37], with mainly environmental advantages [38]. However, the investment costs are higher than those of other types of drying and are mainly a factor of the cost of the site, civil works and machinery [39]. For example, the construction and commissioning of a solar drying system for fruit and vegetables in Thailand involved an initial cost of 200.90 EUR/t, with a drying capacity of 1000 kg every 2–3 days [40]. Literature reviewed on the applicability for sludge from WWTPs showed values in a similar order of magnitude. Four greenhouse sheds for drying a daily amount of 48.84 tons of sludge, with a surface area of more than 6000 m$^2$, involved an initial cost of 230.33 EUR/t [41]. In another study on several WWTPs of different sizes, a model was established to optimise the possible costs of the implementation of solar sludge drying. The results for the construction of greenhouses, combined with the installation of solar panels, were similar, regardless of the plant size, with initial costs of 116.26 and 134.56 EUR/t, for sludge production of 226,884.00 and 35.04 tons per year, respectively [42]. The examined dataset showcases the utilisation of solar drying across various feedstocks, volumes of feedstock and geographical contexts, resulting in a diverse array of potential scenarios. To summarize, the introduction of solar drying as the primary phase of *SRF* production could incur an initial cost ranging from 116.26 to 230.33 EUR/t of wet screening waste.

Thermal drying is the most established method in waste management for MSW [43], sludge [44] or biomass transformation processes [45]. However, in most cases, this is neither very cost-effective nor environmentally friendly [18]. In one study, for a wood pellet production process, the investment cost of a dryer with a feed of 6 t/hour was 397,543.60 EUR, equivalent to 2.45 EUR/t of wet wood [46]. The initial cost for five dryers and a capacity of 75,000 tons per year was 22.93 EUR/t [47]. In a study comparing the framework conditions for the respective pellet production of Austria and Sweden, the wet waste was dried with different types of dryers, which impacted its initial cost. The tube bundle dryer had an investment cost of 7.92 EUR/t, for Austria, whereas the drum dryer doubled the cost to 14.07 EUR/t for Sweden [48]. In the context of thermal drying, for the purpose of comprehensive analysis, the conducted literature review has examined diverse thermal drying methods across various raw materials. This variability offers a wide range of values, with the minimum value for this phase being 2.45 EUR/t, while the maximum value is 22.93 EUR/t.

Regarding economic data related to shredding, Zakrisson [49], comparing the economic costs of pellet production, presented investment costs of 0.94 and 0.74 EUR/t for plants with a capacity of 10 and 3 t/h, respectively. In the same study, pelletising had investment costs of 1.58 and 4.67 EUR/t for 10 and 3 t/h, respectively [50]. In the work cited above, the total cost of shredding and pelletising for the Austrian model was 11.58 EUR/t. At the same time, for Sweden, it was lower, with a total of 3.5 EUR/t [48].The maximum initial cost for both processes was derived from the same study, with 3.56 EUR/t for shredding and 18.74 EUR/t for pelleting [47]. For these two phases, costs have been mainly analysed based on the difference in the volume of raw material that has been shredded and densified.

As a result, the possible price range for shredding is between 0.74 and 3.56 EUR/t, while for pelletising, it is from 1.58 to 18.74 EUR/t.

#### 3.1.2. Operation and Maintenance Costs

The *OMC* data for solar drying were derived from greenhouse studies. The greenhouse built in Thailand [40], intended for fruit and vegetable drying, had an *OMC* of 13.63 EUR/t, corresponding to repair and maintenance costs as well as gas and electricity demand. This value is similar to that reported by Lapuerta and Fonseca [41], with an *OMC* of 14.22 EUR/t. Based on experimental work at the laboratory scale to study sludge drying, it was concluded that drying using transparent covers is more effective than conventional drying. Extrapolating the results of Khanlari and Gungor [51] would mean an *OMC* of 28.51 EUR/t. At the industrial level, data were found on implementing a greenhouse for solar sludge drying in New Zealand. This installation, which allows 500 tons of sludge with 18% moisture to be obtained per year, has an *OMC* of 38.23 EUR/t of wet sludge [52]. The most economic values found in the literature corresponding to the study of the implementation of drying greenhouses, which are complemented with the installation of solar panels, reducing the *OMC* to 0.97 EUR/t [42]. These data indicate that the range of *OMC* for solar drying is between a minimum of 0.97 EUR/t and a maximum of 38.23 EUR/t. This range of values is wide due to the variability of the studies analysed, with differences between the cost of electricity or gas. In addition, the literature review contrasts data extrapolated from laboratory work with industrial data.

In the study on pellet production in Austria and Sweden [48], the *OMC* of thermal drying was 25.1 and 13.0 EUR/t, respectively, contrary to the initial installation costs, for which the most significant investment was found for Sweden. Similar values were found in a study on pellet production in Canada [25], with an *OMC* of 20.73 EUR/t. In the United States, a value of 61.45/t for the thermal drying of a pellet production plant was obtained, which can be explained by the high energy consumption of drying, accounting for 70% of the energy consumption of the entire process. Thus, the minimum *OMC* obtained was 9.54 EUR/t, with a maximum of 61.45 EUR/t.

In the comparison proposed by Zakrisson [49] for pellet plants with different production capacities, the *OMC* values for crushing and pelletising are 3.5 and 5.5 EUR/t, respectively. These results did not vary with the production volume of the plants and were similar for both 10 and 3 tons of pellets. In a comparative study between countries [48], the *OMC* values and the initial costs were also higher for Austria, both for shredding (2.70 vs. 2.30 EUR/t) and pelletising (7.60 vs. 4.10 EUR/t). In conclusion, and based on all results found, the *OMC* values for a shredding range between 2.30 and 5.07 EUR/t, whereas those for pelletising range from 3.63–13.00 EUR/t.

#### 3.1.3. Scenario Costs

From the combination of the minimum and maximum costs for each process, both the initial costs and *OMC* values were defined for each scenario. The values are also shown in EUR/t of the treated material. For the first drying stage, for both solar and thermal drying, the input stream is the raw screening waste, with 77.3% moisture, and the costs are therefore relative to the weight of this input. The crushing process has the dry screening waste, containing 15% moisture, as input material. Thus, the costs for this phase were defined according to the material to be shredded, which, after drying, corresponds to 37.7% of the gross input waste. The values for the last stage, concerning pelletising, were specified for non-densified *SRF* obtained after shredding, considering that there are no losses. The results for the defined alternative scenarios can be found in Table 2.

**Table 2.** Value ranges for initial cost as well as operation and maintenance cost (*OMC*) of the proposed scenarios.

| Items | | Scenario 1 | | Scenario 2 | | Scenario 3 | | Scenario 4 | |
|---|---|---|---|---|---|---|---|---|---|
| | | Min | Max | Min | Max | Min | Max | Min | Max |
| Cost | Initial Cost | 116.54 | 231.67 | 2.73 | 24.27 | 117.13 | 238.74 | 3.32 | 31.34 |
| | *OMC* | 1.84 | 40.14 | 10.41 | 63.36 | 3.21 | 45.11 | 11.78 | 68.33 |

Regarding the investment costs, there is an evident difference between the scenarios that use solar drying, Scenarios 1 and 3, with ranges of 116.54–231.67 EUR/t and 117.13–238.74 EUR/t, respectively, and those that processed the waste via thermal drying, Scenarios 2 and 4, with values between 2.73–24.27 EUR/t and 3.32–31.34 EUR/t. Solar drying is the phase with the highest investment cost, representing, in average values, 99.53% and 97.39% of the total cost in Scenarios 1 and 3, respectively. Thermal drying, with lower investment costs, represents a substantial reduction in the total costs, with 94.00% for Scenario 2 and 73.35% for Scenario 4. These results highlight the significant importance of drying in *SRF* production processes [53]. In financial terms of the initial cost, thermal drying should be selected as the best option. The next phase of the *SRF* production, related to shredding, is common to all four alternative scenarios and therefore does not present any change in the total investment costs. The last process, leading to the conditioning of the final product as pellets, is common to Scenarios 3 and 4, with increased initial costs. The return on this added cost should be evaluated according to a possible price of the *SRF* produced, which, once densified, would be higher [54]. Considering the above, the scenarios with the highest investment costs would be Scenarios 1 and 3, mainly due to solar drying. Scenario 0, which is currently being performed, does not involve any initial cost since the waste is being disposed of in an external landfill.

The *OMC* of Scenario 0 is composed of the transport and treatment and includes the fees for landfill disposal, depending on the country and the location [55]. For this research, the *OMC* of Scenario 0 (disposal in landfill) corresponds to the actual values of waste management in the municipality where the primary research for this work was carried out [56]. The cost was set at 115 EUR/t, double the maximum values defined for the most expensive scenarios, 2 and 4. Regarding the proposed alternatives, the presence of the drying process in the *OMC*, as for the initial costs, continues to be the reference process, with percentages of 93.38%, 96.23%, 81.12% and 88.61% for the four scenarios. This relevance of drying is also present in the production of wood pellets [47], where it accounts for 70% of the costs of the entire process. In this case, the trend changes with respect to the type of drying, with thermal drying contributing more *OMC* to the total than solar drying. Therefore, the optimal option for this phase would be thermal drying. Shredding, accounting between 9.14% and 17.55%, is common to all scenarios, and therefore, its *OMC* has no impact on the decision-making process. Pelletisation represents an increase of approximately 5 EUR/t for Scenarios 3 and 4, which, as with the initial costs, would theoretically be made profitable by the better quality of the *SRF* [57]. In final terms, the *OMC* values are higher for Scenarios 2 and 4, largely because of the expense related to thermal drying, as noted by Thirugnanasambandam [58].

It can be concluded that the drying process, regarding both initial costs and *OMC*, governs the remaining processes. However, by comparing each drying type's economic advantages and disadvantages, it should be possible to determine the choice that would optimise the *SRF* production process in monetary terms.

Under the financial conditions of this study, the $NPV_f$ for landfill disposal (Scenario 0) is −649.78 EUR/t. To compare the remaining alternatives and considering the hypothesis of $NPV_f = 0$, an *SP* of *SRF* was determined to find the most effective scenario in financial terms. Table 3 displays an overview of the results obtained, with minimum (Min), maximum (Max) and average (Av) values for each scenario, applying MC analysis. Scenarios 1 and 3, with solar drying, cause the *SP* of *SRF* to be the highest, with average values of 159.96 and

172.57 EUR/t, respectively. Therefore, it is considered that the scenarios with thermal drying (Scenarios 2 and 4), with average costs of 123.25 and 133.71 EUR/t, are the most economically efficient, since they do not require the large initial investment required for solar drying. For densification, Scenarios 3 and 4 would mean an increase in the *SP* of 7.88% and 8.48% compared to Scenarios 1 and 2. These percentages are very close, which shows that the decision to carry out pelletising or not does not vary in relation to the type of drying used. At this point, the potential market for both non-densified and densified *SRF* should be evaluated to determine the inclusion of pelletising in fuel production.

**Table 3.** Value ranges for initial cost as well as operation and maintenance cost (*OMC*) of the proposed scenarios.

| Items | Value | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|---|---|---|---|---|---|
| *SP* (EUR/t *SRF*) | Min | 74.30 | 39.49 | 79.63 | 44.06 |
| | Max | 245.42 | 207.01 | 264.10 | 224.77 |
| | Av | 159.96 | 123.25 | 172.57 | 133.71 |

Optimising transport as a subsequent step in the production of *SRF* is crucial in environmental and economic aspects [59]. The pelletisation of the product substantially increases its density [60] and according to the results obtained in a study developed in Granada [9], bulk density increased from 58.16 $kg/m^3$ for non-densified *SRF* to 461.78 $kg/m^3$ for densified *SRF*. This decreases the transportation cost of the final product, which is another variable in the choice of a suitable scenario.

To include all results from the MC analysis simulation, graphs of the density function and the price distribution for each scenario are presented in Figure 2. The range class was defined between 0 and 300 EUR/t to cover the whole set of values obtained via the MC simulation rates in all scenarios.

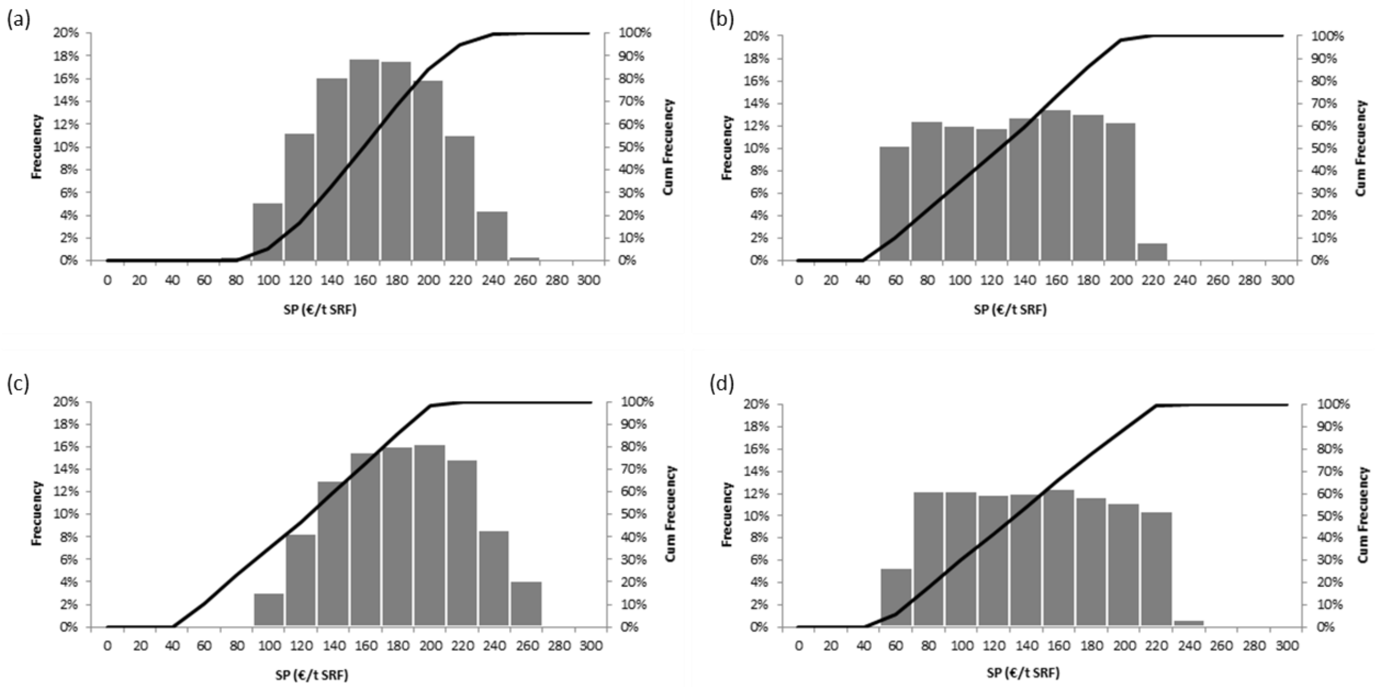


**Figure 2.** Simulated price (*SP*) per ton of solid recovered fuel (*SRF*) distribution and density function. (**a**) Scenario 1. Non-densified *SRF* production with solar drying. (**b**) Scenario 2. Non-densified *SRF* production with thermal drying. (**c**) Scenario 3. Densified *SRF* production with solar drying. (**d**) Scenario 4. Densified *SRF* production with thermal drying.

Following the comparison of the scenarios according to the type of drying used, solar drying (Scenarios 1 and 3) reaches the highest percentages for several classes, obtaining 17.82% and 17.30%, respectively, both for the 180–200-EUR/t class (Figure 2a,c). The two scenarios with thermal drying (Scenarios 2 and 4) did not reach a 14% frequency for any of the classes considered (Figure 2b,d). Based on these data, the possibilities for each of the established classes would be more distributed in the scenarios with thermal drying, with their distribution being more homogeneous and covering more range classes.

As a reference, the *SP* of 100 and 200 EUR/t, present in all scenarios, a probability (P) of the *SRF* price being below 100 EUR/t or above 200 EUR/t can be observed. For Scenario 1 (Figure 2a), P ($SP \leq$ 100 EUR/t) was 4.90%, with a further decrease when the pelletisation phase is included, resulting in a P ($SP \leq$ 100 EUR/t) of 2.64% for Scenario 3 (Figure 2c). Regarding thermal drying, the probability increases substantially with a P ($SP \leq$ 100 EUR/t) of 37.10% and 28.64% for Scenarios 2 (Figure 2b) and 4 (Figure 2d), respectively. The results for P ($SP >$ 200 EUR/t) agree with the financial advantages of the scenarios with thermal drying. For Scenario 2, the probability was 1.34%, whereas Scenario 4, due to the inclusion of pelletisation, presented a result of 11.70%. Solar drying, as the primary source of variation in the scenarios, would generate a P ($SP >$ 200 EUR/t) of 16.10% for Scenario 1 and of 26.40% for Scenario 3.

Thus, considering the financial analysis performed, Scenario 2 (non-densified *SRF* with thermal drying) is the most viable one, with the lowest simulated price. In contrast, Scenario 3 (densified *SRF* with solar drying) is the least feasible one.

### 3.2. Environmental Analysis

This analysis relates the results obtained based on the initial costs and the *OMC*s with the $CO_2$ emissions generated, obtaining results that evaluate the environmental impact of the scenarios linked to their purely economic cost.

#### 3.2.1. $CO_2$ Emission

The literature provides data for the $CO_2$ emissions associated with each process in the different scenarios of this study, including Scenario 0. Table 4 shows the amounts of $CO_2$ (minimum and maximum) generated in each of the processes in the different scenarios.

**Table 4.** Value ranges for $CO_2$ emissions of landfill, solar and thermal drying, shredding and pelletising.

| Process | $CO_2$ Emissions (kg $CO_2$/t) | |
|---|---|---|
| | Min | Max |
| Landfilling | 145.00 | 1610.00 |
| Solar drying | 12.16 | 141.73 |
| Thermal drying | 62.58 | 137.56 |
| Shredding | 0.75 | 39.30 |
| Pelletising | 1.22 | 56.90 |

Emissions generated through landfill disposal have been a relevant issue for years [61]. Concerning Scenario 0, according to a study on waste disposal in South Africa, Friedrich and Trois [62] concluded that greenhouse gas emissions could range from 145.00 to 1016.00 kg $CO_2$/t of wet waste, depending on the type of landfill. However, based on a report by IEA Bioenergy [63], that value could reach up to 1610.00 kg $CO_2$/t for the landfill disposal of municipal solid waste. A life cycle assessment conducted for a landfill site in northern Germany recorded an intermediate emission value of 398.51 kg $CO_2$/t [64]. The overall range is between 145.00 and 1610.00 kg $CO_2$/t.

Regarding solar drying, a 384-m$^2$ pilot plant for drying food waste generated 132.01 kg $CO_2$/t of wet waste [65]. Almost identical values resulted from the solar drying of tomatoes, with emissions of 132.15 kg $CO_2$/t produced from substrate with a water content of 94.6% to 10% [66]. A study of photovoltaic panels in solar-drying greenhouses reported the lowest values for the CIGS PV system (40.96 kg $CO_2$/t), whereas c-Si modules generated the maximum value (141.73 kg $CO_2$/t) [67]. The lowest values for $CO_2$ emissions were found by extrapolating the results obtained for the solar drying of pumpkins. The amount was 12.16 kg $CO_2$/t for a natural convection greenhouse and 16.44 kg $CO_2$/t for forced convection [68]. Based on these findings, the $CO_2$ emissions for solar drying range from 12.16 to 141.173 kg $CO_2$/t.

The thermal drying of wood sawdust resulted in 72.75 kg $CO_2$/t in a plant where 20 t of pellets were produced per hour [46]. In a study conducted in Sweden, similar values were found, with 62.58 kg $CO_2$/t for the production of 80 tons per year of pellets [49]. The emissions generated in a simulation of a small-scale plant in Italy were 137.56 kg $CO_2$/t for 37% water content drying [48]. Overall, the emissions from thermal drying fall within a range of 62.58 to 137.56 kg $CO_2$ per ton.

In the literature, the $CO_2$ emission levels of shredding and pelletising differ greatly. The minimum value for shredding is 0.75 kg $CO_2$/t [46], similar to that found by Zakrisson [49], which is 0.82 kg $CO_2$/t. However, some authors report values of up to 39.3 kg $CO_2$/t [48]. The data for pelletisation follow the same dynamics, with a minimum value of 1.22 kg $CO_2$/t in [46] and a maximum of 56.9 kg $CO_2$/t [48]. The remaining values for pelletising, reported by Thek and Obernberger [48], Urbanowski [50] and Zakrisson [49], are within this range.

According to the processes in each scenario and based on the emission price defined above (80.87 EUR/t of $CO_2$), the costs for each scenario are shown in Table 5. Any of the proposed alternatives (Scenarios 1, 2, 3 and 4) has a substantially lower cost derived from the generation of emissions than landfill disposal (Scenario 0). The results are hardly comparable, with Scenario 0 having a maximum value of 130.20 EUR/t, while the maximum value of the remaining scenarios is 14.39 EUR/t. Although the alternative scenarios showed similar maximum values, considering the mean value as a reference, there were slightly higher average results, 8.70 and 9.59 EUR/t, for the scenarios that include thermal drying (Scenarios 2 and 4) compared to those that include solar drying, with 6.83 and 7.71 EUR/t (Scenarios 1 and 3). The minimum and maximum values show a high variability, since these depend on, among other factors, the size of the installation or its location.

**Table 5.** Value ranges for initial cost as well as operation and maintenance cost (*OMC*) of the proposed scenarios.

| Items | Value | Scenario 0 | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|---|---|---|---|---|---|---|
| $CO_2$ emissions | Min | 145.00 | 12.44 | 62.86 | 12.90 | 63.32 |
| (kg $CO_2$/t) | Max | 1610.00 | 156.55 | 152.38 | 178.00 | 173.83 |
| $CO_2$ cost | Min | 11.73 | 1.01 | 5.08 | 1.04 | 5.12 |
| (EUR/t) | Max | 130.20 | 12.66 | 12.32 | 14.39 | 14.06 |

3.2.2. Social NPV

Considering the $NPV_s$ as a relevant factor in a decision-making process, both financially and socially, it was calculated using Equation (3), based on the monetised cost of $CO_2$ emissions described in Section 3.2.1. and the $NPV_f$. The $NPV_s$ values for each scenario, whose minimum, maximum and average values are shown in Table 6, were obtained via MC analysis. The values obtained are negative, since Equation (3) has the $NPV_f$ as a variable, which is neutral for the alternative scenarios and whose value is −649.78 EUR/t for Scenario 0.

**Table 6.** Value range and average values for the social net present value ($NPV_s$) of the proposed scenarios.

| Items | Value | Scenario 0 | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|---|---|---|---|---|---|---|
| $NPV_s$ (EUR/t) | Min | −1384.93 | −71.53 | −69.62 | −81.33 | −79.43 |
| | Max | −716.29 | −5.69 | −28.73 | −5.90 | −28.94 |
| | Av | −1052.60 | −38.39 | −49.25 | −43.90 | −53.91 |

The results further highlight the different order of magnitude for costs between Scenario 0 and the proposed alternatives, indicating the non-comparability of the $NPV_s$. Concerning the scenarios leading to *SRF* production, thermal drying (Scenarios 2 and 4) is more costly than the options using solar drying (Scenarios 1 and 3). According to the average values, Scenario 2 is the most viable one, with an $NPV_s$ of −38.39 EUR/t for CSR production without densification. The inclusion of densification together with thermal drying resulted in the maximum $NPV_s$ of −53.91 EUR/t for Scenario 4, making this one the least viable one.

Figure 3 shows the results of the MC simulation for the $NPV_s$. The values ranged from −85 to 0 EUR/t. The distribution of values was more comprehensive for the scenarios with solar drying (Figure 3a,c), covering the entire proposed range with a frequency of approximately 7% for most range classes. The scenarios with thermal drying reached values above 13% for the class between −65 and −60 EUR/t, Scenario 2 (Figure 3b), and 10% for five different classes, Scenario 4 (Figure 3d).

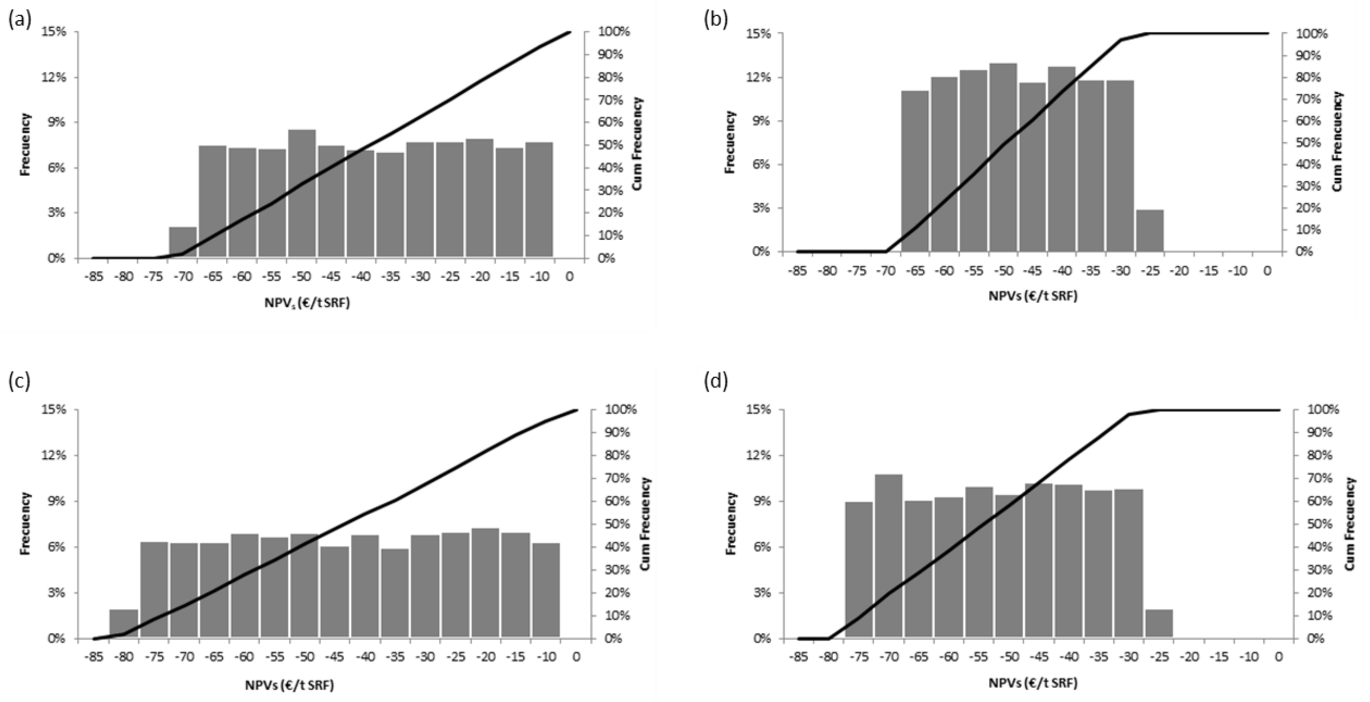


**Figure 3.** Simulated price (*SP*) per ton of solid recovered fuel (*SRF*) distribution and density function. (**a**) Scenario 1. Non-densified *SRF* production with solar drying. (**b**) Scenario 2. Non-densified *SRF* production with thermal drying. (**c**) Scenario 3. Densified *SRF* production with solar drying. (**d**) Scenario 4. Densified *SRF* production with thermal drying.

For the study of the probability (P) of the different ranges, and to compare mainly the drying type, the classes in which Scenario 2 (Figure 3b) had its maximum and minimum limits were considered the reference values. These values for $NPV_s$ would be −65 and −25 EUR/t with a P ($NPV_s$ < −65 EUR/t) of 0% and a P ($NPV_s$ > −25 EUR/t) equal to 100%, respectively, for Scenario 2. Scenario 4 (Figure 3d) coincides with the P ($NPV_s$ > −25 EUR/t), equal to 100%. However, when including the densification process, the P ($NPV_s$ < −65 EUR/t) was higher, reaching 18.82%. The scenarios with solar drying outperformed Scenario 4 in terms of the most expensive values, with a maximum P ($NPV_s$ < −65 EUR/t) of 15.12%. However, the P ($NPV_s$ > −25 EUR/t) was 27.94% for Scenario 1 (Figure 3a) and 25.86% for Scenario 3 (Figure 3c).

Taking into consideration the values obtained for the $NPV_s$, Scenario 1 (production of *SRF* without densification using solar drying) is most acceptable in social terms, with the lowest $NPV_s$. In contrast, Scenario 4 (production of densified *SRF* with thermal drying), with the highest $NPV_s$, is the least acceptable alternative. So, solar drying is more acceptable than thermal drying and non-densified *SRF*. However, this difference must be evaluated concerning the logistical benefits attributed to the densified *SRF* to evaluate the effectiveness of densification.

## 4. Conclusions

The production of solid recovered fuel (*SRF*), densified and non-densified, was proposed through four scenarios as an alternative to the landfill disposal of screening waste. Based on the results obtained via the economic and environmental evaluation of the proposed scenarios, the following conclusions regarding sustainability can be drawn:

- In the decision making, both the initial costs and the operation and maintenance costs (*OMC*s) should be considered, as well as the costs derived from $CO_2$ emissions, which can be combined with the net present value. MC simulation is a valuable tool for quantitative risk analysis.
- Current landfill disposal does not require any investment costs. However, the costs derived from its management and the high $CO_2$ emissions produce $NPV_s$ of −1052.60 EUR/t. This value, compared to that determined for the other scenarios (−53.91 to −38.39 EUR/t), means that landfill disposal is not considered a viable option. The values of the *SRF* production scenarios vary: firstly, according to the type of drying, solar drying being the least harmful in terms of $CO_2$ emissions; and secondly, according to the inclusion of densification in the process.
- Drying costs are the most relevant in *SRF* production, regardless of whether it is densified or not. Although the *OMC* values for thermal drying are slightly higher than those for solar drying, the initial investment is substantially lower, making thermal drying the most economically viable option.
- The densification of the *SRF* implies an increase in the simulated selling price of 7.88% (solar drying) and 8.48% (thermal drying). However, this economic difference must be evaluated concerning the logistical benefits attributed to densified *SRF* to evaluate the effectiveness of densification.

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## Abbreviations

Wastewater treatment plant (WWTP); solid recovered fuel (*SRF*); municipal solid waste (MSW); net present value (*NPV*); financial net present value ($NPV_f$); social net present value ($NPV_s$); Monte Carlo (MC); annual revenues (*RE*); industrial benefit (*BE*); discount rate (*r*); operation and maintenance costs (*OMC*); simulated price (*SP*); probability (P).

## References


1. Gherghel, A.; Teodosiu, C.; De Gisi, S. A Review on Wastewater Sludge Valorisation and Its Challenges in the Context of Circular Economy. *J. Clean. Prod.* **2019**, *228*, 244–263. [CrossRef]
2. Puyol, D.; Batstone, D.J.; Hülsen, T.; Astals, S.; Peces, M.; Krömer, J.O. Resource Recovery from Wastewater by Biological Technologies: Opportunities, Challenges, and Prospects. *Front. Microbiol.* **2017**, *7*, 2106. [CrossRef] [PubMed]
3. Cadavid-Rodriguez, L.S.; Horan, N. Reducing the Environmental Footprint of Wastewater Screenings through Anaerobic Digestion with Resource Recovery. *Water Environ. J.* **2012**, *26*, 301–307. [CrossRef]
4. Boni, M.R.; Polettini, A.; Pomi, R.; Rossi, A.; Filippi, A.; Cecchini, G.; Frugis, A.; Leoni, S. Valorisation of Residues from Municipal Wastewater Sieving through Anaerobic (Co-)Digestion with Biological Sludge. *Waste Manag. Res.* **2021**, *40*, 814–821. [CrossRef] [PubMed]
5. Tsiakiri, E.P.; Mpougali, A.; Lemonidis, I.; Tzenos, C.A.; Kalamaras, S.D.; Kotsopoulos, T.A.; Samaras, P. Estimation of Energy Recovery Potential from Primary Residues of Four Municipal Wastewater Treatment Plants. *Sustainability* **2021**, *13*, 7198. [CrossRef]
6. European Parliament and Council. Directive (EU) 2018/850 of the European Parliament and of the Council of 30 May 2018 Amending Directive 1999/31/EC on the Landfill of Waste. *Off. J. Eur. Union* **2018**, *2018*, 100–108.
7. Ballesteros, I.; Duque, A.; Negro, M.J.; Coll, C.; Latorre-Sánchez, M.; Hereza, J.; Iglesias, R. Valorisation of Cellulosic Rejections from Wastewater Treatment Plants through Sugar Production. *J. Environ. Manag.* **2022**, *312*, 114931. [CrossRef]
8. Wid, N.; Horan, N.J. Anaerobic Digestion of Screenings for Biogas Recovery. In *Green Energy and Technology*; Springer: Singapore, 2018; pp. 85–103. [CrossRef]
9. De la Torre-Bayo, J.J.; Martín-pascual, J.; Torres-rojo, J.C.; Zamorano, M.; Jesús, J.; Torre-bayo, D.; Martín-pascual, J.; Torres-rojo, J.C. Characterization of Screenings from Urban Wastewater Treatment Plants: Alternative Approaches to Landfill Disposal. *J. Clean. Prod.* **2022**, *380*, 134884. [CrossRef]
10. *Norma Española 21640:2021*; Combustibles Sólidos Recuperados Especificaciones y Clases. AENOR: Madrid, Spain, 2021.
11. Wu, H.; Glarborg, P.; Frandsen, F.J.; Dam-Johansen, K.; Jensen, P.A.; Sander, B. Trace Elements in Co-Combustion of Solid Recovered Fuel and Coal. *Fuel Process. Technol.* **2013**, *105*, 212–221. [CrossRef]
12. Bessi, C.; Lombardi, L.; Meoni, R.; Canovai, A.; Corti, A. Solid Recovered Fuel: An Experiment on Classification and Potential Applications. *Waste Manag.* **2016**, *47*, 184–194. [CrossRef]
13. Garg, A.; Smith, R.; Hill, D.; Longhurst, P.J.; Pollard, S.J.T.; Simms, N.J. An Integrated Appraisal of Energy Recovery Options in the United Kingdom Using Solid Recovered Fuel Derived from Municipal Solid Waste. *Waste Manag.* **2009**, *29*, 2289–2297. [CrossRef] [PubMed]
14. Di Lonardo, M.C.; Franzese, M.; Costa, G.; Gavasci, R.; Lombardi, F. The Application of *SRF* vs. RDF Classification and Specifications to the Material Flows of Two Mechanical-Biological Treatment Plants of Rome: Comparison and Implications. *Waste Manag.* **2016**, *47*, 195–205. [CrossRef] [PubMed]
15. Kaartinen, T.; Sormunen, K.; Rintala, J. Case Study on Sampling, Processing and Characterization of Landfilled Municipal Solid Waste in the View of Landfill Mining. *J. Clean. Prod.* **2013**, *55*, 56–66. [CrossRef]
16. Kaless, M.; Palmowski, L.; Pinnekamp, J. Carbon Recovery from Screenings for Energy-Efficient Wastewater Treatment. *Water Sci. Technol.* **2017**, *76*, 3299–3306. [CrossRef]
17. Đurđević, D.; Blecich, P.; Jurić, Ž. Energy Recovery from Sewage Sludge: The Case Study of Croatia. *Energies* **2019**, *12*, 1927. [CrossRef]
18. Juchelková, D. Drying Methods for Municipal Solid Waste Quality Improvement in the Developed and Developing Countries: A Review. *Environ. Eng. Res.* **2019**, *24*, 529–542.
19. Le Hyaric, R.; Canler, J.P.; Barillon, B.; Naquin, P.; Gourdon, R. Characterization of Screenings from Three Municipal Wastewater Treatment Plants in the Region Rhône-Alpes. *Water Sci. Technol.* **2009**, *60*, 525–531. [CrossRef]
20. Gilbert, P.; Ryu, C.; Sharifi, V.; Swithenbank, J. Effect of Process Parameters on Pelletisation of Herbaceous Crops. *Fuel* **2009**, *88*, 1491–1497. [CrossRef]
21. Nixon, J.D.; Dey, P.K.; Ghosh, S.K.; Davies, P.A. Evaluation of Options for Energy Recovery from Municipal Solid Waste in India Using the Hierarchical Analytical Network Process. *Energy* **2013**, *59*, 215–223. [CrossRef]
22. Jewiarz, M.; Mudryk, K.; Dziedzic, K. Parameters Affecting RDF-Based Pellet Quality. *Energies* **2020**, *13*, 910. [CrossRef]
23. Fernández-González, J.M.; Grindlay, A.L.; Serrano-Bernardo, F.; Rodríguez-Rojas, M.I.; Zamorano, M. Economic and Environmental Review of Waste-to-Energy Systems for Municipal Solid Waste Management in Medium and Small Municipalities. *Waste Manag.* **2017**, *67*, 360–374. [CrossRef] [PubMed]
24. Iacovidou, E.; Hahladakis, J.; Deans, I.; Velis, C.; Purnell, P. Technical Properties of Biomass and Solid Recovered Fuel (*SRF*) Co-Fired with Coal: Impact on Multi-Dimensional Resource Recovery Value. *Waste Manag.* **2018**, *73*, 535–545. [CrossRef]
25. Reza, B.; Soltani, A.; Ruparathna, R.; Sadiq, R.; Hewage, K. Environmental and Economic Aspects of Production and Utilization of RDF as Alternative Fuel in Cement Plants: A Case Study of Metro Vancouver Waste Management. *Resour. Conserv. Recycl.* **2013**, *81*, 105–114. [CrossRef]
26. Arena, U.; Di Gregorio, F.; De Troia, G.; Saponaro, A. A Techno-Economic Evaluation of a Small-Scale Fluidized Bed Gasifier for Solid Recovered Fuel. *Fuel Process. Technol.* **2015**, *131*, 69–77. [CrossRef]
27. Matignon, G.P. *Trends in the Use of Solid Recovered Fuels*; IAE Bioenergy: Ottawa, Canada, 2020; ISBN 9781910154724.

28. Chavando, J.A.M.; Silva, V.B.; Tarelho, L.A.C.; Cardoso, J.S.; Eusébio, D. Snapshot Review of Refuse-Derived Fuels. *Util. Policy* **2022**, *74*, 101316. [CrossRef]
29. Shen, Y.; Linville, J.L.; Ignacio-de Leon, P.A.A.; Schoene, R.P.; Urgun-Demirtas, M. Towards a Sustainable Paradigm of Waste-to-Energy Process: Enhanced Anaerobic Digestion of Sludge with Woody Biochar. *J. Clean. Prod.* **2016**, *135*, 1054–1064. [CrossRef]
30. Ni, T.; Si, J.; Lu, F.; Zhu, Y.; Pan, M. Performance Analysis and Optimization of Cascade Waste Heat Recovery System Based on Transcritical CO2 Cycle for Waste Heat Recovery in Waste-to-Energy Plant. *J. Clean. Prod.* **2022**, *331*, 129949. [CrossRef]
31. Alwaeli, M. Economic Calculus of the Effectiveness of Waste Utilization Processed as Substitutes of Primary Materials. *Environ. Prot. Eng.* **2011**, *37*, 51–58.
32. Cucchiella, F.; D'Adamo, I.; Gastaldi, M. Sustainable Waste Management: Waste to Energy Plant as an Alternative to Landfill. *Energy Convers. Manag.* **2017**, *131*, 18–31. [CrossRef]
33. Alao, M.A.; Popoola, O.M.; Ayodele, T.R. Projecting the Energetic Potential and Economic Viability of Renewable Power Generation from Municipal Solid Waste: Indication from South African Provinces. *Energy Sustain. Dev.* **2022**, *71*, 352–367. [CrossRef]
34. Ministerio de Hacienda. *Real Decreto 1098/2001*; Ministerio de Hacienda: Madrid, Spain, 2001; pp. 1–111.
35. Martín-Pascual, J.; Fernández-González, J.M.; Ceccomarini, N.; Ordoñez, J.; Zamorano, M. The Study of Economic and Environmental Viability of the Treatment of Organic Fraction of Municipal Solid Waste Using Monte Carlo Simulation. *Appl. Sci.* **2020**, *10*, 9028. [CrossRef]
36. Bennamoun, L.; Arlabosse, P.; Léonard, A. Review on Fundamental Aspect of Application of Drying Process to Wastewater Sludge. *Renew. Sustain. Energy Rev.* **2013**, *28*, 29–43. [CrossRef]
37. Mathioudakis, V.L.; Kapagiannidis, A.G.; Athanasoulia, E.; Paltzoglou, A.D.; Melidis, P.; Aivasidis, A. Sewage Sludge Solar Drying: Experiences from the First Pilot-Scale Application in Greece. *Dry. Technol.* **2013**, *31*, 519–526. [CrossRef]
38. Boguniewicz-Zablocka, J.; Klosok-Bazan, I.; Capodaglio, A.G. Sustainable Management of Biological Solids in Small Treatment Plants: Overview of Strategies and Reuse Options for a Solar Drying Facility in Poland. *Environ. Sci. Pollut. Res.* **2021**, *28*, 24680–24693. [CrossRef] [PubMed]
39. Kamarulzaman, A.; Hasanuzzaman, M.; Rahim, N.A. Global Advancement of Solar Drying Technologies and Its Future Prospects: A Review. *Sol. Energy* **2021**, *221*, 559–582. [CrossRef]
40. Janjai, S. A Greenhouse Type Solar Dryer for Small-Scale Dried Food Industries: Development and Dissemination. *Int. J. Energy Environ.* **2012**, *3*, 383–398.
41. Risueño, M.L.C.F.V. Secado Solar de Lodos de Depuradora para el Ahorro Energético en los Procesos de Post-Tratamiento. Master's Thesis, Universidad Politécnica de Madrid, Madrid, Spain, 2020. No. Enero.
42. Kurt, M.; Aksoy, A.; Sanin, F.D. ScienceDirect Evaluation of Solar Sludge Drying Alternatives by Costs and Area Requirements. *Water Res.* **2015**, *82*, 47–57. [CrossRef]
43. Li, X.; Takaoka, M.; Zhu, F.; Wang, J.; Oshita, K.; Mizuno, T. Environmental and Economic Assessment of Municipal Sewage Sludge Management-A Case Study in Beijing, China. *Water Sci. Technol.* **2013**, *67*, 1465–1473. [CrossRef]
44. Kelessidis, A.; Stasinakis, A.S. Comparative Study of the Methods Used for Treatment and Final Disposal of Sewage Sludge in European Countries. *Waste Manag.* **2012**, *32*, 1186–1195. [CrossRef] [PubMed]
45. Del Giudice, A.; Acampora, A.; Santangelo, E.; Pari, L.; Bergonzoli, S.; Guerriero, E.; Petracchini, F.; Torre, M.; Paolini, V.; Gallucci, F. Wood Chip Drying through the Using of a Mobile Rotary Dryer. *Energies* **2019**, *12*, 1590. [CrossRef]
46. Mobini, M.; Sowlati, T.; Sokhansanj, S. A Simulation Model for the Design and Analysis of Wood Pellet Supply Chains. *Appl. Energy* **2013**, *111*, 1239–1249. [CrossRef]
47. Pirraglia, A.; Gonzalez, R.W.; Saloni, D. Techno-Economical Analysis of Wood Pellets Production for US Manufacturers. *BioResources* **2010**, *5*, 2374–2390. [CrossRef]
48. Thek, G.; Obernberger, I. Wood Pellet Production Costs under Austrian and in Comparison to Swedish Framework Conditions. *Biomass Bioenergy* **2004**, *27*, 671–693. [CrossRef]
49. Zakrisson, M. *Comparison of International Pellet Production Costs, Examensarbeten Nr 39*; Department of Forest Management and Products: Uppsala, Sweden, 2002.
50. Urbanowski, E. Strategic Analysis of a Pellet Fuel Opportunity in Northwest British Columbia. Master's Thesis, Simon Fraser University, Burnaby, BC, Canada, 2005.
51. Khanlari, A.; Gungor, A. Energetic, Environmental and Economic Analysis of Drying Municipal Sewage Sludge with a Modified Sustainable Solar Drying System. *Sol. Energy* **2020**, *208*, 787–799. [CrossRef]
52. Paredes, L.; Murgolo, S.; Dzinun, H.; Dzarfan Othman, M.H.; Ismail, A.F.; Carballa, M.; Mascolo, G. Application of Immobilized TiO2 on PVDF Dual Layer Hollow Fibre Membrane to Improve the Photocatalytic Removal of Pharmaceuticals in Different Water Matrices. *Appl. Catal. B Environ.* **2019**, *240*, 9–18. [CrossRef]
53. Velis, C.A.; Longhurst, P.J.; Drew, G.H.; Smith, R.; Pollard, S.J.T. Biodrying for Mechanical-Biological Treatment of Wastes: A Review of Process Science and Engineering. *Bioresour. Technol.* **2009**, *100*, 2747–2761. [CrossRef] [PubMed]
54. Štofová, L.; Szaryszová, P.; Mihalčová, B. Testing the Bioeconomic Options of Transitioning to Solid Recovered Fuel: A Case Study of a Thermal Power Plant in Slovakia. *Energies* **2021**, *14*, 1720. [CrossRef]

55. Tan, S.T.; Ho, W.S.; Hashim, H.; Lee, C.T.; Taib, M.R.; Ho, C.S. Energy, Economic and Environmental (3E) Analysis of Waste-to-Energy (WTE) Strategies for Municipal Solid Waste (MSW) Management in Malaysia. *Energy Convers. Manag.* **2015**, *102*, 111–120. [CrossRef]
56. De la Torre-Bayo, J.J.; Zamorano, M.; Torres-Rojo, J.C.; Rodríguez, M.L.; Martín-Pascual, J.; Jesús, J.; Torre-Bayo, D.; Torres-rojo, J.C.; Rodríguez, M.L.; Martín-Pascual, J.; et al. Analyzing the Production, Quality, and Potential Uses of Solid Recovered Fuel from Screening Waste of Municipal Wastewater Treatment Plants. *Process Saf. Environ. Prot.* **2023**, *172*, 950–970. [CrossRef]
57. Kliopova, I.; Makarskiene, K. Improving Material and Energy Recovery from the Sewage Sludge and Biomass Residues. *Waste Manag.* **2015**, *36*, 269–276. [CrossRef]
58. Thirugnanasambandam, M.; Iniyan, S.; Goic, R. A Review of Solar Thermal Technologies. *Renew. Sustain. Energy Rev.* **2010**, *14*, 312–322. [CrossRef]
59. Hilber, T.; Maier, J.; Scheffknecht, G.; Agraniotis, M.; Grammelis, P.; Kakaras, E.; Glorius, T.; Becker, U.; Derichs, W.; Schiffer, H.-P.; et al. Advantages and Possibilities of Solid Recovered Fuel Cocornbustion in the European Energy Sector. *J. Air Waste Manag. Assoc.* **2007**, *57*, 1178–1189. [CrossRef]
60. Ramos Casado, R.; Arenales Rivera, J.; Borjabad García, E.; Escalada Cuadrado, R.; Fernández Llorente, M.; Bados Sevillano, R.; Pascual Delgado, A. Classification and Characterisation of *SRF* Produced from Different Flows of Processed MSW in the Navarra Region and Its Co-Combustion Performance with Olive Tree Pruning Residues. *Waste Manag.* **2016**, *47*, 206–216. [CrossRef] [PubMed]
61. Gollapalli, M.; Kota, S.H. Methane Emissions from a Landfill in North-East India: Performance of Various Landfill Gas Emission Models. *Environ. Pollut.* **2018**, *234*, 174–180. [CrossRef] [PubMed]
62. Friedrich, E.; Trois, C. GHG Emission Factors Developed for the Collection, Transport and Landfilling of Municipal Waste in South African Municipalities. *Waste Manag.* **2013**, *33*, 1013–1026. [CrossRef]
63. IEA Bioenergy. *Municipal Solid Waste and Its Role in Sustainability*; IEA Bioenergy: Rotorua, New Zealand, 2003.
64. Wittmaier, M.; Langer, S.; Sawilla, B. Possibilities and Limitations of Life Cycle Assessment (LCA) in the Development of Waste Utilization Systems-Applied Examples for a Region in Northern Germany. *Waste Manag.* **2009**, *29*, 1732–1738. [CrossRef]
65. Abeliotis, K.; Chroni, C.; Lasaridi, K.; Terzis, E.; Galliou, F.; Manios, T. Environmental Impact Assessment of a Solar Drying Unit for the Transformation of Food Waste into Animal Feed. *Resources* **2022**, *11*, 117. [CrossRef]
66. Eltawil, M.A.; Azam, M.M.; Alghannam, A.O. Energy Analysis of Hybrid Solar Tunnel Dryer with PV System and Solar Collector for Drying Mint (MenthaViridis). *J. Clean. Prod.* **2018**, *181*, 352–364. [CrossRef]
67. Saini, V.; Tiwari, S.; Tiwari, G.N. Environ Economic Analysis of Various Types of Photovoltaic Technologies Integrated with Greenhouse Solar Drying System. *J. Clean. Prod.* **2017**, *156*, 30–40. [CrossRef]
68. Chauhan, P.S.; Kumar, A.; Nuntadusit, C. Thermo-Environomical and Drying Kinetics of Bitter Gourd Flakes Drying under North Wall Insulated Greenhouse Dryer. *Sol. Energy* **2018**, *162*, 205–216. [CrossRef]