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Techno-Economic Analysis of Scenarios on Energy and Phosphorus Recovery from Mono- and Co-Combustion of Municipal Sewage Sludge

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Abstract: This study evaluates the techno-economic feasibility of energy and phosphorus (P) fertilizer (PF) recovery from municipal sewage sludge (MSS) through incineration in new combustion plants. We evaluated the economic impact of five critical process design choices: (1) boiler type, (2) fuel (MSS mono-combustion/co-combustion with wheat straw), (3) production scale (10/100 MW), (4) products (heat, electricity, PF), and (5) ash destination. Aspen Plus modeling provided mass and energy balances of each technology scenario. The economic feasibility was evaluated by calculating the minimum selling price of the products, as well as the MSS gate fees required to reach profitability. The dependency on key boundary conditions (operating time, market prices, policy support) was also evaluated. The results showed a significant dependency on both energy and fertilizer market prices and on financial support in the form of an MSS gate fee. Heat was preferred over combined heat and power (CHP), which was feasible only on the largest scale (100 MW) at maximum annual operating time (8000 h/y). Co-combustion showed lower heat recovery cost (19–30 €/MWh) than mono-combustion (29–66 €/MWh) due to 25–35% lower energy demand and 17–25% higher fuel heating value. Co-combustion also showed promising performance for P recovery, as PF could be recovered without ash post-treatment and sold at a competitive price, and co-combustion could be applicable also in smaller cities. When implementing ash post-treatment, the final cost of ash-based PF was more than four times the price of commercial PF. In conclusion, investment in a new combustion plant for MSS treatment appears conditional to gate fees unless the boundary conditions would change significantly.

Keywords: municipal sewage sludge; energy recovery; phosphorus recovery; techno-economic analysis; mono-combustion; co-combustion

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1. Introduction

Phosphorus (P) is a critical and irreplaceable element in human nutrition. However, the primary P resource, phosphate rock, is limited and geographically concentrated to a few regions, and the dependency of agriculture on mineral P causes increases in fertilizer price and uncertainty in the P market [1–3]. The world's economic reserves of high quality, low extraction cost P have been estimated at about 17 billion tons [4], and the agriculture sector alone consumes 20 million tons on P each year [5]. The P market experienced an 800% price increase in 2008, and even after the peak dropped, the new P price was twice that of before 2008 [6]. Therefore, efforts to recover P from P-rich wastes have been intensified [7]. MSS, the solid waste residue of wastewater treatment plants, is considered one of the most promising P-rich sources due to both high P concentration and large volumes [8,9]. It is expected that 17–31% of the currently used mineral fertilizer could be substituted by P from biogenic materials, mainly MSS, via advanced technologies by 2030 [10,11]. Land application and composting of MSS are simple P recovery methods and the dominant practice in Europe for disposal or recovery [12]. However, using those methods also leads to the inclusion of heavy metals (HMs), pathogens, and pharmaceuticals with the nutrients [13,14].

Conversely, the combustion of MSS encompasses advantages such as significant volume reduction, energy recovery, and the destruction of organic contaminants and pathogens without necessarily impairing the P recovery opportunity [15,16]. Energy and P recovery from MSS is directly related to the United Nations Sustainable Development Goals 7 and 12, where replacement of non-renewable energy with green energy resources and reuse of valuable material is crucial for a sustainable society. Sewage sludge ash (SSA) typically contains 10–25 wt.% P_2O_5, which is comparable with phosphate rock (5–40 wt.% P_2O_5) [17], and allows for 5–10 times higher P recovery compared to recovery from MSS and leachates due to higher concentration of P [8,18,19].

Primary drawbacks of MSS mono-combustion are high moisture content [20], simultaneous potential accumulation of P and HMs in the ash [17], and low plant availability of the dominant P species in the SSA apatite [21]. The first issue makes MSS mono-combustion inefficient from an energy perspective, while the latter two make direct land application of SSA less suitable and limit the possible substitution of phosphate rock in commercial fertilizer production to 10–20% [22]. Thermochemical treatment and wet extraction methods have been used to transfer ash-based P to a more water-soluble species with lower HMs content [23–25]. Extracted P by the wet process still needs post-treatment to achieve an adequate quality regarding HMs content and plant availability [26]. However, Herzel et al. [27] showed that thermochemical treatment of the SSA under reducing conditions with Na- or K-based alkaline additives, such as NaOH, Na_2CO_3, K_2CO_3, and KOH, results in a marketable fertilizer, as indicated by the ash-based PF solubility in neutral ammonium citrate. Similarly, in the thermochemical conversion process Ash Dec, the SSA is treated with alkaline additives in a rotary kiln at 1000 °C [27]. This process leads to plant-available P species and more than 90% decontamination of HMs. Ash Dec has been applied commercially and has shown high P recovery, with a final product that does not need further post-processing [19,28,29].

Alternatively, the plant availability of SSA-based P can be improved by altering the ash formation during the combustion process, which can also decrease the accumulation of P and HMs in the same ash fraction. According to previous studies, co-combustion of MSS and K-rich agricultural fuels with low moisture (e.g., wheat straw) may directly both provide more plant-available phosphates in the combustion process [24,30,31] and eliminate the need for energy-intensive drying. Furthermore, the type of combustion technology can affect how P and HMs accumulate in different ash fractions, thereby stimulating HMs separation [32].

Energy recovery from MSS via combustion with subsequent P recovery from SSA requires expensive technology [33,34], and the possibility of moving from disposal to recovery for MSS is substantially tied to economic feasibility [35]. Sustainable MSS management thus needs to be built around technology that enables a high recovery rate, cost-effectiveness, and a marketable output that can compete with conventional products and preferably be used directly. Various techno-economic analysis studies have been conducted on either P or energy recovery from MSS rather than SSA. The benefits of P recovery by considering the environmental externalities have been shown by [36]. The economic feasibility of P recovery from wastewater and sludge for a pilot-test condition was evaluated by comparing the experiment's operation costs (mainly energy and chemical costs) with the market price of fertilizer [37]. Horttanainen et al. reported a 2.5–10 years payback period of heat and power generation through MSS combustion in different technical conditions [15]. In general, the focus of previous studies has been either on various technical options for P and energy recovery or on comparison between different available options for either P or energy recovery [5,35–38]. However, techno-economic investigations of combined energy and P recovery through mature technologies, requirements of final products' marketability by calculation of the minimum selling prices and gate fees in various market conditions, and comparisons with different ash handling practices have, to the best of our knowledge, not yet been addressed together.

This study aims to explore the economic feasibility of energy and P recovery from MSS through combustion under different technology, operation, and market conditions. We consider investment in a new combustion plant for different technology design options regarding combustion technology, plant scale, fuel composition, energy and material outputs, and the final destinations of the ash residue. Specific objectives are to investigate (i) to what extent the economic feasibility can be affected by the technical design, (ii) the requirement of financial support, and (iii) necessary energy and fertilizer market conditions. The objectives are addressed by developing a techno-economic analysis that evaluates the minimum selling price of sewage sludge-based energy and PF. The assessment is performed for a number of technology scenarios designed to investigate the inherent relations between heat, power, and PF production, as well as for different economic variations designed to investigate the influence of non-technical and operational parameters. The results provide insights into economic performance and required financial support to produce energy carriers from MSS and replace mineral P products with sludge-based ones in Europe.

2. Technology Scenarios

The following sections describe the main perspectives behind the scenario selections. Sixteen technology scenarios were developed based on variations of (1) boiler type and size, (2) fuel composition, (3) final destination of the ash residue, and (4) outputs from the plant. Figure 1 gives a schematic overview of the plants, with descriptions in the following sections.

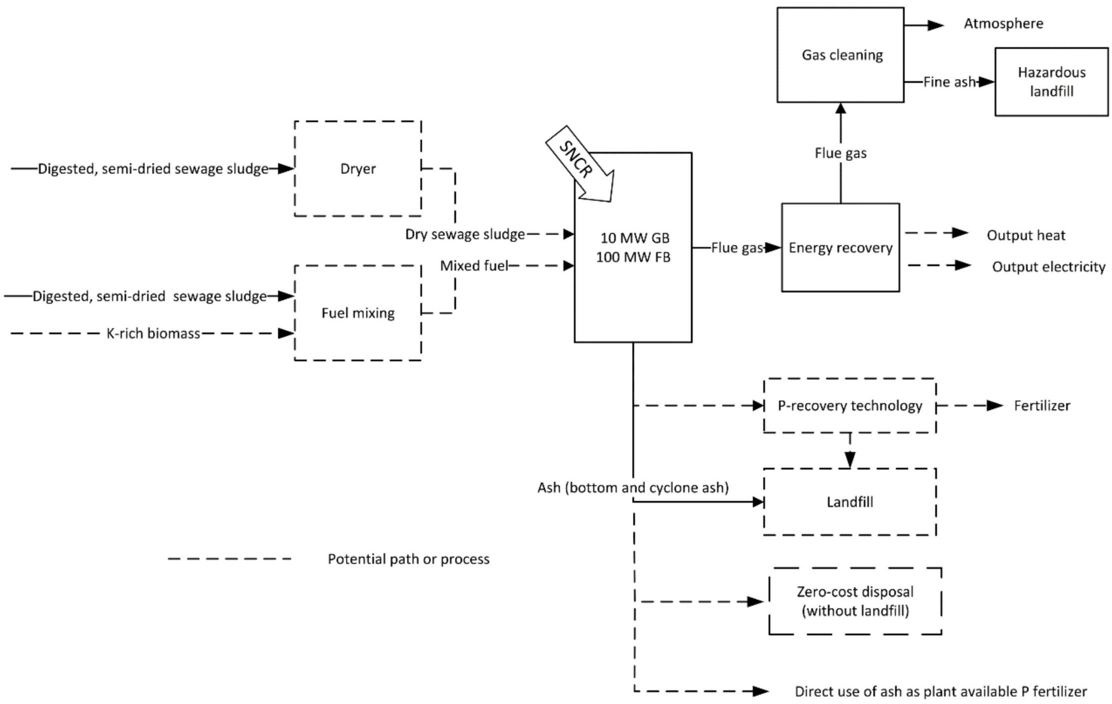

Figure 1. Schematic overview of variations in the modeled technology scenarios.

2.1. Boiler Type, Size, and Ash Distribution

Fluidized bed (FB) boilers and grate boilers (GB) respectively constitute the most common type of MSS and municipal solid waste combustion incinerators [39–41]. The selection of boiler technology for waste and biomass is affected by a number of parameters, such as the need for storage, fuel characteristics and preparation, combustion efficiency, emission, and other region-related conditions such as availability of specific biomass types and potential policy instruments related to, e.g., renewable energy [42]. The optimal boiler type selection is beyond the scope of this paper, and both FB and GB were selected as commercially available options.

Because of the low energy density on a mass basis of biomass compared to fossil fuels and the potentially high transportation costs associated with the large spatial distribution of biomass resources, biomass combustion plants in Europe usually have a small scale (10–15 MW), compared to, e.g., coal power plants [40]. Since the GB is the most common combustion technology for biomass and solid waste in Europe [41], GB scenarios were designed for 10 MW boiler capacity. FB is commonly applied for MSS combustion at a larger scale than GB [31,34,39]. In order to also consider the effects of economy-of-scale and to represent larger CHP plants, FB technology was thus selected for scenarios with 100 MW boiler capacity.

To comply with emission limits, SO_2, HCl, NO_x, HMs, and particle emissions must be carefully controlled; therefore, the same gas cleaning system that is particularly suggested for MSS-burned plants is considered in all scenarios [34,43,44]. In this system, a cyclone extracts fly ash, and an electrostatic precipitator separates the fly ash left after the cyclone [45]. Subsequently, a wet scrubber using (Ca $(OH)_2$) is applied for desulfurization. Lime or urea is directly injected into the boiler to reduce nitrogen oxides to eliminate nitrogen through selective non-catalytic reduction (SNCR) [46]. Finally, coke is used for Hg, Cd, dioxins, and furans separation, and the flue gas is polished from fine ash particles through a fabric filter capture [34,47]. As shown in Figure 1, the fly ash collected in the cyclone and bottom ash are discharged together, whereas fine ash is discharged separately.

2.2. Fuel Composition

The high moisture content of MSS causes a low heating value, lower furnace temperature, and/or high energy demand for drying to the moisture content required by the thermochemical process [38,48]. The solid content of digested MSS after mechanical dewatering can typically be found in the ranges of 20–28% (belt presses), 20–35% (decanting centrifuges), and 28–45% (filter presses), respectively [49,50]. At least 28–33 wt.% of solid is typically needed in theory to initiate auto-thermal combustion of sewage sludge without auxiliary fuel [17]; however, 40–50 wt.% of solid material is the minimum practical requirement for MSS incineration [51]. Total energy gain from sludge combustion must be considered against the drying demand for higher solid content. Therefore, waste incineration plants typically accept sludge with 60 wt.% of solid material and higher for co-incineration [16,34] to not disturb their positive energy balance. For sludge, mono-combustion positive energy balance occurs when solid content is more than 70 wt.% [20].

Besides the mentioned issues regarding moisture content, MSS undergoes a sticky phase at a solid content of 55–70 wt.% [52], which makes it difficult to handle and feed to the incinerator. Since combustion plants are usually centralized and sludge feed is completely or partially transferred to the plant from different wastewater treatment plants, sludge with higher solid content is favorable unless it crosses the sticky phase zone. To meet these practical requirements, this study assumed that, in the case of mono-combustion, digested semi-dried MSS with 50 wt.% solid content enters the combustion plant, dried to 80 wt.% solid by a hot air dryer.

There is an opportunity to decrease the energy demand for drying and enhance P recovery by blending MSS with agricultural residues with low moisture content. Through thermochemical post-treatment with K and Na additives apatite ($Ca_5(PO_4)_3OH$) in SSA, which is poorly plant-available, alters to a more plant-available form of P such as $CaNaPO_4$ [22]. Agriculture residues can be K-rich and applicable as K additives [53]. It has been shown that the co-combustion of MSS with K-rich agricultural residue, such as wheat straw (WS), analogously transfers the ash formation pathway toward K-bearing phosphates instead of the Ca/Fe/Al phosphates otherwise dominate the SSA [30]. Typical characteristics of MSS and WS are shown in Table 1 [54,55]. Häggström et al. examined the co-combustion of MSS with various agriculture residues in different mass ratios. They showed desirable P species ($Ca_9MgK(PO_4)_7$ and $CaKPO_4$) only forms when MSS is in a low share of the fuel mixture

(90% WS and 10% MSS) [30]. They also showed that in this fuel mixture, at least 42% of P in the ash was found in a plant-available form (28% $Ca_9MgK(PO_4)_7$ and 14% $CaKPO_4$) [30].

Table 1. Typical MSS and WS characteristics and ash composition (ar: as received, db: dry base) [54,55].

Fuel Characteristics	WS		MSS	
	min	max	min	max
Moisture content (wt% ar)	8.3	17.4	53	77.6
Ash content (wt%,db)	3.06	9.55	29	54.5
Volatile material (VM) (wt%,db)	71.1	81.2	39.7	60.4
Fixed carbon (FC) (wt%,db)	14.9	19.3	2.1	11.5
C (wt%,db)	42.9	48.3	23.1	36.5
H (wt%,db)	3.1	5.96	2.6	5.3
O (wt%,db)	38.3	45.6	10.3	32.5
N (wt%,db)	0.28	1.54	1.4	5.6
S (wt%,db)	0.03	0.29	0.5	1.88
Cl (mg/kg)	200	500	300	800
High heating value (MJ/kg,db)	16.4	20.7	7.2	16.7
Ash Analyses (mg/kg ash)	WS		MSS	
	min	max	min	max
Si	217,371	339,380	72,778	200,000
Al	1535	3017	30,278	116,000
Fe	1259	4057	100,000	233,645
Pb	n.a	n.a	22	424
Mn	387	697	421	1938
Ca	67,896	109,348	37,400	94,884
Mg	12,062	20,505	3673	13,256
Na	5564	7419	1430	8500
K	9132	152,747	1102	18,600
P	7419	16,583	48,900	105,030

In summary, by co-combusting MSS with carefully selected agricultural residues, a plant-available ash-based PF can potentially be obtained without subsequent post-treatment while simultaneously avoiding energy-intensive and expensive drying. Therefore, both co-combustion of an optimal fuel mixture (90% WS, 10% MSS) and mono-combustion (100% MSS) were considered in the technology scenarios in this study.

2.3. The Final Destinations of the Ash Residue

Although significant volume reduction is one of the main advantages of MSS combustion [22,56], it is not a zero-waste operation. Thus, combustion plants always have an output in the form of ash, which is normally not associated with any economic gains, but typically instead incurs a cost for the plant owner. In the mono-combustion scenarios in this study, the effect of three different ash destinations on the economic performance of the combustion plant was investigated: landfilling, transfer of the ash to another industrial process (zero-cost disposal), and implementation of a post-treatment process.

On a dry base, MSS usually contains around 30–50% ash [34] which mainly contains SiO_2, CaO, Al_2O_3, Fe_2O_3, MgO, and P_2O_5) (see Table 1) [57]. The high amount of CaO and SiO_2 enables the ash to be a partial alternative ingredient of building materials [58,59]. This option removes the ash disposal cost, but it may eliminate the opportunity to recover the P instead. The Ash Dec process was selected for the post-treatment as it is a commercially available and approved process for producing fertilizer from SSA without further treatment [19,29,30].

As mentioned in Section 2.2, a well-selected fuel mixture was hypothesized to yield ash with plant-available P without any requirement for post-treatment in the co-combustion case. Research is still ongoing on different fuel mixtures, and how much of the P in the ash could be sellable as a competitor to commercial fertilizers [33]. Here, it was assumed that 50% of P [30] in the ash of the given fuel mixture has fertilizer value and that it would be directly sellable as plant-available PF in the applicable cases (co-combustion direct PF, see below).

2.4. Products

Three different potential products were considered from the combustion plant: heat for district heating, electricity, and PF, in different combinations. Of those, electricity and heat are already well-established market products, while full-scale production PF from SSA has yet to reach its full potential [13,57].

2.5. Scenario Summary

Table 2 summarizes the modeled scenarios, as described in the previous sections, regarding the four selected technology variations.

Table 2. Overview of modeled technology scenarios. For details, see the text.

Scenario	Boiler Capacity (MW)	Boiler Type	Fuel (MSS/WS wt%,db)	Ash Destination				Energy Recovery	
				Ash Landfill	Zero-cost Ash Handling [a]	Ash Post-Treatment [b]	Direct Use	Heat	Electricity
(1)-10MW-mono-heat only-with landfill	10	GB	100/0	yes	no	no	no	yes	no
(2)-10MW-mono-heat only-without landfill	10	GB	100/0	no	yes	no	no	yes	no
(3)-10MW- mono-heat and PF	10	GB	100/0	no	no	yes	no	yes	no
(4)-10MW-mono-CHP with landfill	10	GB	100/0	yes	no	no	no	yes	yes
(5)-10MW-mono-CHP-without landfill	10	GB	100/0	no	yes	no	no	yes	yes
(6)-10MW-mono-CHP and PF	10	GB	100/0	no	no	yes	no	yes	yes
(7)-10MW-co-heat-direct PF	10	GB	10/90	no	no	no	yes [c]	yes	no
(8)-10MW-co-CHP-direct PF	10	GB	10/90	no	no	no	yes [c]	yes	yes
(9)-100MW-mono-heat only-with land fill	100	FB	100/0	yes	no	no	no	yes	no
(10)-100MW-mono-heat only-without landfill	100	FB	100/0	no	yes	no	no	yes	no
(11)-100MW-mono-heat and PF	100	FB	100/0	no	no	yes	no	yes	no
(12)-100MW-mono-CHP and landfill	100	FB	100/0	yes	no	no	no	yes	yes
(13)-100MW-mono-CHP without landfill	100	FB	100/0	no	yes	no	no	yes	yes
(14)-100MW-mono-CHP and PF	100	FB	100/0	no	no	yes	no	yes	yes
(15)-100MW-co-heat-direct PF	100	FB	10/90	no	no	no	yes [c]	yes	no
(16)-100MW-co-CHP-direct PF	100	FB	10/90	no	no	no	yes [c]	yes	yes

[a] Labeled "without landfill" in the scenarios, as there is no landfill cost in this case except the landfill of the residue of flue gas cleaning system. The ash was assumed to be transferred to another industrial process at zero cost. [b] Ash post-treatment using Ash Dec. The waste of ash post-treatment process is landfilled. [c] Co-combustion scenarios include the landfill cost of the fine ash.

3. Methodology and Input Data

The different combustion plant configurations in the technology scenarios were modeled using Aspen Plus®in order to obtain mass and energy balances. The obtained balances were used as the basis for the economic evaluations to calculate the required minimum selling prices (MSP) of the considered products (energy carriers and PF) for different operation and market conditions.

3.1. Process Modeling

A combustion plant flowsheet model, partly based on Salman et al. [59], was developed using the commercial software Aspen Plus®to obtain mass and energy balances for the technology scenarios (Figure 2). The characteristics of digested MSS and WS taken in this study are shown in Table 3, which falls in the typical range of characteristics of MSS and WS by considering the data shown in Table 1. Digested MSS is dried by a hot air dryer before entering the boiler for plant configurations involving a dryer. MSS was modeled as a non-conventional solid through ultimate and proximate analyses according to data in Table 3. For this reason, the boiler section was modeled as two reactors: an RYield reactor that decomposes the MSS to its constituent elements, in tandem with an RGibbs reactor that simulates the combustion reactions considering thermodynamic equilibrium by minimizing the Gibbs free energy. These two reactors are connected with a heat stream to include the decomposition energy in the combustion. The steam generation section contains three heat exchangers to represent the economizer, evaporator, and superheater, where the combustion products from the boiler section pass on one side of the heat exchangers, and boiler feed water flows on the other side. Flowrates of hot air for the dryer, excess air for combustion, and boiler feedwater were calculated based on the mass and energy balance using the calculator box and design spec options in Aspen Plus®. Calculations for unknown variables were calculated using in-line Fortran.

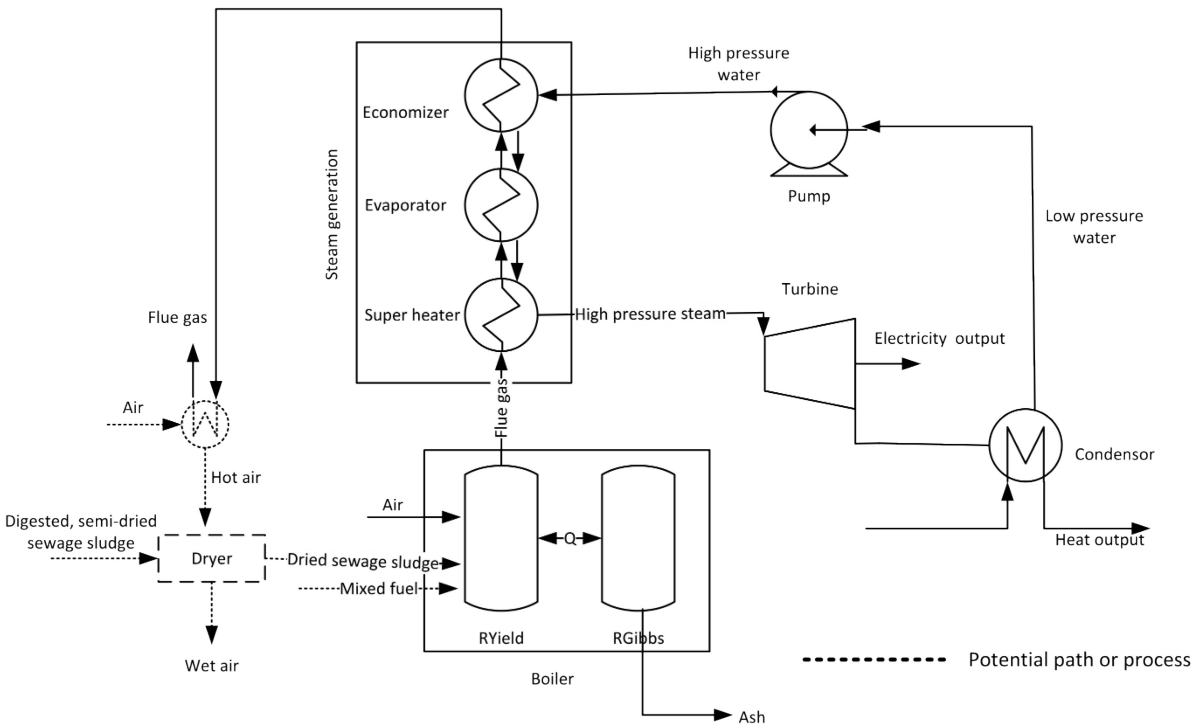

Figure 2. Simplified process flow diagram of the modeled combustion plant. Boxes represent modules containing two or more pieces of equipment.

Table 3. Data applied in the simulations.

Fuel Characteristics		
	MSS [a]	WS [b]
Proximate	%	%
Moisture	50	10.25
FC	8.6	18.68
VM	53	77.2
Ash	38.4	4.12
Ultimate	wt%,db	wt%,db
Ash	38.4	4.1
C	31.1	46.56
H	4.2	5.68
N	3.3	0.43
Cl	0.9	0.2
S	1.1	0.064
O	21	42.9
P_2O_5 in the ash	21	2.7
High heating value (MJ/kg)	13.9	18.8
Process Data		
Dryer output moisture content (%)		20
Combustion temperature (°C)		900
Steam pressure (bar)		45
Steam temperature (°C)		450
Stack temperature (°C)		120
Excess air (%)	GB	80
	FB	30
District heating temperature (°C)	inlet	40
	outlet	95

[a] Digested MSS based on the work of [44]. [b] Wheat straw based on the work of [30].

All the P in the MSS transfers to the SSA in combustion [32], although it can be collected from different ash fractions; therefore, in this study, the entire fuel P content was considered in the calculation. A black box method based on data from the literature [29] was used for the ash post-treatment for P recovery through the Ash Dec process. Detailed data can be found in Appendix A (Table A1).

3.2. Economic Analysis

The economic viability of energy recovery and PF production from MSS was evaluated by calculating the final products' MSP (Equation (1)), which indicates the break-even point for the investment. In addition, a feedstock gate fee (receiving fee paid by local authorities to the waste processing facility, per unit of inlet waste) was applied to indicate the financial dependency of MSS-based products on external support. The gate fee per ton of received MSS was thus considered as potential revenue, when applicable. The fuel price for the MSS price was correspondingly set to zero.

$$MSP_i = \frac{Annualized\ CAPEX + OPEX - revenue_j}{annual\ production\ of\ i} \quad (1)$$

where MSP_i is the minimum selling price of the target product *i*, where product *j* represents other sold products. The total capital investment cost *(CAPEX)* of each scenario was estimated from the literature. Details of included equipment can be found in Appendix A (Table A2). The CAPEX was inflation-adjusted to €$_{2020}$ using the chemical engineering plant cost index and an exchange rate of 0.85 €/US$. The reference costs were also adjusted to the desired scale through Equation (2).

$$Cost\ in\ desired\ scale = Cost\ in\ reference\ scale \times \left(\frac{desired\ scale}{reference\ scale}\right)^{0.8} \quad (2)$$

The *CAPEX* was annualized applying an annuity factor of 10%, corresponding to an internal rate of return of 8% and 20 years of lifetime. The costs associated with land, design, engineering, and construction were excluded from the investment costs. Regarding operation cost (*OPEX*) of each scenario, labor, scheduled maintenance, routine component/equipment replacement, and insurance costs were considered in the fixed operation costs, which were set as 4% of the CAPEX [60,61]. The variable operation costs include chemicals required for the flue gas cleaning and Ash Dec process, energy (electricity and natural gas), disposal costs (ash and hazardous waste), and fuel price (WS) (see Table A1 in Appendix A). The 50–100% increase in fuel price based on WS price was also considered to capture the effect of fuel preparation costs. Hazardous waste refers to the flue gas cleaning waste containing fine ash with high HMs concentrations. Based on Hermann et al. [29], it was assumed that the fine ash constitutes 3% of the total ash in all scenarios. Produced electricity, in CHP scenarios, first covers internal demands, and then the rest can be sold to the market.

The gate fee for the target product *i* manifests the gap between MSP_i and the estimated market price *i*, which must be compensated by external revenue based on inlet feedstock Equation (3). Table 4 contains the details of MSP and gate fee calculations for each scenario.

$$Gate\ fee_i = \frac{MSP_i - Market\ price\ _i}{Requried\ sewage\ sludge\ per\ unit\ of\ i} \quad (3)$$

Operation and Market Variations

Energy costs and revenues for heat, electricity, and PF can be subject to significant volatility, following various market conditions, which was reflected here by applying different prices. The impact of electricity and heat market prices on the plant's economic viability was further evaluated for three different annual utilization hours; 3500, 5000, and 8000 h/year, where 5000 h/year was used as the base case. Table 5 summarises the applied energy and chemical prices, as well as variations in prices and other varied operational parameters.

Table 4. MSP and gate fee calculation for the scenarios.

Scenarios	Scenario Number	MSP	Gate Fee
Heat-only [a]	1,2,9,10	$MSP_{heat} = \frac{Annualized\ CAPEX+OPEX}{Annual\ production\ of\ heat}$	$Gate\ fee_{heat} = \frac{MSP_{heat} - Heat\ market\ price}{t_{sewage\ sludge}\ per\ MWh_{heat}}$
CHP [b]	4,5,12,13	$MSP_{heat} = \frac{Annualized\ CAPEX+OPEX-electricity\ revenue}{Annual\ production\ of\ heat}$	
Heat+ direct PF [c]	7,15	$MSP_{heat} = \frac{Annualized\ CAPEX+OPEX-direct\ PF\ revenue}{Annual\ production\ of\ heat}$	
CHP+ direct PF [c]	8,16	$MSP_{heat} = \frac{Annualized\ CAPEX+OPEX-electricity\ revenue-direct\ PF\ revenue}{Annual\ production\ of\ heat}$	
Heat+PF [d]	3,7,11,15	$MSP_{PF} = \frac{Annualized\ CAPEX+OPEX-heat\ revenue}{Annual\ production\ of\ P\ fertilizer}$	$Gate\ fee_{PF} = \frac{MSP_{PF} - PF\ market\ price}{t_{sewage\ sludge}\ per\ t_{PF}}$
		$MSP_{heat} = \frac{Annualized\ CAPEX+OPEX-Recoverd\ PF\ revenue}{Annual\ production\ of\ heat}$	
CHP+PF [e]	6,8,14,16	$MSP_{PF} = \frac{Annualized\ CAPEX+OPEX-heat\ revenue-electricity\ revenue}{Annual\ production\ of\ P\ fertilizer}$	
		$MSP_{heat} = \frac{Annualized\ CAPEX+OPEX-electricity\ revenue-Recoverd\ PF\ revenue}{Annual\ production\ of\ heat}$	

[a] No products besides heat. [b] The MSP was calculated for the output heat as the electricity market can be regarded as a more distinct market than heat. [c] Co-combustion of MSS with WS. A total of 50% of the P in the produced ash was assumed to be sellable at the market price of a commercial fertilizer (triple superphosphate), based on [30]. The MSP was calculated for the output heat for all scenarios as the electricity market can be regarded as a more distinct market than heat. [d] The MSP was calculated for both PF and heat. For MSP_{PF}, the estimated market heat price is taken since the SSA-based PF market is unclear. However, for comparison with other scenarios, MSP $_{heat}$ is calculated when produced P was assumed sellable at the market price of commercial fertilizer (triple superphosphate) [62]. [e] The MSP was calculated for both PF and heat. For MSP_{PF}, electricity and estimated heat market prices are taken since the SSA-based PF market is unclear. However, for comparison with other scenarios, MSP heat is calculated when produced P was assumed sellable at the market price of commercial fertilizer (triple superphosphate) [62].

Table 5. Energy and chemical prices and operational parameters used in the economic evaluations.

Parameter	Unit	Base Value	Variation	Reference
Varied Parameters				
Electricity selling price [a]	€/MWh	40	10/40/60	[63,64]
Electricity buying price [b]	€/MWh	81	40/81/140	
Heat selling price [c]	€/MWh	-	5/30	[15]
WS [d]	€/t	14	21–28	[65]
Annual plant operation time	h/y	5000	3500/5000/8000	
Fixed parameters				
Natural gas price [e]	€/MWh	31	-	[66]
Na_2SO_4	€/t	80	-	[28,29]
$Ca (OH)_2$	€/t	90	-	
Coke	€/t	400	-	
NaOH	€/t	90	-	
NH_3 25%	€/t	150	-	
Water	€/m^3	0.5	-	[67]
Ash landfilling	€/t	50	-	[28]
Hazardous waste landfilling [f]	€/t	120	-	
Sewage sludge	€/t	0	-	-
Commercial fertilizer (triple superphosphate) [g]	€/t	267	-	[62]

[a] Electricity wholesale market price in Europe, variation covers minimum, mean, and maximum electricity wholesale market prices during 2020. [b] Average national price in the EU without taxes applicable for the first semester of each year for medium-sized industrial consumers [63]. [c] A ratio of 0.5 between heat and electricity market prices was assumed. [d] Fuel preparation cost (e.g., mixing and pelletizing) in the co-combustion plant was considered from 50% to 100% increase compared to WS price reported by [65]. [e] Natural gas is included in the energy balance of the Ash Dec process, which was incorporated as a black box. Natural gas price is fixed based on non-household consumers in the first half of 2020 in the EU [66]. [f] Flue gas cleaning waste that contains HMs in high concentration. In all scenarios, the hazardous waste was assumed at 3% of the total ash [29]. [g] Used to estimate the value of the ash P in the direct PF scenarios. The sellable P in the ash was assumed to amount to 50% of the total P of the ash.

4. Results

4.1. Mass and Energy Balances

The results from the Aspen Plus®simulations are summarized in Table 6. The heat demand for drying in the mono-combustion scenarios (1–6, 9–14) accounts for 27–36% of the total output heat. Contrarily, the co-combustion scenarios (7, 8, 15, 16) eliminate the drying demand and result in a fuel mix heating value 32% higher than for the pure MSS fuel. The co-combustion thus shows a dual-energy advantage compared to the mono-combustion: no dryer needed and an overall higher heat production potential. Regarding ash residues and P production, the results show that mono-combustion yields a higher output of P per ton of fuel (scenarios 1–6, 9–14) than co-combustion (scenarios 7, 8, 15, 16). This demonstrates the presence of technical and financial trade-offs regarding fuel selection for a combustion plant. It is worth noting that local limiting factors, such as city size or availability of suitable biomass fuels for co-combustion, would obviously also affect the fuel selection.

Table 6. Summary of resulting mass and energy flows for all simulated scenarios.

Scenario	Heat Output (MWh)	Electricity Output (MWh)	Drying Energy (MWh)	Electricity Demand (MWh)	Fuel [a] (t/h)	Ash (t/h)	P Production (kg/h)
(1)-10MW-mono-heat only-with landfill	6.6	0	1.8	0.61	5.29	1.01	0
(2)-10MW-mono-heat only-without landfill	6.6	0	1.8	0.61	5.29	1.01	0
(3)-10MW- mono-heat and PF	6.6	0	1.8	0.65	5.29	1.01	90
(4)-10MW-mono-CHP- with landfill	4.9	1.35	1.8	0.61	5.29	1.01	0
(5)-10MW-mono-CHP-without landfill	4.9	1.35	1.8	0.61	5.29	1.01	0
(6)-10MW-mono-CHP and PF	4.9	1.35	1.8	0.65	5.29	1.01	90
(7)-10MW-co-heat+direct PF	8.7	0	0	0.46	2.25	0.14	1.39 [b]
(8)-10MW-co-CHP+direct PF	7.0	1.43	0	0.46	2.25	0.14	1.39 [b]
(9)-100MW-mono-heat only-with landfill	67	0	19	6.17	53.7	10.3	0
(10)-100MW-mono-heat only-without landfill	67	0	19	6.17	53.7	10.3	0
(11)-100MW-mono-heat and PF	67	0	19	6.58	53.7	10.3	919
(12)-100MW-mono-CHP and landfill	53	14.0	19	6.17	53.7	10.3	0
(13)-100MW-mono-CHP-without landfill	53	14.0	19	6.17	53.7	10.3	0
(14)-100MW-mono-CHP and PF	53	14.0	19	6.58	53.7	10.3	919
(15)-100MW-co-heat+direct PF	89	0	0	4.67	22.6	1.40	13.8 [b]
(16)-100MW-co -CHP+ direct PF	71	18.2	0	4.67	22.6	1.40	13.8 [b]

[a] As received. [b] P balance calculation is performed based on the assumption that 50% of the P content of the ash is as useful as commercial PF.

4.2. Economic Results

Table 7 summarises the resulting investment costs, operation costs, heat and PF MSPs, and gate fees for all analyzed technology scenarios, for the base parameter values used in the evaluations, and for the minimum and maximum applied heat and electricity market prices (according to Table 5). The following sections explore the results per group of technology scenarios and for all economic parameter variations. 'Direct PF' scenarios are explored in relation to landfilling and zero-cost ash handling ('without landfill') for heat-only and CHP scenarios (Section 4.2.1 Heat−Only and Heat+Direct PF Product Scenarios and Section 4.2.2), while the 'PF' scenarios (with ash post-treatment) are explored separately (Section 4.2.4 PF Production Scenarios).

4.2.1. Heat−Only and Heat+Direct PF Product Scenarios

This group of scenarios (1, 2, 7, 9, 10, 15) found the lowest heat MSPs in the 100 and 10 MW co-combustion scenarios (15 and 7), at 19 and 27 €/MWh, respectively. For these scenarios, the lower investment, energy, and chemicals costs of the co-combustion thus had a bigger impact than economy-of-scale effects (compare to scenario 10, with the lowest MSP of the mono-combustion scenarios, at 29 €/MWh). Planning for ash destination is critical for the plant's economic performance since ash landfilling, as a common approach, accounts for 17% to 25% of the operation cost in the studied mono-combustion plants. Even with zero-cost disposal ('without landfill' scenarios), the heat MSP for mono-combustion was still 52% to 63% higher than for co-combustion, for 10 and 100 MW, respectively, because of the drying demand.

Conversely, the contribution of direct PF recovery in the co-combustion scenarios ('direct PF') was negligible, with revenue covering less than 0.1% of the operation costs. This is due to the low initial P content of the ash. Even if all the ash P would be plant-available, the revenue would still cover less than 1% of the operation costs. A change of the fuel cost (co-combustion) of 50–100% caused an increase in the heat MSP of 4–11% (10 MW) and 20–21% (100 MW), respectively.

Table 7. Summarizing economic results for all scenarios, for the base parameter values (average electricity prices, operation time of 5000 h/y). MSPs and gate fees are given for the minimum (5 €/MWh) and maximum (30 €/MWh) heat market prices.

Scenarios	Specific Investment Cost (€/kW [a])	Specific Operation Cost (€/MWh [b])	MSP_{heat} (€/MWh)	MSP_{PF} (€/kg PF)	Gate Fee_{heat} [c] (€/t)	Gate Fee_{PF} [c] (€/t)
(1)-10MW-mono-heat only-with landfill	1187	28	53	-	60–29	-
(2)-10MW-mono-heat only-without landfill	1187	19	44	-	49–17	-
(3)-10MW- mono-heat and PF	2175	82	77 [d]	5.6–3.8	90–59	92–61
(4)-10MW-mono-CHP-with landfill	2004	71	66	-	57–34	-
(5)-10MW-mono-CHP-without landfill	2004	60	55	-	47–23	-
(6)-10MW-mono-CHP and PF	3328	111	98 [d]	5.5–4.1	87–64	90–66
(7)-10MW-co-heat+direct PF	619	14	27	59–0	86–0	731–0
(8)-10MW-co-CHP+direct PF	1050	35	30	55–0.3	78–0	682–0.9
(9)-100MW-mono-heat only-with landfill	646	23	37	-	40–9	-
(10)-100MW-mono-heat only-without landfill	646	15	29	-	30–0	-
(11)-100MW-mono-heat and PF	1271	56	51 [d]	3.7–1.9	57–26	60–29
(12)-100MW-mono-CHP and landfill	1352	52	47	-	41–16	-
(13)-100MW-mono-CHP-without landfill	1352	42	36	-	31–6	-
(14)-100MW-mono-CHP and PF	2143	77	64 [d]	3.8–2.4	58–33	61–36
(15)-100MW-co-heat+direct PF	371	11	19	40–0	59–0	487–0
(16)-100MW-co-CHP+direct PF	902	31	23	41–0	57–0	506–0

[a] Boiler capacity. [b] Output heat. [c] Given as €/t received MSS. [d] It is assumed that the produced PF is sold at market price to calculate heat MSP in a uniform method.

Figure 3 indicates the sensitivity of the economic performance to the annual utilization hours and the electricity buying price. The difference between the heat MSPs and the heat market prices depicts how far the plant is from economic viability. Longer annual utilization time, larger plant size, and lower electricity buying price are all factors contributing to a decreasing heat MSP.

However, city size and transportation distance are local limiting elements for scaling MSS combustion plants. Assuming MSS production per capita is 19 kg/inhabitant, y dry base [68] with 8000 h/year operation, a city with 1.1 million inhabitants would be needed to provide sludge for one 10 MW mono-combustion plant and 11 million inhabitants for 100 MW. Therefore, the applicability of 10 MW mono-combustion plants would narrow down to relatively few cities, from a European perspective, and 100 MW mono-combustion plants would inevitably be centralized plants, the economic feasibility of which would be bound to transportation costs affected by distance and moisture content. For co-combustion, the scale of the plant would be less sensible to MSS supply and population, but the availability of suitable biomass and transportation costs would be instead ruling factors for decision makers.

Although co-combustion resulted in lower MSP, none of the scenarios were cost-efficient without a high heat market price or the existence of a gate fee. Depending on the fuel, the heat market price, plant size, and ash handling options, a gate fee between 0 and 86 € per ton of received MSS was needed to achieve the economic feasibility of heat production from sewage sludge. Co-combustion, with high solid content, low total amount of fuel, and low share of sewage, resulted in higher required gate fee per ton of MSS to fill the gap between production cost and market price. Therefore, the external financial support to prompt investments in co-combustion for P recovery should focus on output energy rather than the feedstock. Otherwise, for decision makers, mono-combustion with a lower gate fee gets priority, even though it excludes P recovery.

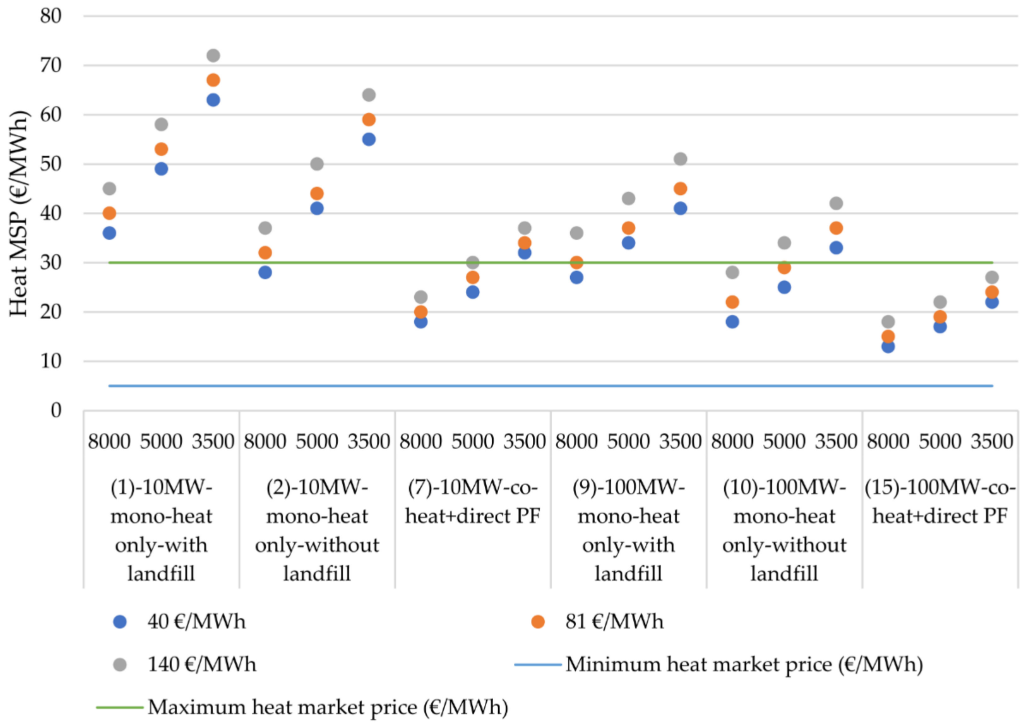

Figure 3. Heat MSPs (€/MWh) for varying annual utilization hours (8000, 5000, 3500 h/year) and buying electricity prices (40, 81, 140 €/MWh).

4.2.2. CHP and CHP+direct PF Product Scenarios

In this group of scenarios (4, 5, 8, 12, 13, 16), electricity production accounted for a 20% increase in investment cost for 10 MW and a 40% increase for 100 MW plants compared to the corresponding heat-only plants, with a subsequent higher heat MSP. However, at low heat market price (5 €/MWh), a slightly lower gate fee was in fact needed compared to in the corresponding heat-only and heat+direct PF scenarios due to the electricity production revenues. This advantage of CHP declined with the higher heat price (30 €/MWh).

Similar to the heat-only scenarios, the MSP for mono-combustion was higher than for co-combustion, while co-combustion required a higher gate fee per ton of received MSS at the low heat price. When changing the fuel cost by 50–100% for co-combustion, the heat MSPs increased by 7–13% (10 MW) and 13–21% (100 MW), respectively. Electricity market price is the main trigger of investing in electricity production in MSS combustion plants. Figure 4 shows the annual CAPEX related to electricity production versus the economic benefits of either supplying internal demand (saving revenue) or selling to the market (selling revenue) in 10 MW and 100 MW mono-/co-combustion plants respectively. Generally, a plant with high annual utilization hours is economically preferable, yet the level of economic benefits as the main motivation of investment builds upon the market prices. In relative terms, saving revenues contribute more to the mono-combustion plants' economic performance due to the higher energy demand compared to co-combustion. Conversely, the higher electricity production for co-combustion results in higher selling revenues.

Although end-use electricity prices are linked to various factors such as wholesale market price (taken as selling price in this study), it is reported that the coupling of wholesale and end-use electricity prices is not close in many countries [69]. Therefore, the analysis consists of the comparison of extreme prices. According to the result, even if the buying and selling electricity prices are the same, plants still need to have high utilization hours to be economically feasible. Otherwise, electricity production is economically inefficient, or the benefits of electricity production only compensate for the costs. The economic feasibility of the 10 MW plant shows more flexibility toward lower market prices caused by the scaling method. This method is common in pre-feasibility that is in favor of small-scale equipment. In the extreme prices, a high electricity buying price stimulates investment in CHP in mono-combustion plants, and a high electricity selling price promotes investment in CHP in co-combustion plants, especially in 100 MW plants.

Figure 5 summarizes the heat MSPs of CHP scenarios (4, 5, 8, 12, 13, 16) for different annual utilization hours. When the utilization time is 8000 h/ year, 100 MW CHP plants show better economic performance than heat-only production (See Figure 3), while the reverse is true for lower annual operation time. The reason is that the internal electricity demand is covered by produced electricity, and the cost difference between buying and selling electricity prices makes a significant saving revenue. For a given boiler capacity, co-combustion has lower heat MSP and less sensitivity to the utilization hours due to several reasons such as higher heat revenue, the reduction in ash landfilling cost from operation costs, and lower energy cost in comparison to mono-combustion.

4.2.3. Comparing Heat-Only to CHP Scenarios

Figure 6 explores in more detail the share of different costs and revenues in all CHP and heat-only scenarios for the base parameter values (Table 5) except 'PF' scenarios (3,6,11,14). When comparing the corresponding co- and mono-combustion scenarios, in particular, the CAPEX and the avoided cost for landfilling contribute to the lower heat MSP. The general economic benefits of co-combustion regarding the deduction of investment on the dryer and drying energy demand may provide a better economic opportunity for energy and P recovery from sewage sludge. However, the mixing of MSS with WS dilutes the MSS P content and PF revenue. The increase in CAPEX for electricity production outweighs the economic benefits of electricity production unless the plant has a 100 MW boiler with 8000 h per years of operation (see Figure 4).

4.2.4. PF Production Scenarios

Part A of Figure 7 shows the PF MSPs in relation to the market heat price for the ash post-treatment ('PF') scenarios (3, 6, 11, 14) and part B for co-combustion ('direct PF') scenarios (7, 8, 15, 16). Here, electricity production revenues were found to only marginally affect the financial driving force for PF production from SSA, and only at very low heat market prices in 10 MW plants. For all the instances with ash post-treatment, the PF MSP was, in fact, found to be up to a magnitude higher than the considered commercial fertilizer price. The 100 MW heat-only scenario (11) resulted in the lowest PF MSP with 1.95 €/kg at a market heat price of 30 €/MWh, which can be compared to the commercial fertilizer price of 0.44 €/kg. Economically speaking, P recovery from SSA in the mono-combustion plant through post-treatment in all cases resulted in uncompetitive final prices and inefficient investment with heavy reliance on the gate fee (Table 7).

The direct PF production scenarios (7, 8, 15, 16) entail an opportunity for being a cost-effective P recovery strategy at a high market heat price. In these cases, the economic feasibility of the plant was independent of P production revenue since the heat revenue covered the annual costs, and the final PF could be sold at the market price. However, P recovery through post-treatment required external financial support in all cases. Despite the high initial P content of ash in mono-combustion, which is important to obtain feasibility of post-treatment implementation, the final product was several times more expensive than the commercial fertilizer product.

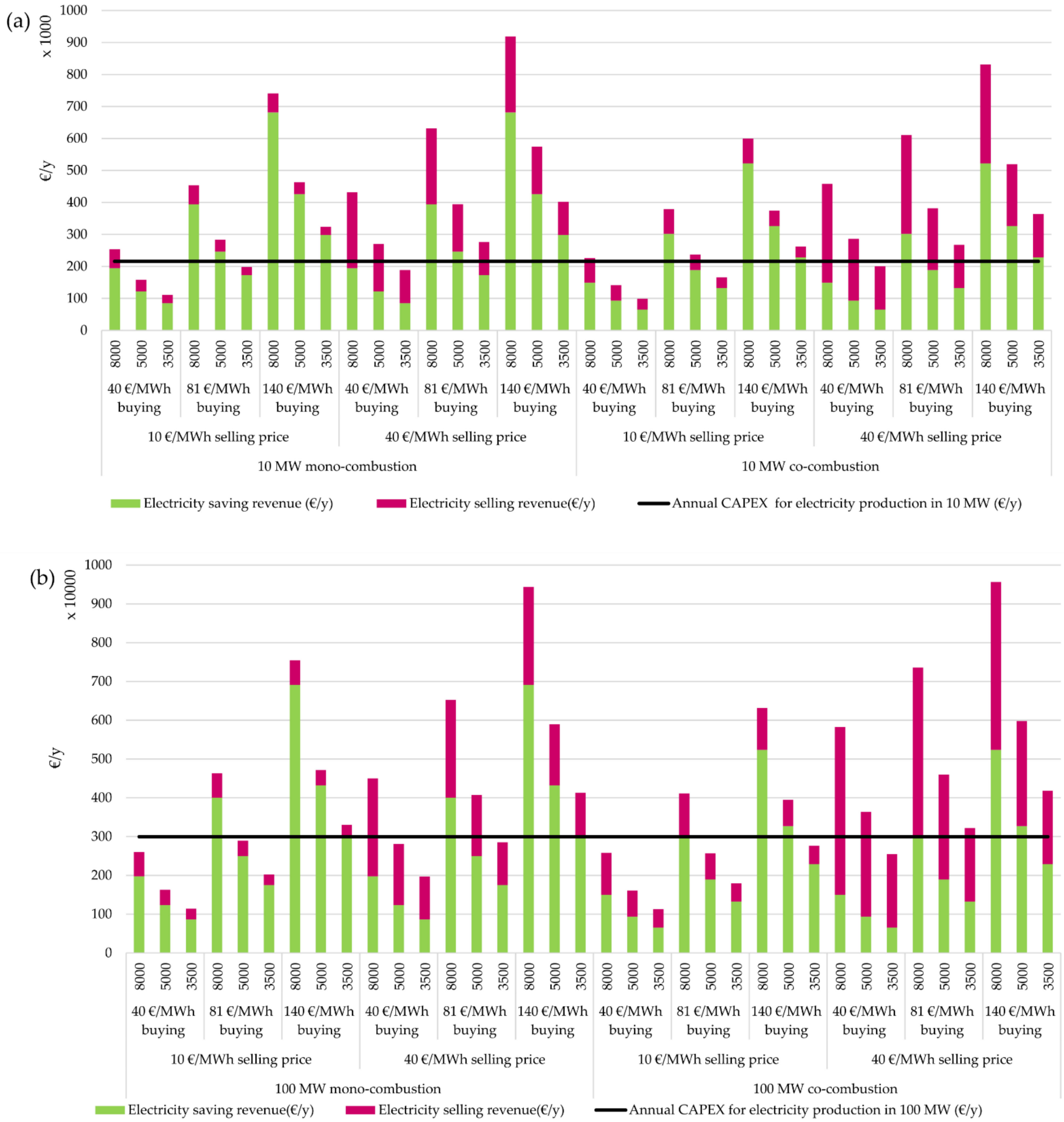

Figure 4. Total annual costs versus economic benefits of electricity production in the (**a**) 10 MW and (**b**) 100 MW mono-/co-combustion scenarios, respectively and for different electricity buying prices (40, 81, 140 €/MWh) and selling prices (10, 40, 60 €/MWh).

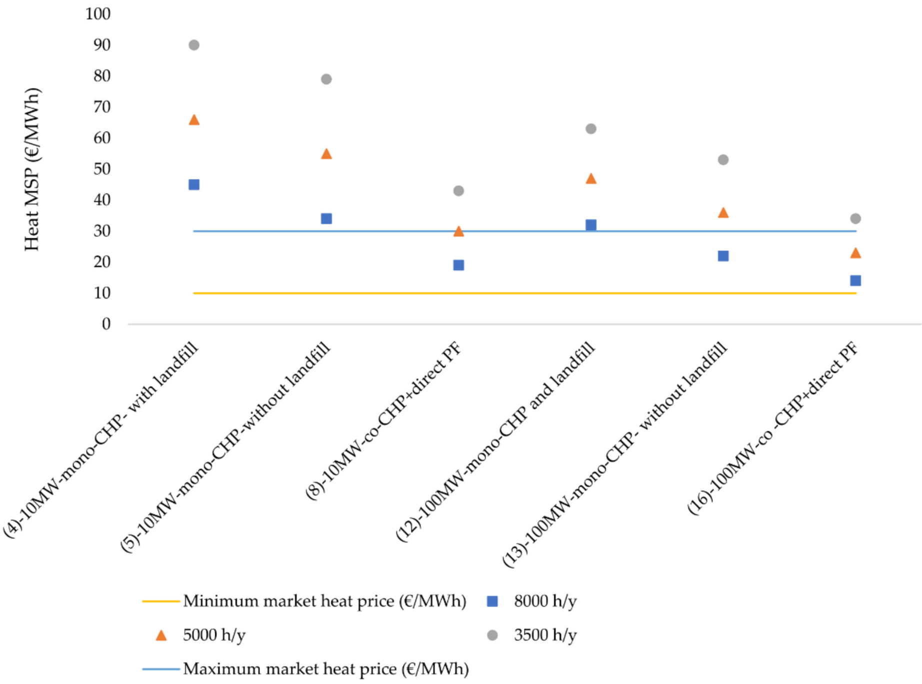

Figure 5. Heat MSP (€/MWh) for varying annual utilization hours for base value for electricity price.

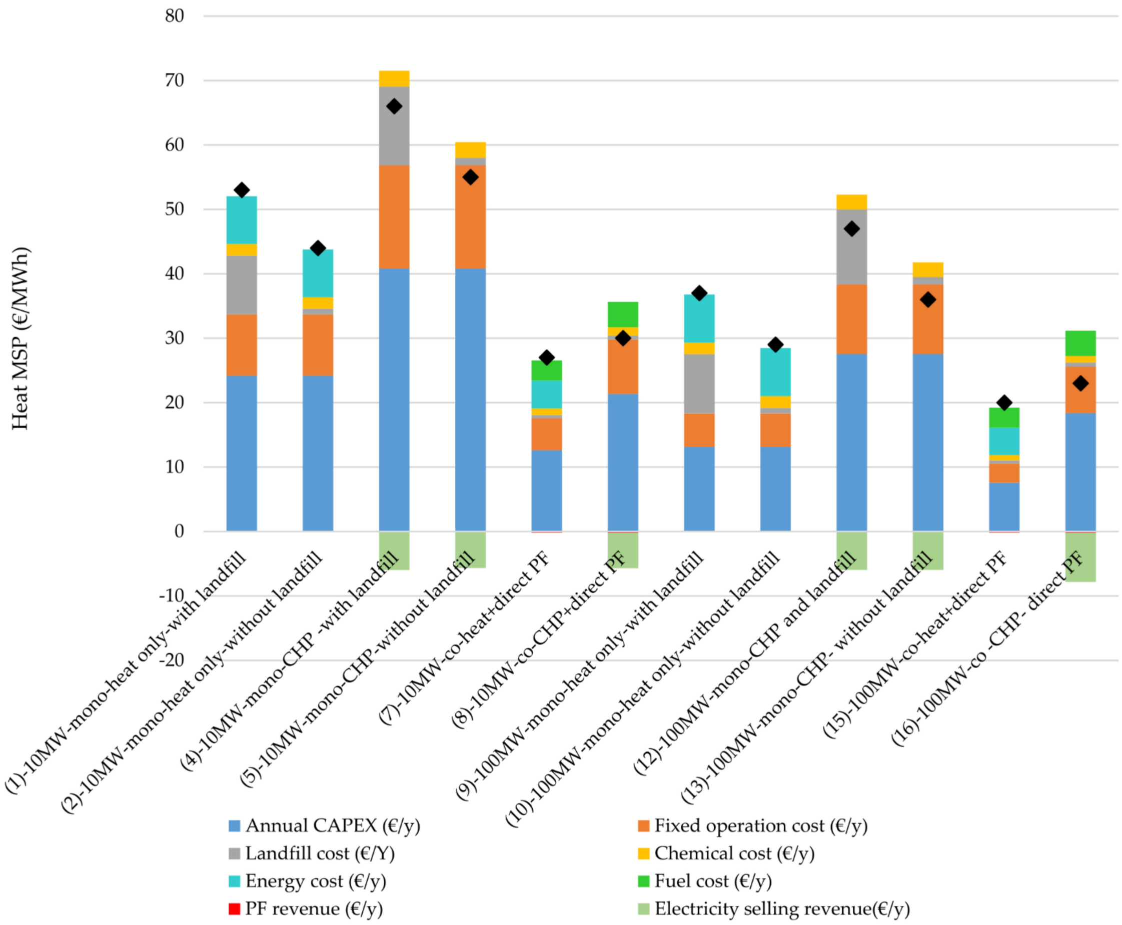

Figure 6. Cost and revenue break-down of the heat MSP in heat-only and CHP plants, at an annual utilization time of 5000 h/year.

Figure 8 shows the range of heat MSPs in the PF production scenarios that would be required to reach the point where ash-based PF can be sold at the market price. With the same utilization hours, electricity production impaired the economic feasibility of P recovery from MSS in both 10 and 100 MW plants. By selling ash-based PF at the market price, none of the cases were economically feasible regarding energy market prices. For example, the resulting heat-based gate fee for 100 MW heat-only and PF (scenario 11) was 26 €/t $_{\text{received MSS}}$, while the corresponding 100 MW heat-only landfill scenario (9) resulted in a gate fee of 9 €/t $_{\text{received MSS}}$.

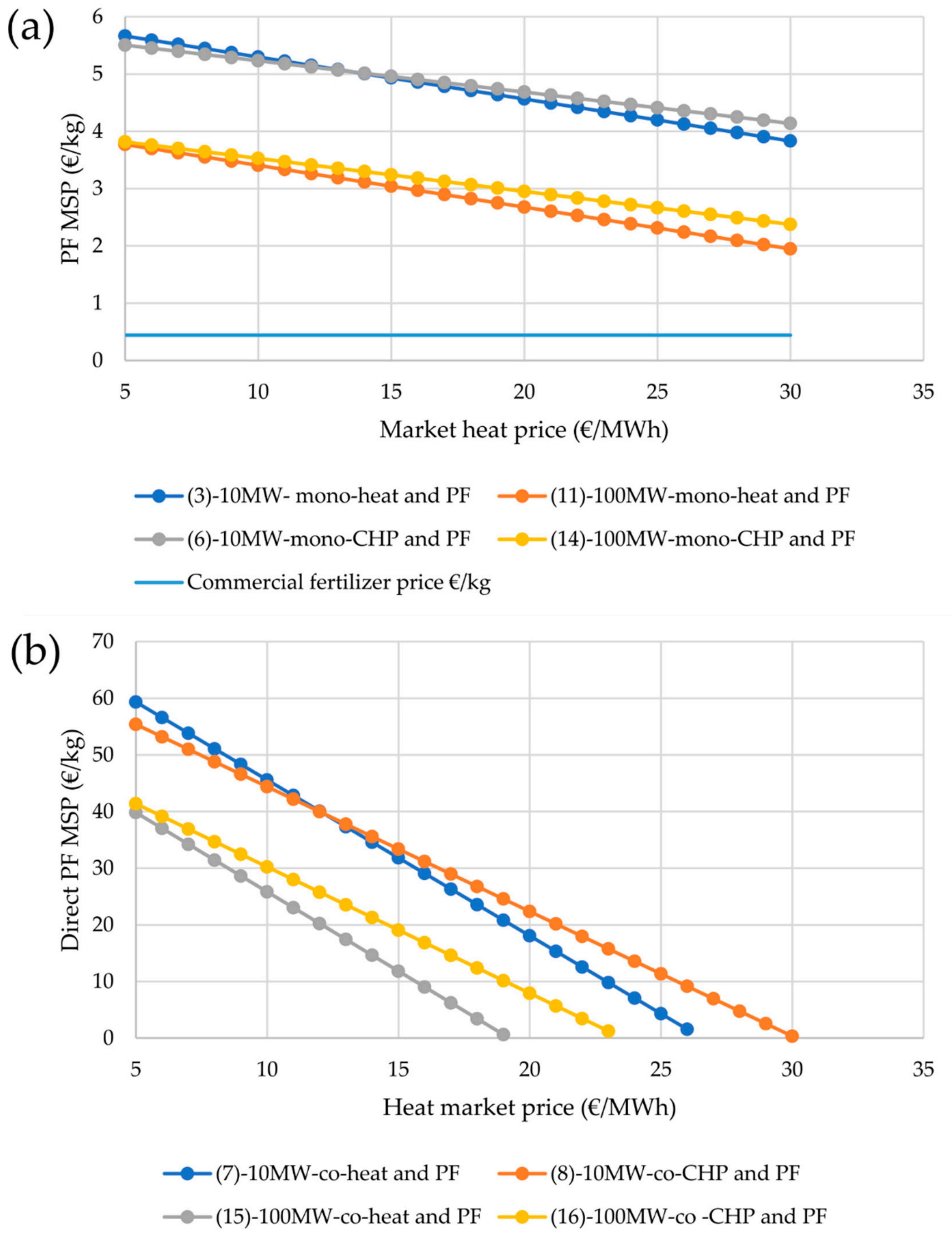

Figure 7. Sewage sludge-based fertilizer (PF) MSP (€/kg), for the base parameter values (average electricity prices, operation time of 5000 h/y), for (**a**) PF produced via ash post-treatment ('PF' scenarios), and (**b**) PF produced via co-combustion ('direct PF' scenarios).

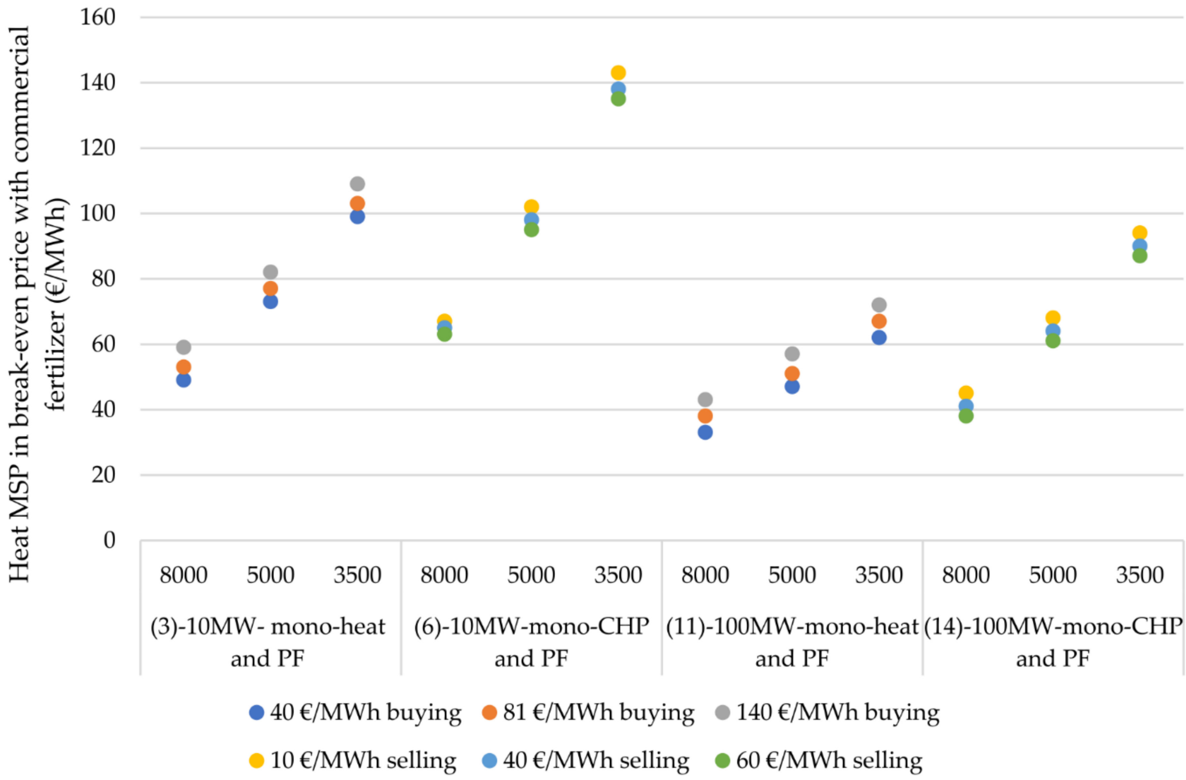

Figure 8. Required heat MSP (€/MWh) to reach break-even for ash-based versus commercial P fertilizer, for varying annual utilization hours (8000, 5000, 3500 h/year) and electricity prices.

5. Discussion

The development of MSS mono-combustion plants to recover both P and energy imposes higher financial responsibility on policymakers compared to only energy recovery or direct PF production through co-combustion development. P recovery from MSS ash through post-treatment appears to be an inefficient investment, and external financial support would be crucial to circulate P from MSS to the food production process.

The studied fluctuation of energy market prices along with different utilization hours can change production costs by 50%. Green energy subsidies or other financial support can be used as tools to aid investments in energy recovery from MSS and buffer against market uncertainty. On the other hand, the feedstock of the combustion plant must be semi-dried; otherwise, the process itself consumes most of the combustion heat to evaporate the moisture content. Therefore, the energy revenue of the plant drops dramatically, and the gate fee turns into the main income of the plant rather than the return on the recovered energy. MSS management strategy is conditional on the decision maker's perspective. When decision makers consider MSS as a waste to dispose of, the mono-combustion plant would be the most efficient option because of the lower required gate fee. However, when policymakers aim to recirculate P from MSS into the food production system, the advantages of co-combustion may outweigh the implementation of ash post-treatment in the mono-combustion plants.

Moreover, heat is an economically more favorable form of energy than electricity due to the MSS quality and local scalability barriers of MSS combustion plants. However, market heat prices depend on several aspects, the most prominent being the local heat demand, the availability of district heating distribution system, and alternative heat production costs (e.g., the presence of low-cost waste heat), and this adds more economic uncertainty to energy recovery from MSS mono-combustion.

Although 100 MW plants show better economic performance, the scalability of studied plants depends on the size of the collection area (availability of sludge), availability of desired biomass (low moisture and high K content) for fulfilling co-combustions goals (eliminate drying demand and direct PF production), and transportation demand. Costs related to centralization and transportation are unavoidable for 100 MW mono-combustion due to cities' populations. Therefore, trade-offs between the benefits of large-scale plants and transport costs require further investigation.

The direct PF revenue was insignificant in the studied scenarios due to the low total P in the co-combustion ash, but it reduces the complexity of the MSS treatment system while containing both energy and P recovery. Direct PF also contains K, S, Ca, and Mg, which are valuable for agriculture. The effect of these added values must be considered in the economic evaluation of direct PF. For this, better knowledge of plant availability of P and HMs content of direct-produced PF is needed.

Another opportunity that can improve the economic feasibility of energy and P recovery from MSS is the adaptation of existing incineration infrastructure to either mono- or co-combustion. However, switching the fuel of an existing plant may be accompanied by both investment and operational costs, related to, e.g., fuel handling, flue gas cleaning, and auxiliary boiler capacity to cover the difference in output energy when MSS is substituted with high heat value fuel. For mono-combustion, existing waste incineration plants are favorable since they are already equipped with advanced flue gas cleaning. For co-combustion, the partial introduction of MSS to boilers combusting K-rich biomass could both reduce bed agglomeration problems and the risk of alkali-related fouling and corrosion [70], i.e., significant challenges of K-rich biomass combustion. Therefore, further investigation is needed on the costs of using existing plants versus investing in dedicated new mono- or co-combustion plants for MSS.

6. Conclusions

Techno-economic analysis was performed to evaluate the feasibility of energy and P recovery from municipal sewage sludge (MSS) considering 16 different technology scenarios of investments in new combustion plants. The scenarios covered variations in five technical affecting aspects: (a) type of boiler (FB; GB), (b) fuel mixture (100% MSS; 10% MSS mixed with 90% wheat straw (WS)), (c) co-products (heat; electricity; P fertilizer (PF)), (d) economy-of-scale (10 MW; 100 MW boiler), and (e) final ash destinations (landfilling; zero-cost disposal; PF production by either ash post-treatment using Ash Dec or direct ash utilization).

Co-combustion improved the economic viability of energy and P recovery in the studied plants due to (i) elimination of drying demand, which consumed 25–35% of the output heat in the mono-combustion plants, (ii) removal of the ash landfill cost that accounted for 17–25% of the annual cost of the mono-combustion plants, and (iii) increased fuel mix heating value (32% higher). However, the availability of the WS could be a limiting factor.

None of the studied cases were economically feasible without either the revenue of a gate fee paid by the local authority for received MSS or simultaneous high plant capacity and high revenues from sold energy carriers when the market prices are high or green energy subsidies are available. Therefore, the economic feasibility of the given scenarios is interconnected with volatile revenues from sold energy carriers (heat and/or electricity) and external financial support for waste disposal. The over-reliance of the economies of scale to improve the economic performance of the given plants is conditional to MSS and WS availability (population or transportation).

The heat was, in general, the economically favorable energy carrier recoverable from MSS, the exception being the 100 MW plant with 8000 h/year of operation. In this case, electricity production benefits (saving and selling) improved the economic feasibility of the combustion plant. P recovery through Ash Dec post-treatment in mono-combustion plants had a higher PF yield than direct PF production from co-combustion due to the higher P concentration in the ash. However, the production cost was still four times higher than the commercial fertilizer price in the best-performing case (100 MW mono-combustion with heat production). In addition to being less dependent on the size of cities for the supply of sufficient quantities of MSS, 10 and 100 MW co-combustion were the only cases where the economic feasibility was independent of the PF price at a high heat market price. Consequently, ash-based PF could potentially be sold at a competitive market price, thus stimulating the marketability of P recovered from MSS. Of particular importance are conditions related to energy markets, policies for energy and P recovery from MSS, or drastically increased prices of mineral fertilizer due to, e.g., fertilizer shortages on the market. The findings shed light on the importance of less energy-intense drying technologies and further study on the co-combustion of MSS and agriculture residue.

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Abbreviations

ar	As received
CAPEX	Total capital costs
db	Dry base
FB	Fluidized bed
FC	Fixed carbon
GB	Grate boiler
HMs	Heavy metals
h	Hour
MSP	Minimum selling price
MSS	Municipal sewage sludge
OPEX	Operational costs
P	Phosphorus
PF	Phosphorus fertilizer
SNCR	Selective non-catalytic reduction
SSA	Sewage sludge ash
VM	Volatile material
WS	Wheat straw

Appendix A

Table A1 provides the input and output material flows for Ash Dec technology based on one ton of phosphate (P_2O_5) and the corresponding cost for each flow, investment cost [29], and chemicals needed for the flue gas cleaning system. Table A2 presents the investment cost of equipment in a combustion plant.

Table A1. Ash Dec inlet and outlet material flow and the chemicals cost.

Input Elements	Unit	Amount	Reference Per Feed	Price Unit	Price	Ref
Hot ash	kg/h	1725	0	-	0	[28,29]
Na_2SO_4	kg/h	640	0.37	€/t	80	
Ca $(OH)_2$	kg/h	26	0.02	€/t	90	
Electricity	kWh/kg ash	150	0.04	€/MWh	81 [a]	
Natural gas	kWh/kg ash	670	0.39	€/MWh	31 [b]	
Calcined fertilizer	kg/h	2273	1.32			
Waste (filter residue, concentrated metals)	kg/h	43	0.03			
Water	Liter/t waste		0.3	€/m^3	0.5	[67]
Flue Gas Cleaning System	**Unit**	**Amount**	**Price unit**	**Price**	**Ref**	
Coke	g/kg TS	0.3	€/t	400	[28]	
Lime	g/kg TS	5	€/t	90		
NaOH	g/kg TS	16.5	€/t	90		
Electricity for flue gas cleaning	kWh/kg TS	0.23	€/MWh	81 [a]		
Ca $(OH)_2$	kg /kg off gas	0.005	€/t	90		
NH_3 25%	g/kg TS	16.5	€/t	150		
Ash landfill			€/t	50		
Hazardous waste landfill			€/t	120		
Wheat straw			€/t	13.65	[65]	

[a] Average national price in Euro without taxes applicable for the first semester of each year for medium-sized industrial consumers [71]. [b] Natural gas prices for non-household consumers [66].

Table A2. Equipment cost of MSS combustion plant (inflation-adjusted to $€_{2020}$ using the Chemical Engineering Plant cost index and an exchange rate of 0.85 €/US$).

Element	Base Capacity	Capacity Unit	Value (1000 € 2020)	Description	Ref
Dryer	100	MW	1467	includes conveyor to and from the dryer	[72]
GB	150	MW	24,641	Steam generation cost and cyclone are included	[73]
FB	355	MW	49,566	Steam generation cost and cyclone are included	[72]
Turbine	275	MW	63,578	Generator cost in included	
Fuel conveyor	17	MW	96	It is included in co-combustion scenarios	[73]
Ash container and conveyor	17	MW	145		[73]
Electrostatic precipitator	18	Tons of waste/h	1909	Particle's remover in gas cleaning system	[67,74]
Wet scrubber	18	Tons of waste/h	5967	included of the water treatment system	[67,74]
Bag filter	18	Tons of waste/h	2625		[67,74]
SNCR	18	Tons of waste/h	1193	To remove NOx from flue gas	[67,74]
Ash Dec	30,000	Tons of ash/y	18,600		Contact with company

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