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Keywords: animal bedding; bioethanol; biorefinery; techno-economics; BioSTEAM

1. Introduction

In order to limit the global temperature increase to 2 °C, almost three-quarters of the global energy supply mix would need to be based on low-carbon technologies such as wind, solar or bioenergy, by 2050 [1]. The supply of bioenergy would be especially important in the transport sector, where the use of biofuels would need to triple by 2030, with advanced biofuels accounting for two thirds of this increase [2]. However, the production cost of biofuels is still too high for them to be commercially competitive with fossil fuels in the energy market [3]. The capital and feedstock costs have been identified as the main contributors to the total production cost of biofuels and are therefore the main hurdles to commercialization [3].

Zero- or negative-value waste could provide early market opportunities for the production of low-cost biofuels, although the most significant potential for cost reduction lies in reducing the capital cost through experience gained in deploying demonstration and early commercial plants [4]. In fact, biofuel researchers have started to investigate wastes that currently have no commercial use or value, such as municipal solid waste, food waste, slaughterhouse waste and industrial waste [5–8]. Another example of such a waste is animal bedding, consisting of straw mixed with manure, urine, and soil.

The problem in harnessing these early market opportunities lies in the lower conversion efficiency achieved with low-value wastes. For example, ethanol yields from wheat straw are typically around 70% [9,10], while the highest yield reported from animal bedding is 55% [11], and in many cases it is less than 50% [12,13]. This low conversion efficiency could eradicate the saving in feedstock costs, thus eliminating the opportunities associated with low-value waste. However, it has been shown that the introduction of a conditioning step, based on washing with water, in the biorefinery process allows the same conversion efficiency to be achieved with animal bedding as with wheat straw [14]. Similar conditioning processes, where the feedstock is fractionated into several streams, have also been proposed for other low-value wastes such as municipal solid waste and textile waste [15,16].

Even if conditioning allows the same conversion efficiency to be achieved as with high-value waste, it is still unclear whether the overall economics of the process would improve, as the conditioning step would increase both the capital and operational costs. To the best of our knowledge, no economic evaluation of such a process has been presented in the literature. This study was therefore undertaken to perform a techno-economic analysis of a biorefinery based on animal bedding as feedstock, and to compare the results to those for a biorefinery based on wheat straw, as this is a very similar facility at a higher maturity level. Our intention was to ascertain whether animal bedding actually represents an early market opportunity, by reducing the biofuel production cost. The software used to perform the techno-economic calculations was the open-source BioSTEAM suite, which means that this study also expands the portfolio of cases for which this software has been proven to be valid and reliable.

2. Materials and Methods

The modelling and economic estimations were performed according to the default settings in version 2.1.9 of the BioSTEAM software, written in Python v3.7 (Python Software Foundation, Wilmington, DE, USA, 2018), unless otherwise stated [17,18]. The models and economic estimations were taken from the biorefinery based on corn stover in the Bioindustrial-Park GitHub repository of examples provided by the developers of the software [19]. Thus, only the differences in modelling and the incorporation of new models are described in detail below.

Several tables (S1–S7) providing information on the specific reactions and conversion factors in each system (where applicable) together with block diagrams (Figures S1–S7) are given in the Supplementary Materials to facilitate the reproduction of the simulations without making the description here unduly long.

2.1. Modelling the Wheat Straw Biorefinery

The wheat straw biorefinery was based on 6 different systems: (i) pretreatment, (ii) hydrolysis and fermentation, (iii) ethanol purification, (iv) anaerobic digestion, (v) combined heat and power plant (CHP), and (vi) wastewater treatment. The first 3 systems model the production of ethanol from wheat straw. The liquid streams generated in these systems (apart from the final ethanol) are the input to the anaerobic digestion system, which models dedicated biogas production, while the solid stream (lignin residue) is the input to the CHP system, which models the production of steam and electricity. Finally, the residual water from anaerobic digestion is the input to the wastewater treatment system, which accounts for the cost of handling this residue.

2.1.1. Pretreatment System

A higher amount of water than in the original software [19] was used to model the soaking step, so the liquid-to-solid ratio in this step was increased to 20:1, and the sulfuric acid concentration in the liquid was set to 0.2 wt%. A filter press was therefore included after soaking to achieve a total solids (TS) content of 50% in the solid stream after this step. The soaking liquid removed by filtration was recycled to the soaking tank to minimize the consumption of fresh water and sulfuric acid.

Prior to steam pretreatment, the soaked biomass was preheated to 90 °C by mixing it with the residual and flashed steam after pretreatment. In order to do this, a split was included prior to the

waste vapor condenser so that a fraction of the steam could be used for this purpose, while the rest of the residual steam was condensed for heat recovery.

Although the default model for steam pretreatment was retained [19], the temperature and residence time were assumed to be 190 °C and 10 min, and the conversion factors of the reactions were modified so that the simulation would match the experimental data presented by Erdei et al. [20]. A filter press was also included after the flash unit to fractionate the pretreated slurry into a solid fraction, used for ethanol production, and a liquid fraction, used for biogas production.

2.1.2. Hydrolysis and Fermentation System

The (solid) pretreated biomass was mixed with fresh water and ammonia in order to reduce the temperature to 50 °C and to obtain a pH of 5, in contrast to the original model [19], where a heat exchanger was used to reduce the temperature of the stream. This was done as it might be difficult to operate a heat exchanger with non-pumpable solid biomass in the stream. Fresh water is needed to dilute the stream to the water-insoluble solids (WIS) content at which enzymatic hydrolysis is carried out, so this strategy does not increase resource consumption, but avoids the need to design and operate a heat exchanger with solid biomass.

However, the amount of water required to cool the biomass to 50 °C is slightly greater than the amount needed to dilute the stream to the desired WIS content, which in this case was set to 20% (after the addition of the enzymes). Thus, a filter press was included prior to the addition of enzymes to remove the excess water, which was subsequently used in biogas production.

The flow of the enzyme stream (purchased externally) was modified to achieve a loading of 0.05 g enzymes/g WIS (assuming an activity of 200 FPU/g enzymes) in the enzymatic hydrolysis reactor, and the cultivation of yeast was designed to reach a yeast concentration of 3 g/L in the fermenter.

Although the hydrolysis reactions were not changed, the growth reactions in fermentation and cultivation were modified to match those of *S. cerevisiae*, as presented by Joelsson et al. [21], and the pentose fermentation reactions were removed, as naturally occurring *S. cerevisiae* was used as the fermenting microorganism. The new growth reactions required inclusion of an input stream of air in both cultivation and fermentation, and ammonia was assumed to be the nutrient source, instead of dihydrogen ammonium phosphate, as in the original software. The conversion factors of all reactions (hydrolysis and fermentation) were assigned to achieve an overall ethanol yield of 70% (0.35 g ethanol/g glucan in wheat straw), which corresponds to the experimental results presented by Ballesteros et al. [22].

2.1.3. Ethanol Purification System

Although the default distillation models were retained [19], the distillation scheme in the purification system was modified to increase the opportunities for energy integration and, therefore, reduce the energy consumption in the process. The new scheme included two strippers and a rectifier, the pressures of which were chosen so that the energy obtained in the condensers could be used in the reboilers. The pressure in the rectifier was set to 2 bar and the pressures in the strippers were designed to maximize the energy integration in the process, assuming a temperature difference of 5 °C in the heat transfer.

2.1.4. Anaerobic Digestion System

The dedicated biogas production system was modelled according to the anaerobic digestion model in the wastewater treatment system in the original software [19]. The default reactions and conversion factors were retained, but the biogas production was modified so that the methane flow would match the following experimental yields: 188 m^3 CH_4/ton TS from thin stillage and excess water (hydrolysis and fermentation system) [23], 0 m^3 CH_4/ton TS from condensed steam and rectifier stillage, and 350 m^3 CH_4/ton volatile solids from the liquid fraction of the pretreated slurry. The flow of biogas was then calculated under the assumption that the biogas had a molar methane content of 60%.

2.2. Modelling the Animal Bedding Biorefinery

The animal bedding biorefinery was based on the same systems as the wheat straw biorefinery, apart from the following three aspects: (i) a conditioning step was introduced in the pretreatment system, (ii) pretreatment was operated at 200 °C for 5 min and the acid concentration during soaking was 0.4 wt%, and (iii) it was assumed that the methane yield from the liquid fraction of the pretreated slurry was 550 m^3 CH_4/ton volatile solids [24], instead of 350 m^3 CH_4/ton volatile solids.

Conditioning and Pretreatment System

The conditioning step consisted of washing the animal bedding with water to transfer part of the manure to the liquid phase, to fractionate the different biomasses in the material. This was modelled as a series of dissolution reactions of the manure, assuming that the manure was insoluble in the starting material. The initial dissolution reactions took place in a new unit, the washing tank, where the animal bedding was mixed with 20 kg water/dry kg animal bedding, which was introduced after feedstock handling in the original system. This was followed by a filter press, which was designed to deliver a stream with a TS content of 50%. Only the solid fraction (washed fiber) was processed in the soaking step, while the liquid containing the manure (washing liquid) was directed to the anaerobic digester for biogas production. The conversion factors of the dissolution reactions were designed such that 60% of the manure in the starting material was removed during washing, according to the experimental data presented by Victorin et al. [24].

Additional dissolution reactions were introduced in the soaking tank, whose conversion factors were designed such that an additional 15% of the manure in the starting material was removed in this step. This corresponds to the manure removal that could be expected from an additional washing step with water, which means that the removal of manure in the actual process would be slightly higher due to the presence of the acid in the soaking water (animal bedding causes buffering in the soaking). Dissolution reactions were also introduced in steam pretreatment, so that all the remaining manure in the solid material was dissolved after this step, in accordance with our experimental observations. The conversion factors for the rest of the reactions in the pretreatment were designed such that the simulation would match the experimental data presented by Victorin et al. [24].

The possibility of recycling water in the washing step was investigated in a second version of the conditioning model. This model included a belt filter after the filter press to concentrate the washing liquid to a TS content of 5%. The filtered liquid (permeate) was subsequently mixed with fresh water to achieve the required flow, based on a value of 20 kg water/dry kg animal bedding, and the mixture was recycled to the washing tank. The concentrated liquid (retentate) was directed to the anaerobic digester for biogas production, as in the case of the washing liquid in the version without water recycling.

2.3. Economic Estimations

The majority of the economic estimations were the same as in the original BioSTEAM software, that is, the estimations presented by Seider et al. [25] for conventional units, and the estimations presented by Humbird et al. [26] for specific biorefining units. However, the economic estimations of the filter press and the distillation units under vacuum conditions were modified. The capital cost of the filter presses was estimated based on the required filtration area, instead of the volumetric flow rate, which was calculated based on a flux of 1220 kg/h m^2 for all units, except the filter press in the ethanol purification system, where a lower flux of 976 kg/h m^2 was assumed due to the high concentration of residual lignocellulosics in the stream. The capital cost of the distillation units under vacuum conditions was assumed to be the same as if the distillation had been performed at atmospheric pressure, since the vacuum applied was not sufficiently high to justify a cost increase [27].

New economic estimations were implemented for the models added to the original software: the soaking tank and its filter press, the anaerobic digester, the washing tank and its filter press, and the belt filter. The capital cost of the washing and soaking tanks was calculated based on the estimates of

the capital cost of tanks, agitators, and transfer pumps in the fermenter model of the original software. The electricity consumption was assumed to be the same as that of the agitator in the fermenter tank in both cases.

The cost of the filter presses after the soaking and washing tanks could not be estimated with the same method as the filter press in the original software because of the large volumetric flow rate in these units, which required an initial draining step prior to filtration. Thus, the cost of the draining step, in which water was drained so that the resulting stream had a TS content of 20%, was estimated in the same way as the primary wastewater treatment cost presented by Seider et al. [25], while the cost of the filter press, where the stream was filtered to achieve the desired TS content, was estimated as in the original software (with modified fluxes as mentioned above).

The capital cost of the anaerobic digester was based on a personal quote of USD 14 million for an 18,000 m^3 digester (O. Wallberg, personal communication, Apr 2020), and it was assumed that this cost increases linearly with digester size. The other costs related to the anaerobic digester (heating, mixing, power consumption, etc.) were estimated with the same method as that used for the fermenter in the original software. An additional cost was also included in the economic estimation of the anaerobic digester to account for the upgrading of the biogas to vehicle fuel quality. This cost was calculated based on the assumption that the capital cost for such an installation would be USD 1430 per Nm^3/h of biogas produced, and that its electricity demand would be 0.25 kWh/Nm^3 of biogas produced [28].

The capital cost of the belt filter was based on a personal quote of USD 91,000 for a filter with a hydraulic capacity of 20 m^3/h (M. Sjölin, personal communication, May 2020), under the assumption that this cost increased linearly with the volumetric flow rate. In terms of operating costs, it was assumed that the belt filter would consume 80 W per m^3/h of liquid input.

3. Results and Discussion

3.1. Simulation of the Wheat Straw Biorefinery

Although a plant size of 2000 dry ton/day of feedstock was assumed in the economic estimations, simulations based on a plant size of 1000 dry kg/h of feedstock were performed in order to facilitate the interpretation of the results, comparison with the results of previous studies, and to confirm the validity of the models. Thus, the results presented and discussed in the two following sections are based on a plant capacity of 1000 dry kg/h, whereas the economic data presented in the final section are based on a plant capacity of 2000 dry ton/day.

The biorefinery based on wheat straw would produce 120 kg/h of ethanol, 60 kg/h of methane (approximately 170 kg/h of biogas) and 532 kW of electricity (Figure 1). Apart from the electricity, the combined heat and power plant would also produce enough steam to cover all the heating duties in the biorefinery. This means that the process based on wheat straw would not consume any utility, since the electricity consumed was less than the electricity produced in the combined heat and power plant; thus, the biorefinery would deliver a surplus of electricity, together with the biofuels, to the energy market.

The mass and energy flows for each individual system can be found in the Supplementary Materials (Figures S1–S7) and only the most relevant aspects in evaluating the validity of the models are discussed in this section. The pretreatment system consumed 426 kW of high-pressure steam (522 kg/h), of which 361 kW could be recovered in the waste vapor condenser. This result is consistent with previous models of biorefineries based on wheat straw [21] which, together with the fact that the composition of the streams matched the experimental data presented by Erdei et al. [20], proves the validity of this part of the model.

The fermentation broth in the saccharification and fermentation system had an ethanol concentration of 4.4 wt%, which is similar to the concentration obtained experimentally in fermentations based on (pretreated) lignocellulosic material. Apart from the production of ethanol, the (solid) pretreated biomass was used to produce the amount of yeast required in the process. It was necessary

to divert 15% of the saccharified biomass for this purpose, a value similar to the 10% obtained in the example based on corn stover provided by the developers of the BioSTEAM software [29].
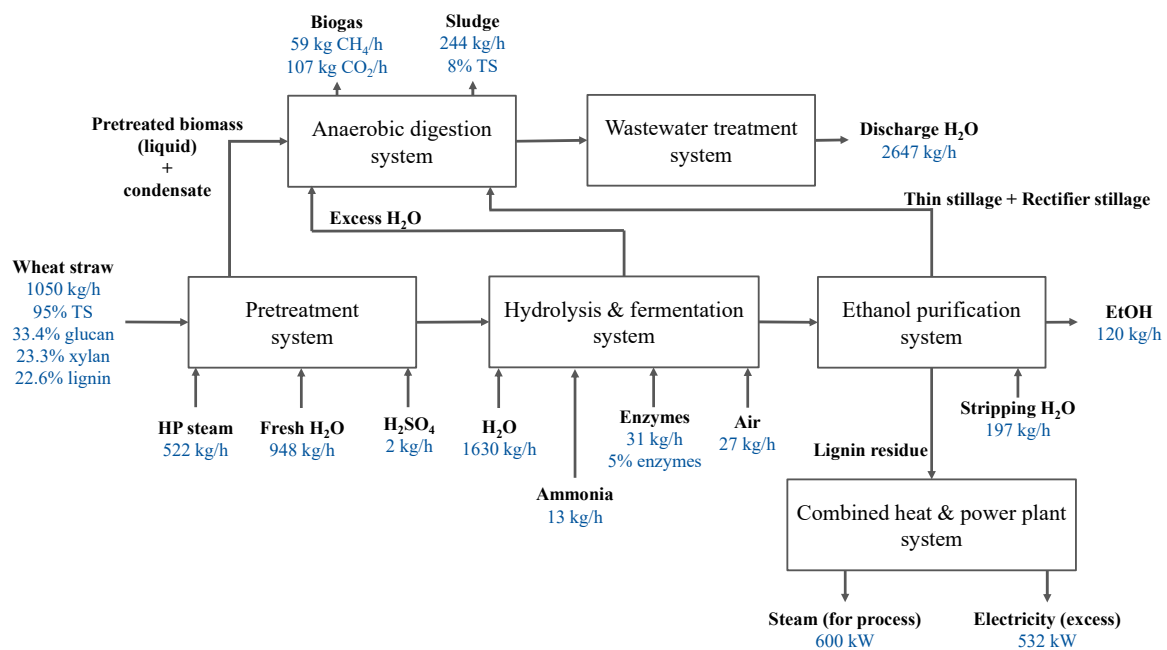

Figure 1. Mass and energy flows in the wheat straw biorefinery, assuming a plant capacity of 1000 dry kg/h of feedstock.

The energy consumed in distillation could be completely supplied through energy integration as the low-pressure stripper was supplied with energy by the high-pressure stripper (78 kW), which in turn was provided with energy from the rectifier and the cooling of the product after molecular sieving (90 kW). The energy recovered in the waste vapor condenser (361 kW) would be more than enough to supply the energy required by the rectifier (97 kW). Thus, the recovery of ethanol in the fermentation broth had no utility cost in terms of heating duty, which is consistent with the conclusions presented previously by Joelsson et al. [21].

Based on the above results, it was concluded that the model of the wheat straw biorefinery closely reflects the real process, provides similar results to previous models, and thus provides a valid benchmark that can be used to evaluate the biorefinery based on animal bedding.

3.2. Simulation of the Animal Bedding Biorefinery

The biorefinery based on animal bedding would deliver different amounts of the products: 94 kg/h of ethanol, 90 kg/h of methane (approximately 260 kg/h of biogas) and 145 kW of electricity (Figure 2). The reason for this is that the lignocellulosic fiber (straw) is a smaller fraction of the material, which implies that there is less substrate for ethanol production and less lignin available for combustion for heat and electricity production. However, the manure provides an additional substrate for biogas production, which means that this biorefinery would rely on biogas production considerably more than the biorefinery based on wheat straw.
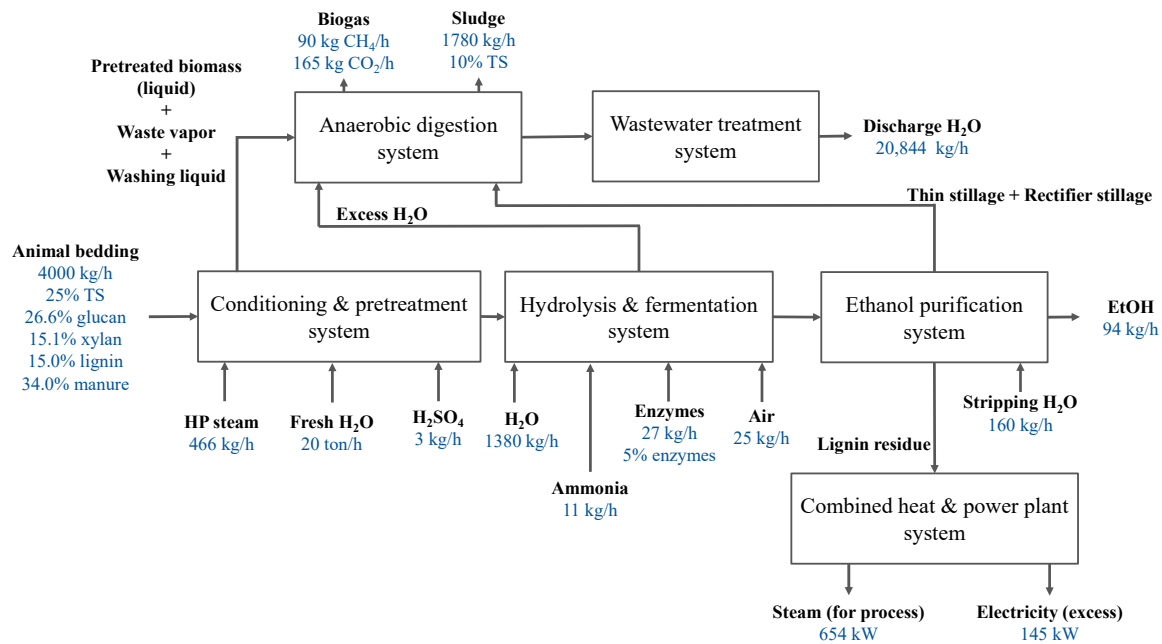
Figure 2. Mass and energy flows in the animal bedding biorefinery without water recycling, assuming a plant capacity of 1000 dry kg/h of feedstock.

The process for the production of ethanol from animal bedding was very similar to that for wheat straw, thanks to the introduction of conditioning. The composition of the (solid) pretreated material was very similar, and the ethanol concentration in the fermentation broth was in the same range (3.9 wt%). Distillation was operated at the same temperature, but the energy consumption of the boilers was slightly lower due to the smaller mass flow in this part of the process (222 kW, compared to 265 kW in the wheat straw model). The lignin stream used in the combined heat and power plant contained only 2 wt% manure, so its quality as a fuel would be approximately the same, and only a minor fraction of the manure would not reach the anaerobic digestion step and would be incinerated instead of being converted into biogas.

This process would require a slightly higher heating duty than the process based on wheat straw, as the combined heat and power plant was required to deliver 654 kW of steam (compared to 600 kW in the wheat straw model). The reason for this is that the heat recovered in the waste vapor condenser could not be used to supply the energy required by the rectifier, as it was instead used to heat the incoming stream to the anaerobic digester to the operating temperature. The introduction of the washing liquid in the anaerobic digestion step decreased the temperature of the incoming stream considerably, due to the large volumetric flow used in washing, which created a heating duty that did not exist in the process based on wheat straw.

The volumetric flow in the anaerobic digestion and wastewater treatment systems was almost eight times higher than in the wheat straw model due to the presence of the washing liquid. This led to a higher electricity consumption in these units (for both pumping and agitation) and a greater consumption of chemicals in the wastewater treatment system (mainly caustic soda). The electricity consumption was no longer less than the amount of electricity produced, which was further aggravated by the fact that less electricity was produced due to the lower lignin production. As a result of this, the biorefinery based on animal bedding would not be able to deliver electricity to the energy market. In fact, since it was necessary to supply electricity to the process, there was an additional utility cost compared to the wheat straw model.

The introduction of a belt filter to recycle water in the conditioning step reduced the additional flow in the anaerobic digestion and wastewater treatment systems considerably (approximately 4000 kg/h instead of 20,000 kg/h) and reduced the fresh water consumption of the conditioning step to 1700 kg/h. As a result of this, it was no longer necessary to heat the incoming stream to anaerobic digestion, so it

was possible to supply energy to the rectifier through energy integration, as in the wheat straw model. However, although the electricity consumption decreased, the process still consumed more electricity than was produced in the combined heat and power plant, so water recycling did not completely eliminate the need for electricity supply.

Another negative effect created by water recycling was that the water used in conditioning contained 0.5 wt% manure, which might reduce the washing efficiency, and therefore modify the subsequent ethanol production, although this effect was not included in the model due to the lack of experimental data.

3.3. Techno-Economic Feasibility

The wheat straw biorefinery had revenues of approximately USD 1500 million, in terms of net present value (Figure 3). The largest source of revenue was from ethanol, which accounted for 53% of the total revenue, followed by biogas (38%) and, lastly, electricity (9%). The revenue from ethanol was calculated based on the minimum ethanol selling price (MESP), that is, the selling price at the break-even point, which was USD 0.61 per liter.
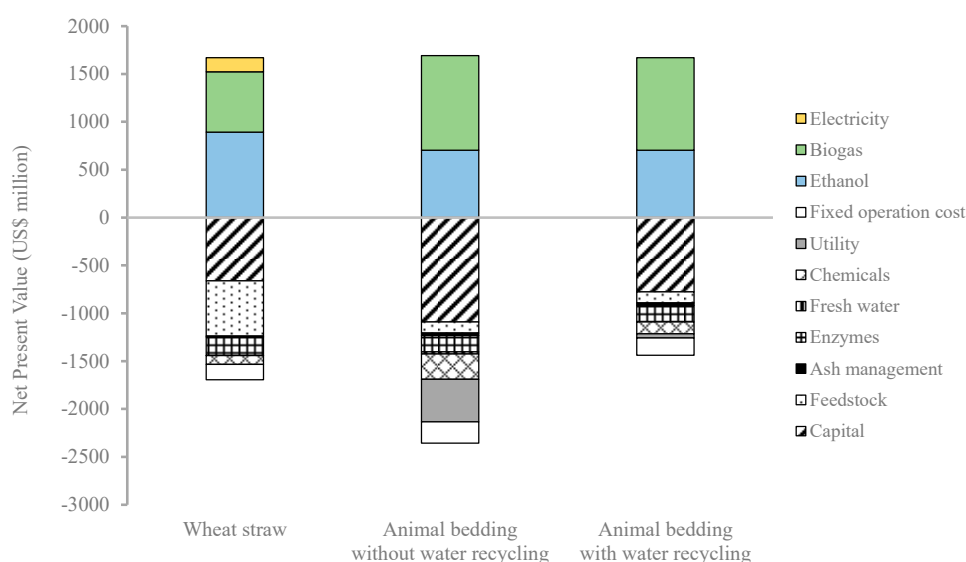
Figure 3. Net present value of revenues, capital cost, operational costs in the wheat straw biorefinery and the animal bedding biorefinery, with and without water recycling in the conditioning step.

In terms of costs, the three main contributors to the total cost of the wheat straw biorefinery were the capital cost (39%), the feedstock (34%), and the enzymes (11%). These findings are in accordance with previously reported results that the capital cost and the feedstock are the main contributors to the total cost [3], and that the feedstock usually accounts for a third of the total cost in production processes based on lignocellulosic material [30]. Thus, the economic estimations implemented in the model are valid. The large contribution of the feedstock to the total cost clearly illustrates the opportunity for cost reduction through the use of feedstocks with lower value.

The sources of revenue in the animal bedding biorefinery without water recycling differed considerably from those in the wheat straw biorefinery (Figure 3), due to the different amounts of products mentioned above. Assuming an ethanol selling price of USD 0.61 per liter, the ethanol revenue decreased to USD 704 million (20% lower than the benchmark), while the biogas revenue increased to USD 987 million (57% higher than the benchmark). This means that biogas became the main revenue in the biorefinery based on animal bedding, which implies that the two kinds of biorefineries might not be competing in the same markets.

The total cost of the animal bedding biorefinery without water recycling was much higher than that of the benchmark: USD 2356 million, compared to USD 1694 million, which represents an increase

of almost 40% (Figure 3). The implication of this is that the MESP almost doubled, to a value of USD 1.1 per liter, despite the savings in feedstock cost, which were assumed to be 80% compared to the benchmark. The main reason for this cost increase was a higher capital cost; an increase of 65% compared to the benchmark. Although the conditioning step increased the capital cost by USD 5.7 million, its contribution was insignificant compared to the increases in cost resulting from the need for a larger anaerobic digester and a larger wastewater treatment system, which amounted to USD 87.5 and 88.4 million more, respectively, than the corresponding units in the benchmark. Thus, water recycling in conditioning seems to be a promising alternative, as the increase in capital cost was due to the larger volumetric flow in the anaerobic digestion and wastewater systems, rather than the introduction of conditioning in the process.

The higher consumption of electricity and chemicals were additional reasons for the cost increase in the animal bedding biorefinery without water recycling. The utility cost was the second highest contributor to the total cost, USD 444 million (Figure 3), and the cost of chemicals was greater than the cost of enzymes (USD 265 million, compared to USD 173 million). The sources of these new contributions to the cost were again the anaerobic digester and the wastewater treatment system, which underlines the importance of water recycling in the conditioning system.

When implementing water recycling in the conditioning step, the total cost of the animal bedding biorefinery decreased to USD 1439 million (Figure 3), which is 15% lower than the benchmark. This means that the MESP decreased to USD 0.38 per liter as a result of water recycling, demonstrating that low-value feedstocks represent an opportunity for early production of low-cost biofuels, as this MESP was almost 40% lower than the benchmark. The main reason for this improvement was the decrease in the capital cost to USD 776 million (Figure 3), which was still 17% higher than the benchmark, but did not counterbalance the 80% savings in feedstock cost.

The reduction in the volumetric flow in the anaerobic digester and wastewater treatment systems reduced the consumption of chemicals considerably, so this contribution to the cost was in the same range as in the benchmark. The electricity consumption was also decreased, but not to a degree that the biorefinery could sell electricity to the energy market, and therefore the revenue structure remained the same as in the biorefinery without water recycling: biogas being the main source of revenue, followed by ethanol. However, despite the fact that the ethanol revenues remained the same, the biogas revenue decreased by 2% compared to the biorefinery without water recycling, due to the accumulation of manure in the water recycling loop. This was, nevertheless, an insignificant effect compared to the considerable cost savings resulting from water recycling.

Sensitivity Analyses

In the simulations described above, animal bedding was assigned a price that was 20% of that of wheat straw, which was assumed to cover transportation costs, but no additional cost for the material itself. However, it has been suggested that a higher price of the feedstock could have positive effects on the biorefinery, as more farmers would be willing to deliver biomass to the facility, increasing the biomass availability for the biorefinery [31]. We therefore conducted a sensitivity analysis to evaluate the effect of the price of the feedstock and to determine whether a higher price could be paid for animal bedding.

The MESP increased linearly with increasing price of the feedstock, from USD 0.28 per liter assuming no feedstock cost, to USD 0.78 per liter assuming the same cost as wheat straw (Figure 4). This means that the animal bedding biorefinery with water recycling requires a reduction of at least 35% in the feedstock price (65% of the wheat straw price) to compete with the benchmark in terms of process economics. This is considerably higher than our assumption in the simulations (20% of the wheat straw price), which means that the process would still outperform the benchmark if the price of animal bedding was higher than we initially assumed. For example, if the price of animal bedding was twice that assumed in the initial simulations, the MESP would still be 20% lower than the benchmark.
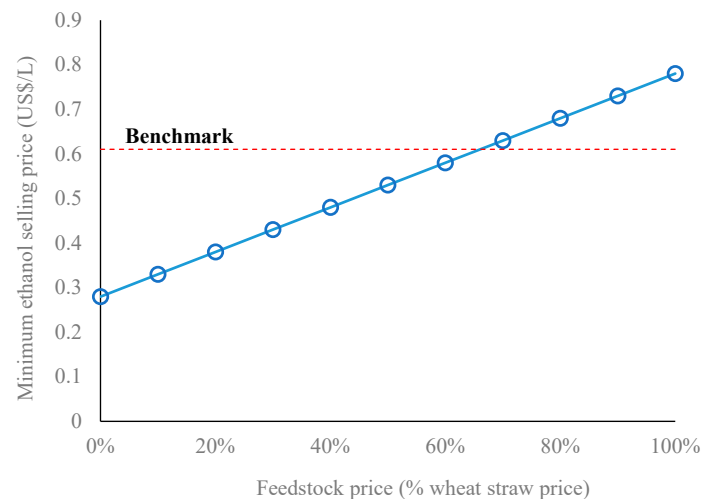
Figure 4. Minimum ethanol selling price as a function of the feedstock price in the animal bedding biorefinery with water recycling.

It is uncertain whether the efficiency of conditioning would remain the same in the system with water recycling, due to the accumulation of manure in the recycling loop, which might compromise the efficiency of the ethanol production process [32]. Although further studies are required on conditioning to quantify the effect of manure accumulation on the washing efficiency, we investigated the possibility of filtering and recycling only a fraction of the washing liquid. This would reduce the concentration of manure in the recycling loop, but would also have a negative impact on the process economics (Figure 5). The reason for this is that recycling only a fraction of the washing liquid increases the volumetric flow through the anaerobic digestion and wastewater systems, causing the process economics to shift towards that of the biorefinery without water recycling, although less manure would accumulate in the recycling loop due to the higher input of fresh water for conditioning.
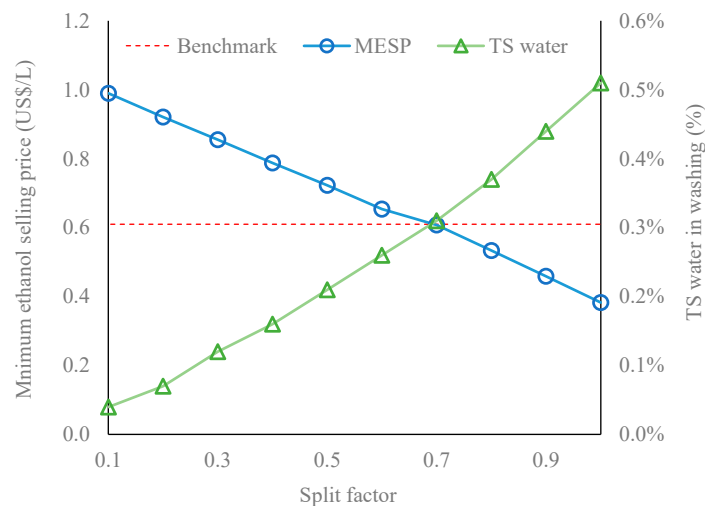
Figure 5. Minimum ethanol selling price (MESP) and total solids (TS) content in the water used in the conditioning step as a function of the split factor in the water recycling loop, expressed as the fraction of the washing liquid that was filtrated and recycled to conditioning. The feedstock price was assumed to be 20% of the wheat straw price.

It was found that the MESP would be the same as the benchmark when only 70% of the washing liquid was filtrated and recycled, which would reduce the manure concentration in the recycling loop from 0.5% to 0.3% (Figure 5). This implies that it would be possible to alleviate the problem of

manure accumulation, but the benchmark would still economically outperform the process with water recycling if a manure concentration below 0.3% was required to maintain the efficiency of conditioning.

4. Conclusions

A biorefinery based on wheat straw would be able to deliver ethanol at a minimum ethanol selling price of USD 0.61 per liter, as a result of the additional revenues from biogas and electricity. Using a lower quality feedstock, such as animal bedding, would reduce the minimum ethanol selling price to USD 0.38 per liter, despite the introduction of a conditioning step in the biorefinery process. This demonstrates that low-value feedstocks could represent early opportunities to produce low-cost biofuels, as the feedstock savings easily overcome the conditioning cost. However, the animal bedding biorefinery required water recycling to the conditioning step to economically outcompete the wheat straw biorefinery. The reason for this was the large increase in volumetric flow in the subsequent steps of the process (anaerobic digestion and wastewater treatment) when water was not recycled, as the cost of conditioning itself was not significant. Thus, introducing a conditioning step in a biorefinery might affect other parts of the production process, which means that, apart from designing the conditioning technology, it would also be necessary to appropriately design its integration in the biorefinery.

Further sensitivity analyses showed that the animal bedding biorefinery with water recycling required a reduction of only 35% in the feedstock price, compared to straw, to economically outcompete the wheat straw biorefinery. This means that it would be possible to increase the price of animal bedding, which might have positive effects on feedstock availability, without compromising the competitiveness of the process. The sensitivity analyses also revealed that it would be possible to filtrate and recycle only 70% of the water used in conditioning, and still outperform the wheat straw biorefinery. This shows that the accumulation of manure in conditioning, which might compromise its efficiency, could be alleviated to a certain extent, if required.

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