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Sustainability of Systems Producing Ethanol, Power, and Lignosulfonates or Lignin from Corn Stover: A Comparative Assessment

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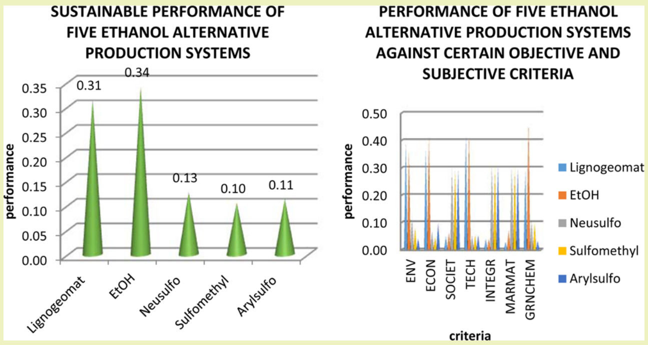
Ⓢ *Supporting Information*



ABSTRACT: Bad economics and low environmental performance are considered to be typical of ethanol production systems deriving from lignocellulosic material such as agricultural wastes. Integrated ethanol production systems where various byproducts are also exploited have been proposed as a solution to the above-mentioned problems. The main contribution of this study is the development of a model for the examination of the sustainability of five ethanol production systems so as to discern and eventually chose the most attractive ones. This model can be used as a managerial tool for assessing biofuel production systems in general. Interdisciplinary methods and tools from engineering, economics, and operational research have been employed for the systems' evaluation. More specifically, mass balances were used for the systems' inventory determination, while their environmental performance is calculated by means of a life cycle impact assessment method and a relevant tool (SimaPro software). Economic analysis is used to access the alternatives' economics. Moreover, in order to determine the combined performance of each system against certain environmental, economic, and societal criteria, both objective and subjective, the analytic hierarchy process has been employed. The systems' overall performances are compared with each other, and the systems are ranked in order of preference. Sensitivity analysis has also been used for testing the results' robustness. For the particular criteria selected and assumptions made, the study claims that the performance of the system producing ethanol and electricity is equal to that of the system producing ethanol, electricity, and lignin as geomaterial, while both outdistance the systems producing ethanol, electricity, and lignosulfonates. Thus, the former systems are more appealing to extensive research and further development.

KEYWORDS: *Bioethanol production, Sustainability, Life cycle impact assessment, Lignin, Lignosulfonates*

■ INTRODUCTION

The use of biofuels has been proposed as a solution to both climate change and fossil fuels depletion problems because biofuels are considered as CO_2 neutral (which is partly true) and can be produced from recyclable and abundant materials.[1] This premise has led to a big growth of biofuels production systems in the recent years.

Various bioethanol production systems, using lignocellulosic agricultural wastes, are among them, although their poor economics compared to systems producing fossil fuels constitute a major problem. The U.S. National Renewable Energy Laboratory (NREL) has investigated the complete process design and economics of such a system and proposed a plant where bioethanol is produced by fermentation of such sugars that are contained in corn stover biomass, and the remaining lignin is burnt for power generation.[2] This is a novel production technology and is considered as state-of-the-art, while the researchers direct their efforts to lower ethanol production cost. Examples of bioethanol industrial-scale plants using similar technology include the DuPont cellulosic ethanol facility in Nevada and the Iowa cellulosic ethanol plant of POET-DSM.[3,4]

A big issue under discussion is how lignin can be best used to support the economic performance of such plants. An approach that only considers the process heat is shortsighted for some researchers, while higher-value chemical/material coproducts coming out from the remaining lignin may present economic opportunities.[5]

The areas in which lignin is applicable include[6] multipolarity-related products (applications as in emulsions and dispersants), materials (binders, thermoset, etc.), agriculture (formation of soils and in plant and animal nutrition), and high purity/value applications (food and cosmetic applications comprising gels or

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emulsifiers, active substances with antioxidant, antibacterial, and antiviral properties, fuels, etc.).

In this context, the following solutions have been proposed, among others, for enhancing the economics of bioethanol production systems from lignocellulosic material: (1) Lignosulfonates production using the remaining lignin from the ethanol production process as the raw material.[7] Lignosulfonates can be used as admixtures in concrete and cement, as a dispersant agent, as a raw material for vanillin production, etc. (2) Utilization of the remaining lignin as a geomaterial in civil engineering projects (roads, infrastructure, etc.).

In this paper, we aim to assess the sustainability of the previous proposed solutions and compare them to the one proposed by the NREL where the remaining lignin is solely burned for power generation. Hence, we envisaged the following five systems from corn stover which produce (1) ethanol and electricity to be used in the plant and for sale to the grid (EtOH alternative),[2] (2) ethanol and electricity for use in the plant and lignosulfonates through a neutral sulfonation process (NEUSULFO alternative),[7] (3) ethanol and electricity for use in the plant and lignosulfonates through a sulfomethylation process (SULFOMETHYL alternative),[7] (4) ethanol and electricity for use in the plant and lignosulfonates through an arylsulfonation process (ARYLSULFO alternative),[7] and (5) ethanol and electricity for use in the plant and sale of the remaining lignin for use as a geomaterial (LIGNOGEOMAT alternative).[8]

For the assessment of the sustainability of each of the above systems, and for their comparison, a decision-making model is proposed in this study, where the following are determined in sequence: inventory for each system through appropriate mass balances, environmental performances through a life cycle impact assessment (LCIA) tool (SimaPro software), economics through an appropriate economic analysis, societal performance through the number of jobs created, and performance against specific subjective criteria regarding their sustainability. The analytic hierarchy process is then employed in order to combine the aforementioned performances in a unique overall performance value. Finally, the alternatives according to this value are ranked, and the best systems are selected.

The rest of the paper is structured as follows. In the Scope and Methods section, the alternatives are presented, followed by the description of the alternative systems boundaries, production capacity, data of their life cycle inventories, criteria used (objective and subjective in sequence), measured alternatives' performances against each criterion, and their overall combined performance. In the Results and Discussion section, the results and how they are affected by differentiating the criteria weights are presented. The Conclusion section closes the paper with references to suggested future work.

■ SCOPE AND METHODS

The main hypothesis tested in this study is "does any of the NEUSULFO, SULFOMETHYL, ARYLSULFO, and LIGNOGEOMAT alternatives have better sustainability performance than the well-established EtOH alternative?". In the positive answer case, the preferable alternative will be a candidate for further development toward industrial-scale implementation. The evaluation is conducted from a sustainability point of view, taking into account economic, environmental, and societal criteria and based on a set of assumptions. The methodology employed in the study includes the following steps.

Step 1. Alternatives Description. The basic procedures forming the alternative production systems are briefly described in the sequel.

Biomass Collection and Transportation to the Ethanol Plant. The NREL report does not include data about the inventory of the biomass collection procedure.[2] Consequently, the inventory of a corn stover collection and transportation model had to be examined in order to collect the necessary data for the environmental and economic analysis. The biomass collection procedure includes the corn stalks cutting using tractors and cutters and baling them in large cylindrical bales using tractors and balers.[9] The bales are loaded from fields to trailers hauled by tractors and are transferred to open depots near the fields, from where they are finally transported to the ethanol plant by 28 t lorry fleets. Trucks were considered to travel empty along one way. Key figures of the biomass collection and transportation stages are presented in Table 1.

Table 1. Key Figures of Biomass Collection and Transportation System

parameter	value
biomass moisture (% w/w)	20
biomass price (delivered at plant) ($/t)	58.50
biomass transport, tractor, and trailer for 1 kg EtOH (tkm)	0.0204
biomass transport, 28t lorry fleet, for 1 kg EtOH (tkm)	0.2645

Ethanol and Byproducts Industrial Processes. The five alternative ethanol production processes assessed in this study are (1) ethanol production using dilute acid prehydrolysis of corn stover followed by enzymatic hydrolysis and lignin combustion for power generation for use in the plant and for sale to the grid (EtOH scenario),[2] (2) ethanol production and lignin combustion for power generation for use in the plant and lignosulfonate production through a process including phenolation of the remaining lignin, hydroxymethylation of phenolated lignin, and neutral sulfonation of the produced hydroxymethylated-phenolated lignin (NEUSULFO scenario),[7] (3) ethanol production and lignin combustion for power generation for use in the plant and lignosulfonate production through phenolation of the remaining lignin and sulfomethylation of the produced phenolated lignin (SULFOMETHYL scenario),[7] (4) ethanol production and lignin combustion for power generation for use in the plant and lignosulfonate production through phenolation of the remaining lignin and arylsulfonation of the produced phenolated lignin (ARYLSULFO scenario),[7] and (5) ethanol production and lignin combustion for power generation for use in the plant and sale of the remaining lignin for use as a geomaterial (LIGNOGEOMAT scenario).[8]

Simplified flow sheets of the systems processes are presented in Figures 1–5, while some operation key figures for each alternative are presented in Table 2.

Step 2. Production Capacity Selection, Systems Boundaries, and Data for Life Cycle Inventory. In the NREL report, 770,000 t of feedstock corn stover per year has been set as the optimum capacity for the EtOH production system.[2] The same quantity has been selected as feedstock capacity for this study's alternatives. One kilogram of ethanol was selected as the functional unit for the LCIA. The boundaries of the production systems include the collection of the corn stover in the field, transport of corn stover in the

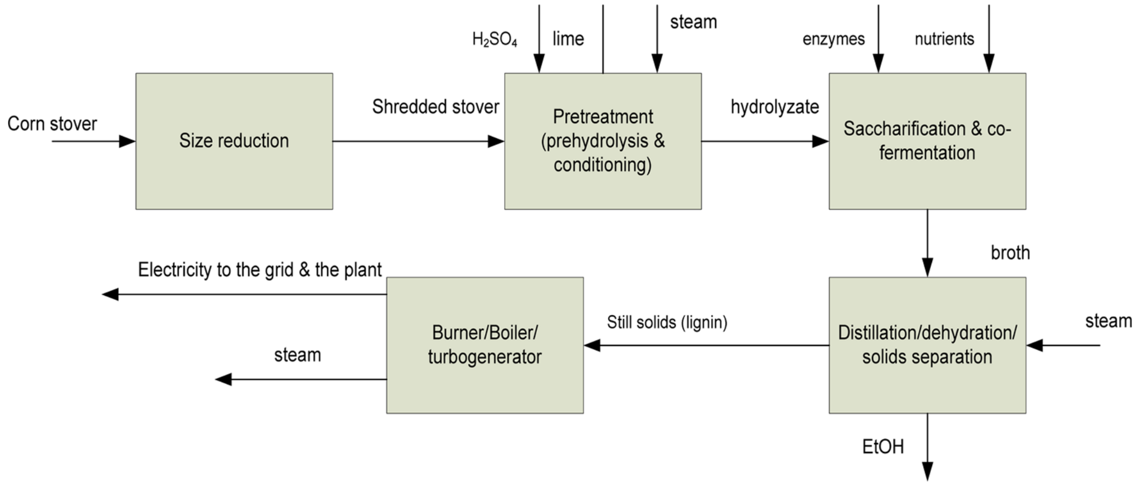

Figure 1. Flow sheet of the EtOH system.

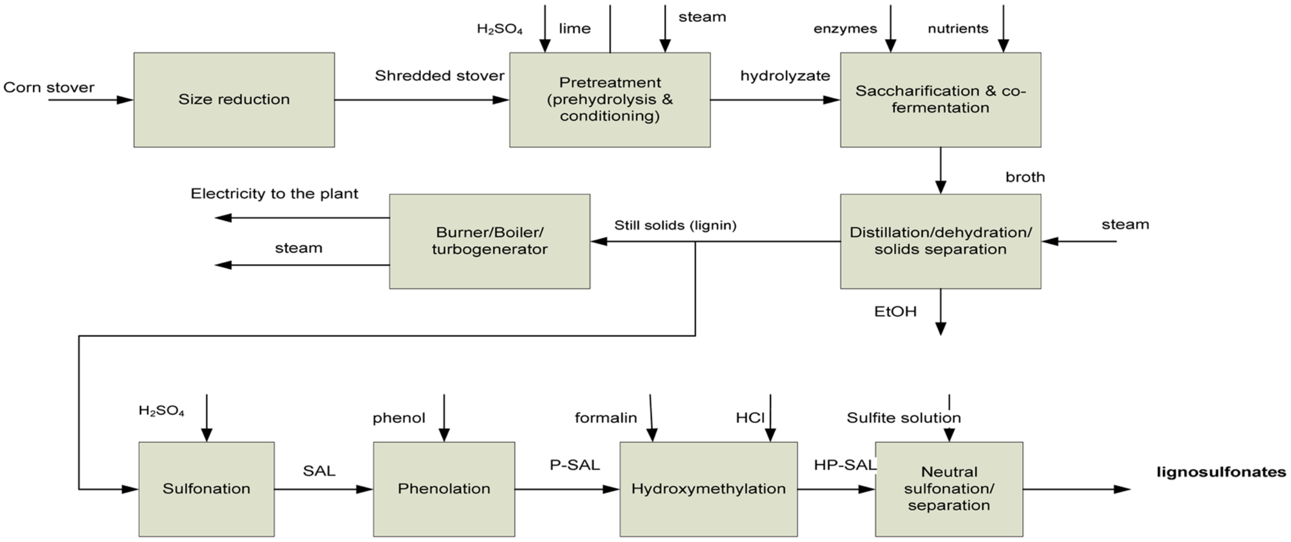

Figure 2. Flow sheet of the NEUSULFO system.

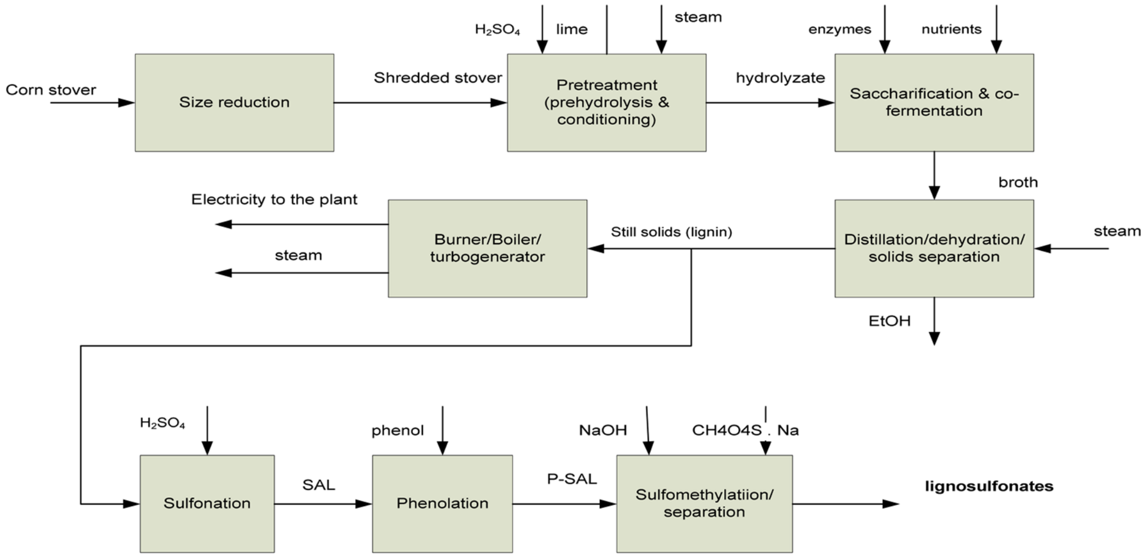

Figure 3. Flow sheet of the SULFOMETHYL system.

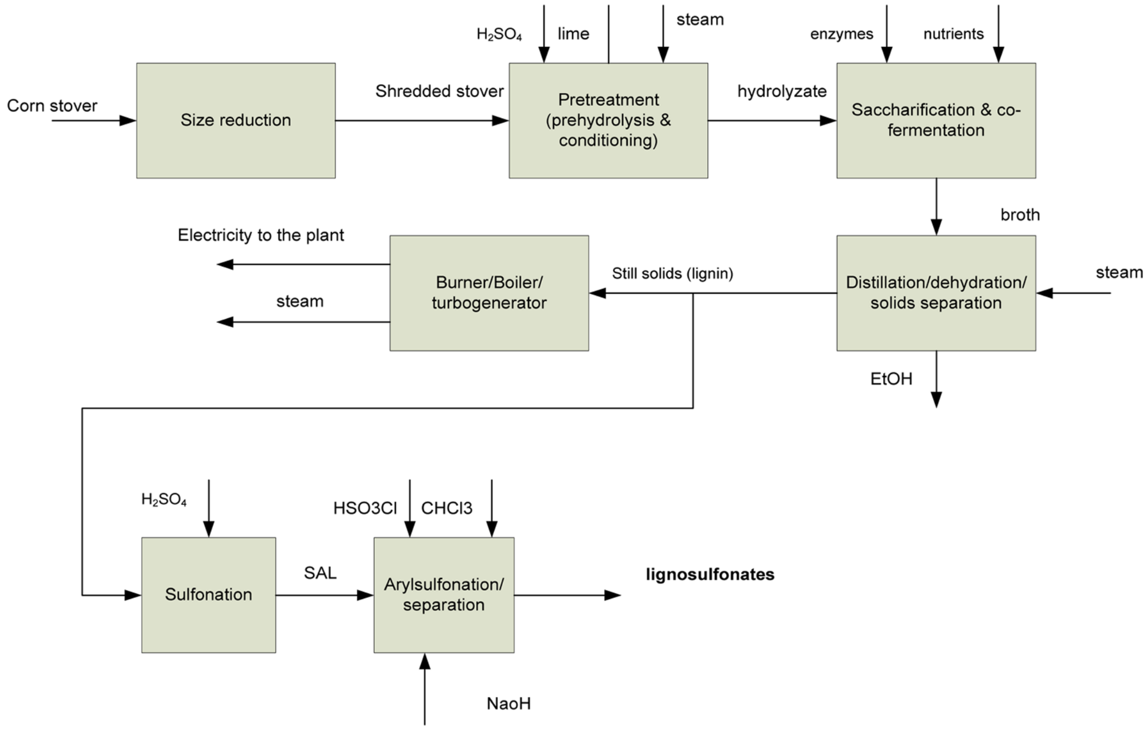

Figure 4. Flow sheet of the ARYLSULFO system.

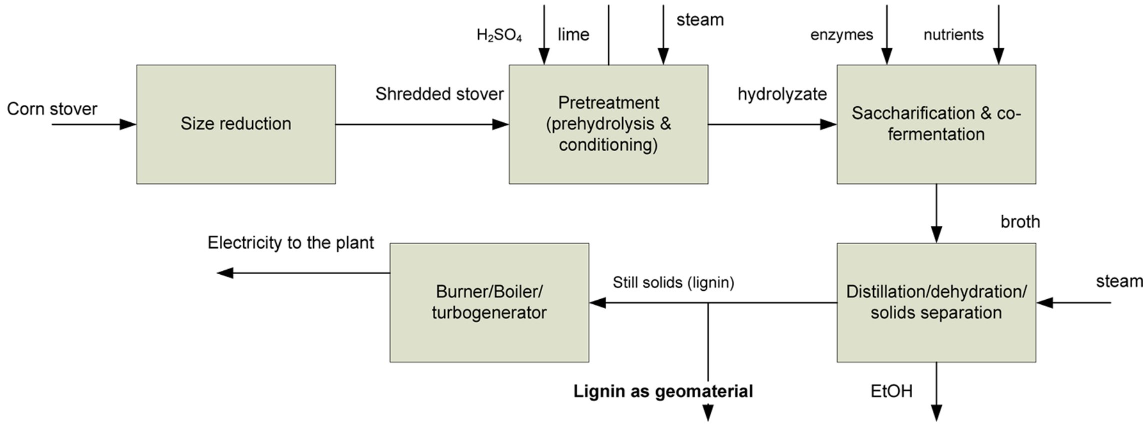

Figure 5. Flow sheet of the LIGNOGEOMAT system.

Table 2. Key Figures of the Alternative Production Systems

	EtOH	NEUSULFO	SULFOMETHYL	ARYLSULFO	LIGNOGEOMAT
feedstock (t corn stover on a dry basis/year)	770,000	770,000	770,000	770,000	770,000
ethanol capacity (t/year)	213,000	213,000	213,000	213,000	213,000
lignosulfonates capacity (t/year)	0	78,000	68,900	81,400	0
geomaterial capacity (t/year)	0	0	0	0	97,000
power to grid (Mw)	12.71	0	0	0	0

plant of the production system, and production of ethanol and byproducts.

Data related to each system's inventory was collected from the available literature. For the alternatives where no inventory data was available, material balances based on appropriate assumptions were implemented. Data concerning corn production and corn stover collection and transport (machinery, volumes, labor, etc.) was collected from farmers and from the Ecoinvent Report No. 17.[10] Table 3 summarizes the inventory of key materials and emissions for each alternative.

Step 3. Criteria. Theoretically, the metrics used for the measurement of sustainability involves the performance in certain domains such as environmental, social, and economic because these are its three pillars.[11] Thus, environmental, economic, and societal criteria were selected for the systems' sustainability evaluation in this study. These can be either objective (quantitative) or subjective, which can be quantified. In any case, the selected criteria fulfill the main requirements of a general identification criteria procedure such as value relevance, understandability, measurability, nonredundancy,

Table 3. Inventory Key Figures for Alternative Systems

material/emission/waste	EtOH	NEUSULFO	SULFOMETHYL	ARYLSULFO	LIGNOGEOMAT
sulfuric acid (kg/kg EtOH)	0.0330	0.5998	0.5998	0.5998	0.0330
sulfite (kg/kg EtOH)	–	0.0172	–	–	–
formaldehyde (kg/kg EtOH)	–	0.1282	–	–	–
phenol (kg/kg EtOH)	–	0.8413	0.8413	0.8413	–
sodium hydroxide 50% (kg/kg EtOH)	–	0.6410	0.6410	2.5639	–
hydrochloric acid 36% (kg/kg EtOH)	–	2.0040	–	2.5200	–
chloroform (kg/kg EtOH)	–	–	–	0.0882	–
CO_2 biogenic (kg/kg EtOH)	2.9	2.3	2.3	2.3	1.1
CO biogenic (kg/kg EtOH)	0.0005	0.0004	0.0004	0.0004	0.0034
heat waste (MJ/kg EtOH)	12.13	11.58	11.57	11.57	11.51

and judgmental independence.[12] In the following, the selected criteria are presented.

Objective (Quantitative) Criteria. Environmental Performance (ENV). This may be assessed using life cycle impact assessment and, more specifically, the SimaPro software. With this, a certain environmental index is assigned to each production system. SimaPro calculates the environmental load of a production system using various methods. The most recent one is the ReCiPe method, whose primary scope is to transform the long list of life cycle inventory results into a limited number of indicator scores. These scores express the relative severity on an environmental impact category and are classified in two levels as midpoint (that are relatively robust, but not easy to interpret) and endpoint (which are easy to understand, but more uncertain) indicators. Each method (midpoint, endpoint) contains factors according to three cultural perspectives identified by the terms individualist (I), hierarchist (H), and egalitarian (E).[13] These perspectives represent a set of choices on issues like time or expectations so that proper management or future technology development can avoid damages in the future. The endpoint indicator (R) from an individualist perspective (short term, optimism that technology can avoid many problems in future) is selected to represent each alternative's performance severity on the environment. It must be noted that the endpoint method aggregates the most midpoint impact categories such as climate change, ozone depletion, human toxicity, agricultural land occupation, fossil fuel depletion, etc. into three impact categories: damage to human health, damage to ecosystem diversity, and damage to resource availability.[13] Additionally, it must be noted that the mass basis approach is selected for the allocation of total energy and emissions into the various products and byproducts. According to this, the energy needed and the materials substances emitted by each production system are allocated by taking into account the partial contribution of the corresponding products and byproducts masses to the total product mix mass.

The results obtained by the SimaPro−ReCiPe method are presented in Table 4. R is a single score that aggregates the impacts of the following three endpoint impact categories: damage to human health, damage to ecosystem diversity, and damage to resource availability.

Table 4. SimaPro−ReCiPe Results for Alternatives

	SimaPro−ReCiPe result (R)	$1/R$	EI 99 result
EtOH	0.42	2.38	0.19
NEUSULFO	1.03	0.97	0.52
SULFOMETHYL	1.12	0.89	0.59
ARYLSULFO	1.29	0.78	0.75
LIGNOGEOMAT	0.30	3.37	0.18

The results obtained by the Environmental Index 99 (EI99) method (one of the alternative methods proposed by SimaPro) are also presented in the same table just for comparison. It is obvious that the LIGNOGEOMAT alternative has the best environmental performance. EtOH comes next, while NEUSULFO, SULFOMETHYL, and ARYLSULFO arrive last. Commenting on these results, we may note that they are reasonable because the technology used by EtOH is optimized by the NREL and is mature enough. The same technology is used by the LIGNOMATE alternatives too. The use of a small number of chemicals (H_2SO_4, NH_3) in the wastewater treatment, recycle of the treated water, minimization of waste disposal, and use of economizing heat exchangers contribute to the good environmental performance of this technology. On the other hand, the NEUSULFO, SULFOMETHYL, and ARYLSULFO alternatives are technologies under lab-scale development stage. The use of many and/or severe chemicals (H_2SO_4, phenol, chloroform, tetrachloroethane, etc.) and their vast consumption because the processes are not optimized contribute to the bad environmental performance.

Economic Performance (ECON). This is related to the profitability of each system's investment that can be expressed through the internal rate of return (IRR) and may be assessed using economic analysis. IRR is determined taking into account for each scenario the total capital investment and the expected cash flows for a period of 30 years. Cash flows are calculated using the anticipated sales and the variable cost of each scenario for the same period. The IRR expresses the economic performance of each system.

Table 5 summarizes these economic key figures for each alternative. All values refer to the year 2007. The IRR calculation was based on the discounted cash flow analysis. The plan lifetime is set to 30 years.

In Table 6, market prices for the products and some key materials used are given. These values were used in the economic analysis performed.

Societal Performance (SOCIET). This may be expressed via the number of jobs created by each alternative. The creation of jobs is a typical measure of societal performance of any plant investment. In Table 7, the jobs created by each alternative is presented.

Subjective (Quantifiable) Criteria. The subjective criteria used in the analysis should illustrate the systems' ability in the economic and environmental domains. Of course, a decision maker may opt to rely only on objective criteria. Nevertheless, including some relevant subjective criteria in the analysis guarantees some extra advantages regarding completeness of

Table 5. Alternatives' Economics

	EtOH	NEUSULFO	SULFOMETHYL	ARYLSULFO	LIGNOGEOMAT
total capital Investment ($)	422,500,000	822,500,000	822,500,000	822,500,000	422,500,000
sales ($/y)	144,557,000	169,165,000	165,542,000	170,535,000	138,186,000
variable cost ($/y)	82,551,000	123,375,000	123,375,000	123,375,000	82,551,000
IRR	0.170	0.040	0.033	0.043	0.149

Table 6. Market Prices of Products and Some Key Materials Used

	market price	note
ethanol	0.57 ($/l)	
electricity	0.125 ($/Kwh)	The price includes subsidy for power generation from biomass.
lignin	0.02 ($/kg)	The price is equal to the market price of fly ash (provided by coal fired power plants), which is currently used as geomaterial in civil works.
lignosulfonates	0.4 ($/kg)	
sulfuric acid (93%)	0.088 ($/kg)	
sodium hydroxide (50%)	0.2 ($/kg)	
hydrochloric acid (36%)	0.15 ($/kg)	
phenol (crystal)	0.5 ($/kg)	

Table 7. Jobs Creation of Each Alternative

	jobs	note
EtOH	60	as in the NREL report[2]
NEUSULFO	85	assumption taking into account the operation of two to three additional departments
SULFOMETHYL	85	assumption taking into account the operation of two to three additional departments
ARYLSULFO	85	assumption taking into account the operation of two to three additional departments
LIGNOGEOMAT	65	assumption taking into account the operation of one additional departments

the decision. The following subjective criteria may be considered to be relevant in the present case, as they can express the systems' response on market and technical requirements: (1) Maturity of each system's technology level (TECH) used on each production system (concept, lab scale, pilot plant, or industrial implementation) is of economic importance because the more mature it is the less expenses are needed for its development. (2) System's integration level (INTEGR) is an economic criterion that relates to the number of products that each system produces because the more products are produced the less is the cost and the environmental burden allocated in each product. This happens because some flat costs and standing environmental burdens of a plant can be divided among the total number of the products. Therefore, the greater the number of the products are the less are the cost and environmental burdens allocated per product. (3) Market maturity (MARMAT), namely, the market ability to absorb each system's products. It relates to the existing market competition from other products, market size, products shares, etc. (4) Implementation of green chemistry axioms in each production system (GRNCHEM). Green chemistry, also known as sustainable chemistry, is the design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances.[14]

The above subjective criteria are arbitrarily selected for the analysis. However, some researchers have already proposed similar criteria for the evaluation of energy systems, such as technical maturity/reliability, market maturity, and sustainability according to pollutant emissions other than greenhouse ones.[15] On the other hand, these criteria satisfy the requirement for providing information to the decision makers about fields where no objective data can be easily and economically acquired. Table 8 summarizes the performance of each alternative in the subjective set of criteria in qualitative terms. This performance is quantified using the AHP in the next step.

Commenting on Table 8, we can note the following for each alternative.

EtOH and LIGNOGEOMAT have the best performance against the TECH criterion. On the contrary, they hold lower performance against the INTEGR criterion than the lignosulfonate systems because they output two products (ethanol and electricity) compared to the three products (ethanol, lignosulfonates, and electricity for self-consumption) of the ligosulfonates alternatives. The performance of the NEUSULFO, SULFOMETHYL, and ARYLSULFO alternatives against the TECH criterion is clearly lower than EtOH and LIGNOGEOMAT because they are in the lab-scale development stage. The latter also have better performance against the MARMAT criterion than the EtOH and LIGNOGEOMAT alternatives because the lignosulfonates market is well established. ARYLSULFO has the worst performance against the GRNCHEM criterion because it uses chloroform (or tetrachloroethane) as solvent. Both chloroform and tetrachloroethane have been characterized as undesirable solvents in industry, and their use must be avoided, as guided by the green chemistry axioms.[14] Here, it must be noted that the SimaPro–ReCiPe method (individualist perspective) does not take into account substances such as tetrachloroethane classified by the International Agency for Research on Cancer (IARC) as group 3 (not classifiable as to its carcinogenicity to humans).

Step 4. AHP Implementation. The analytic hierarchy process (AHP) is implemented to measure each alternative's

Table 8. Decision Maker's Satisfaction Relevant to Subjective Criteria[a]

subjective criterion	EtOH	NEUSULFO	SULFOMETHYL	ARYLSULFO	LIGNOGEOMAT
TECH	+	−	−	−	+
INTEGR	0	+	+	+	0
MARMAT	0	+	+	+	−
GRNCHEM	0	0	0	−	0

[a] +: Satisfied decision maker. −: Unsatisfied decision maker. 0: Neutral decision maker.

Table 9. Alternatives Performance against the Criteria

criterion	weight	EtOH	NEUSULFO	SULFOMETHYL	ARYLSULFO	LIGNOGEOMAT
ECON	0.43	0.42	0.07	0.05	0.10	0.37
ENV	0.29	0.36	0.12	0.08	0.04	0.40
SOCIET	0.09	0.06	0.30	0.30	0.30	0.05
TECH	0.04	0.42	0.05	0.05	0.05	0.42
INTEGR	0.04	0.04	0.31	0.31	0.31	0.04
MARMAT	0.05	0.07	0.30	0.30	0.30	0.03
GRNCHEM	0.06	0.47	0.11	0.10	0.03	0.29
alternative combined performance (V_j)		0.34	0.13	0.10	0.11	0.31

performance by combining the performance against the environmental and economic criteria.[16] According to AHP, alternative A is preferable to B, if $v_A > v_B$, where v_A and v_B are the corresponding performance values against a certain criterion. The previous statement is true for the economic performance criterion (ECON), so the decision maker always prefers a system that has a high IRR value. This, however, is not valid for the environmental criterion (ENV) because if a system has a higher ReCiPe R value than another, it means that it also has a more severe effect on the environment than the other system. Thus, the inverse values $(1/R)$ are considered for the determination of preference order against the ENV criterion.

More specifically, seven pairwise comparison matrices (one for each criterion) are constructed for the determination of each alternative's scores against each criterion. The values in these matrices give the decision maker's strength of preference between the five alternatives if only one criterion is taken into consideration at a time. Weights of the criteria used are calculated through the classic AHP procedure. For each pair of criteria, the decision maker is required to respond to the question "How important is criterion i relative to criterion j?". Rating the relative "priority" of the criteria is done by assigning a weight between 1 (equal importance) and 9 (extreme importance) to the more important criterion, whereas the reciprocal of this value is assigned to the other criterion in the pair. The weights are then normalized and averaged in order to obtain an average weight for each criterion. The consistency of values obtained is then checked.

Finally, the combined performance of each alternative V_i is calculated using eq 1.

$$V_i = \sum w_j v_{ij} \qquad (1)$$

for i = EtOH, NEUSULFO, SULFOMETHYL, ARYLSULFO, and LIGNOGEOMAT and j = ENV, ECON, SOCIET, TECH, INTEGR, MARMAT, GRNCHEM, where w_j is the weight of the jth criterion and v_{ij} is the performance of alternative i against the jth criterion.

■ RESULTS AND DISCUSSION

The results must be discussed in light of the following. The primary aim of the study is to propose a method and a set of criteria for the evaluation and screening of bioethanol production systems. Undoubtedly, many similar other methods as well as criteria already exist or can be developed. The proposed rough method can be improved by additions, corrections, or supplements but the main context of the analysis will remain indifferent as set by this study. On the other hand, precision and accuracy characterize the method because it is based on the broadly used analytic hierarchy process. All these constitute the study's contribution to the efforts for a more sustainable bioethanol system and moreover for more sustainable biofuel production systems in general.

Of course, the alternatives' performances against the objective criteria are obtained based on a set of assumptions expressing subjective evaluations and preferences regarding the criteria and weights used. Thus, the performances can vary depending upon the decision maker.

The calculated criteria weights and alternatives' performance against each criterion, as well as their combined performance, are presented in Table 9. Apparently, production economics (ECON criterion) overweigh the environmental performance (ENV criterion) in the decision making. This reflects the most common decision makers' preference.

The EtOH alternative has the best performance against ECON followed by LIGNOGEOMAT. The latter is the best alternative against the ENV criterion succeeded by EtOH. Lignosulfonate alternatives (NEUSULFO, SULFOMETHYL, and ARYLSULFO) take the lead against the INTEGR and MARMAT criteria.

EtOH has obviously the best overall performance, while LIGNOGEOMAT follows closely. Both of them outdistance the lignosulfonates alternatives.

For testing the robustness of the previous results, we used an iteration method by which retaining the subtotal of the all other criteria weight values at the current level of 0.28, we increased the environmental criterion (ENV) weight by a factor of 0.01 (for initial value $w_{ENV} = 0.29$). We find, after 29 iterations, that the LIGNOGEOMAT alternative starts to become more attractive than EtOH for a value of the environmental criterion (ENV) weight ≥ 0.58 (or for ECON criterion weight ≤ 0.14), while the order of preference of the other alternatives remains the same. It is obvious that this is an extremely hypothetical case, which is out of discussion in the real business world, because it means that an imaginary investor would have chosen a project relying by more than 58% on its environmental performance or that the environmental performance is weighing more than four times the economic performance criterion.

As far as uncertainty evaluation is concerned, it is noted that any uncertainty in the final decision would be mainly due to uncertainties characterizing the alternatives' performance values against the **objective** criteria only. As a general rule, the alternatives' performance values against the **subjective** criteria are not characterized by uncertainty due to calculations. Additionally, no uncertainty regarding the performance values against the SOCIET criterion is noticeable because the jobs created by the alternatives are well specified.

So, the performance values against the ECON and ENV (objective) criteria are the ones that may mainly contribute to any uncertainty regarding the alternatives' overall performance and, finally, their ranking. Regarding this consideration, we note first that the values used in the analysis performed derive from valid and up-to-date databases. Furthermore, even assuming an uncertainty rate (value variations) of ±3%, the analysis shows that this would imply an overall uncertainty of the alternatives' performance values of ±4%. This level of uncertainty does not influence the overall ranking of the alternatives because the EtOH combined performance (ranking first) surpasses that of the LIGNOGEOMAT alternative (ranking second) by 9%. For an uncertainty rate of the performance values against the ECON and ENV criteria larger than ±3%, the decision becomes unclear regarding the ranking of the EtOH and LIGNOGEOMAT alternatives. In any case, the EtOH and LIGNOGEOMAT overall performance values outdistance those of NEUSULFO, SULFOMETHYL, and ARYLSULFO twice as much, so the preference of the former against the latter is not actually affected by uncertainty.

CONCLUSIONS

The sustainability assessment and evaluation of the proposed production systems play important roles in the selection of those that can scale up from a concept stage to commercial production. This becomes more evident in the case of the biofuels production systems because within the past decade many concepts or patents have been introduced as environmentally and economically sustainable solutions. In this study, we evaluate the sustainability of five alternative production systems producing ethanol and certain byproducts from corn stover using a set of objective and subjective economic, environmental, and societal criteria. The determination by the study of the more sustainable systems has obvious economic and financial consequences.

Clearly, the alternatives that produce ethanol and supplement either electricity for the grid or lignin for use as geomaterial, namely, EtOH and LIGNOGEOMAT, are the most sustainable among the alternatives examined by the study. More specifically, while EtOH holds the best economic performance (ECON criterion) and LIGNOGEOMAT the best environmental performance (ENV criterion), EtOH has slightly better overall performance for certain criteria weights ($w_{\mathrm{ECON}} = 0.43$, $w_{\mathrm{ENV}} = 0.29$). The main advantage of these alternatives is that their technology is under a pilot plant scale, which means that their process including material and energy balances, recycling streams, equipment life cycle, etc. are well studied and optimized. Additionally, their product market demand is considered as developed and validated.

On the contrary, the alternatives producing ethanol and lignosulfonates have distinctly worse sustainable performance. This is mainly due to their poor economic and environmental performance because they are systems under a lab-scale development stage, and obviously, their processes are not optimized. More specifically, a big problem concerning the lignosulfonates production systems relates to the vast consumption of sulfuric acid, sulfite, phenol, hydrochloric acid, and similar other chemicals. This leads to high production cost and of course to high environmental burden. Replacing them with other less expensive and appropriate materials and optimizing the process can contribute to a reduction in cost and environmental burden. Among the lignosulfonate production alternatives, the one using the arylsulfonation process (ARYLSULFO) has the worst environmental performance. This system uses undesirable solvents (chloroform or tetrachloroethane) scoring in such a way very low against the implementation of the green chemistry criterion. Obviously, due to this reason, it must be excluded from further development toward commercial production.

Further research work in the field of this study should include, among others, the redesign and optimization of the ethanol/lignosulfonates production systems in order to enhance their sustainability and the acquisition of more precise data about the logistics of the biomass feedstocks and their characteristics toward a better and less uncertain determination of the alternatives' sustainability. The sensitivity analysis should be further improved for better understanding the robustness of the systems. Finally, issues regarding the results uncertainty should be further investigated.

ASSOCIATED CONTENT

Ⓢ Supporting Information

AHP decision process tree and calculations for criteria weights and alternatives' scores estimation. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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