AIChE

Minimization of the Nonrenewable Energy Consumption in Bioethanol Production Processes using a Solar-Assisted Steam Generation System

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DOI 10.1002/aic.14267
Published online October 28, 2013 in Wiley Online Library (wileyonlinelibrary.com)

The multiobjective optimization of a corn-based bioethanol plant coupled with a solar-assisted steam generation system with heat storage is described. Our approach relies on the combined use of process simulation, rigorous optimization tools, and economic and energetic plant analysis. The design task is posed as a bicriteria nonlinear programming problem that considers the simultaneous optimization of the plant profitability and the energy consumption. The capabilities of the proposed methodology are illustrated through a 120,000,000 kg/year corn-based bioethanol plant considering weather data of Tarragona (Spain). © 2013 American Institute of Chemical Engineers *AIChE J*, 60: 500–506, 2014
Keywords: bioethanol, corn dry-grind, solar panels, cost analysis, energy consumption

Introduction

The continued use of fossil fuel to meet most of the world's energy demand is threatened by increasing concentrations of CO_2 in the atmosphere and concerns over global warming. The combustion of fossil fuel is responsible for 73% of the CO_2 production.[1] To reduce the contribution of green house gases to the atmosphere, bioethanol is probably the most mature alternative to petroleum-derived transportation fuel.[2]

Bioethanol is the most important biofuel today with a production of about 32,394 millions of gallons in 2012.[3] Bioethanol can be produced from a large variety of natural renewable materials and conversion technologies. The corn dry-grind process is the most widely used method in the United States for generating fuel ethanol by fermentation of grain.[4] However, corn grain as other first generation bioethanol processes has raised questions regarding its feasibility as an alternative fuel. Its main drawback is the high energy input required to produce corn and to convert it into bioethanol.[5,6]

In order to analyze the potential economic and energetic benefits of bioethanol production processes, several works have used process simulation techniques. Kwiatkowski et al.[7] modeled in SuperPro Designer the fermentation of corn dry-grind for the production of bioethanol. Quintero et al.[8] presented an economical and environmental comparative study between fuel ethanol production from sugarcane and corn using Aspen Plus. Dias et al.[9] simulate different scenarios of the bioethanol production from sugarcane using SuperPro Designer. More recently, Tasic and Veljkovic[10] developed a simulation model for bioethanol production from potato tubers using Aspen Plus.

Apart from these works based on rigorous process simulation, there are other contributions that address the optimal design of bioethanol production processes using "short-cut" models combined with optimization techniques. Karuppiah et al.[11] were the first to propose a superstructure optimization approach for the optimal design of corn-based bioethanol plants. Grossmann and Martin[12] presented a general approach based on mathematical and Grossmann[13,14] presented also an optimization approach for energy reduction in bioethanol production processes via gasification and hydrolysis of switchgrass.

As shown, many approaches have focused on minimizing the energy consumption in corn-based bioethanol facilities. Pimentel[5] was the first to address this issue in bioethanol production plants, calculating an energy consumption of 75,118 Btu/gal. Shapouri et al.[6] estimated a lower energy consumption of 51,779 Btu/gal. Wang et al.[15] presented a process with a significant energy reduction compared to the previous ones, 38,323 Btu/gal. Finally, Martin and Grossmann,[13] used rigorous optimization techniques for the minimization of the energy consumption, which was reduced to 19,996 Btu/gal.

The aforementioned works were focused on improving the bioethanol production process by changing the operating conditions and structural configuration of the plant. An alternative approach to reduce the energy consumption of bioethanol plants consists of coupling them with renewable energy sources. In a recent work, Lewis and Nocera[16] highlighted the benefits of integrating solar energy with other technologies. Shinnar and Citro[17] claimed that solar thermal energy can be an environmentally friendly and economically competitive energy source. More recently, Gebresslassie et al.[18] addressed the minimization of the life cycle impact

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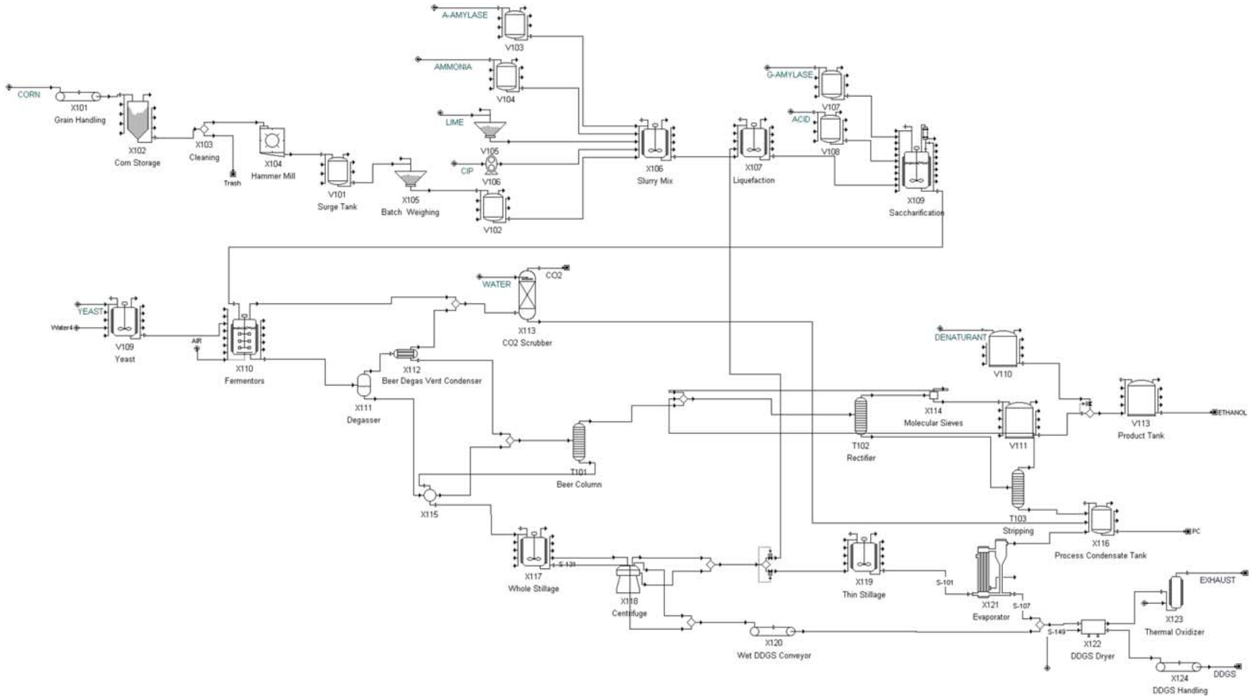

Figure 1. Flowsheet for the corn-based bioethanol production model.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

in cooling systems using solar collectors, while Salcedo et al.[19] developed a model for the optimization of reverse osmosis desalination plants coupled with solar-assisted Rankine cycles.

With all of these works in mind, the aim of this article is to present a systematic method for the optimal design of corn-based bioethanol facilities considering economic and energetic concerns in the decision-making process. Our approach relies on the combined use of process simulation, optimization tools and economic and energetic analysis within a unified framework. The optimization problem is formulated as a bicriteria nonlinear program (biNLP), involving economic and energetic objective functions. The solution approach presented combines process simulators (SuperPro Designer) and optimization software (Matlab and GAMS) in an integrated framework. The optimization algorithm provides as output a biobjective optimization set of Pareto solutions representing the optimal compromise between plant profitability and energy consumption. The methodology presented has been tested in a 120,000,000 kg/year corn-based bioethanol production, considering weather data of Tarragona (Spain) for the solar collectors.

Process Description

As mentioned in the previous section, our approach includes both a simulation and an optimization model. The first is used to estimate the performance of the bioethanol plant, while the second allows to determine the energy savings by coupling the production facility with a solar steam generation system. The simulation model has been implemented in SuperPro Designer, and it is based on the one proposed by Kwiatkowski et al.[7] In contrast, the optimization model has been developed in GAMS, and it is based on the one proposed by Salcedo et al.[19] Next, we describe in detail each of these models.

Bioethanol production plant

We consider a corn-based bioethanol production facility. There are two general manners of processing corn to produce ethanol: dry-grind and wet-mill. The corn dry-grind process is the most widely used method in the United States for generating fuel ethanol by fermentation of grain. This is because dry-grind processes are less capital and energy intensive than wet-mill processes. The corn-based bioethanol production process comprises six-stages: milling, liquidification, saccharification, fermentation, distillation, and dehydration. A simplified flow diagram of the process is shown in Figure 1.

In the milling stage (Stage 1) of the dry-grind process, corn grain is cleaned in a hammer mill (X104) and sent through weighing tanks to the liquefaction step (Stage 2). To begin stage 2, the measured ground corn is sent to a slurry tank (X106) where is treated with alpha-amylase, ammonia, and lime. This mixture is then gelatinized using a "jet-cooker" and hydrolyzed with thermostable alpha-amylase into oligosaccharides, in the liquefaction unit (X107).

The conversion of the oligosaccharides by glucoamylase to glucose takes place in the saccharification stage (Stage 3). The reaction is done in the saccharification reactor (X109) where g-amylase and sulfuric acid are added. The reaction takes 5 h and it is performed at 60°C with a pH of 4.5. Then, the slurry is transferred to the fermentation vessel (X110). In the fermentation stage (Stage 4) the glucose is converted into ethanol. The reaction takes places in the fermenter X110 and it takes 68 h at 32°C.

The output stream from the fermentation, named beer liquor, is then sent through a degasser drum (X111). The obtained vapor stream is then condensed and recombined with a liquid stream prior to being sent to the distillation stage (Stage 5).

In the distillation stage, all the ethanol produced during the fermentation is recovered in the beer column (T101). This is accomplished through the combined action of the

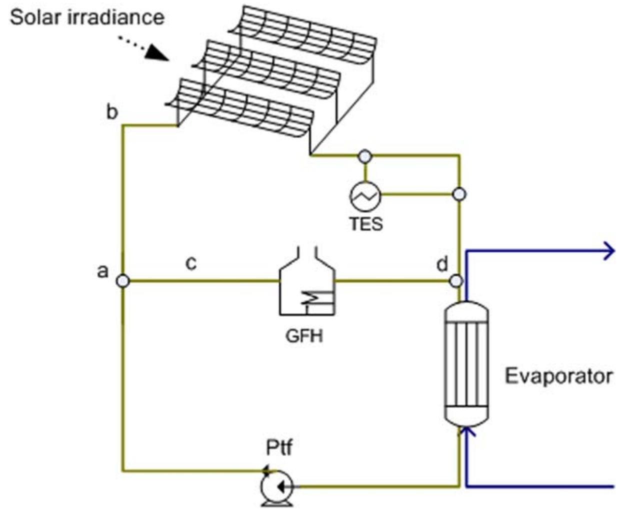

Figure 2. Solar-assisted steam generation system with heat storage.

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rectifier (T103) and molecular sieves (X114). The distillate of the rectifier, containing primarily ethanol, feeds the molecular sieves, which captures the remaining water, obtaining 99.6% pure ethanol. Finally, the main product, fuel ethanol, is produced after mixing the refined ethanol with approximately 5% denaturant (gasoline) and is stored in the product tank (V113).

Concerning the by-products, the mixture of the nonfermentable material from the bottom of the beer column (T101) is fed to the whole stillage tank (X117). Then, the centrifuge (X118) removes the 83% of the water content. The liquid product from the centrifuge is splitted. The concentrate from the evaporator is mixed with the wet distiller's grains coming from the distiller conveyor (X120). The mixture goes to the drum dryer which reduces the moisture content of the mixture of wet grains and evaporator concentrate from 63.7 to 9.9%, and this stream becomes the coproduct known as distiller's dried grains with solubles.

Solar-assisted energy system

One of the main sources of energy consumption in the process described above is in the reboilers of the distillation columns. According to our simulations, this consumption is 12.239 BTU per gallon of bioethanol produced.

To decrease the energy requirements, we propose to couple the bioethanol facility with a solar-assisted steam generation system with heat storage. Figure 2 shows the diagram of the steam generation system proposed, which is integrated with the bioethanol plant.

In the system presented, we use parabolic collectors to transfer solar energy to the heat mineral oil; however, other types of solar collectors can be used for the same purpose. A thermal energy storage (TES) is connected to the solar panels to use the solar energy more efficiently, especially with the intermittent radiation. Additionally, a gas fire heater (GFH) is coupled in the system as a backup unit in order to maintain the oil temperature constant. Note that molten salt is used as the heat transfer fluid that transports thermal energy between the storage unit and the remaining parts of the power system.

Proposed Approach

In this work, the optimization of the integrated system is performed in two sequential steps. A rigorous simulation model is first constructed in SuperPro Designer, while the optimization of the steam generation system is implemented in GAMS. The outcome of the optimization is combined with the simulation results, which provides the performance of the overall integrated system. Note that the emphasis here is on assessing the economic and energetic performance of the integrated facility.

We, therefore, assume that the bioethanol plant is already under operation, and we focus on optimizing the solar system that will power the reboilers of the facility. The optimization of the combined biofuel facility with solar collectors is, therefore, out of the scope of this contribution. Finally, let us note that this general approach can be applied to other chemical processes, and it is, therefore, not restricted only to biofuel plants.

The following sections describe the modeling tools applied to each part of the process.

Process model of the bioethanol plant

The bioethanol simulation model has been implemented in SuperPro Designer, and it is based on the one proposed by Kwiatkowski et al.[7]

The process simulator (SuperPro Designer) quantifies the mass and energy balances of each unit for the specified operating plant. Volumes, compositions, and other physical characteristics of input and output streams are also computed. This information becomes the basis for the subsequent calculation of the economic analysis (purchased equipment costs, raw material cost, utility consumptions cost, etc.) in Matlab.

Mathematical formulation of the solar-assisted energy system

The model of the solar-assisted energy system has been developed in GAMS and it is based on mass and energy balances. These equations ensure the mass and energy conservation and are applied to each unit of the system. The mass balance is defined by Eq. 1

$$\sum_{i \in \mathrm{IN}_k} m_{i,t} \cdot x_{i,p,t} - \sum_{i \in \mathrm{OUT}_k} m_{i,t} x_{i,p,t} = 0 \quad \forall k, p, t \tag{1}$$

where IN_k and OUT_k are the sets of streams entering and leaving unit k, respectively. $m_{i,t}$ is the mass flow of stream I in period t, and $X_{i,p,t}$ is the mass fraction of component p in stream i in period t. The total summation of the mass fractions of components p in every stream I must equal 1 (see Eq. 2)

$$\sum_{p} x_{i,p,t} = 1 \quad \forall i, t \tag{2}$$

The energy balance is defined by Eq. 3

$$\sum_{i \in \mathrm{IN}_k} m_{i,t} \cdot h_{i,t} - \sum_{i \in \mathrm{OUT}_k} m_{i,t} \cdot h_{i,t} + Q_{k,t} - W_{k,t} = 0 \quad \forall k, t \tag{3}$$

where h_i is the enthalpy of stream i in period t, $Q_{k,t}$ is the thermal power supplied to unit k in period t, and $W_{k,t}$ is the mechanical power output of unit k in period t.

In the model of the solar-assisted steam generation system with heat storage, we define the global energy balance

$$Q_{k,t}+Q_{k',t'}+Q_{k'',t-1}=Q_{k''',t}+Q_{k'',t} \quad k=\text{col}, \\ k'=\text{GFH}, k''=\text{TES}, k'''=E, \forall t \quad (4)$$

where $Q_{\text{col},t}$ is the thermal energy captured by the collectors, $Q_{\text{GFH},t}$ is the energy provided by the fossil fuel combusted in the GFH, $Q_{\text{TES,t}}$ is the thermal energy accumulated in the storage at the end of period t and $Q_{\text{E,t}}$ is the energy required by the evaporator.

The maximum amount of thermal energy that can be accumulated is given by the maximum storage capacity CAP

$$\bar{Q}_{\text{TES},t} \leq \text{CAP} \quad \forall t \quad (5)$$

The heat produced in the solar collectors is calculated from Eq. 6

$$Q_{k,t}=G_t \cdot A_k \cdot \eta_k \quad k=COL, \forall t \quad (6)$$

where G_t represents the solar radiation, which depends on the time period of the day. The daily solar radiation expressed in MJ/m^2 day is available in Catalonia.[20] The efficiency of the medium-high temperature parabolic trough collectors η_{Col} is calculated according to the work by Bruno[21] (Eq. 7)

$$\eta_{k,t}=\eta_{t^0}-a_1\left(T_t^{\text{av}}-T_t^{\text{amb}}\right)-a_2\left(\frac{T_t^{\text{av}}-T_t^{\text{amb}}}{G}\right) \\ -a_3\left(\frac{T_t^{\text{av}}-T_t^{\text{amb}}}{G}\right)^2 \quad k=\text{COL}, \forall t \quad (7)$$

where $\eta^0{}_t$ is collector optical efficient, a_1, a_2, a_3 are coefficients, T_t^{amb} is the ambient temperature in time period t, and T_t^{av} is the average temperature of the solar collector, which is determined by Eq. 8

$$T_t^{\text{av}}=\frac{T_{\text{OUT}_k}-T_{\text{IN}_k}}{2} \quad k=\text{COL}, \forall t \quad (8)$$

The heat produced by the combustion of natural gas in the heater is given by Eq. 9

$$Q_k=m_{\text{NG}} \cdot \text{LHV} \cdot \eta_k \quad k=\text{GFH}, \forall t \quad (9)$$

In this equation, m_{NG} is the mass flow rate of natural gas, LHV is the lower heating value of natural gas, and η_{GFH} is the thermal efficiency of the natural gas heater.

Economic and energetic analysis

The economic objective function is the net present value (NPV), which quantifies the plant profitability and it is equal to the sum of the net profit in year j plus the depreciation

$$\text{NPV}=\sum_{j=1}^{J}\frac{N_j+d_j}{(1+ir)^j} \quad (10)$$

Where N_j is the annual gross profit minus the income tax, d_j is the depreciation of that year, parameter ir is the interest rate, and j is the number of year that the plant is working, in this case 25 years. This economic assessment is based on the costs analysis of Henderson et al.,[22] Tiffany et al.,[23] and Bryan and Bryan.[24]

With regard to the energy objective function, we analyze here the energy in BTU required to produce 1 gallon of bioethanol. We select this energetic parameter because it is the parameter used to indicate the process energy performance in the previous works.[5,6,13,15]

biNLP model

The design of the integrated system with economic and environmental concerns can be expressed in mathematical terms as a biNLP. We solve this model using the ε constraint method.[25,26] This technique is based on calculating a set of single-objective models in which one objective is kept in the objective function while the others are transferred to auxiliary constraints and forced to be lower than a set of epsilon parameters

$$\begin{aligned} &\min_{x,y} \quad z=f_1(x,y) \\ &s.t. \quad f_2(x,y) \leq \varepsilon \\ &\underline{\varepsilon} \leq \varepsilon \leq \overline{\varepsilon} \\ &f_1(x,y)=f_1^P(x^P,y^P)+f_1^S(x^S) \\ &f_2(x,y)=f_2^P(x^P,y^P)+f_2^S(x^S) \\ &\quad hp(x^P,y^P)=0 \\ &\quad hs(x^S)=0 \\ &\quad gp(x^P,y^P) \leq 0 \\ &\quad gs(x^S) \leq 0 \end{aligned} \quad (11)$$

The economic objective function, represented by $f1$, is quantified using the NPV and the objective functions $f2$ measure energetic costs. ε is an auxiliary parameter that bounds the values of the objectives transferred to the auxiliary inequality constraints. While x and y represent continuous and discrete variables defined for the plant and solar-assisted system (x^p, y^p, and x^s, respectively). For simplicity, in this formulation, we fully decouple the optimization of the plant and that of the steam generating system. Furthermore, we consider that the plant will not be modified, so variables x^p and y^p are fixed, while variables x^s are optimized using a gradient-based method. This reflects the situation in which we aim to retrofit an existing facility by adding the energy system but without changing neither the operating conditions nor the topology of the plant.

Numerical Results

We study the design of a 120.000.000 kg/year solar-assisted corn-based bioethanol production plant considering weather data of Tarragona (Spain). We first present the economic and energetic analysis of the base case, a bioethanol plant in which the heat capacity is just generated by the GFH. We will then analyze the alternative system proposed here in which the solar-assisted steam generation with heat storage is used to cover the steam required by the plant. We finally discuss the Pareto curve of optimal results of the bioethanol plant integrated with the solar-assisted steam generation system.

Bioethanol production plant

The presented bioethanol cost information is based on equipment and operating costs. We used general accepted methods for conduction conceptual technical and economic methods in the process industry.[27–29] The purchased costs for the major equipment items were based on budgetary quotations from equipment suppliers. Additional literature on the construction of bioethanol plants is available in.[22–24]

The capital costs calculations are summarized in Table 1. The estimated total capital cost of the 120.000.000 kg/year corn dry-grind bioethanol production plant is 60.52 MM$. The cost of the process equipments is 19.03 MM$. The total

Table 1. Capital Costs Summary of the Bioethanol Production Process

Item	Costs ($)
Process equipment	
Grain Handling (101MH)	121,000
Corn Storage (102V)	979,000
Cleaning (103MH)	61,000
Hammer Mill (104M)	98,000
Batch Weighing (106W)	51,000
Slurry Mixer (307V)	69,000
Liquefaction (310V)	161,000
Saccharification (321V)	103,000
Fermenter (405V)	2,812,000
Degasser (412V)	62,000
Beer Column (501T)	597,000
Rectifier (503T)	254,000
Molecular Sieve (504X)	1,718,000
Scrubber (409V)	91,000
Stripping (507T)	168,000
Centrifuge (603X)	825,000
Evaporator (607Ev)	3,418,000
DDGS Dryer (610D)	2,278,000
Thermal Oxidizer (611X)	925,000
DDGS Handling (612MH)	123,000
Total Tanks	1,340,000
Total Heat exchangers	2,380,000
Total Pumps	311,000
	19,028,000
Utility equipment	
Cooling tower	1,003,880
Steam generation	2,522,388
Instrument air system	144,417
Electrical system	577,682
	4,248,376
Other cost	
Installation	34,914,564
Miscellaneous	2,327,637
	37,242,201
Total Capital Investment	**60,518,577**

cost of the utility equipments is 4.24 MM$. Additionally, other costs are taken into account such as the installation and miscellaneous costs.

The plant operating costs are based on material and utility costs. Costs agree with actual production cost information collected in surveys conducted by USDA.[6] Ethanol dry-grind plant operates 24 h/day with time set aside for maintenance and repairs. A basis of 330 days per year (7920 h) operating time was used for this model, and the nominal capacity of the plant is approximately 35,837 kg/h of corn.

The projected annual operating costs for the modeled biodiesel production facility are shown in Table 2. The cost of raw materials is the most significant, specially the cost of the corn (50.57 MM$/year) which represents the 92.96% of the raw materials total cost (54.40 MM$/year) and 57.83% of the total operational costs (80.27 MM$/year). The other raw materials are: lime, ammonia, alpha-amylase, glucoamylase, sulfuric acid, caustic, yeast, water, and octane. The cost of utilities (steam, cold water, electricity, wastewater treatment, and natural gas) is 15.11 MM$/year. Finally other costs are: miscellaneous, maintenance, operating labor, laboratory, supervision, capital charges, and insurance.

Table 3 shows the NPV of the plant along with the most significant items related with the economic analysis.

We studied the operating energy analysis to produce 1 gallon of bioethanol. The energy required to obtain 1 gallon of bioethanol is 20,968 BTU. In these calculations, we follow the standard approach used in the literature that considers the steam and electricity used in the process. Note that most

Table 2. Operating Costs Summary of Bioethanol Production Process

Item	Costs ($/yr)
Raw materials	50,567,713
Corn ($/yr)	39,437
Lime ($/yr)	161,334
Ammonia ($/yr)	578,562
Alpha-amylase ($/yr)	835,669
Sulfuric Acid ($/yr)	80,667
Caustic ($/yr)	223,296
Yeast ($/yr)	179,426
Water ($/yr)	7,037
Octane ($/yr)	1,722,266
	54,395,407
Utilities	
Steam ($)	5,150,241
Cooling water ($)	4,348,379
Electricity ($)	1,471,453
Natural gas ($)	4,140,705
	15,110,779
Other costs	
Miscellaneous ($)	5,439,541
Maintenance ($)	5,439,541
Operating Labor ($)	1,760,000
Lab Costs ($)	352,000
Supervision ($)	352,000
Overheads ($)	880,000
Capital Charges ($)	8,159,311
Insurance ($)	2,175,816
	24,558,209
Operating Costs	**94,064,209**

of the energy 58.37% is used in the reboiler of the beer column, rectifier, and stripping. Table 4 presents the energy consumed by each item included in the energy balance of the bioethanol production process.

As we will discuss later in the article, the solar collectors are integrated with the biofuel plant in order to reduce the energy consumption in the reboilers.

Optimal design of the solar-assisted dry-grind bioethanol production

In this section, we present the optimal results of the dry-grind bioethanol production plant coupled with solar-assisted steam generation with heat storage. The process model was implemented in SuperPro Designer, whereas the biNLP model of the solar system was coded in GAMS and solved with CONOPT3. The algorithm took around 23.5 s to generate 10 Pareto solutions on a computer AMD PhenomTM 86000B, with Triple-Core Processor 2.29 GHz and 3.23 GB of RAM.

Figure 3 shows the Pareto curve of the NPV of the plant, including the steam generation system, and the energy consumed per 1 gallon of bioethanol produced (NRG). The NRG consumed is reduced by 38.77% (20,968 Btu/gal vs. 12,838 Btu/gal) along the Pareto curve. This is accomplished by reducing the consumption of the natural gas. However, the

Table 3. Executive Economic Summary of Biodiesel Production Process

Item	Bioethanol Process
Net Present Value ($)	92,752,281
Total Capital Investment ($)	60,518,577
Operating Cost ($/yr)	94,064,209
Production Rate (kg/ yr)	119,171,463
Unit Production Cost ($/kg)	0.67
Unit Selling Price ($/kg)	0.69
Total revenues($)	81,826,000

Table 4. Operating Costs Summary of Bioethanol Production Process

Item	(BTU/gal)
Grain Handling (101MH)	361.57
Cleaning (103MH)	122.46
Hammer Mill (104M)	554.68
Slurry Mixer (307V)	37.00
Liquefaction (310V)	243.04
Saccharification (321V)	407.48
Fermenter (405V)	164.57
Degasser (412V)	175.68
Beer Column/Reboiler (501T)	7,978.75
Rectifier /Reboiler (501T)	2,130.59
Molecular Sieve (504X)	92.72
Scrubber (409V)	406.34
Stripping/Reboiler (507T)	2,130.59
Centrifuge (603X)	306.01
Evaporator (607Ev)	2.940,46
DDGS Dryer (610D)	1,473.15
Thermal Oxidizer (611X)	221.09
DDGS Handling (612MH)	52.67
Total Heat exchangers	475.80
Total Pumps	200. 64
	20,968.98

NPV is dramatically decreases from design A to B (92.75 MM$ vs. −328.81 MM$), this is because the solar collector area in the minimum NRG is extremely large and the total capital investment to produce all the steam for the plant just using solar collectors is very expensive. However, design C has similar plant profitability as design A (92.75 MM$ vs. 82.61 MM$), but the main factor is that the environmental impact in design C is 25.87% lower than the environmental impact in design A (20,968 Btu/gal vs. 13,903 Btu/gal), this is because in design C, we use 71,053 m^2 of solar collectors and we save the 45.20% of natural gas used in design A.

Table 5 summarizes the main characteristics of designs A, B, and C. As shown, in the design A, the NPV is the highest. Mainly, because the total capital investment is lower. In design B, the NPV is dramatically decreased to the point that the profitability of the plant is negative. This is because to generate almost all of the steam with just solar collectors, you need a very high area, up to 5,000,000 m^2 and the associated

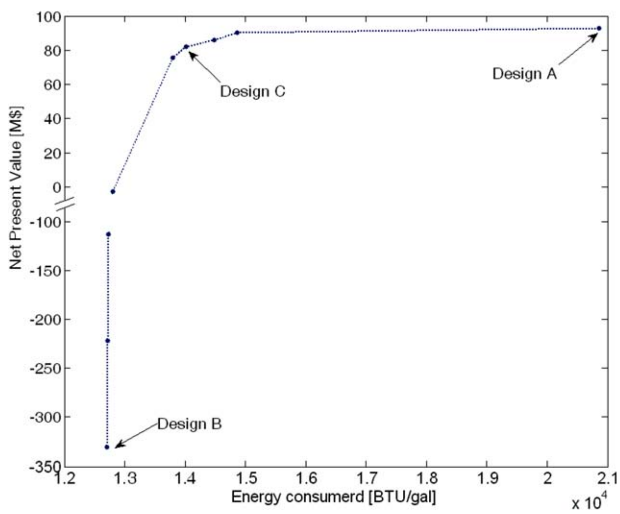

Figure 3. Pareto set of optimal solutions in the bioethanol production plant.

[Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table 5. Economic and Energetic Summary of the Bioethanol Process

Item	Design A	Design B	Design C
Net Present Value ($)	92,752,281	−328,817,003	75,610,887
Energy consumed (Btu/gal)	20,968	12,838	13,903
Total Capital Investment ($)	37,159,397	316,441,020	44,862,192
Operating Cost ($/yr)	63,021,995	79,893,062	62,606,124
Production Rate (kg/ yr)	119,171,463	119,171,463	119,171,463
Unit Production Cost ($/kg)	0.67	1.12	0.68
Unit Selling Price ($/kg)	0.69	0.69	0.69
Total revenues($)	81,826,000	81,826,000	81,826,000
Area solar panels (m^2)	0	5,430,794	71,053
Natural gas consumed (kg/yr)	22,066,980	10,570,180	12,102,040

cost is very high. In the design C, the NPV is very similar to the design A because on one hand the total capital investment is increased but on the other the operating cost is decreased. Concerning the NRG, in design A the natural gas consumed is very high compared to that associated with the other two designs. In light of these results, solution C seems to be the most appealing. Therefore, we propose to the decision-makers to adopt the design C as the most adequate plant design.

Conclusions

In this work, we have proposed a systematic method based on the combined used of process simulation and mathematical programming techniques, for the optimal design of corn dry-grind bioethanol production processes with economic and energetic concerns. The design task was formulated as biNLP that minimizes simultaneously the NPV and the energy consumed to produce 1 gallon of bioethanol (NRG).

The capabilities of the approach presented were tested in the design of a 120,000,000 kg/year corn dry-grind bioethanol production plant considering weather data of Tarragona (Spain). The Pareto solutions set were generated using the epsilon constraint methodology. The results obtained show that is possible to achieve reductions in the energetic consumption with respect to the maximum profitability design.

As explained, our method provides a comprehensive framework for the design of bioethanol plants integrated with solar energy that systematically identifies the best process alternatives in terms of economic and energetic performance. This information is valuable for decision makers, as it allows them to adopt more sustainable technological alternatives for bioethanol processes.

Acknowledgments

The authors wish to acknowledge the financial support received from the support from the Spanish Ministry of Economy and Competitiveness(CTQ2012-37039-C02, DPI2012-37154-313C02-02 and ENE2011-28269-C03-03).

Notation

Sets/Indices

i = streams
j = year
k = units
P = plant variables
p = components

rm = raw materials
S = solar system variables
t = time period
ut = utilities

Abbreviators

biNLP = bicriteria nonlinear programming
COL = solar collectors
DDGS = distiller dried grains with soluble
E = evaporator
GFH = gas fire heater
MINLP = mixed-integer nonlinear programming
NEB = net energy balance
NLP = nonlinear programming
NPV = net present value
TES = thermal energy storage

Variables

A = solar collector area
d = depreciation
df = damage factors of component b
G = solar radiation
m = mass flow
N = annual net profit
Q = thermal power
r = annual revenues
T^{amb} = ambient temperature
T^{av} = average temperature
V = volume of the equipment
W = mechanical power
x = continuous variables
y = integer variables
η = collector optical efficiency
ε = auxiliary parameter

Parameters

a1 = solar collector coefficient equation 7
a2 = solar collector coefficient equation 7
a3 = solar collector coefficient equation 7
CAP = maximum storage capacity
LHV = lower heating value of natural gas
ir = = interest rate
top = operation time

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Manuscript received May 1, 2013, revision received July 26, 2013, and final revision received Oct. 13, 2013.