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# Exergy Analysis of the Production of lignocellulosic Ethanol

Ala Modarresi*, Philipp Kravanja and Anton Friedl

Vienna University of Technology, Institute of Chemical Engineering
Getreidemarkt 9/166-2, 1060 Vienna, Austria
alae.hosseini@tuwien.ac.at

Exergy analysis is applied to a process for production of bio-ethanol from lignocellulosic. A tool based on Mathematica has been developed to calculate the exergy of compounds and streams of lignocellulosic ethanol production process. The whole process was simulated using the suitable chemical process simulation software (IPSEpro). Some different scenarios are analyzed for handling stillage waste from ethanol production. Parametric studies show the influence of the proper selection of scenario on exergy efficiency. It is shown that process integration reduces process irreversibilites. Internal use of waste streams for providing process heat and electricity as well as generation of some useful by-products such as animal feed and pellets using additional steps could increase exergy efficiency.

## 1. Introduction

Today production of bio-ethanol from lignocellulosic materials is a suitable chemical process according to some reasons. First, the greenhouse gas mitigation potential compared to both, fossil fuels and bio-ethanol from starchy crops is high (Eisentraut, 2010) and second usage of additional acreage can be avoided if residual materials from food production or forest industry are employed.

In this work we investigate the production of ethanol from straw from an exergetic point of view. Several production scenarios for a process based on steam pretreatment with acid impregnation and enzymatic hydrolysis are compared using the steady state process simulation software IPSEpro. Besides mass and energy balance, exergy analysis is applied to the bio-ethanol production of from lignocellulosic. To obtain an economic and competitive overall process, careful selection of upstream and downstream processes as well as optimal integration of all steps in terms of minimizing residual streams and heat demand is crucial.

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## 2. Process Description

Figure 1 summarizes the scenarios considered in this work. As can be seen, the scenarios are identical as far as the upstream process, ethanol recovery and stillage separation is concerned.

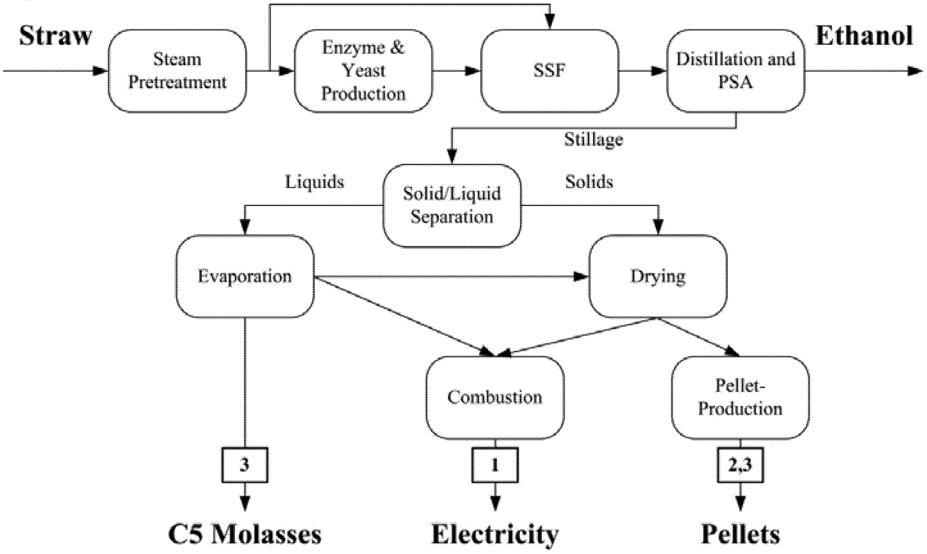

*Figure 1: Schematic summary of process scenarios for the production of ethanol from straw.*

For all the scenarios process steam is generated by burning part of the stillage reducing the processes' demand for fossil energy largely. In scenarios 2 and 3 electricity is bought from the grid whereas in scenario 1, electricity is produced on-site. For scenarios 2 and 3 the byproducts pellets (Scenario 2 and 3) and C5-molasses (Scenario 3) are produced. Ethanol production capacity is 100,000 t/y.

### 2.1 Upstream process, ethanol recovery and purification

The upstream process consists of the process steps steam pretreatment, enzyme production, yeast propagation and simultaneous saccharification and fermentation (SSF). For ethanol recovery a heat integrated distillation system is used. Ethanol purification is realized using pressure swing adsorption.

### 2.2 Stillage utilization

The stillage from distillation is sent to a filter press, separating liquids and soluble solids from insoluble solids. The liquid fraction containing most of the soluble solids is concentrated in a 5 effect evaporation train working. Insoluble Solids are dried to 90% drymatter in a superheated steam dryer. Now several ways to utilize the residual streams exist, as indicated by the numbers 1 through 3 in Figure 1.

### 2.2.1. Combined Heat and Power

In scenario 1 the dried insoluble solids as well as the concentrated soluble are burnt in the boiler. Steam is produced and expanded in a turbine to produce electricity for the process. Excess electricity can be sold to the grid. Process steam is extracted at the two pressure levels required.

### 2.2.2. Pellets

In scenario 2 process electricity is supplied from the grid. The dried insoluble solids are pelletized and can be sold as solid fuel. Concentrated soluble solids (65%drymatter) burnt to provide process heat. Since the energy content of the concentrated soluble solids is more than sufficient to meet the processes heat demand, excess solubles are dried and pelletized together with the insoluble solids.

### 2.2.3. C5-Molasses

In scenario 3 process electricity is supplied from the grid. The dried solids are used as fuel for the boiler, whereas the concentrated solubles (C5 sugars and other soluble components) can be sold as a product. Since the energy content of the dried solids exceeds the processes heat demand, a small amount of excess solids are pelletized and sold.

## 3. Exergy Analysis and Exergy Efficiencies

Exergy analysis is a useful approach to identify the kind, location and quantity of thermal and material losses in chemical and thermal processes (Szargut and Styrylska, 1964).

### 3.1 Exergy efficiencies

Two different definitions of exergy efficiency are introduced by (Cornelissen, 1997). Simple efficiency, Eq. (1), expresses the ratio of total exergy output and total exergy input of a process. Rational efficiency, Eq. (2), presents the ratio of exergy of the product to the total exergy input. Another option is to use the chemical efficiency, defined as the ratio between chemical exergy of the product and the chemical exergy of input, expressed in Eq. (3).

$$\eta_1 = \frac{\mathrm{Ex}_{\mathrm{Out}}}{\mathrm{Ex}_{\mathrm{In}}} \tag{1}$$

$$\eta_3 = \frac{\mathrm{Ex}_{\mathrm{Product(s)}}}{\mathrm{Ex}_{\mathrm{In}}} \tag{2}$$

$$\eta_4 = \frac{\mathrm{Ex}_{\mathrm{Chem,Product(s)}}}{\mathrm{Ex}_{\mathrm{Chem,biomass}}} \tag{3}$$

### 3.2 Mathematica-based exergy calculator

A tool based on Mathematica (V7.01.0) has been developed to calculate the exergy of compounds and streams of bio-ethanol production process in a systematic way (Hinderink et al., 1996). The structure of the model for exergy calculation is shown in Figure 2.

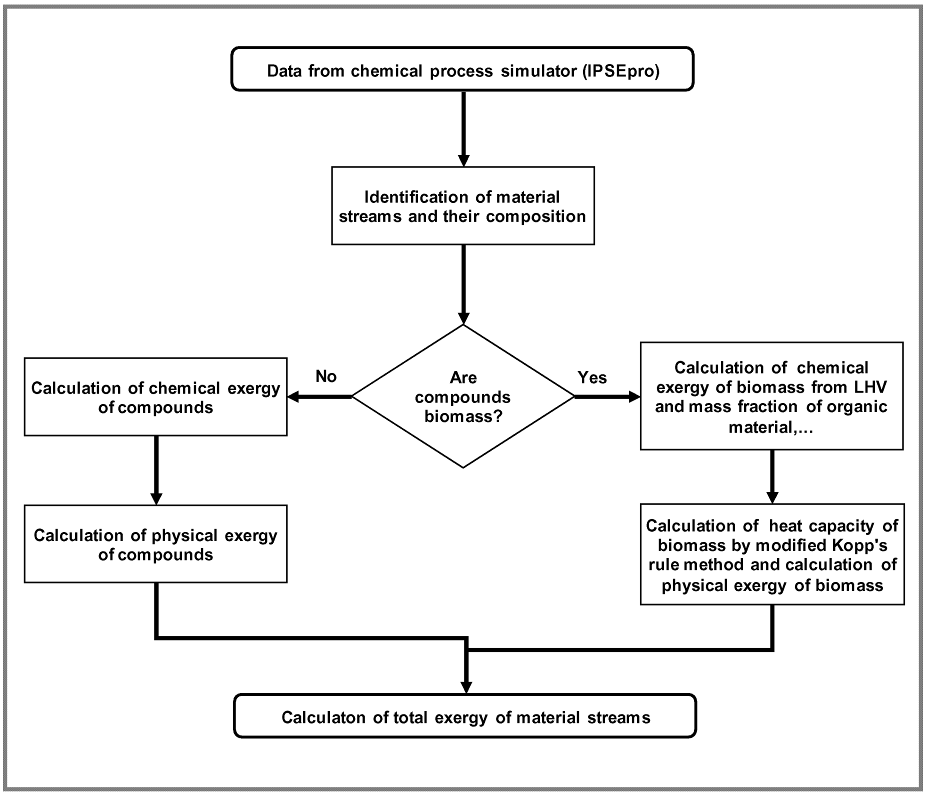

*Figure 2: Structure of algorithm used for calculation of exergy of process streams (Modarresi et al., 2010).*

## 4. Results

Although introduction of combustion step for producing process electricity reduces exergy losses in the process, a considerable part of the exergy of process input is found in by-products such as C5 sugars as well as pellets and not in the produced bio-ethanol. It should be noticed that C5-Molasses would be feedstock for other chemical processes. Investigated scenarios are summarized in Table 1.

*Table 1: Investigated options of product definition representing the use of by-products.*

| **Exergy Efficiencies** | **Scenario** | **Product(s)** |
|---|---|---|
| Eff_3A, Eff4A | 1 | Ethanol |
| Eff_3D, Eff4D | 1 | Ethanol, electricity |
| | | |
| Eff_3A, Eff4A | 2 | Ethanol |
| Eff_3D, Eff4D | 2 | Ethanol, Pellets |
| | | |
| Eff_3A, Eff4A | 3 | Ethanol |
| Eff_3D, Eff4D | 3 | Ethanol, C5-Molasses, Pellets |

Efficiencies 3A and 4A refer to the produced bio-ethanol as sole product of the process. Additionally to the bio-ethanol, other residuals could be considered as by-products to provide process heat and electricity (efficiencies 3D and 4D)

### 4.1 Exergy efficiency of overall process

Figure 3 shows the exergetic efficiency of the different cases in terms of simple exergetic efficiency 1, rational exergetic efficiency 3 and chemical exergetic efficiency 4 according to Eq. (1-3). Introducing drying and evaporation steps, the exergetic efficiencies 1, 3 and 4 are increased. The amount of increase of (η,3) and (η,4) corresponds with the amount of usable by-products following from mass- and energy-balance. Highest increase in efficiency 3 occurs when considering residual biomass from the process as valuable product (pellets and C5-Molasses). Due to the strong impact of chemical exergy compared to physical exergy in the investigated low temperature process there is a small difference between efficiency 3D and 4D. As can be seen, total exergy efficiency ranges from 44.5% for scenario 1 to 69.7% for scenario 2.

### 4.2 Parameter study on product definition

As seen Figure 3 presents the results of a parameter study investigating the influence of definition of products on rational exergetic efficiency (η,3) and chemical exergetic efficiency (η,4).

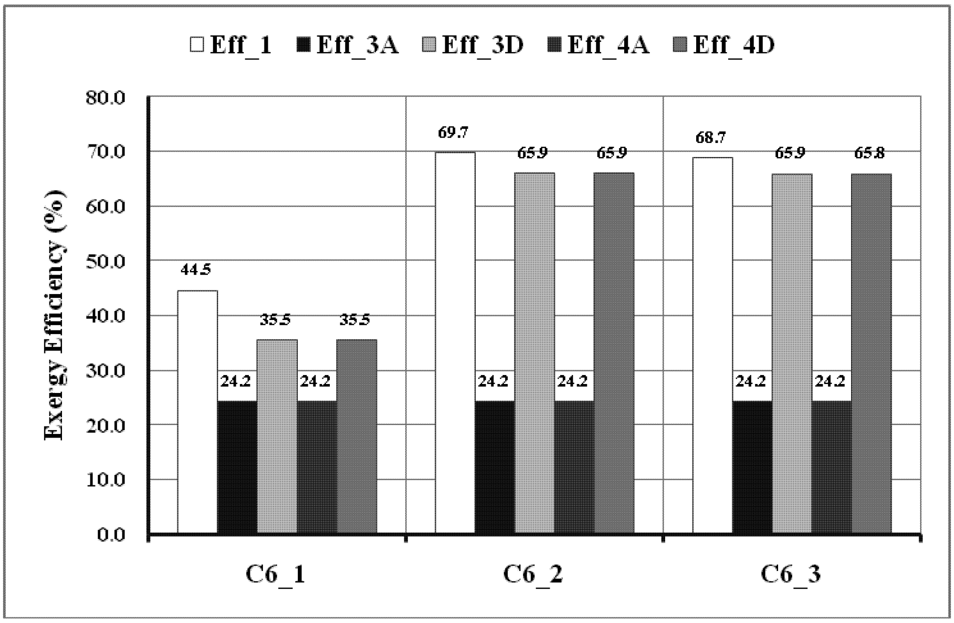

*Figure 3: Exergetic efficiency of the different cases in terms of simple, rational and chemical exergetic efficiency*

A significant increase of exergetic efficiency of the overall process can be achieved, when defining remaining biomass as usable product of the process or when producing electricity internally.

## 5. Conclusions

Exergy analysis was applied to a process for biological production of ethanol. A promising chemical exergetic efficiency of 24.2 % was obtained without considering any by-products. A parameter study underlines the strong dependency of obtained exergetic efficiency on the obtained products and shows options for process improvement and optimization. Following the results, it is recommended to produce electricity (pure exergy) by combustion of residuals to use the chemical exergy of solids. Most important contribution to an increase of exergetic efficiency comes from (re-) use of C5 sugars and pellets for heat and power generation or for sale. The calculated improvement of exergetic efficiencies only represents a theoretical maximum. Impact on exergy balance and exergetic efficiency has to be investigated in more detail considering also additional process steps necessary to implement the suggested process improvements.

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