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Comparison of energy efficiency assessment methods: Case Bio-SNG process

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ABSTRACT

The goal of biofuel production is to partially replace fossil fuels in energy generation and transport. For the evaluation of biofuel production processes different criteria are applied and usually they include costs, efficiency aspects and emissions. However, evaluation of the energy efficiency of biofuels production is difficult since no general standard method exists for that. This paper compares three different assessment methods of energy efficiency both qualitatively and quantitatively. The methods are: thermal efficiency, exergy analysis and primary energy analysis. The feasibility of the methods is tested on a Bio-SNG (synthetic natural gas) production process which was modelled in AspenPlus and MS Excel. The results show that the exergy analysis seems to be advantageous when it comes to detailed (sub-) process analysis whereas the primary energy analysis offers the advantage of showing how the system is influencing the global primary energy resources. The results obtained by the thermal efficiency analysis do not add any new information to the results obtained by exergy and primary energy analyses. Exergy and primary energy analyses should be the preferred means for process assessment. Especially a combination of the two methods could offer the chance to develop a more holistic energy efficiency indicator.

1. Introduction

The European Union (EU) is currently following the targets, known as the "20–20–20" targets (European Council, 2009). They set three key objectives for 2020: a 20% reduction in EU greenhouse gas emissions from 1990 levels; raising the share of EU energy consumption produced from renewable resources to 20%; and a 20% improvement in the EU's energy efficiency.

To facilitate the use of renewable sources and to reduce greenhouse gases, the global community seeks to develop new ways for the production of bio-based fuels. As a part of this process interest towards bio-based fuels is increasing.

One of the potential biofuels is Bio-SNG (synthetic natural gas produced from biomass resources). Bio-SNG is produced by gasification or digestion of cellulosic materials (e.g. forestry residues, energy crops). A typical gasification-based Bio-SNG production core process comprises of initial gasification, gas conditioning, SNG synthesis and gas upgrading. SNG can be used to replace natural gas and, more importantly, other fossil energy carriers such as coal in heat and power generation. Its use also seems particularly beneficial when replacing conventional transport fuels. Bio-SNG can utilise the same infrastructure as natural gas. Natural gas corresponds to roughly around 25% of the world's primary energy (PE) consumption, and its share is still rising. The popularity of natural gas can be attributed to its clean combustion, the high conversion efficiency, and the ease of distribution. Natural gas consists mainly of methane.

While developing new ways to utilise renewable sources (EU 20% target) and while aiming towards carbon neutrality through use of bio-based fuels (EU 20% target) one should make sure that manufacturing of new biofuels is made in an energy efficient manner. In case the manufacturing efficiency is lower than the one for fossil-based fuels, there will be a lower chance to meet the energy efficiency improvement targets (EU 20%). This means that

Abbreviations: AGR, acid gas removal; DH, district heating; PE, primary energy; ASU, air separation unit; EXE, exergy efficiency; PEE, primary energy efficiency; BM, biomass; EU, European Union; PEF, primary energy factor; CPP, condensing power plant; HOB, heat-only boiler; SNG, synthetic natural gas; CHP, combined heat and power; LHV, lower heating value; TE, thermal efficiency.

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attention should be paid on how much energy is consumed in transportation and processing and to the utilisation of the full bioenergy potential in conversions. For this, a comparative study between energy efficiencies of bio-based fuels manufacturing and fossil-based fuels manufacturing is needed. However, no standard methods exist for the evaluation of energy efficiency of biofuels manufacturing.

In engineering, the ways to evaluate the efficiency of power conversion are quite established. One measure for efficiency is the *thermal efficiency (TE)*. That is the ratio between work, heat or work and heat output and the heat input in a heat-engine cycle. More generally, the TE can be defined as the ratio between the useful output and energy input of the process. This approach that is based on calculating the conversion efficiencies can be applied to traditional energy conversion systems, like heat-only boilers. However, in biofuel-based energy systems it becomes important to widen the system boundaries and, in particular, include more upstream processes into the analysis as it is routinely done e.g. in life-cycle assessment since the processes utilising biomaterials involve several transportation and pre-treatment steps.

Primary energy analysis is another method that is used to evaluate energy efficiency of energy conversion systems. It considers all the PE input to a production system that is required for yielding a certain product at the system boundary. It is the sum of all the PE inputs to the system divided by the useful energy delivered at the system border, thus yielding a *primary energy factor* (the reciprocal of that being called *primary energy efficiency*).

PE is a general concept but such analysis can be made e.g. based on EN 15603 [1]. The PE analysis according to this standard is an integral part of the Energy Performance of Buildings Directive, EPBD (European Council, 2010). PE analysis based on EN 15603 has been used for evaluation of biomass (BM) pre-treatment systems [1,2] and in a more general way in different fields of process engineering ranging from evaluation of carbon capture and storage [3], over power, heat and cooling generation [4–7] to vehicle powertrains [8] and cement plants [9], respectively.

Exergy, by definition, is the maximum useful work that can be obtained from a system at a given state in a given environment. Exergy analysis is a method based on the second law of thermodynamics. Exergy is a combination property of a system and its environment, because unlike energy it depends on the state of both, the system and the environment. Exergy is a state property for a fixed environment and the exergy of a system in equilibrium with the environment is zero. Exergy analysis is used to compare, improve and optimise processes. It provides efficiencies that measure how far the process studied is from ideal and in which parts of the process exergy losses occur. Previously exergy analysis has been applied to a Bio-SNG process in the work by Vitasari [10] and Juraščík et al. [11]. Exergy analysis has been applied also in many other fields. An introduction to these can be found in the book from Dincer and Rosen [12].

The drawback of the TE analysis is that it does not take the energy quality issues into account. The challenge in the use of the primary energy efficiency (PEE) is to calculate all energy inputs as PE. The use of exergy method is often considered complex to be used in practical engineering problems. The drawback of all the methods is that they cannot directly recommend how the process could be improved. A standard accounting framework would help to ensure consistency and transparency. This is far from the current case and one of the reasons is the lack of a comprehensive and formal study.

This study compares three different efficiency assessment methods in a single case-study: TE analysis, exergy analysis and PE analysis. The objective is to clarify which of these methods provide an objective analysis of the energy efficiency of a biofuel production system. In addition, it is interesting to know where the biggest losses in the biofuels production occur and how the by-products are taken into account in the analysis. The study is made for a Bio-SNG production process and its sub-processes. As a result, the study clarifies the benefits in the use of each method. More generally, with the results obtained, new methods that exploit the benefits of the current methods can be developed.

2. The Bio-SNG process

The system considered in this study comprises the Bio-SNG production chain starting from extraction of BM until the final product gas fulfils all quality requirements to be fed in the national gas grid.

2.1. Bio-SNG: general process description

The interest in production of Bio-SNG resulted in a large amount of publications. More recent work, giving more detailed insight in the process and in current drawbacks are the papers of Vitasari et al. [10], van der Meijden et al. [13] and Ruiz et al. [14]. Additionally it was shown that heat- and/or power-integrated production of Bio-SNG is crucial for the realisation of an efficient and economic process [15–17].

In general Bio-SNG is methane that is produced by gasifying lignocellulosic BM such as forest residue including tree tops, branches, stumps, and small diameter trees from forest thinning and partly decayed logs. The overall process chain is presented in Fig. 1.

BM is harvested and transported to the biorefinery and then crushed to an appropriate particle size. The crushed raw material is dried from about 40 to 50% of moisture to approximately 20%. Dried wood chips then enter the gasification reactor, where gasification takes place in a steam/oxygen atmosphere. Oxygen is usually provided by an air separation unit (ASU). The heat for reaction is produced by partial oxidation of the raw material. The product gas comprises of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2), water (H_2O), methane (CH_4) and some impurities such as tars and hydrogen sulphide (H_2S). As the impurities will harm the downstream equipment, further treatment is necessary. Tars are cracked inside the gasifier and/or in an additional catalytic tar reformer. Tar-free gas is filtered for removal of particles and heavy metals. The filtered gas enters a water scrubber for removal of ammonia, hydrogen cyanide and chlorides. As the CH_4 content of

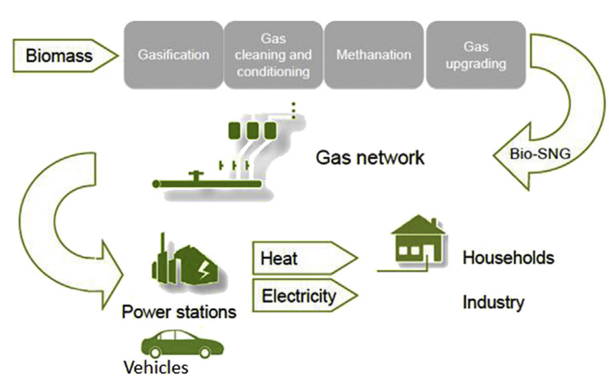

Fig. 1. Process overview of the Bio-SNG production process.
Source: Gasum Oy.