Applied Energy 141 (2015) 167–174

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Energy return on investment for alternative jet fuels

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HIGHLIGHTS

- Definition and comparison of three variants of the energy return on investment (EROI) metric.
- Application of EROI to conventional and alternative jet fuel production pathways.
- The relative ranking of results for alternative and conventional jet fuel pathways is dependent on the definition of EROI.
- Total energy input requirements are the lowest for conventional jet fuel.

ARTICLE INFO

Article history:
Received 11 March 2014
Received in revised form 3 November 2014
Accepted 6 December 2014
Available online 5 January 2015

Keywords:
EROI
Jet fuel
Alternative fuel
Energy return
Energy input

ABSTRACT

We quantify energy return on energy investment (EROI) as one metric for the sustainability of alternative jet fuel production. Lifecycle energy requirements are calculated and subsequently used for calculating three EROI variants. $EROI_1$ is defined as the ratio of energy in fuel output to lifecycle (direct and indirect) fossil fuel energy inputs, excluding the energy content of fossil feedstock that ends up in the produced fuel. $EROI_2$ is defined as the ratio of energy in fuel output to total fossil fuel energy inputs, including the energy content of fossil feedstock that ends up in the produced fuel. $EROI_3$ is defined as the ratio of energy in fuel output to lifecycle (direct and indirect) fossil and non-fossil energy inputs, excluding the energy content of fossil and non-fossil feedstock that ends up in the produced fuel. We also define an approximation for $EROI_1$ using lifecycle CO_2 emissions. This approach agrees to within 20% of the actual $EROI_1$ and can be used as an alternative when necessary. The feedstock-to-fuel pathways considered include conventional jet fuel from crude oil; Fischer–Tropsch jet (FT-J) fuel from natural gas (NG), coal and/or switchgrass; hydroprocessed esters and fatty acids jet (HEFA-J) fuel from soybean, palm, rapeseed and jatropha; and advanced fermentation jet (AF-J) fuel from sugarcane, corn grain and switchgrass. We find that $EROI_1$ for jet fuel from conventional crude oil ranges between 4.9 and 14.0. Among the alternative fuel pathways considered, FT-J fuel from switchgrass has the highest baseline $EROI_1$ of 9.8, followed by AF-J fuel from sugarcane at 6.7. HEFA-J fuel from oily feedstocks has an $EROI_1$ between 1.6 (rapeseed) and 2.9 (palm). $EROI_2$ differs from $EROI_1$ only in the case of fossil-based jet fuels. Conventional jet from crude oil has a baseline $EROI_2$ of 0.9, and FT-J fuel from NG and coal have values of 0.6 and 0.5, respectively. $EROI_3$ values are on average 36% less than $EROI_1$ for HEFA-J pathways. $EROI_3$ for the AF-J and FT-J fuels considered is 50% less than $EROI_1$ on average. All alternative fuels considered have a lower baseline $EROI_3$ than conventional jet fuel.

1. Introduction

Alternative jet fuels have the potential to diversify energy sources for aviation beyond petroleum. In addition, the use of biomass-derived alternatives may contribute to the mitigation of aviation's impact on climate change, which has been estimated at ∼4.9% of total anthropogenic radiative forcing [1]. Although alternative jet fuel usage is currently small relative to conventional jet fuel (<0.01% of total jet fuel consumption in the US in 2013 for example [2]), national and international bodies have introduced goals for alternative fuel usage, which are aimed at facilitating large scale adoption of alternative jet fuels. The International Air Transport Association (IATA) targets 10% alternative fuel use in global aviation by 2017 [3], and the US Federal Aviation Administration (FAA) has a goal of one billion gallons of alternative fuel consumption by 2018 [4]. Moreover, 21 of the 36 billion gallons of alternative fuel production mandated by the Renewable

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http://dx.doi.org/10.1016/j.apenergy.2014.12.016
0306-2619/

Fuels Standard in the US for 2022 could come from renewable jet fuel [5].

Previous studies have investigated the viability of alternative jet fuels from a production cost perspective [6] and from an environmental perspective, including emissions [7], associated health and economic impacts [8] and impacts on land and water resources [9]. In this study we quantify the energy return on energy investment (EROI) as an additional metric for evaluating the long-term viability of alternative aviation fuels. EROI is the ratio of fuel energy return to the amount of energy required to obtain it [10]. It gives an indication of the extent to which an energy investment pays off in terms of the energy contained in the resulting jet fuel. Based on existing EROI frameworks, we compute variants of EROI for alternative feedstock-to-jet-fuel pathways, and compare the results with those for conventional jet fuel from crude oil on a field/well-to-tank basis.

There has been previous research on the EROI of biofuels such as corn ethanol and soybean biodiesel, but the results are not applicable to aviation [11–16]. This is because these fuels are not suited for use in aircraft engines due to incompatible fuel properties, such as increased risk of fire or explosion in the case of ethanol, and poor thermal stability and a high freezing point in the case of biodiesel [17,18]. Therefore, we assess the applicability and appropriateness of EROI variants specifically in the context of alternative jet fuel production. Although they make use of potentially similar biomass feedstocks, alternative jet fuel production technologies use feedstock-to-fuel conversion technologies different from those of conventional biofuels. In particular, the technologies considered in this analysis have energy and utility requirements and conversion efficiencies distinct from the ethanol and biodiesel production processes previously discussed in the literature.

This study is the first archival publication to quantify EROI for a broad range of novel alternative jet fuel production pathways, including:

1. Hydroprocessed esters and fatty acids jet (HEFA-J) fuel from soybean, rapeseed, palm and jatropha.
2. Fermentation and advanced fermentation jet (AF-J) fuel from sugarcane, corn grain and switchgrass.
3. Fischer–Tropsch jet (FT-J) fuel from natural gas (NG), coal and switchgrass.

The pathways (Fig. 1) are selected on the basis of near-term viability: FT-J and HEFA-J fuels have already been evaluated under ASTM D4054 [19] and certified under ASTM D7566 [20]. In June 2014, a subset of the AF-J pathway (renewable farnesene) was also certified by ASTM, and another subset of AF-J (alcohol-to-jet) is expected to be one of the next set of pathways to be certified [21,22].

2. Method

2.1. Lifecycle energy use

EROI is defined as the energy that is returned in the form of jet fuel to the energy required to obtain it. Different accounting techniques for conversion energy requirements can lead to variants in the EROI metric [10,12,23,24]. Our lifecycle energy requirement calculations for alternative aviation fuels are carried out using the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model [25]. The conventional jet, HEFA-J and FT-J pathways are analyzed in GREET version 2012 and the AF-J pathway is analyzed in GREET.net [26]. The assumptions used to build lifecycle energy use inventories for the AF-J pathways are sourced from Staples et al. [27], while others are sourced from Stratton et al. [28].

We adopt the net-energy balancing approach suggested by Shapouri et al. [29], and Wang [30] in the development of the GREET transportation fuel-cycle model. This method is consistent with EROI analysis frameworks suggested in the literature [10,11]. We account for direct and indirect energy usages at all stages of the fuel lifecycle. Direct energy inputs are calculated from the lower heating values (LHV) of process fuel and feedstock inputs, and indirect energy inputs are calculated from the inputs required for the production of process fuel, feedstock, and other resources used in the fuel production lifecycle, such as fertilizer and grid electricity.

The total energy input for converting a feedstock to fuel can be traced back to the LHV of feedstocks used to produce the process fuels in the lifecycle. For example, consider diesel as a fuel input for transportation. We account for the energy content of the diesel used in addition to the process energy input for producing diesel, starting from crude oil recovery. Due to thermodynamic and process inefficiencies, some feedstock energy is lost during conversion to fuel; we include this loss as an energy input. Some studies suggest including the embodied energy in fuel production infrastructure [31], following Shapouri et al. [29], and the impact of including these elements has been estimated as 1–4% of the total lifecycle energy requirements for liquid fuel production [13]. We do not consider energy requirements for the construction of facilities, supporting infrastructure or machinery. However, we conduct an analysis of the sensitivity of our results to this assumption by adopting the Hill et al. [13] numbers for soybean biodiesel to our soybean HEFA pathway. We find that our results are robust to inclusion of the energy required for machinery fabrication and facility construction. See the supplementary information (SI) for the detailed calculations.

The following definitions are used to formulate the EROI variants:

1. Energy content of jet fuel, E_J — One energy unit output of produced jet fuel.
2. Energy input, E_I – Direct and indirect energy inputs (including all feedstock, non-feedstock, and utility inputs) required for one energy unit output of produced jet fuel.
3. n – Binary variable used in EROI variant definition.

The subscript 'F' is appended to E_I where only fossil fuel inputs are accounted for.

We address three key issues associated with the lifecycle analysis (LCA) approach:

1. **System boundaries**: The system boundaries for the LCA are drawn around the direct and indirect material and energy flows associated with the jet fuel lifecycle. The lifecycle steps include feedstock cultivation/extraction, transport, jet fuel production, and fuel distribution prior to combustion. We limit our system boundary to terrestrial biomass; therefore our analysis does not consider the energy flow from the sun nor the solar energy efficiency during biomass growth. This aspect would be important to consider if the goal of the analysis were different, for example to determine the most efficient use of land resources.
2. **Co-product allocation**: We follow recommendations set forth by Wang et al. (2011) [32] and allocate energy use among different fuel products on the basis of fuel energy content. Upstream energy usages are allocated on the basis of the relative market values of upstream co-products (such as soy meal), provided a market exists for the co-product. We believe this is an appropriate method because some upstream co-products are valued on the basis of their commercial utility rather than