Evaluation Method for Power-to-Liquids Concepts for e-Kerosene Production

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Abstract

The escalating climate crisis has prompted stringent regulations to curb emissions. However, many solutions are insufficient and face challenges in certain sectors. Biofuels offer partial relief, yet sustainable biomass availability is limited. Power-to-liquids (PtL) technologies provide a means to produce renewable drop-in fuels independently of biomass constraints. Increased R&D and commercial activity necessitate a standardized method for evaluating PtL technologies. This study introduces a 3E performance criteria framework for PtL technologies, employing the Analytical Hierarchy Process to establish a weighed evaluation system. Initial findings revealed a notable bias towards specific indicators, highlighting the need for further indicator inclusion under economic and environmental criteria for a balanced assessment. The framework's future validation involves PtL technology assessment through spreadsheet modelling. Enhancements may include additional indicators and sensitivity analysis to bolster route ranking robustness.

**Keywords**: Power-to-Liquids, Sustainable Aviation Fuel, Analytical Hierarchy Process

* 1. Introduction

The escalating climate crisis has spurred a growing interest in new sustainable technologies. As sustainable biomass is increasingly utilized, the need for renewable solutions decoupled from biomass becomes imperative. Moreover, technologies capable of demand-side response are essential to support the large-scale deployment of intermittent renewable electricity generators. Power-to-X (PtX) technologies, particularly Power-to-Liquids (PtL), offer intriguing drop-in solutions. To navigate the diverse landscape of PtL, a tailored approach is necessary for a levelized, comprehensive assessment. This research focuses on developing an evaluation framework designed for concept-level assessment of PtL fuel production routes, specifically targeting e-kerosene production. The framework comprises 17 indicators grouped under the 3E (Engineering, Economic, and Environmental) performance criteria. The goal is to facilitate an initial screening of PtL technologies, aiding in the selection of promising alternatives for further in-depth evaluation. The more detailed motivation and description of the approach, along with a case-study of evaluating a Fischer-Tropsch (FT) route using the framework, will be given in a full-length journal paper (Nyholm et al., 2024).

This paper introduces the evaluation method and key performance indicators for a nuanced assessment of PtL technologies in conceptual e-kerosene production. The framework integrates indicators under the 3E criteria, providing a holistic evaluation of engineering performance, economic viability, and environmental sustainability. Scores for PtL routes are determined based on their performance against the indicators. The Analytical Hierarchy Process (AHP), developed by Thomas L. Saaty in the 1970s, is employed to weight indicator and criteria scores objectively, considering their perceived importance (Saaty, 1977). Previous studies utilizing similar evaluation frameworks have focused on hydrogen production or general carbon capture, utilization, and storage (Janosovský et al., 2022) (Chauvy et al., 2019). Other studies, such as those by Dieterich et al. (2020) and Schemme (2020), have reviewed several PtL technologies, but without focus on a single product and the use of a multi-criteria evaluation framework. This study narrows its focus to PtL technologies for kerosene production, customizing indicators to reflect the challenges of synthesizing sustainable liquid hydrocarbons. By developing a robust, early concept stage evaluation framework specific to kerosene production via PtL processes, this research aims to contribute to the advancement and adoption of sustainable and efficient methods for meeting the aviation industry's fuel requirements.

* 1. Evaluation framework
     1. Selection of key performance indicators

This section introduces the chosen indicators essential for the comprehensive evaluation of PtL production routes under the 3E criteria. Each indicator is described, accompanied by the reasoning behind its selection. Details including definitions and scoring considerations are presented in Table 1, Table 2 and Table 3. The main references used for setting the scoring limits are provided under the tables. The engineering performance indicators are intended to capture technical feasibility, energy utilization, carbon efficiency, selectivity to kerosene and liquid hydrocarbon products in general, along with safety and logistical aspects of PtL routes. The economic indicators reflect the economic viability, financial attractiveness and investment recovery potential. The environmental indicators assess the environmental impact, sustainability and resource efficiency.

Table 1. Engineering evaluation indicators and requirements for scoring.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Indicator** | **Notes on requirement selection** | **Requirements** | **Score** | **Source** |
| **TRL** |  | R&D (1 - 3) | 0 | a |
| Development Scale (4 - 6) | 1 |
| Demonstration Scale (7 - 9) | 2 |
| **Energy Efficiency (%)** | Around 50 % in literature, requirements set slightly lower due to lack of heat integration in the concept level study. | < 40 | 0 | b |
| 40 - 80 | 1 |
| > 80 | 2 |
| **Carbon-to-Jet Efficiency (mol-%)** | Researchers and vendors typically report kerosene or diesel selectivity around 70 - 80 %, target limit set accordingly and outstanding limit a bit higher. | < 70 | 0 | c |
| 70 - 90 | 1 |
| > 90 | 2 |
| **CO2 Intensity (tCO2/tHC,liquid)** | Stoichiometric minimum, if every carbon atom from the CO2 ends up in the -CH2- units of the fuel, is 3.1 t/t. Gaseous byproducts increase the intensity. | > 5 | 0 | d |
| 3.5 - 5 | 1 |
| < 3.5 | 2 |
| **H2 Intensity (tH2/tHC,liquid)** | Similar minimum as above is 0.14 t/t. If removal of O from CO2 by H2 is considered, the minimum is 0.43 t/t. Gaseous byproducts increase the intensity. | > 0.6 | 0 | d |
| 0.45 - 0.6 | 1 |
| < 0.45 | 2 |
| **Recycle Ratio (trecycle/tkerosene)** | A FT modeling study found a recycle ratio of 2.4 per liquid hydrocarbon product for the model with highest distillate selectivity. | > 3 | 0 | e |
| 2 - 3 | 1 |
| < 2 | 2 |
| **CISI** | No suitable references found in literature for the limits. The FT score calculated in this work ±50 % was used instead. | > 835 | 0 | f |
| 278 - 835 | 1 |
| < 278 | 2 |
| **Flexibility and Dynamic Operation** | Ability to follow the electricity profile gets max. points. Some credit is given for handling capacity adjustments. | No/No information | 0 | g |
| Considerable turndown | 1 |
| Fully flexible | 2 |
| **Storage and Shipping of Intermediates** | Processes with intermediate products that can be stored/shipped without significant extra measures receive max points. | Practically impossible | 0 |  |
| To some extent | 1 |
| Readily storable | 2 |

a (Chauvy et al., 2019). b (Becker et al., 2012), (Peters et al., 2022), (Schmidt et al., 2018). c (Conkle et al., 2011), (Dieterich et al., 2020), (Haldor Topsoe, 2022). d (Schemme 2020), (Hank et al., 2023). e (Kauppi, 2021). f (Gangadharan et al., 2013), (Nyholm et al., 2024). g (Karjunen, 2022).

**Technology Readiness Level** (TRL) serves as a measure of the system's technical maturity, offering insights into technical feasibility and development stage. It provides valuable information about the readiness of PtL production routes (Chauvy et al., 2019).

**Energy Efficiency** reflects the effectiveness of energy utilization in the conversion process, quantifying the ratio of energy content in produced hydrocarbons to the energy input required for the PtL process. (Hannula et al., 2020. **Carbon-to-Jet Efficiency** measures the carbon conversion efficiency from CO2 by considering the amount of input carbon atoms bound to the final jet fuel product (Hannula et al., 2020). **Recycle Ratio** quantifies the mass of material recycled in the PtL process per ton produced kerosene in order to raise the yield of jet fuel. The magnitude of recirculation required in the process gives an indication of the efficiency, complexity and selectivity of the process.

**CO2** and **H2 intensities** measure the material efficiency and environmental load of a technology by indicating the CO2 and hydrogen consumption per unit of liquid hydrocarbon output (Calemma et al., 2013).

**Comprehensive Inherent Safety Index** (CISI) is a method of quantifying the inherent safety of chemical processes during the early design stage. It is based on chemical, process and connectivity scores and its application ensures prioritization of safety (Gangadharan et al., 2013). **Flexibility and dynamic operation** evaluates a PtL route's capacity to address electricity grid imbalances caused by intermittent renewable energy generation (Karjunen, 2022). **Storage and shipping of intermediates** examines the practical aspects of storing and transporting intermediate products within PtL production routes, with a key role in enabling geographically decentralized production concepts and flexible operation using storage of intermediates.

Table 2. Economic evaluation indicators and requirements for scoring.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Indicator** | **Notes on requirement selection** | **Requirements** | **Score** | **Source** |
| **CAPEX Intensity (€/tkerosene)** | Previous studies indicate a range of 1,000-10,000 €/t, but most estimates seem to fall around 3,000-5,000 €/t. | > 5,000 | 0 | a |
| 3,000 – 5,000 | 1 |
| < 3,000 | 2 |
| **OPEX Intensity (€/tkerosene)** | These estimates also vary widely, roughly around 1,000-5,000 €/t. A suitable range could be 1,000-2,000 €/t, due to most estimates falling within it.. | > 2,000 | 0 | a |
| 1,000 – 2,000 | 1 |
| < 1,000 | 2 |
| **NPV (M€)** | Rough estimates scaled from previous work range from negative to over 600 M€, the average being ca 200 M€. Limits set around the average, with some margin. | < 150 | 0 | a |
| 150 - 250 | 1 |
| > 250 | 2 |
| **IRR (%)** | To add value to the company, the IRR should exceed the company’s Weighted Average Cost of Capital, which is the average rate that a company expects to pay to finance its business. Various oil & gas and chemical industries have a WACC of around 10 %. An IRR clearly exceeding this level is given the highest score. | < 6.1 | 0 | b |
| 6.1 - 20 | 1 |
| > 20 | 2 |
| **Payback Time (years)** | Previous studies roughly indicate payback times of 5-10 years. Periods above this are not given any points, while periods below this receive maximum points. | > 10 | 0 | c |
| 5 - 10 | 1 |
| < 5 | 2 |

a (Schemme, 2020), (Peters et al., 2022), (Kauppi, 2021). b (McCamish, 2021), (Neste Oyj, 2023). c (Oztemel et al., 2022).

**CAPEX intensity** measures the capital investment required per ton installed capacity of kerosene production. This describes the economic efficiency and cost-effectiveness of investments. **OPEX intensity** represents the operational and maintenance costs associated with PtL production per ton of e-kerosene output (Janosovský et al., 2022).

**Net Present Value** (NPV) is a common economic indicator for assessing investments. It assesses the economic attractiveness of PtL routes by quantifying the net monetary value of the project over its lifetime. **Internal Rate of Return** (IRR) is the discounting rate at which the NPV becomes zero. It is used to describe the annualized return rate of an investment and can be regarded as an indicator of the project's profitability and efficiency over time. **Payback time** is the duration required for the initial investment in the PtL routes to be recovered through generated revenues (Scipioni et al., 2023). It describes the time it takes for an investment to reach break-even.

**GHG reduction** quantifies the potential percentage of greenhouse gas emissions reduced by the e-kerosene versus a fossil comparator specified by the European Parliament (2022) Renewable Energy Directive RED II. **Water footprint** measures the net amount of water consumed per unit of e-kerosene output, with the assumption that all generated wastewater can be recycled as feed for the water electrolysis (Peters et al., 2022). This indicates the water consumption of the process and its load on surrounding water bodies.

**Wastewater generation** quantifies the volume of wastewater produced per unit of e-kerosene output. It evaluates the environmental impact associated with wastewater treatment and disposal (Peters et al., 2022).

Table 3. Environmental evaluation indicators and requirements for scoring.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Indicator** | **Notes on requirement selection** | **Requirements** | **Score** | **Source** |
| **GHG Reduction (%)** | The technology is given full points if it can fulfill the RED II reduction target. If no reductions are achieved, the route does not receive any points. | < 0 | 0 | a |
| 0 - 70 | 1 |
| > 70 | 2 |
| **Water Footprint (tH2O/tkerosene)** | Other studies indicate a bit above 1 tH2O/tkerosene, assuming the wastewater is recirculated. A process causing double the load receives no score, while a ratio of under 1 gets max. score. | > 2 | 0 | b |
| 1 - 2 | 1 |
| < 1 | 2 |
| **Wastewater Generation (tWW/tkerosene)** | Stoichiometry gives a 2.57 ratio. E-factors and results from previous studies land at around 2-3 tWW/tkerosene. Limits set accordingly. | > 3 | 0 | c |
| 2 - 3 | 1 |
| < 2 | 2 |

a (European Parliament, 2022). b (Peters et al., 2022). c (Schemme, 2020), (Peters et al., 2022), (Janosovský et al., 2022).

* + 1. Weighing framework

This section outlines the application of the Analytical Hierarchy Process (AHP) in assessing PtL technologies for e-kerosene production. Developed by Saaty, AHP is widely used across various disciplines (Janosovský et al., 2022). It facilitates systematic comparison and prioritization of options based on multiple criteria, making it particularly useful for complex problems with conflicting objectives.

Table 4. Indicator weights and comparison matrix consistency ratios (CR) calculated with the Excel file of Goepel (2013) using the traditional linear 1-9 AHP scale. A CR < 0.10 is generally considered acceptable.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Indicator** | **Weight** | **Indicator** | **Weight** | **Indicator** | **Weight** |
| Engineering | CR = 0.01 | Economic | CR = 0.01 | Environmental | CR = 0.00 |
| *TRL* | *0.313* | *CAPEX Intensity* | *0.097* | *GHG Reduction* | *0.571* |
| *Energy Efficiency* | *0.203* | *OPEX Intensity* | *0.128* | *Water Footprint* | *0.286* |
| *Carbon Efficiency* | *0.137* | *NPV* | *0.238* | *Wastewater gen.* | *0.143* |
| *CO2 Intensity* | *0.040* | *IRR* | *0.436* |  |  |
| *H2 Intensity* | *0.062* | *Payback Time* | *0.101* |  |  |
| *Recycle Ratio* | *0.035* |  |  |  |  |
| *CISI* | *0.035* |  |  |  |  |
| *Flexibility* | *0.088* |  |  |  |  |
| *Storage and Shipping* | *0.088* |  |  |  |  |

AHP breaks down decision problems hierarchically, starting with the overall objective, followed by criteria and sub-criteria. A pairwise comparison method is employed, where decision-makers assign scores based on perceived importance (Chauvy et al., 2019). These scores populate comparison matrices used to derive weights reflecting the relative importance of each criterion or indicator. The weights assigned to these criteria are 0.20, 0.31, and 0.49, respectively, as proposed by Chauvy et al. (2019). Indicator weights are derived using classical AHP and the resulting weights are presented in Table 4.

Inconsistencies are addressed by keeping the consistency ratio below 0.1, following Saaty's rule of thumb. The final score for each PtL route is determined by the weighed sum of its performance against the 3E criteria.

* 1. Results and conclusions

The 3E performance criteria framework for PtL technologies studied exhibits significant weighting towards a single indicator. The concentration is exacerbated by the limited number of indicators in the environmental and economic criteria. Introducing additional indicators would distribute the weight more evenly, allowing for a well-rounded performance. More indicators would give a good criterion score if the route’s performance is good all-around in that aspect, like the engineering criterion now does. A good performance in a single engineering indicator will not significantly increase the route’s performance, but decent all-around performance in the engineering aspect will still give a noticeable boost to the total score of the route.

Despite the apparent concentration issue, a strong engineering performance is crucial for achieving good environmental and economic outcomes. In the context of deploying PtL technologies for environmental benefits, poor performance in the environmental aspect diminishes the significance of engineering and economic considerations. The indicator weights in this study are not extreme compared to the largest indicator weights per criterion in the work by Chauvy et al. (2019), which were in the range of 0.69 – 0.74.

Another paper by the authors of this work details the application of the here presented framework for the evaluation of a FT pathway as a case study (Nyholm et al., 2024). The route scored a 1 on most of the indicators, which was somewhat expected as it was intended to act as a baseline for further evaluations and with most of the literature reviewed for setting the scoring requirements also focused on the FT. The route did well regarding utilizing the CO2 feedstock and in the GHG reduction, and consequently it scored a 2 in both indicators. On the other hand, it is notable that the route scored a 0 on both CAPEX and OPEX intensity, indicating that the cost of producing the fuel was higher than anticipated based on the literature review. The generation of other hydrocarbon byproducts pushed up the kerosene-specific wastewater generation enough to cause the route to score a 0 for this indicator too. The route achieved a total score of 1.15, with the Environmental Performance score making up 60.9 % of the final score, the other criteria contributing roughly equally to the result.

The next step involves deploying the framework to evaluate PtL routes, enabling a meaningful comparison of the fundamental characteristics of various technologies. A large and diverse sample of routes will validate the framework's robustness and functionality. Further development could include adding more indicators under the economic and environmental criteria to distribute the criterion's influence more evenly over its indicators. Additionally, incorporating sensitivity analysis, either on model inputs or framework weights, as proposed by Janosovský et al. (2022), or a combination of both, would enhance the reliability of rankings and reduce the subjectivity in the framework.

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