Optimisation of microalgae-derived aviation biofuel production chain: Short-cut modelling

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1. INTRODUCTION

Conversion of industrial CO2 emissions into advanced biofuels (ABF) is a topical issue in green transition. The FUELGAE (Anon. 2026) concept develops a novel approach with direct CO2 capture/conversion through microalgae in a photo-bioreactor (PBR). The microalgal biomass will be fractionated into its main components: primarily polysaccharides, lipids and microalgal biomass residues. Each fraction will be upgraded by means of fermentation, hydrothermal processes and anaerobic digestion. These downstream technologies will allow to get the most out of the microalgae, with very low amount of waste.

For a holistic approach, advanced control-enabling technologies such as real-time monitoring and digital twin need to be developed simultaneously with the process design. Reconfigurable models can be used to study process interactions, disturbances, and uncertainties and, eventually, to perform plant-wide optimisation with the target of minimising marginal costs and the carbon footprint of the integrated biorefineries.

This work presents a plant-wide model that is suitable for process design analysis and optimisation of process key performance indicators (KPIs). The approach taken involves parameterised short-cut models that are relatively easy to update to different assumptions, such as microalgae species, reactor technologies, separation methods etc. The modelling approach comprises mainly steady-state models that estimate the process performance and the output values as a function of input streams and process conditions.

2. BACKGROUND AND SELECTED MODEL COMPONENTS

2.1 Studied flowsheet

The biorefinery considered in this study collects a flue gas containing approximately 10 w-% of CO2, which is directed to the PBR. In PBR, the biomass is cultivated until required biomass content is achieved. After this, the solution is dewatered around 15 w-% solids content and directed to lipid extraction process. There, the biomass is separated into organic phase containing the lipid, and water phase containing the residue biomass and ash. Organic phase is further processed into advanced liquid biofuel through hydrotreatment (HDT) and distillation, where the former one also comprises hydrogen recovery. Residue biomass is utilised in anaerobic digestion (AD) to produce biomethane that can be utilised in the industrial plant.

2.2 Model components

In this work, air-lift tubular PBR is assumed. The modelling approach implemented to plant-wide model considers a surrogate model describing the biomass productivity as a function of inoculum concentration, light intensity and surface to volume ratio (Ainas et al., 2022). The conditions were changed to match the biomass productivity demonstrated in lab-scale experiments in FUELGAE project.

There are several groups of methods for extracting the lipids including organic solvents, accelerated solvent extraction, supercritical fluids, ionic liquids, deep eutectic solvents, and switchable solvents (Lee et al. 2021). Here, the extraction efficiency was set to value representing the results achieved in project experiments. The energy consumption of lipid extraction was estimated from Aspen simulations performed to water-solvent separation.

HDT step involves utilising excess hydrogen to ensure sufficient product quality. This results in considerable amounts of hydrogen in the effluent gas, and hydrogen recovery step was therefore required to promote overall feasibility of the integrated processing plant. There are several technologies to perform the separation, and the assumption chosen for the plant-wide model was to use vacuum swing adsorption (VSA). The hydrogen recovery, purity and specific energy consumption of VSA process were taken from Zafanelli et al. (2025) with the aim of avoiding over-optimistic scenario for hydrogen recycling in HDT. A hydrogen recovery of 71 wt-% and purity of 99.4 wt.% were thus assumed.

AD performance metrics were taken from simulations with ADM1-R4 model (Weinrich & Nelles, 2021). It was assumed that water scrubbing is used to upgrade the biogas, and the corresponding specific energy consumption and water consumption values were based on Beil & Beyrich (2013). It was also assumed that the heat content in the biomass stream is adequate to provide the necessary heat to AD.

3. RESULTS AND DISCUSSION

Different production scenarios and parameter variability were simulated. One of the scenarios studied the nitrogen recovery potential from AD digestate. 97.8% of excess nutrients soluble in process waters are inherently recycled within the PBR. Nitrogen carried by biomass is directed to AD digestate in the form of ammonia or ammonium. Up to 90% of this is recoverable to PBR as nutrient, when ammonia stripping process is assumed. 50-80% of this is recoverable to PBR, if digestate is used directly after pre-processing. Here, the latter approach is assumed with 80% recovery rate. The same value was applied also to water recycling from digestate to PBR. In addition, the effluent water before AD process is recycled to PBR. As a result, both the amount of water consumed, and the amount of wastewater decreased by 92%. 73.1% of nitrogen can be recycled with digestate pre-processing and direct utilisation in PBR. The analysis does not consider the possible energy penalty of pre-processing and recycling.

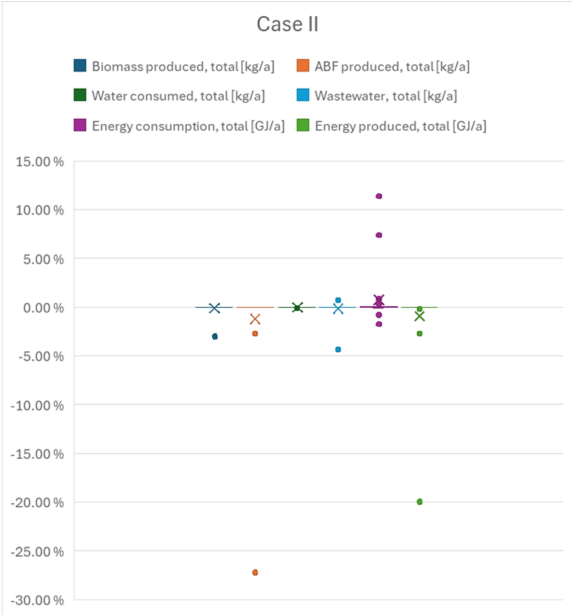

Figure 1. Output variability of process KPIs in uncertainty simulations.

Regarding parameter variability, number of simulations were performed to assess the best-case and worst-case scenarios. The results are depicted in Figure 1. For instance, the biomass productivity changed −3.0% and ABF production by −27.2% between the best and worst cases. The variability in ABF was explained by the sensitivity of lipid mass fraction in biomass to the ABF production. Similar observation was highlighted also in Taipabu et al. (2024). The ranges shown in process KPIs indicate the uncertainties that should be involved in process analysis and optimisation for more robust decision making

4. CONCLUCIONS

The presented plant-wide model offers a holistic view on the microalgae-derived biomass utilisation in advanced biofuels production chains. Short-cut models are sufficient for scenario simulations and optimisation of process concepts. Due to the high number of model parameters and uncertainties related to them, also parameter variability was studied. The future work will extend the model to include also simple process dynamics to be able to optimise the operation in changing environment for example in biomass growth and energy prices.

5. REFERENCES

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