

Quantifying Sustainability Trade-offs in Solar-Driven Biofuel Systems using Life Cycle Assessment

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Introduction

The ALGAESOL project develops three value chains converting CO₂ and solar energy into sustainable fuels:

1. Combines photoanodes with a bioelectrochemical system (BES), convert CO₂ to methane, purified via membrane gas separation.
2. Photoanodes drives CO₂ electroreduction to methanol, followed by membrane pervaporation for product recovery.
3. BES produces acetate for mixotrophic microalgae, which are processed into sustainable aviation fuel (SAF). Residual biomass is further converted to methane via anaerobic digestion BES.

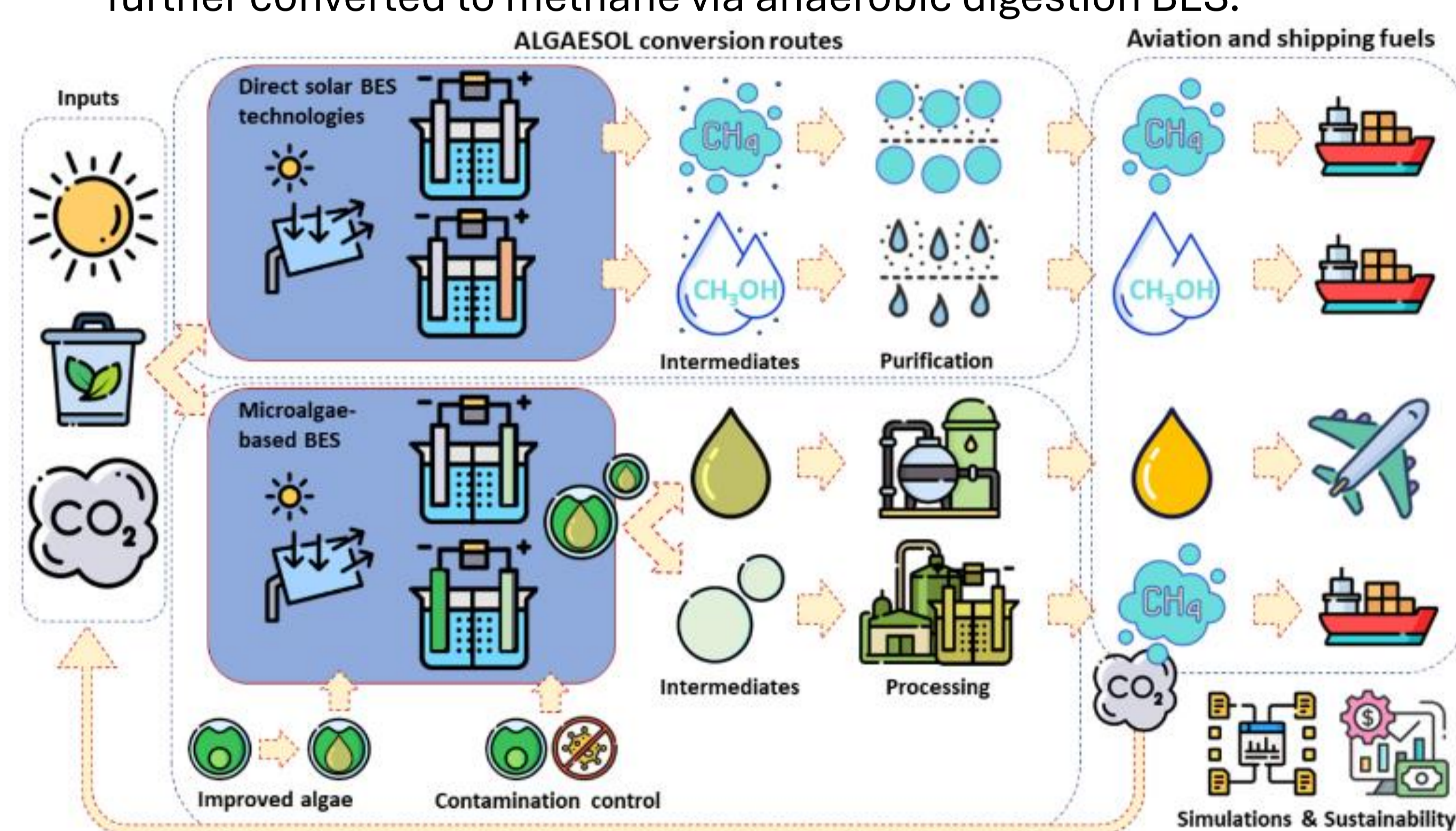


Figure 1 Schematic view of all value chains in the ALGAESOL project.

Materials and methods

Environmental life cycle assessment (LCA) and life cycle costing (LCC) was applied to support sustainable technological development. Two value chain subsystems were chosen to demonstrate this: (I) photoanode fabrication and (II) biomass concentration via downstream dewatering.

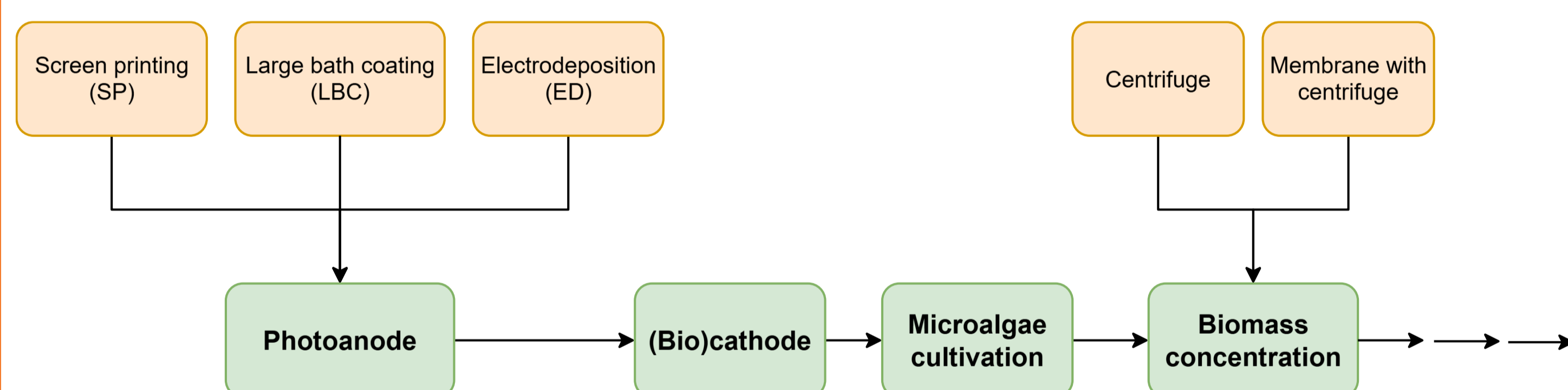


Figure 2 Sustainability assessments focuses on comparing different technical methods for each subsystem in the ALGAESOL value chains.

Technical data and cost data were derived from the experiments and scaled up for the inventory modelling. For photoanodes, all energy balances were calculated based on the equations in table 1:

Table 1: Thermodynamic equations used to describe the processes for fabrication of photoanodes.

Method	Process	Equation
Heating mass	Heat up mass	$m c_p \Delta T$
Annealing	Heat transfer in oven	$A U \Delta T \Delta t$
Large bath coating (LBC)	Heat transfer in bath	$A U \Delta T \Delta t$
Screen printing (SP)	Evaporate mass	$h_{vap} m$
Electrodeposition (ED)	Sonication	$P \Delta t$
	Electrodeposition	$V I \Delta t$

For membranes, operational energy was estimated following Bilad *et al.* (2012):

$$E_{filter} = P_{in} + P_p + r_A(A_c + C_a + CIP)$$

Where P_{in} and P_p are specific energies for influx and permeate pumping respectively, r_A is a ratio between membrane flux and reference flux, and A_c , C_a , CIP are specific energies for aeration, compression and cleaning in process (CIP) respectively. Membrane flux was estimated by experimental parameters.

Preliminary results

Trade-offs in photoanode fabrication approaches

Preliminary results indicate that LBC is the least energy intensive method. Although the incident photon current efficiency of the functional metal used in the LBC and SP configurations was initially lower than that of the material employed in ED, comparable photocurrents can be achieved through doping. However, LBC requires a larger amount of functional metals, which substantially increases overall production costs. As a result, SP is ultimately favoured cost-wise.

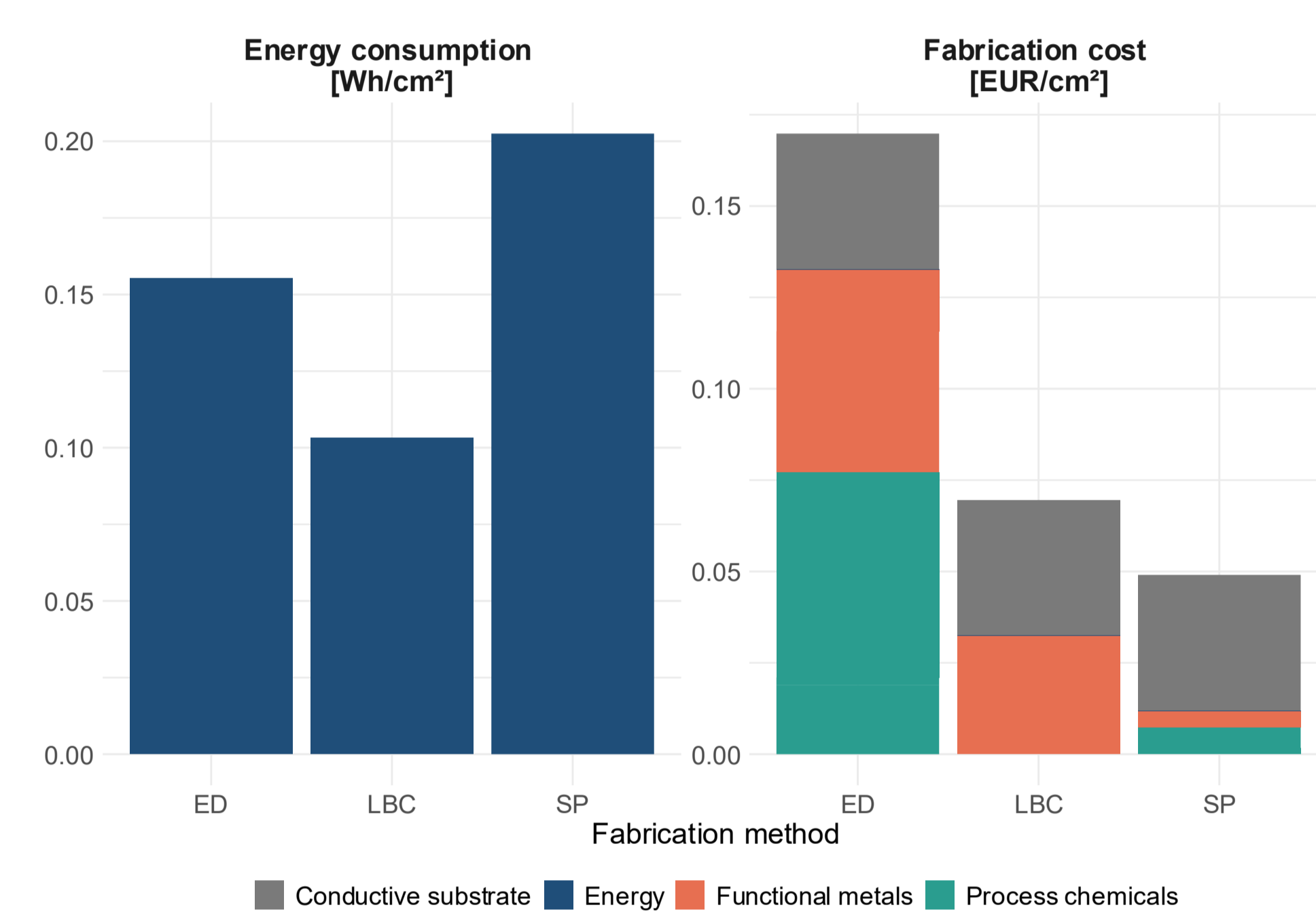


Figure 3 Total costs and energy requirement of photoanode fabrication per m² comparing 3 different scalable fabrication methods (columns). The colours show a breakdown of the costs in materials and energy.

A sustainable membrane filtration method

Estimates suggest that membrane concentration could reduce operational energy consumption by >50% compared to centrifuge. While manufacturing costs were comparatively inexpensive, they require frequent replacement, affecting costs. Despite this, the cost was lower than the alternative. Material consumption during membrane fabrication was the dominant contributor to fabrication costs.

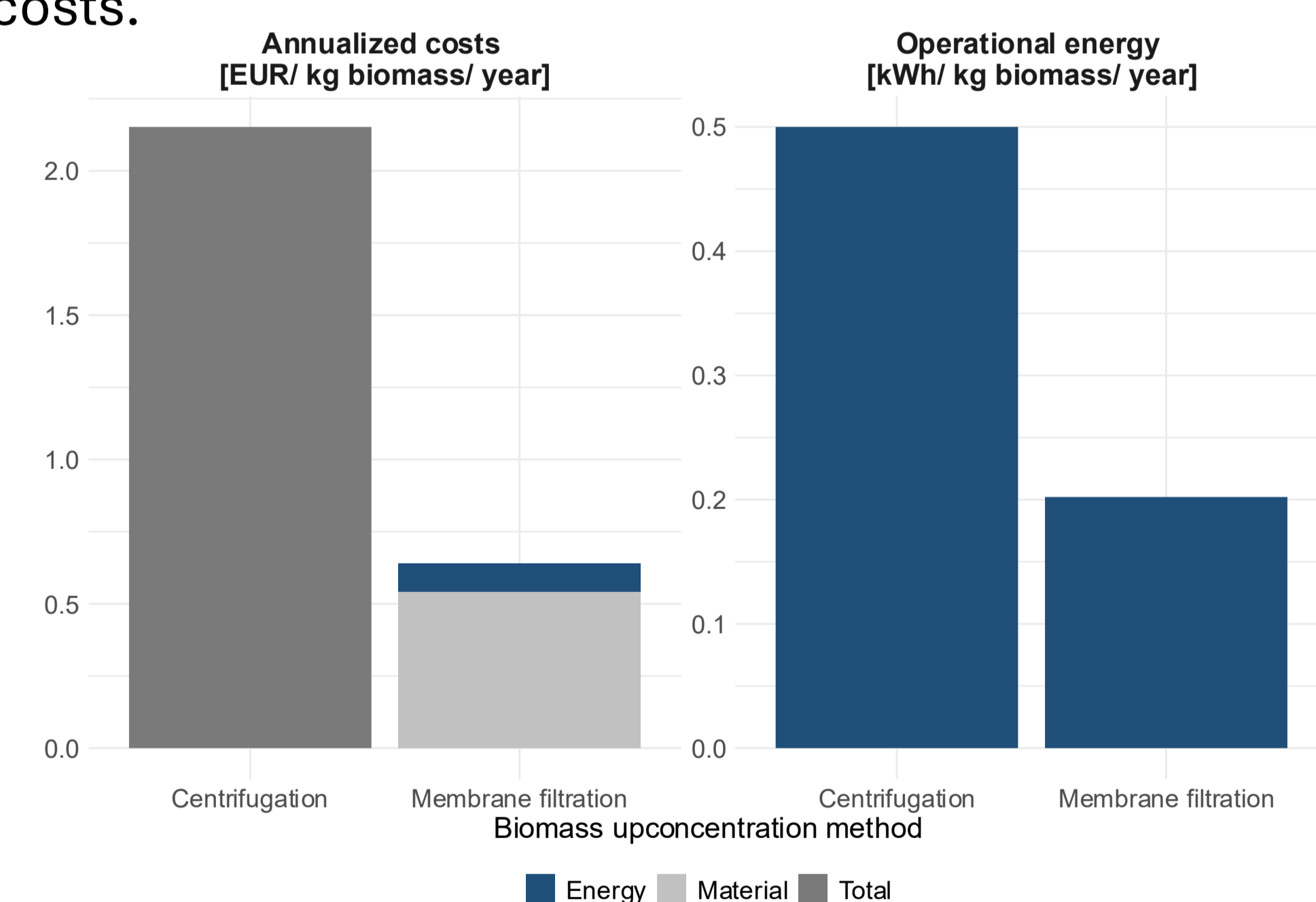


Figure 4 Annualized costs and operational energy of biomass upconcentration methods: Upconcentration with centrifuge only (right columns) and membrane filtration with a smaller centrifuge (right columns). Colours indicate general cost categories.

Conclusions

Initial findings reveal key trade-offs among the ALGAESOL value chains and are guiding development toward more sustainable configurations. As these results can be sensitive to scale-up and performance uncertainties, upcoming work will quantify these uncertainties and benchmark the optimized pathways against state-of-the-art fuels.

References

Bilad, M. R., Vandamme, D., Foubert, I., Muylaert, K., & Vankelecom, I. F. J. (2012). *Harvesting microalgal biomass using submerged microfiltration membranes*. *Bioresource Technology*, 111, 343-352. <https://doi.org/10.1016/j.biortech.2012.02.009>