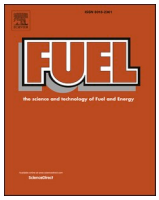
Fuel 430 (2027) 141204

Contents lists available at ScienceDirect

Fuel

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



Full Length Article

Techno-economic and life cycle assessment of a tandem CO_2 and plastic waste-to-fuels system

Baszczeńska Oliwia [a,*], Andretta Antonio [b], Kotowicz Janusz [a], Niesporek Kamil [a], Brzęczek Mateusz [a]

[a] Department of Power Engineering and Turbomachinery, Faculty of Energy and Environmental Engineering, Silesian University of Technology, 44-100 Gliwice, Poland
[b] School of Life Sciences, University of Applied Sciences and Arts, Northwestern Switzerland (FHNW), Hofackerstrasse 30, CH-4132 Muttenz, Switzerland

ARTICLE INFO

Keywords:
Economic analysis
Life cycle assessment
Carbon dioxide
n-propanol
Ethylene glycol
Glycolic acid

ABSTRACT

The transition towards a circular and low-carbon economy requires integrated solutions that enable the simultaneous valorization of waste streams and carbon dioxide. In this context, this study investigates a tandem system combining an electrochemical reactor (PV-EC) and a photo-electrochemical reactor (PEC) for the conversion of CO_2 and ethylene glycol derived from plastic waste into fuels and valuable chemical products (including glycolic acid). The planned research includes an economic analysis, encompassing capital expenditure estimation and investment profitability assessment using the Net Present Value (NPV) method, as well as a Life Cycle Assessment (LCA) aimed at evaluating the environmental impact of the proposed technology. Economic analysis revealed that profitability is mainly determined by the selling price of glycolic acid and the cost of renewable electricity, with glycolic acid accounting for nearly 85 % of total revenue. However, n-propanol is prioritized as the main target product and basis for the Functional Unit because the process was specifically designed for CO2 reduction into high-density liquid fuels. LCA shows that ethylene glycol dominates the environmental footprint, while the PV-EC configuration outperforms PEC due to lower glycol demand and reduced electricity consumption. These results highlight the system as a dual-purpose platform where n-propanol serves as the primary energy carrier while glycolic acid provides the required economic viability. Additionally, reducing ethylene glycol use via low-impact supply chains further improves environmental performance. This approach highlights the potential of the tandem reactor system for sustainable fuel and chemical production within a low-carbon, circular economy framework.

1. Introduction

The transition towards a circular and low-carbon economy requires integrated strategies that simultaneously address greenhouse gas emissions and the growing accumulation of waste. Increasing attention is being paid to technologies that convert waste streams into valuable products while reducing environmental impacts. In particular, the simultaneous use of carbon dioxide and plastic waste represents a promising path toward closing material and carbon cycles, contributing to increased resource efficiency and the development of sustainable production systems [1–3]. In response to numerous climate documents, there has been significant development in renewable energy sources, such as solar and wind power. Energy generated from these sources does not cause carbon dioxide emissions into the environment [1,2]. However, despite its many advantages, it is an unstable source, and electricity production depends on the season and changing weather conditions. As a result, increasing attention is being paid to the development of energy storage and conversion technologies for long-term storage and transport [3]. Liquid fuels and chemical energy carriers, which continue to play an important role in sectors such as transport, aviation, and the chemical industry, are of great importance here. The development of these technologies requires an approach that integrates energy, environmental, and technological aspects, in line with the principles of ecotechnology.

The development of eco-technology enables the integration of energy and fuel production with environmental protection, while at the same time using waste as a resource. Examples include polyethylene terephthalate (PET) waste and carbon dioxide, which can be used as substrates for the production of valuable chemicals such as n-propanol 4,5. The use of photoelectrochemical and electrochemical processes

* Corresponding author.
E-mail address: oliwia.baszczenska@polsl.pl (B. Oliwia).

https://doi.org/10.1016/j.fuel.2026.141204
Received 14 May 2026; Received in revised form 20 August 2026; Accepted 30 August 2026
Available online 9 September 2026

powered by renewable energy sources allows for the development of systems with high energy efficiency and limited climate impact. Fig. 1 shows a simplified diagram of a tandem reactor for the simultaneous conversion of PET and carbon dioxide.

Plastic pollution has become a very serious global threat, and its production is steadily increasing year on year. In 1950, global plastic production amounted to 2 million tons, while in 2024 it reached 430.9 million tons, which illustrates the scale of the growing problem [6,7]. Fig. 2 shows global and European plastic production from 2018 to 2024 [6].

Among various waste streams, plastic waste has become a major global environmental challenge due to its continuously increasing production and limited recycling efficiency. Polyethylene terephthalate plays a special role, accounting for approximately 6.2 % of total global plastic production in 2024 [6,8]. The prevalence of single-use PET packaging means that a significant proportion of this material quickly ends up in the post-consumer waste stream, posing a major environmental challenge. One method of managing polyethylene terephthalate waste is chemical recycling, including the process of alkaline hydrolysis. This process breaks down the chemical bonds in PET and produces low-molecular-weight products such as terephthalic acid (TPA) and ethylene glycol (EG), which can be reused as raw materials in further processes [9]. Fig. 3 shows the decomposition of PET into EG and TPA by alkaline hydrolysis [9].

One option for further processing PET hydrolysis products is to convert ethylene glycol into more valuable compounds, such as glycolic acid (GA). Glycolic acid is a colorless organic chemical compound that dissolves well in water. It has a wide range of applications in the chemical, pharmaceutical, and food industries [10]. In 2025, the glycolic acid market was valued at 522.4 million USD and is projected to reach 819.1 million USD by 2035. This growth is mainly driven by the pharmaceutical industry [11]. The integration of PET streams and captured carbon dioxide enables the production of valuable chemicals and fuels within a sustainable energy economy.

Alongside PET waste management, carbon dioxide conversion is also of significant importance. Carbon capture and storage (CCS) and carbon capture and utilization (CCU) are key technologies that can contribute to reducing global greenhouse gas (GHG) emissions. Carbon dioxide can be converted into high-value compounds and liquid fuels such as n-propanol [8,12,13], which supports the development of a circular carbon economy. The conversion of CO_2 to n-propanol is a complex process that is most often divided into two stages, the reduction of carbon dioxide to carbon monoxide and carbon monoxide to n-propanol, respectively [14]. The resulting n-propanol can be used as a liquid fuel in the energy sector, in transport, and in cogeneration systems. It is characterized by high energy density, which enables efficient storage of electricity from unstable and unpredictable renewable energy sources [15]. Its combustion and co-combustion reduce harmful emissions compared to traditional fuels.

In publication [16], the authors presented high-yield electrochemical conversion pathways for both CO_2 and CO reduction reactions. For the first conversion step, nanoporous Ag-based catalysts were synthesized, which achieved exceptional selectivity and high Faraday efficiency in the CO_2 to CO reduction process. For the next conversion step, homogeneous, bimetallic copper (Cu) catalysts were developed to direct CO reduction toward valuable multicarbon products. Furthermore, using in situ vibrational spectroscopy, the paper provides insight into the mechanism of intermediate product formation, establishing a correlation between catalyst surface properties and product selectivity during conversion at high current densities.

Turning to the analysis of the reaction occurring at the anode, it is worth noting that increasing attention in the literature is being paid to replacing the traditional oxygen evolution reaction (OER) with the valuable oxidation of organic substances. The authors of the [17] paper focused on the electrocatalytic conversion of ethylene glycol (EG) to glycolic acid (GA) on platinum group metal (PGM) surfaces. This study demonstrated that Pt and Pd electrodes exhibited high catalytic activity in the ethylene glycol oxidation reaction (EGOR). Importantly, in an alkaline environment, both Pt and Pd catalysts achieved exceptional selectivity toward glycolate, achieving apparent Faraday efficiency exceeding 85 %. Although the authors indicated that the long-term stability of these systems requires further improvement through modification of the interfacial structure, this work makes a significant contribution to understanding the influence of noble metal properties on the efficiency of this conversion pathway.

In publication [18] authors focus on modulating the active sites of a copper catalyst via lead (Pb) doping to enhance the selectivity of the electrochemical CO reduction reaction toward n-propanol. By utilizing a structure rich in Pb-Cu grain boundaries that strengthened CO adsorption and stabilized key intermediates, the authors achieved a Faradaic efficiency for n-propanol of 47 +/- 3 % in a flow cell. Furthermore, the system was successfully implemented in a membrane electrode assembly (MEA) device, maintaining a stable efficiency above 30 % for over 100 h of operation at a partial current exceeding 300 mA.

1.1. *Scientific originality and novelty*

The originality and scientific novelty of this work lies in the significant expansion of the scope of the techno-economic and environmental (LCA) analysis presented in [19] by shifting from a single-unit model to a complete, integrated technological pathway. While previous studies focused on an isolated process within a single electrochemical reactor, this work introduces a systems-based approach based on a tandem configuration of electrochemical (PV-EC) and photoelectrochemical (PEC) reactors. This approach enables the implementation of a multi-stage carbon conversion cascade, in which captured carbon dioxide is

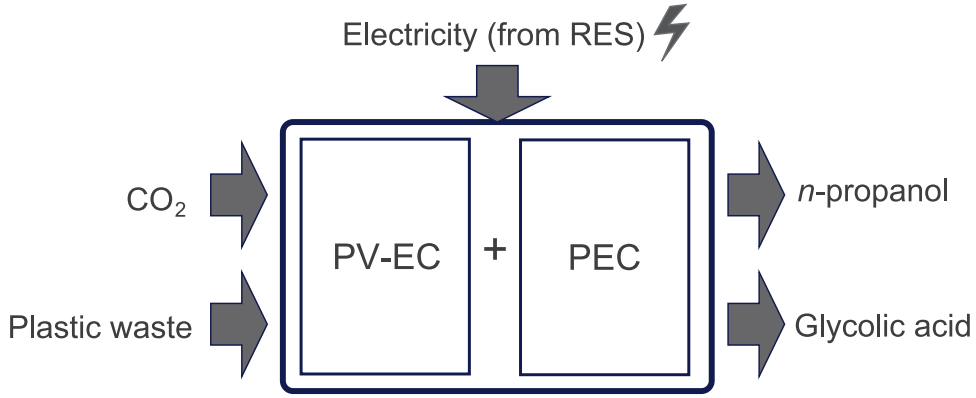


Fig. 1. Schematic diagram of a tandem reactor system for the simultaneous conversion of PET and carbon dioxide.

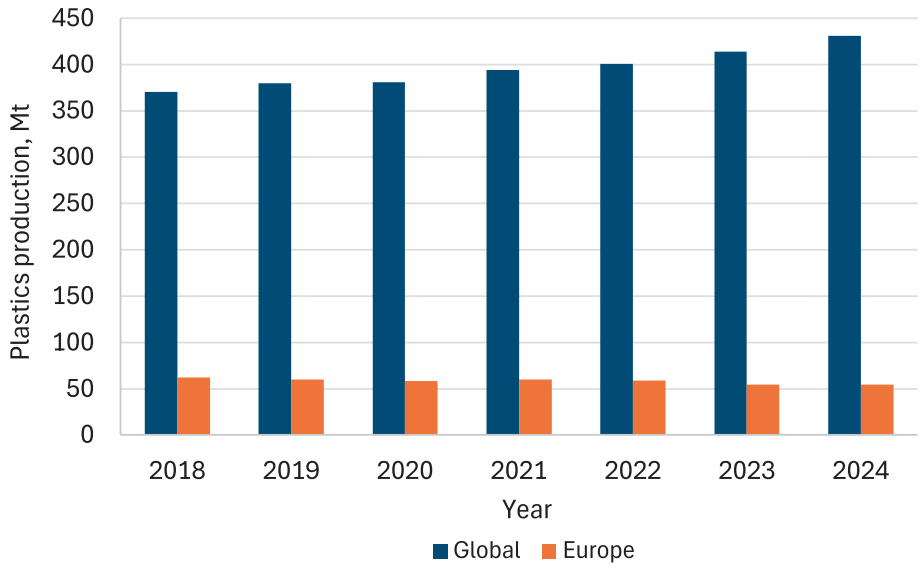


Fig. 2. Global and European plastics production from 2018 to 2024 [6].

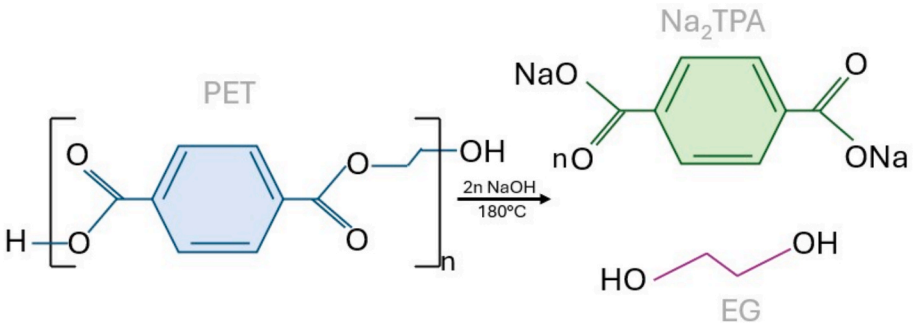


Fig. 3. Decomposition of polyethylene terephthalate into ethylene glycol and terephthalic acid [9].

converted into carbon monoxide and then into high-value n-propanol. In contrast previous work [19], where the process ended with the production of carbon monoxide (CO), this study connects the first reactor directly with second PEC unit. This configuration allows to generated CO to be used immediately as an internal reactant for further conversion into a liquid product (n-propanol). Consequently, this multi-stage approach changes the product yields and the overall utility cost structure, leading to a direct shift in the final Break-even Investment Cost (BIC). The uniqueness of this solution is enhanced by the fact that the carbon dioxide reduction process is closely integrated with the simultaneous valorization of ethylene glycol derived from plastic waste, leading to the production of glycolic acid. As a result, this work

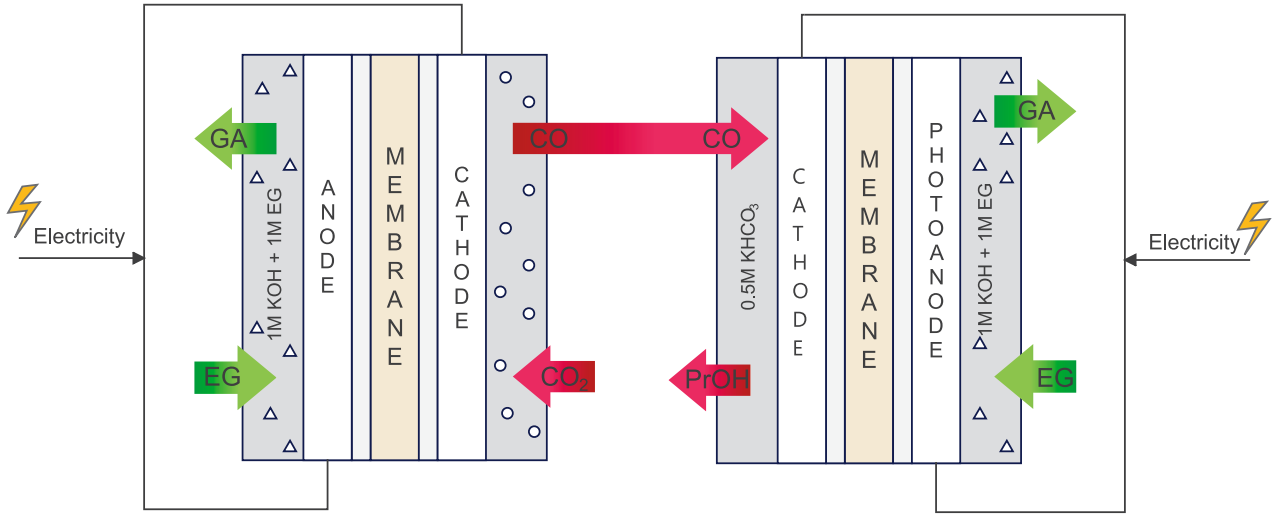


Fig. 4. Scheme of the analyzed tandem PV-EC and PEC reactors.

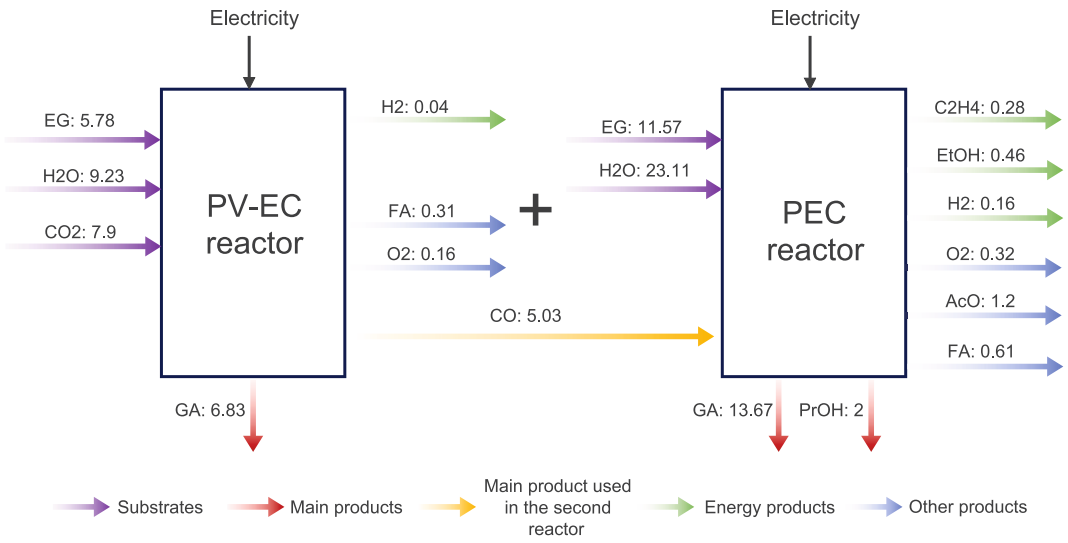


Fig. 5. Scheme of the tandem reactors with substrate and product mass flows (kg/h).

represents one of the first comprehensive studies in the literature modeling the full value chain that combines the utilization of gaseous greenhouse gas emissions with solid waste management for the production of advanced chemicals.

2. Scheme and assumptions of the analyzed reactors

An economic analysis and life cycle assessment (LCA) of a tandem electrochemical (PV-EC) and photo-electrochemical (PEC) reactor system was conducted. Fig. 4 shows a scheme of the analyzed reactors. The total power of the installation is 80.27 kW, of which 24.61 kW is used by the PV-EC reactor and 55.66 kW by the PEC reactor. The electricity supplying both reactors comes from renewable energy sources (RES).

In a electrochemical reactor, ethylene glycol derived from PET waste is converted into glycolic acid (GA), and carbon dioxide is reduced to carbon monoxide (CO). Next, in an photo-electrochemical reactor, the carbon monoxide produced in the first stage of the process is converted into n-propanol. At the same time, in the PEC reactor, ethylene glycol is also converted into glycolic acid, similarly to the process carried out in the PV-EC reactor. During the conversion of carbon monoxide and ethylene glycol in the photo-electrochemical reactor, several by-products are formed in smaller proportions, such as ethylene, ethanol, hydrogen, formic acid, and acetaldehyde. The electrochemical reactor uses an electrode system optimized for the simultaneous conversion of ethylene glycol and reduction of carbon dioxide. The cathode is based on zinc modified with silver nanoparticles (Zn-Ag), which promotes high selectivity of the CO_2 to CO reduction process. The high selectivity of the Zn-Ag cathode results from the synergy between the zinc substrate, which inhibits hydrogen evolution, and the silver nanoparticles. These nanoparticles lower the energy barrier for CO_2 activation by stabilizing the key intermediate COOH, shifting the reaction pathway toward CO formation. The cathodic process is carried out in the gas phase, without a separate catholyte chamber. The anode based on palladium deposited on a nickel and cobalt alloy (Pd/NiCo) enables selective oxidation of EG to GA. This pairing establishes a highly efficient kinetic and electronic harmony between the two electrodes. While the modified Zn-Ag cathode suppresses hydrogen evolution and accelerates CO_2 activation, the robust Pd/NiCO alloy provides rapid electron-donation pathways through selective ethylene glycol oxidation. This adjustment ensures that the number of electrons produced at the anode matches the demand for the reduction process at the cathode. This prevents charge accumulation and allows the reactor to operate more energy efficiently. The carbonation reaction between CO_2 and OH^- ions was omitted in the process modeling due to its marginal impact on the overall reaction balance. The photo-electrochemical reactor is the second stage of the tandem reactors. The main products of carbon monoxide reduction produced on copper electrodes are the aforementioned hydrocarbons and hydrogen from the hydrogen evolution reaction (HER), with electrons from the cathode participating in the reactions. The EG to GA oxidation reaction takes place at the anode and, as in the PV-EC reactor, is based on palladium deposited on a nickel and cobalt alloy. The Faraday efficiency of product formation in the PV-EC reactor is 90 % for glycolic acid and 90 % for carbon monoxide, while for the PEC reactor it is 90 % for glycolic acid and 50 % for n-propanol.

Input parameters and main assumptions for the economic analysis of the PV-EC and PEC reactors are presented in Table 1. The supplementary materials in Table S11 and S12 present detailed assumptions regarding the operation of the reactors along with the calculation methodology: reactor power, reactor surface area and current. Table 2 shows the prices of individual substrates and products involved in the reactions taking place in the analyzed reactors. Fig. 5 shows scheme of the tandem reactors with substrate and product mass flows. The substrate and resulting products are marked in green on the anode and red on the cathode. Equations (1)-(10) represent the reactions occurring at the cathode and anode in the analyzed PV-EC and PEC reactors. For the PV-EC electrochemical reactor, the main electroreduction reaction of carbon dioxide to carbon monoxide is assumed to occur on the cathode side:

$$CO_{2(g)} + H_2O_{(l)} + 2e^- \leftrightarrow CO_{(g)} + 2OH^- \quad (1)$$

In addition, the occurrence of the hydrogen evolution reaction (HER) as a side process is taken into account:

$$2\,H_2O_{(l)} + 2\,e^- \leftrightarrow H_{2(g)} + 2\,OH^- \quad (2)$$

In a photoelectrochemical reactor (PEC), the main cathodic process is the electroreduction of the produced carbon monoxide towards the production of n-propanol:

$$3\,CO + 10\,H_2O + 12\,e^- \leftrightarrow C_3H_7OH + 12\,OH^- \quad (3)$$

In addition to the synthesis of n-propanol, a series of parallel side reactions take place at the cathode of the PEC reactor, leading to the generation of by-products such as acetic acid, ethylene, ethanol and hydrogen:

$$2\,CO + 4\,H_2O + 4\,e^- \leftrightarrow CH_3COOH + 4\,OH^- \quad (4)$$

$$2\,CO + 6\,H_2O + 8\,e^- \leftrightarrow C_2H_4 + 8\,OH^- \quad (5)$$

$$2\,CO + 7\,H_2O + 8\,e^- \leftrightarrow C_2H_5OH + 8\,OH^- \quad (6)$$

$$2\,H_2O + 2\,e^- \leftrightarrow H_2 + 2\,OH^- \quad (7)$$

On the anode side, the same main oxidation processes occur in both reactors, including the conversion of ethylene glycol to glycolic acid (EGOR):

$$C_2H_6O_{2(l)} + 4\,OH^- \leftrightarrow C_2H_4O_{3(s)} + 4\,e^- + 3\,H_2O_{(l)} \quad (8)$$

At the same time, secondary anodic side reactions occur, which lead to the release of oxygen (OER) and the production of formic acid:

$$4\,OH^- \leftrightarrow O_{2(g)} + 4\,e^- + 2\,H_2O_{(l)} \quad (9)$$

$$C_2H_6O_{2(l)} + 6\,OH^- \leftrightarrow 2\,HCOOH + 4\,H_2O + 6\,e^- \quad (10)$$

Calculations of reactor power, reactor surface area, and current were performed according to the methodology presented in the supplementary materials using equations (R2-R4). The current density was assumed to be 200 mA/cm^2 based on data from the literature [38,39], which defines this threshold as the technological minimum necessary for the economic viability of electrochemical systems on an industrial scale. The voltages of the electrochemical cells of the PV-EC and PEC reactors were differentiated due to the specific processes occurring within them. Although the voltage ranges described in the literature for the reduction of carbon dioxide to carbon monoxide and further reduction to multi-carbon products partially overlap, obtaining more complex compounds (such as n-propanol) typically requires higher energy input [40,41]. Therefore, a reference voltage of 2.3 V was adopted for the first reactor (PV-EC), while a higher value of 2.6 V was adopted for the second reactor (PEC).

This method is based on the assumption that the market value of renewable products increases in proportion to their decarbonization potential, which is key to improving the profitability of the reactor tandem under analysis.

$$\partial = \frac{C_{H_{2.green}}}{C_{H_{2.grey}}} \quad (11)$$

Table 1
Input parameters and assumptions for the economic analysis for PV-EC and PEC reactor.

Parameter	Symbol	Value		Unit
		PV-EC	PEC	
Power, [C]	P	24.61	55.66	kW
Reactor surface area, [C]	A	53518.5	107037	cm^2
Current density	i	200	200	mA/cm^2
Current, [C]	I	10703.7	21407.4	A
Voltage	U	2.3	2.6	V
Project duration, [20]	n	20		year
Reactor operating time, [A]	τ	8000		h
Liquidation ratio, [A]	l	20		%
Income tax, [21]	α_{PD}	19		%
Share of credit, [A]	U_K	75		%
Loan interest rate, [22]	r_K	6		%
Loan repayment period, [A]	n_K	10		year
Deprecation rate, [23]	a	4		%
Share of own funds, [A]	U_{own}	25		%
Unit operation and maintenance cost, [A]	$k_{O\&M}$	20		EUR/kW

[A] – authors assumption, [C] – calculations.

Table 2
Prices of individual substrates and products involved in reactions occurring in the analyzed reactors.

Parameter	Symbol	Value	Unit
Price of CO_2, [24]	C_{CO2}	0.15	EUR/kg
Price of PrOH, [25]	C_{PrOH}	1.28	
Price of green PrOH	$C_{PrOH.G}$	2.2	
Price of AcO, [26]	C_{AcO}	0.55	
Price of EtOH, [27]	C_{EtOH}	0.84	
Price of C_2H_4, [28]	C_2H_4	0.97	
Price of green H_2, [29]	$C_{H_{2.green}}$	5.95	
Price of grey H_2, [30]	$C_{H_{2.grey}}$	3.46	
Price of H_2O, [31]	C_{H_2O}	0.07	
Price of CO, [32]	C_{CO}	0.4	
Price of GA, [33]	C_{GA}	1.29	
Price of FA, [34]	C_{FA}	0.7	
Price of O_2, [35]	C_{O_2}	0.14	
Price of EG, [36]	C_{EG}	0.53	
Price of electricity, [37]	$C_{en.g}$	0.2	EUR/kWh

The price of green n-propanol was estimated using the price ratio of green hydrogen to gray hydrogen.

3. Methodology

The economic analysis was performed based on previously defined calculation assumptions. A similar methodology is presented in the publication and refers to the PV-EC reactor [19]. An integrated approach based on life cycle assessment (LCA) was used to quantitatively assess the key impacts, conducted in accordance with the guidelines of ISO 14040 [42] and ISO 14044 [43]. The structure of the LCA analysis was adapted to the economic model, which made it possible to maintain consistency between the system boundaries and the input data. A detailed description of the LCA methodology used is provided in the supplementary materials.

Net present value (NPV) determines the total value of net cash flows CF_t, individually discounted in subsequent years of the analyzed period, at the assumed discount rate.

$$NPV = \sum_{t=0}^{t=n} \frac{CF_t}{(1+r)^t} \quad (12)$$

where:

CF_t– cash flow in year t, EUR;
r– discount rate, %;
t– subsequent year of the investment project starting from the beginning of construction ($t = 0$), $years$;
n– project duration

The net cash flow CF_t in a given year is calculated as the difference between the total inflows and outflows for that year, and can be expressed as:

$$CF_t = (-J + S - K - L)_t \quad (13)$$

where:

J– investment cost, EUR;
S– revenues from sales, EUR;
K– costs , EUR;
L– decommissioning, EUR.

It is assumed that the investment was made in year 0 and that it will be liquidated in the year immediately following the end of its useful life $(n+1)$:

$$NPV = -J_o + \sum_{t=1}^{t=n} \frac{CF_t}{(1+r)^t} - \frac{L}{(1+r)^{n+1}} \quad (14)$$

Investment cost J_o can be defined as the product of unit expenditure and the capacity of PV-EC and PEC reactors:

$$J_o = j_{o.PV-EC} \bullet P_{PV-EC} + j_{o.PEC} \bullet P_{PEC} = J_{own} + C_C \quad (15)$$

where:

$j_{o.PV-EC}$– unit investment cost of PV-EC reactor, EUR/kW;
P_{PV-EC}– power of the PV-EC reactor, kW;
$j_{o.PEC}$– unit investment cost of PEC reactor, EUR/kW;
P_{PEC}– power of the PEC reactor, kW;
J_{own}- cost of equity capital, EUR;
C_C– cost of loan, EUR.

Sales revenue S is the sum of revenues from the sale of n-propanol (S_{PrOH}) and glycolic acid (S_{GA}) produced in the PV-EC and PEC reactors:

$$S = S_{PrOH} + S_{GA} \tag{16}$$

where:

S_{GA}– revenues from glycolic acid sales, EUR;
S_{PrOH}– revenues from n-propanol sales, EUR.

Revenues from the sale of GA S_{GA} can be calculated as:

$$S_{GA} = S_{GA.PVEC} + S_{GA.PEC} \tag{17}$$

$$S_{GA.PVEC} = C_{GA} \bullet \dot{m}_{GA.PVEC} \bullet \tau \tag{17.1}$$

$$S_{GA.PEC} = C_{GA} \bullet \dot{m}_{GA.PEC} \bullet \tau \tag{17.2}$$

where:

C_{GA}– price of glycolic acid, EUR/kg;
$\dot{m}_{GA.PVEC}$– mass flow of glycolic acid produced in the PV-EC reactor, kg/h;
$\dot{m}_{GA.PEC}$– mass flow of glycolic acid produced in a PEC reactor, kg/h;
τ– reactor operating time, h.

Revenues from the sale of n-propanol PrOH S_{PrOH} can be expressed as the product of the price of n-propanol, the mass flow of n-propanol, and the reactor operating time:

$$S_{PrOH} = C_{PrOH} \bullet \dot{m}_{PrOH} \bullet \tau \tag{18}$$

where:

C_{PrOH}– price of n-propanol, EUR/kg;
$\dot{m}_{PrOH}$– mass flow of n-propanol, kg/h;
τ – reactor operating time, h.

Total costs K consist of operating expenses and income tax, and can be calculated using the following formula:

$$K = K_{op} + P_d \tag{19}$$

where:

K_{op}– operating costs, EUR;
P_d– income tax, EUR.

Operating costs K_{op} include fixed and variable costs, less depreciation:

$$K_{op} = K_s + K_z - K_A \tag{20}$$

where:

K_s– fixed costs, EUR;
K_z– variable costs, EUR;
K_A– depreciation,EUR.

Fixed costs K_s are the sum of operation and maintenance costs and depreciation:

$$K_s = K_{O\&M} + K_A \tag{21}$$

where:

$K_{O\&M}$– operation and maintenance costs,EUR.

Operating costs are the product of unit operating costs and reactors power:

$$K_{O\&M} = K_{O\&M.PVEC} + K_{O\&M.PEC} \tag{22}$$

$$K_{O\&M.PVEC} = k_{O\&M.PVEC} \bullet P_{PV-EC} \tag{22.1}$$

$$K_{O\&M.PEC} = k_{O\&M.PEC} \bullet P_{PEC} \tag{22.2}$$

where:
$k_{O\&M}$- unit operating and maintenance costs, EUR/kW
The cost of straight-line depreciation is calculated as the ratio of capital expenditure to the duration of the project:

$$K_A = \frac{J_o}{n} \tag{23}$$

Variable costs are the sum of costs associated with individual substrates and products of the PV-EC and PEC reactors:

$$K_z = K_{CO2} + K_{EG} + K_{en} + K_{H2O} \tag{24}$$

where:

K_{CO2}– cost of purchasing carbon dioxide, EUR;
K_{EG}– cost of purchasing ethylene glycol, EUR;
K_{en}– cost of purchasing electricity, EUR;
K_{H2O}– cost of purchasing water, EUR.

The cost of carbon dioxide is the product of the price of carbon dioxide, its mass flow, and the reactor's operating time:

$$K_{CO2} = C_{CO2} \bullet \dot{m}_{CO2} \bullet \tau \tag{25}$$

where:

C_{CO2}– carbon dioxide price, EUR/kg;
$\dot{m}_{CO2}$– carbon dioxide mass flow, kg/h;
τ– reactor operating time, h.

The cost of ethylene glycol is the product of the price of ethylene glycol, the mass flow of ethylene glycol, and the reactor operating time:

$$K_{EG} = C_{EG} \bullet \dot{m}_{EG.PVEC} + \dot{m}_{EG.PEC} \bullet \tau \tag{26}$$

where:

C_{EG}– price of ethylene glycol, EUR/kg;
$\dot{m}_{EG.PVEC}$– mass flow of ethylene glycol fed into the PV-EC reactor, kg/h;
$\dot{m}_{EG.PEC}$– mass flow of ethylene glycol fed into the PEC reactor, kg/h;
τ– reactor operating time, h.

The cost of electricity is the product of the price of electricity, the reactor power, and the reactor operating time:

$$K_{en} = C_{en} \bullet (P_{PV-EC} + P_{PEC}) \bullet \tau \tag{27}$$

where:

C_{en}– electricity price, EUR/kWh;
τ– reactor operating time, h;
τ– reactor operating time, h.

The cost of water is the product of the price of treated water, reactor operating time, and water mass flow rate:

$$K_{H2O} = C_{H2O} \bullet \tau \bullet \dot{m}_{H2O.PVEC} + \dot{m}_{H2O.PEC} \quad (28)$$

where:

C_{H2O}– water price, EUR/kg;
$\dot{m}_{H2O.PVEC}$– mass flow of water supplied to the PV-EC reactor, kg/h;
$\dot{m}_{H2O.PEC}$– mass flow of water supplied to the PEC reactor, kg/h;
τ– reactor operating time, h.

4. Economic analysis

The assessment of market prices for substrates and products is a key element of the economic analysis of the proposed tandem reactor system. The price assumptions used in the economic calculations have a direct impact on the estimation of operating costs and revenues related to product sales. Prices have a significant impact on the NPV (Net Present Value) indicator, which provides information on the profitability of the investment. An analysis of market prices for key substrates and products is presented in the supplementary materials.

As part of the economic analysis of the PV-EC and PEC reactor tandem, the break-even investment costs were determined first. They specify the maximum investment costs that can be allocated to the installation in order for it to be profitable. If the marginal investment costs are negative, it means that the installation will not generate profits.

Eq. (14) was transformed to determine the break-even investment costs of the reactor tandem, assuming that NPV = 0. The transformed equation takes the following form:

$$J_o = \frac{\sum_{t=1}^{t=n} \frac{CF_t}{(1+r)^t}}{1 + \frac{l}{(1+r)^{n+1}}} \quad (29)$$

Table 3 presents the results of the economic analysis, i.e., the break-even investment costs of the PV-EC reactor, the PEC reactor, and the tandem of these reactors. Additionally, the annual sales revenues of individual products generated in the reactors are presented. The costs associated with the purchase of substrates such as carbon dioxide, ethylene glycol, water, and the cost of purchasing electricity were also calculated. Operating costs were also included, which take into account all expenses related to the daily operation of the reactors, such as maintenance, servicing, monitoring, and process control. For the baseline assumptions, the break-even investment costs for the tandem reactors amount to 195 kEUR, including 103 kEUR for the PV-EC reactor and 92 kEUR for the PEC reactor. Total annual revenues from product sales amount to approximately 269 kEUR, while installation costs amount to approximately 231 kEUR.

Table 3
Results of the economic analysis, i.e., break-even investment costs of the PV-EC reactor, PEC reactor, and tandem of these reactors, together with annual revenues and costs related to the investment.

Parameter	Symbol	Value, kEUR		
		PV-EC	PEC	Tandem
Break-even investment cost	J_o	103.31	92.06	195.37
Revenue from the sale of:				
GA	S_{GA}	70.49	141.07	211.56
PrOH	S_{PrOH}	–	20.48	20.48
C_2H_4	S_{C2H4}	–	2.17	2.17
EtOH	S_{EtOH}	–	3.09	3.09
H_2	S_{H2}	1.11	4.43	5.54
FA	S_{FA}	1.74	3.42	5.16
AcO	S_{AcO}	–	5.28	5.28
Total		89.42	179.94	269.36
Cost incurred:				
CO_2	C_{CO2}	9.48	–	9.48
EG	C_{EG}	24.51	49.06	73.56
Electricity	C_{En}	39.39	89.05	128.44
H_2O	C_{H2O}	5.17	12.99	18.16
O&M	$C_{O\&M}$	0.49	1.11	1.61
Total		79.04	152.22	231.25

Fig. 6 shows the percentage share of a) revenues from the sale of individual products in the reactor tandem and b) individual operating costs and investment cost in the total costs of the reactor tandem c) revenues from the sale of individual products in the reactor tandem in case we produced green hydrogen and green propanol d) individual operating costs and investment cost in the total costs of the reactor tandem in case that we produced green hydrogen and green propanol. The dominant source of income in the analyzed process is the sale of glycolic acid, which generates almost 85 % of total revenues. Such a high share highlights the key importance of this product for the profitability of the entire reactor tandem. The second largest revenue-generating product is n-propanol, with a share of 8.1 %, valued for its fuel properties in the energy sector. Other products such as ethylene, ethanol, hydrogen, acetaldehyde, and formic acid account for only 8.4 % of total revenues. On the other hand, the largest component of total costs is investment cost, accounting for 45.8 %. Next are electricity costs, which account for 30.1 % of total costs. This reflects the high energy intensity of the processes carried out in the reactors. Ethylene glycol, which is used in later processes to produce glycolic acid, among other things, also has a significant impact on the cost structure. The costs associated with the purchase of water and carbon dioxide, as well as operating costs, account for only 6.9 % of the total costs generated by the reactor tandem. The results of the analysis presented in Fig. 6(c) and (d) take into account an alternative scenario in which the process is integrated with the provisions of the RED III Directive [44]. Under this framework, the directive defines the qualitative criteria for RFNBO (Renewable Fuels of Non-Biological Origin) certification and specifies permissible CO2 sources. While RED III does not introduce direct financial support or funding mechanisms, it establishes regulatory mandates that are expected to drive a market preference for certified green products. Consequently, fuels carrying the RFNBO certificate are projected to command a market-driven 'green premium' price once the directive is fully enforced across EU member states. In this model, carbon dioxide is not treated as a variable cost but as a raw material recovered through industrial emissions capture. This approach allows the produced hydrogen and n-propanol to be classified as renewable non-biological fuels. The application of the circular economy model has a significant impact on the cost structure, eliminating the financial burden associated with the purchase of carbon dioxide. As a result of obtaining RFNBO certification, these products can achieve higher market prices, which directly translates into improved investment profitability. The share of n-propanol in total revenue rose from 8.1 % to 12 %. The share of glycolic acid, on the other hand, fell to 78.6 %. The increase in revenue also led to an increase in the share of capital expenditures for the reactor tandem, reaching 65.3 % of all costs. In quantitative terms, the market premium for certified n-propanol justifies a price increase of 0.92 EUR/kg over the fossil-based baseline (from 1.28 EUR/kg to 2.20 EUR/kg). Furthermore, treating CO_2 as a recovered raw material under the circular economy model eliminates a variable procurement cost of 0.15 EUR/kg of CO_2, which avoids substantial annual operating expenses. Combined, these two policy-driven factors directly increase the annual net cash flow (CF) of the tandem system. This explicit financial shift provides the mathematical basis for the significantly higher break-even investment cost observed in this scenario.

The investment cost and other costs incurred in both reactors differ depending on the substrates used for further processes. It is also worth noting that carbon monoxide, which is a substrate in the PEC reactor, is not included in the costs because it is produced in the PV-EC reactor. Fig. 7 shows the percentage share of individual operating costs and marginal capital expenditures in the total costs in reactors a) PV-EC and b) PEC. In the expenditure structure of both reactors analyzed, the

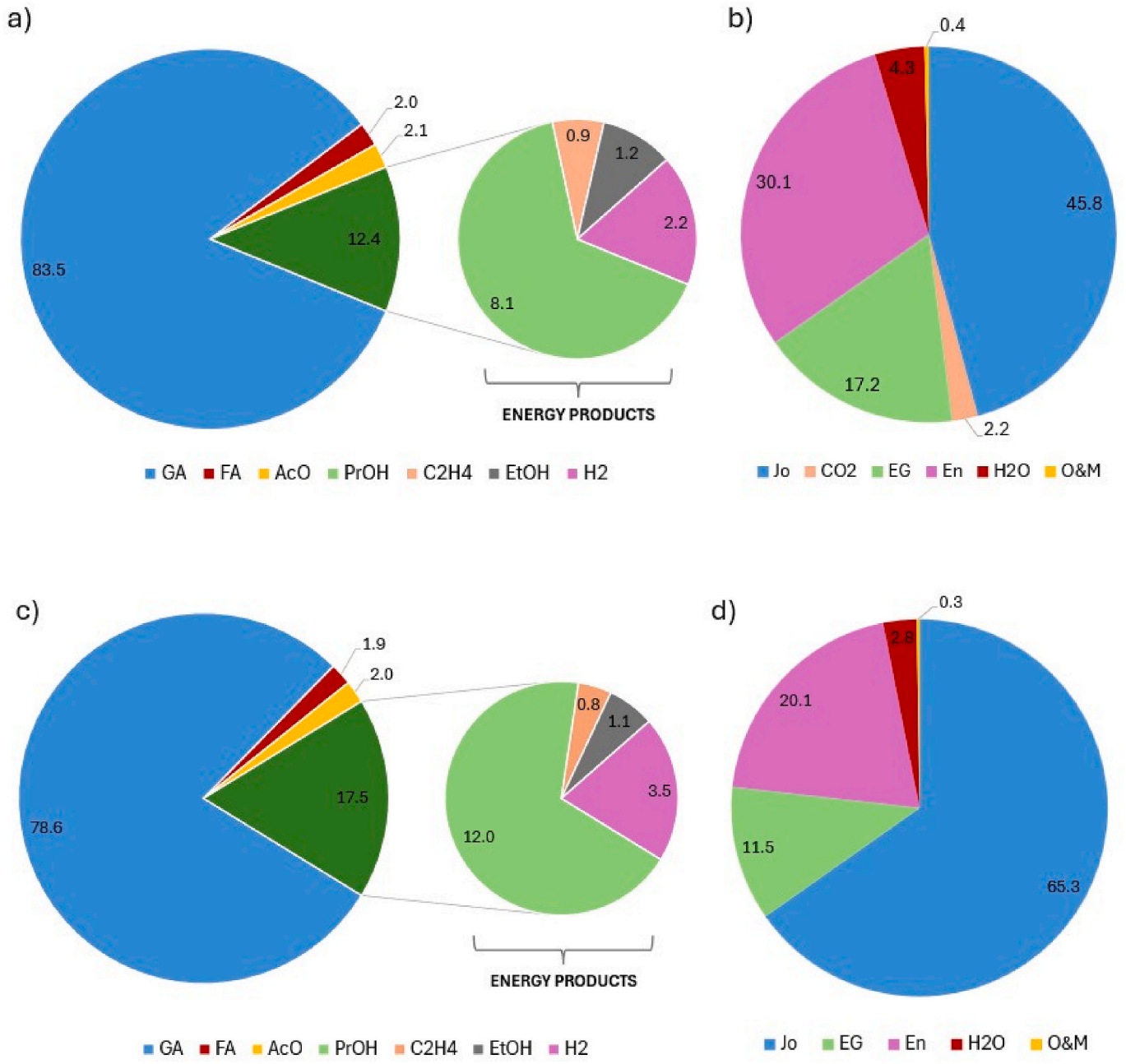


Fig. 6. Percentage share of a) revenues from the sale of individual products in the reactor tandem b) individual operating costs and investment cost in the total costs of the reactor tandem c) revenues from the sale of individual products in the reactor tandem in case we produced green hydrogen and green propanol d) individual operating costs and investment cost in the total costs of the reactor tandem in case that we produced green hydrogen and green propanol.

dominant factor is investment cost, which constitutes the main component of total costs and amounts to 56.7 % for the PV-EC reactor and 37.7 % for the PEC reactor. The second largest expense in both cases is electricity costs, which account for over 1/4 of all expenses. The smallest share is accounted for by O&M costs, which amount to 0.3 % in the PV-EC reactor and 0.5 % in the PEC reactor, respectively.

Fig. 8 shows the standard deviation of prices for individual substrates and products of the analyzed reactor tandem and their impact on the value of break-even investment costs. The price values were determined for standard deviations of 5, 10, and 15 %, respectively. The greatest fluctuations in break-even investment costs can be observed for changes in the price of glycolic acid and electricity, which indicates that these are the two key values with the greatest impact. Changes in the price of ethylene glycol and n-propanol have a smaller impact, while changes in the price of carbon dioxide and water have a negligible effect on the final result of break-even investment costs.

The economic analysis presented focuses on determining the maximum permissible investment costs that guarantee the profitability of the investment. Fig. 9 shows the impact of changes in the price of a) carbon dioxide, b) ethylene glycol, c) electricity, and d) water on the value of the maximum break-even investment costs. In each of the graphs, the value of the base substrate price is marked with a green triangle symbol.

When analyzing the impact of carbon dioxide on break-even investment costs, a linear downward trend can be observed. As the price of carbon dioxide increases in the range from 0.07 EUR/kg to 0.22 EUR/kg, break-even investment costs decrease. When the price of carbon dioxide is 0.22 EUR/kg, break-even investment costs reach 151 kEUR, which is

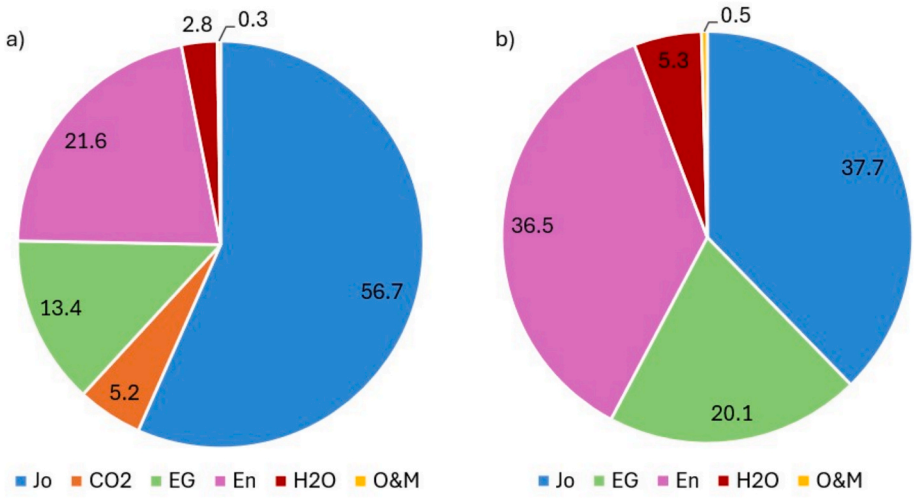


Fig. 7. Percentage share of individual operating costs and break-even capital expenditures in the total costs in reactors a) PV-EC and b) PEC.

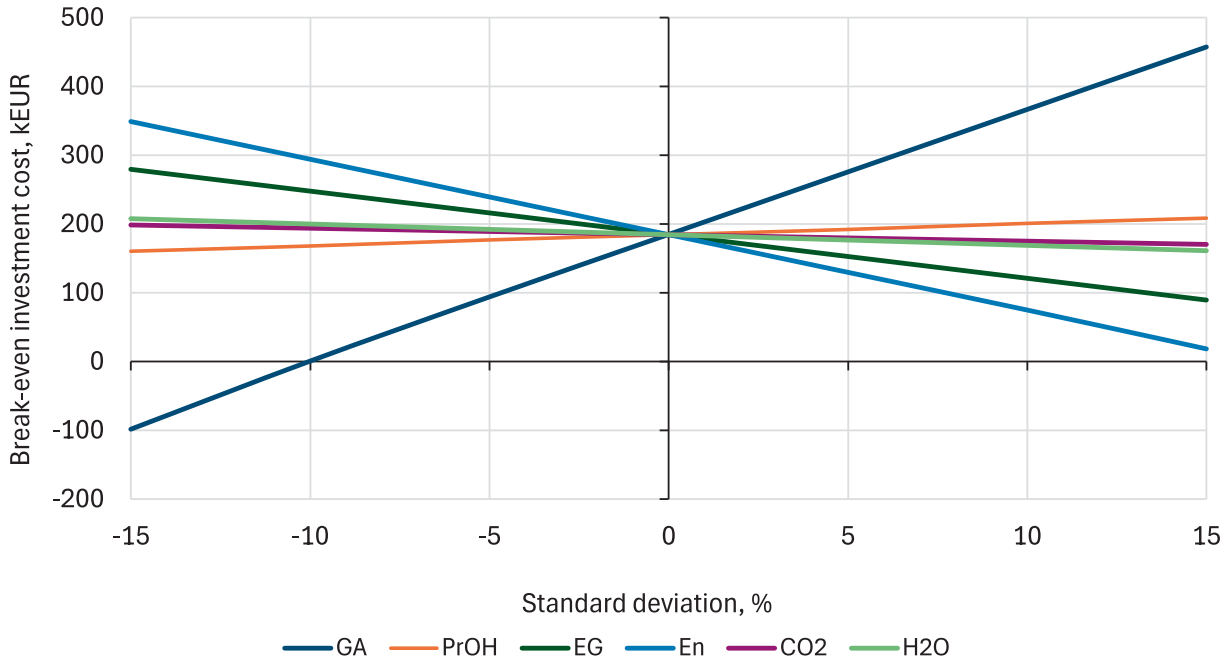


Fig. 8. Standard deviation of the main substrates and products of tandem reactors.

44 kEUR less than for the variant where we take into account its base price. A similar downward trend was observed for the other cost variables. The only difference is the degree of sensitivity of break-even investment costs to changes in the price of individual substrates.

The change in the price of ethylene glycol and its increase to EUR 0.85/kg significantly affected the break-even investment costs, which decreased to −208 kEUR, meaning that the investment is not profitable. The economic analysis showed that this price must be lower than 0.68 EUR/kg for the reactor tandem to be a profitable installation.

Another factor that has a significant impact on the break-even investment costs is the price of electricity, which is 0.2 EUR/kWh for the base case. An increase in this price by as little as 0.4 EUR/kWh could lead to the investment becoming unprofitable. On the other hand, a decrease in the price to 0.1 EUR/kWh raises the acceptable investment threshold to 743 kEUR, which is more than four times higher than in the base case.

The last substrate analyzed is water. The impact of water price fluctuations is relatively small, although greater than in the case of carbon dioxide. Only a more than twofold increase in its cost relative to the base price brings the value of marginal inputs below zero. A decrease in price may have a positive impact on investment costs and increase expenditures related to the analyzed reactor tandem.

It is worth noting that among the factors analyzed, the price of carbon dioxide has the least impact on break-even investment costs. Assuming the least optimistic scenario, where the cost of purchasing carbon dioxide will be 0.22 EUR/kg, break-even investment costs remain at a safe level above 151 kEUR.

The Fig. 10 shows the impact of changes in the price of a) glycolic acid and b) n-propanol on the value of break-even investment costs for a tandem reactor. The prices of glycolic acid and n-propanol were changed within the same range, from 0.5 EUR/kg to 1.9 EUR/kg. Since glycolic acid accounts for nearly 85 % of total revenue, a change in its price is crucial for break-even investment costs. A decrease in this price by as little as 0.2 EUR/kg can lead to a loss of investment profitability. On the other hand, an increase in its price significantly increases the value of break-even investment costs, and for a glycolic acid price of 1.9 EUR/kg,

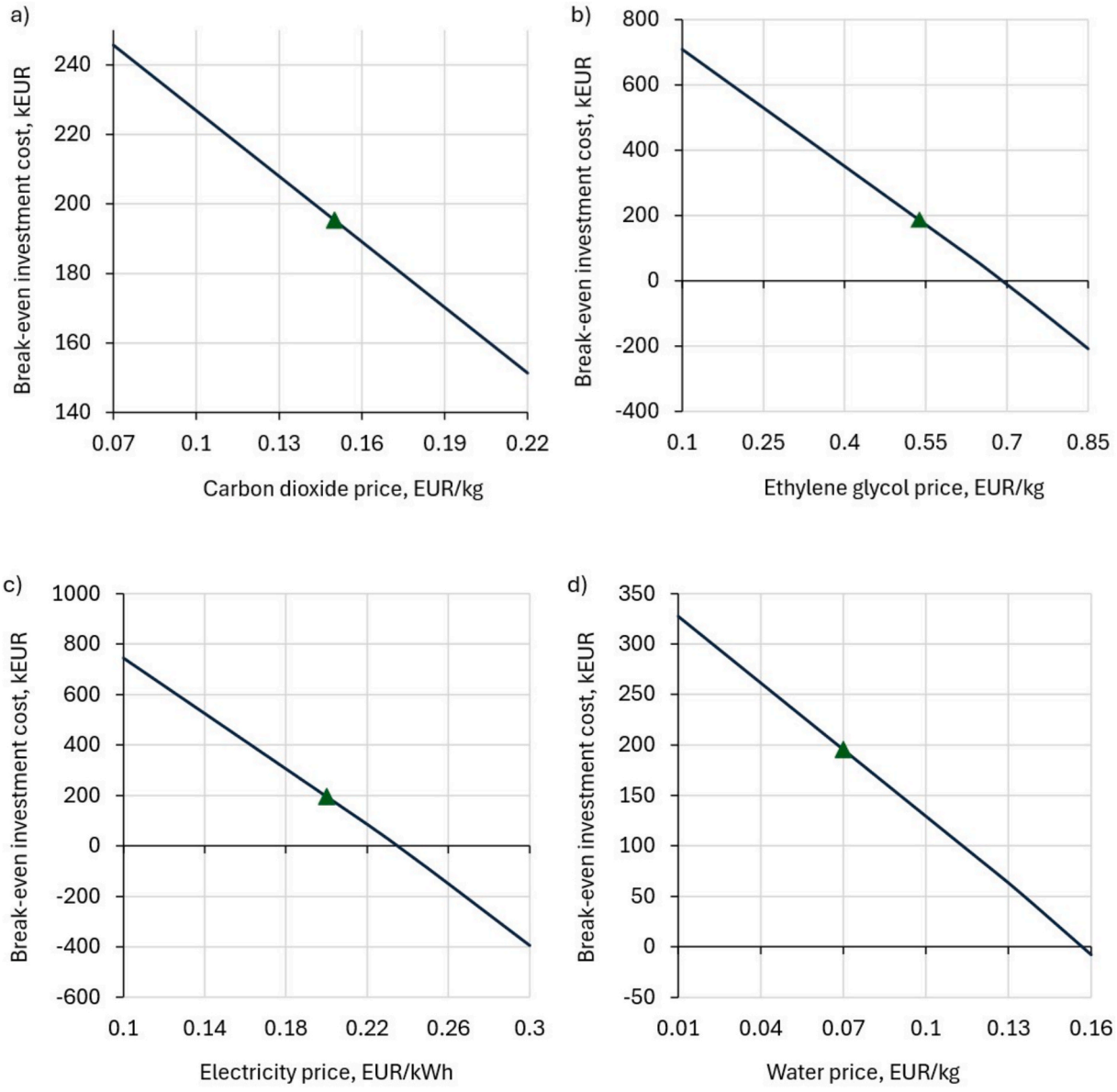


Fig. 9. The impact of changes in the price of a) carbon dioxide, b) ethylene glycol, c) electricity, and d) water on the value of marginal investment costs.

these costs exceed 1000 kEUR, which is almost a sevenfold increase compared to break-even investment costs at the base price of glycolic acid. In the case of n-propanol, a change in its price does not have such a visible impact on break-even investment costs, and a drop in the price of n-propanol to the lowest value in the analyzed range will not result in a loss of profitability.

5. LCA analysis

5.1. Goal & scope

This Life Cycle Assessment evaluates the environmental performance of the tandem reactor system integrating photo-electrochemical and electrochemical technologies to produce n-propanol. The environmental performance of the analyzed tandem reactor configuration is compared with conventional production pathways of the corresponding products.

This assessment is meant to guide internal decision-making, supporting the identification of environmental hotspots and design optimization pathways for the tandem reactor system.

The comparative analysis focuses on two primary metrics: the environmental footprint single score, which expresses the overall environmental impact across different impact categories, and greenhouse gas emissions, which quantify the carbon footprint associated with each production pathway.

5.1.1. System boundaries

All scenarios adopt a cradle-to-gate approach, including all upstream processes from raw material extraction to the production of the products generated in the analyzed tandem reactor system. Due to data availability constraints, infrastructure and downstream stages are excluded. Separately, the production of ethylene glycol is modeled using data from the conventional process as the upcycling of PET into ethylene glycol remains at a low technology readiness level (TRL).

All product system models employ a cradle-to-gate system boundary, encompassing material extraction, processing, electricity generation, and manufacturing stages through factory-gate delivery. Fig. 11 shows system boundaries for the proposed tandem reactor system and the conventional benchmark production. For a more detailed description of the assumptions taken, see the Supplementary Materials.

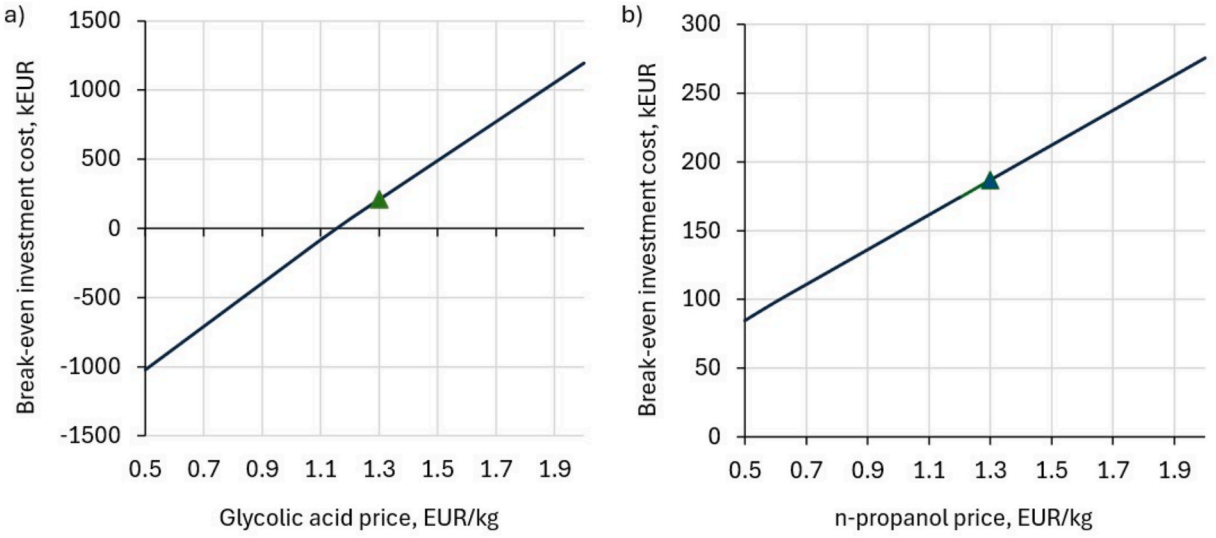


Fig. 10. The impact of changes in the price of a) glycolic acid and b) n-propanol on the value of break-even investment costs for a tandem reactor.

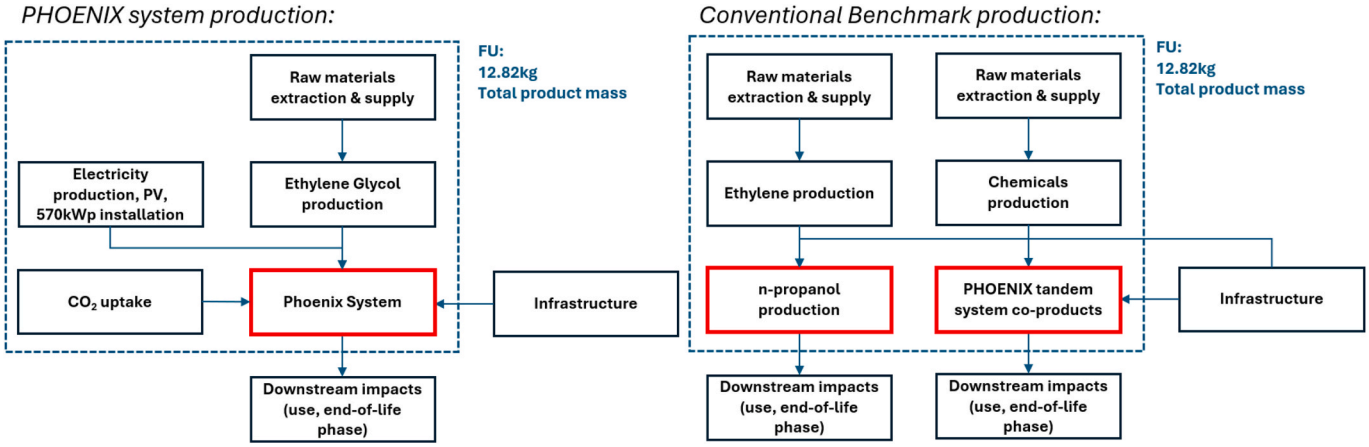


Fig. 11. System boundaries for the proposed tandem reactor system and the conventional benchmark production.

5.1.2. Functional unit (FU)

As outlined in the Introduction, the primary goal of this tandem reactor system is the development of a process that integrates renewable fuel production with long-term energy storage, using waste streams as resources. In this context, n-propanol is identified as the main target product because it serves as a liquid fuel capable of storing intermittent renewable energy and using CO2 as feedstock. While glycolic acid accounts for 80.20 % of the total bulk product mass and dominates the economic value, it is generated as a high-value co-product that supports the economic viability of the primary fuel-production goal. To evaluate the overall system, all mass and energy balances were normalized to the production of 1 kg of n-propanol (Supplementary Material, Fig. S5). This definition ensures the FU captures both the full output portfolio and the process's primary target product, n-propanol. The functional unit therefore includes all distinct chemical and energy outputs generated by the process:

- Main product: n-propanol (1.00 kg)
- Major co-product: glycolic acid, 70 wt% aqueous (10.25 kg)
- Secondary co-products: formic acid (0.46 kg), acetic acid (0.60 kg), ethylene (0.14 kg), ethanol (0.23 kg), hydrogen gas (0.10 kg), oxygen (0.24 kg)

Including all co-products in the functional unit ensures proportionate environmental impact allocation, preventing the underestimation of impacts for higher-value products through dilution across lower-value outputs.

This comprehensive FU definition is justified by system architecture: electrochemistry of the proposed tandem reactor system operates via parallel anode (ethylene glycol oxidation) and cathode (CO_2 reduction) reactions within coupled cell compartments, yielding all eight products from fixed stoichiometric pathways that cannot be independently varied.

For the conventional benchmark, all established industrial production pathways required to generate the same quantities of substances produced by the analyzed tandem reactor installation are considered. The benchmark is modeled to deliver an equivalent product portfolio with identical masses and compositions, thereby ensuring direct methodological comparability. All environmental impacts are expressed by the complete functional unit.

This approach aligns with ISO 14044 guidance on allocation and system boundaries: when co-products are inherently generated through fixed stoichiometry (as in coupled electrochemical systems), they must be included in the functional unit or allocation calculations rather than excluded.

5.1.3. Allocation

In the present study, economic allocation is applied as the primary

method for distributing environmental burdens among co-products of the tandem system. Allocation factors are calculated based on market prices per kilogram for each product, distributed proportionally to their total economic value within the functional unit. Consequently, 83.53 % of environmental impacts were allocated to glycolic acid, 8.09 % to n-propanol, and 8.38 % distributed among minor co-products (Table 4). Glycolic acid production is the dominant contributor, reflecting its high yields and market value. To confirm that this choice does not affect the results, a sensitivity analysis comparing economic, mass-based, and energy-based allocation factors is reported in the Supplementary Materials Table S1. The results demonstrate that economic and mass-based allocation yield consistent outcomes, with glycolic acid remaining the dominant contributor (>80 % of impacts) in both cases. Energy-based allocation also assigns the largest share to glycolic acid, although this method is considered less appropriate here as it would overestimate the burden of energy-dense minor co-products.

5.2. Life cycle inventory (LCI)

The life cycle inventory (LCI) for the analyzed tandem reactor system is established from theoretical mass and energy balance, normalized to 1 kg n-propanol production (Fig. S5, Supplementary Material). The system operates with four input flows: electricity (40.14 kWh, photovoltaic supply), ethylene glycol (8.58 kg, market supply), deionized water (16.71 kg, market supply), and atmospheric CO_2 (−3.95 kg CO_2 directly from the atmosphere). These inputs are converted through parallel electrochemical pathways into eight products, which are generated in fixed stoichiometric ratios as defined by the functional unit. For the conventional benchmark, established industrial production methods for the equivalent products are used instead.

Complete LCI inputs, outputs, data sources, and underlying assumptions detailed in Supplementary Materials Tables S2-S3 (analyzed tandem reactor system) and Tables S4–S5 (conventional benchmark production). Complete input–output flows and detailed source documentation, including Ecoinvent reference processes and custom dataset derivations, and the single-configuration inventories for PEC and PV-EC, are provided in Supplementary Tables S6–S9.

5.3. Life cycle impact assessment (LCIA)

The Life Cycle Impact Assessment was conducted using the Environmental Footprint (EF) v3.1 method implemented in openLCA v2.6.0 with Ecoinvent 3.11 Cutoff database. The method encompasses 17 midpoint impact categories normalized and weighted to derive a single-score Environmental Footprint indicator (mPt/FU).

For each scenario, LCIA was first conducted at midpoint level (e.g. climate change, energy resources, material resources, toxicity and eutrophication), then normalized and weighed according to EF v3.1 to obtain the Environmental Footprint single score expressed in mPt per functional unit.

The results should be interpreted by first quantifying the environmental impacts associated with conventional production methods and then comparing them with those of the proposed tandem system, scaled to the same product output as the conventional process. This approach provides a preliminary life cycle assessment of the tandem reactor configuration based on the stated assumptions.

Table 4
Economic allocation of the PV-EC and PEC tandem system.

Component	Unit Price (EUR/kg)	Quantity (kg)	Cost (EUR)	Impacts share (%)
n-Propanol	1.28	1.00	1.28	8.09
Glycolic acid	1.29	10.25	13.22	83.53
Formic acid	0.70	0.46	0.32	2.03
Acetic acid	0.55	0.60	0.33	2.08
Ethylene	0.97	0.14	0.14	0.86
Ethanol	0.84	0.23	0.19	1.22
H_2	3.46	0.10	0.35	2.19
Total			15.83 EUR	100 %

5.4. Interpretation

The total environmental performance of the proposed tandem reactor system is 1.92 mPt/FU. Fig. 12 shows stacked column of the environmental performances of the studied system. The environmental burden is primarily distributed across three impact categories. Non-renewable energy resource depletion accounts for 30 % of the total impact, while climate change represents 22 %. Both categories are driven by the same underlying factor: the high demand for fossil energy, mainly associated with ethylene glycol production. Material resource depletion (metals and minerals) contributes 16.2 % of the overall burden and is largely attributable to the use of critical materials embedded in the multi-silicon photovoltaic array.

To evaluate the preliminary environmental performance of the two electrochemical pathways, a detailed process-level contribution analysis was conducted by examining the life cycle impacts across the PV-EC (photovoltaic-coupled electrochemistry) and PEC (photo-electrochemical) configurations. This analysis identifies dominant process contributions and assesses the relative performance of each system architecture based on the Environmental Footprint (EF) single-score methodology. Fig. 13 shows comparison PV-EC with the PEC system based on global warming potential and Environmental Footprint.

Comparative analysis of the two electrochemical configurations reveals substantial environmental differences. The PV-EC configuration achieves 0.54 mPt/FU (Environmental Footprint), while the PEC system produces 1.38 mPt/FU. For climate change impacts (GWP), the performance differential is more pronounced.

The PV-EC system achieves 2.20 kg CO_2-eq/FU, while the PEC pathway produces 12.90 kg CO_2-eq/FU. The atmospheric CO_2 used in the PV-EC translates to −3.95 kg CO_2-eq/FU on the GWP indicator, absent in PEC, while ethylene glycol production contributes 5.50 kg CO_2-eq/FU (PV-EC) versus 11.40 kg CO_2-eq/FU (PEC).

Ethylene glycol clearly emerges as the main environmental hotspot in both configurations, contributing roughly 85 % of the total impacts across the Environmental Footprint and GWP indicators. This contribution is further amplified in the PEC system due to its higher ethylene glycol stoichiometric demand (see Tables S6-S9), which is approximately two times that of the PV-EC configuration. As a result, improving the environmental performance of ethylene glycol supply becomes the primary optimization lever.

Transitioning from conventional petrochemical-derived ethylene glycol to a PET-based upcycling route therefore represents the most effective strategy for reducing the overall environmental burden of the process. For such a substitution to be environmentally credible, the upcycling pathway must demonstrate lower life cycle impacts than the conventional petrochemical process while achieving industrial-scale viability at production costs competitive with the current market price of 0.53 EUR/kg (see Table 2). The environmental and economic characterization of PET-derived ethylene glycol is therefore identified as a key priority for future work, and a dedicated comparative LCA against conventional production should be conducted once validated life cycle inventory data becomes available on the relevant scale.

The atmospheric CO_2 utilized as a feedstock contributes a negative climate change impact (−3.95 kg CO_2-eq/FU) under the adopted cradle-to-gate boundary, reflecting temporary carbon uptake during product formation. This benefit does not imply permanent carbon removal and would be neutralized under cradle-to-grave accounting upon product end-of-life. Nevertheless, within a cradle-to-gate framework, the use of atmospheric CO_2 displaces fossil-derived carbon inputs and contributes to reduced upstream emissions.

Electricity consumption represents the second largest contributor,

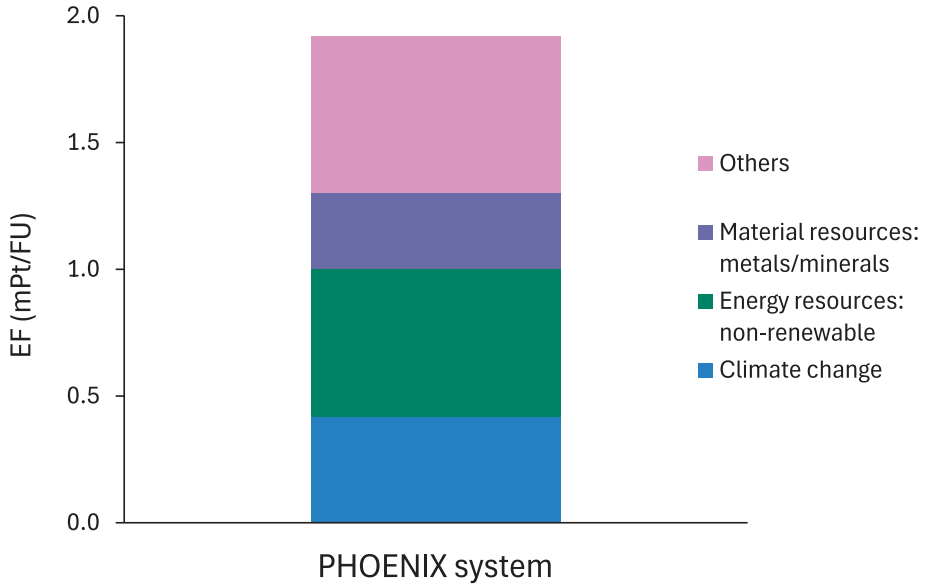


Fig. 12. Stacked column of the environmental performances of the proposed tandem reactor system.

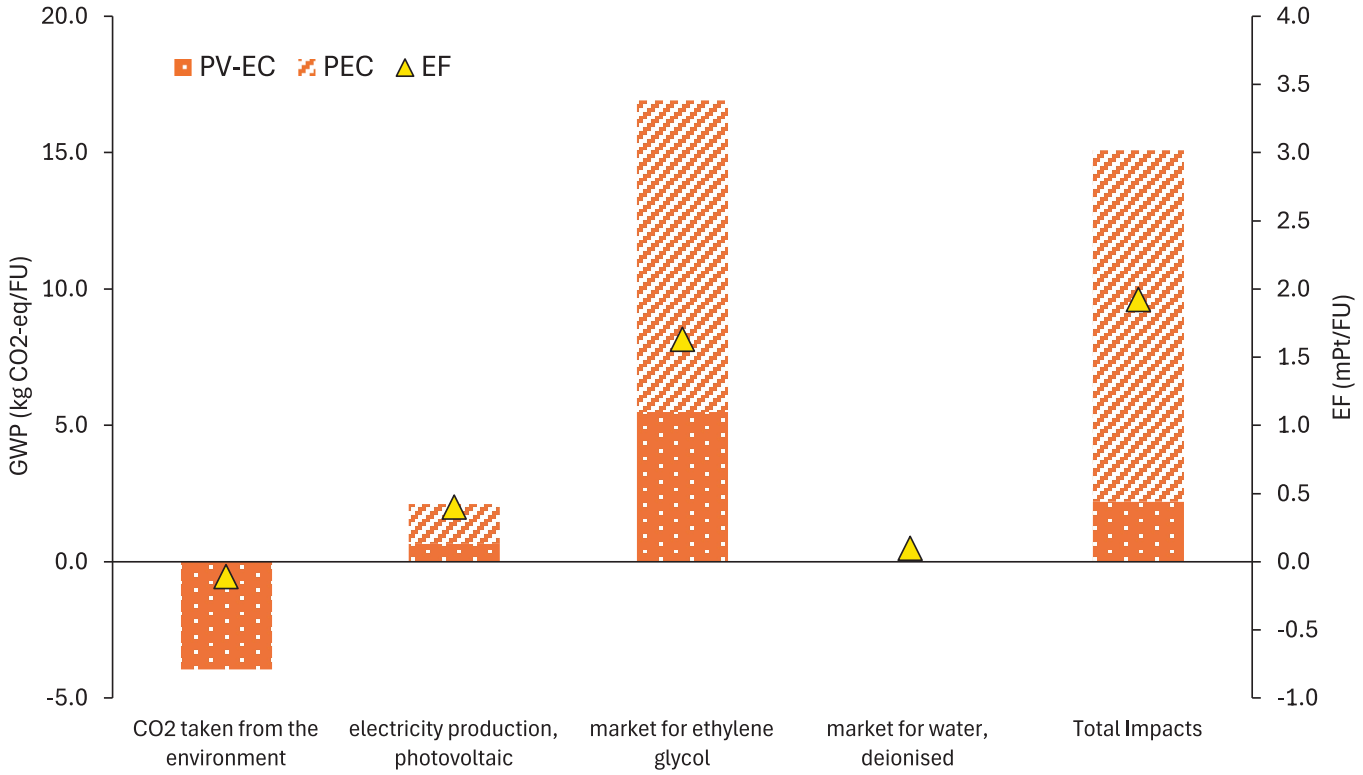


Fig. 13. Comparison of PV-EC and PEC systems based on global warming potential and the Environmental Footprint.

with PV-EC at 0.50 kg CO_2-eq/FU versus 1.80 kg CO_2-eq/FU for PEC, accounting for approximately 10 % of the total GWP difference. This gap is driven by the higher power demand of the PEC reactor (55.66 kW vs. 24.61 kW, Table 1). The higher electricity burden of the PEC configuration is strongly linked to its lower Faradaic efficiency (CO-to-n-propanol 50 % in the PEC compared to the CO_2-to-CO 90 % in PV-EC) and its higher operating voltage (2.6 V for the PEC, 2.3 V for the PV-EC), both of which increase the power required for the final products. In practice, the lower selectivity of the PEC pathway toward n-propanol means that more charge is lost to side reactions, while the higher cell voltage raises the energy input needed to drive the reaction.

The combined effect of lower ethylene glycol demand, the CO_2 feedstock credit and reduced electricity consumption fully explains the environmental advantages of PV-EC over PEC.

Fig. 14 shows comparison of the analyzed tandem reactor system with the conventional benchmark production.

The proposed tandem reactor system shows substantial environmental advantages. Global warming potential is reduced by 56 % (15.09 vs. 34.40 kg CO_2-eq/FU), achieving a reduction of 19.31 kg CO_2-eq/FU. Environmental Footprint improves by 68 % (1.92 vs. 5.95 mPt/FU), with improvements driven by renewable photovoltaic electricity substitution and atmospheric CO_2 valorization as feedstock. Despite

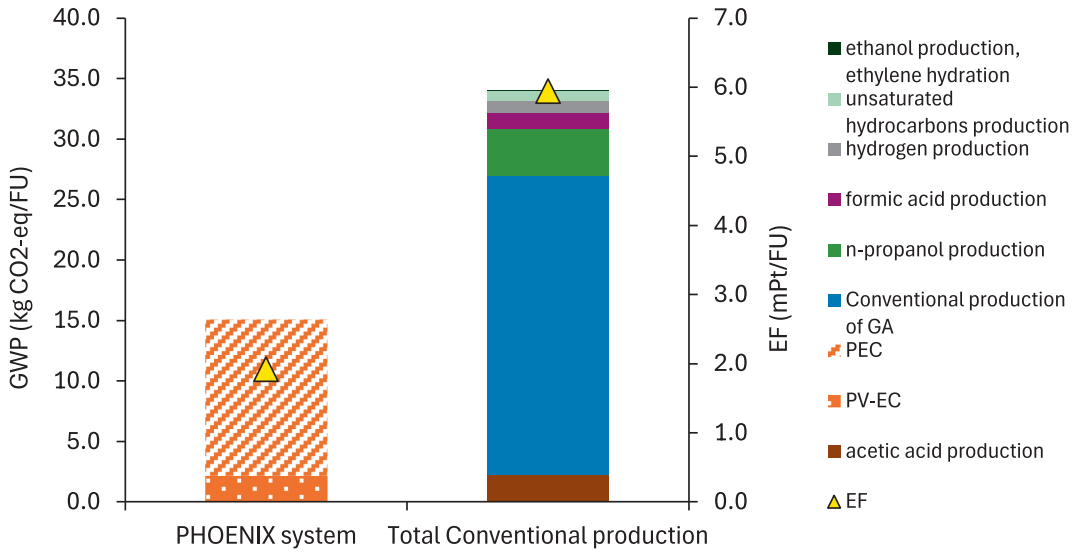


Fig. 14. Comparison of the analyzed tandem reactor system with the conventional benchmark production.

ethylene glycol production remaining a dominant hotspot, systemic decarbonization yields substantial net environmental benefit. Based on this comparison and on the allocation analysis the glycolic acid accounts for 83.53 % of total impacts despite being a co-product. Glycolic acid production (10.25 kg/kg n-propanol) requires substantially greater feedstock and energy input. This finding suggests optimization should prioritize glycolic acid production or consider repositioning it as the platform chemical.

6. Discussion

The system analyzed operates in thermodynamic and economic synergy. Instead of conducting the traditional, energy-intensive oxygen evolution reaction (OER) at the anode, an ethylene glycol oxidation reaction (EGOR) was employed. This change lowers the overall voltage required to operate the system, saving significant amounts of electricity. Furthermore, instead of generating low-value oxygen, high-value glycolic acid is produced at the anode. This synergizes perfectly with CO2 reduction at the cathode, creating a highly efficient process that maximizes both energy savings and financial returns.

To simplify the process modeling, this study assumes that ethylene glycol (EG) already derived from PET hydrolysis is purchased directly, rather than assessing the entire PET sorting and chemical recycling process on-site. Therefore, our model establishes a baseline using purified, recycled EG as the direct commercial feedstock. In wider industrial practice, sourcing EG from actual, unpurified PET waste streams introduces complications related to dyes, additives, and impurities, which require additional filtration or distillation steps. Although these energy inputs for pretreatment were excluded from our current system boundaries due to the assumption of purchased finished feedstock, they constitute important environmental variables that will be detailed in future, broader life-cycle assessments.

In this study, PET hydrolysis was not included in the quantitative LCA model due to critical data gaps resulting from the low technological maturity level (TRL) of current upcycling pathways. Recent prospective LCA work for PET to EG conversion (e.g., alkaline hydrolysis and hydrogenolysis processes) [45] also highlights this challenge. In the alkaline hydrolysis case, the large ethanol demand leads to very high greenhouse gas emissions, on the order of 74.6 kg CO_2 per kg PET processed, for a co product slate of approximately 0.321 kg EG and 0.84 kg terephthalic acid; even accounting for the fact that TPA is the main product, the specific impacts associated with EG are substantially higher than those of conventional fossil based EG. Hydrogenolysis performs better, with roughly 5.8 kg CO_2 per kg PET and around 0.3 kg EG co produced with benzene dimethanol, yet allocation among co products would still leave PET derived EG far from competitive with established market routes at present. These studies are based on laboratory scale systems and prospective designs and therefore cannot be used as a robust basis for the quantitative LCA of an industrial scale tandem reactor. In this light, PET to EG upcycling is identified as a strategic research priority rather than as a directly substitutable input: future work should focus on generating validated mass–energy balances, reducing solvent and energy demands, defining purification and impurity handling requirements, and developing allocation approaches for multi product upcycling systems before revisiting the quantitative GHG performance of PET derived EG in an industrial context.

The cradle to gate boundary adopted in the LCA excludes infrastructure construction and catalyst manufacturing for both the tandem PV EC/PEC system and the conventional benchmark, due to the absence of detailed engineering data for the early stage reactor concept, as explained in the system boundaries assumptions in the supplementary materials. in the As a consequence, the reported impact values represent conservative lower bounds for both systems, and the omission of these stages may bias the comparison. Given the use of Ag, Pd and Cu based electrodes and the low TRL of the tandem system, the relative contribution of reactor hardware and catalyst lifecycles is likely higher for the novel configuration than for mature conventional plants, which means that the true environmental advantage of the tandem route may be smaller than indicated. A more comprehensive assessment will therefore require future work to develop detailed inventories for reactor materials, catalyst manufacture and end of life once the first physical units and operating data become available.

The 80.27 kW system power used in the calculations provides a realistic baseline at pilot scale, aiming to bridge the gap between laboratory test data and full industrial application. The choice of this specific scale is justified by the fact that the co-reduction reactor technology is currently at Technology Readiness Level 4 (TRL 4). The mathematical and economic models developed in this study are universal, utilizing standardized, scalable process parameters, such as current densities, faradaic efficiencies, and modular reactor sizing. As a result, the system can be scaled up to megawatt-scale industrial installations by replicating electrochemical cell blocks (modular stacks), making the methodology fully applicable to larger decarbonization systems. However, it should be noted that while the physical capacity scales through modular replication, the unit capital expenditures are expected to follow a non-linear trend. Similar to commercial hydrogen electrolyzers, larger

megawatt-scale installations will benefit from economies of scale, resulting in significantly lower specific costs per unit of power.

7. Conclusions

An economic analysis of the tandem electrochemical and photoelectrochemical reactors showed that the selling price of glycolic acid has the greatest impact on the marginal investment costs. Revenues from glycolic acid account for nearly 85 % of total revenues, making it the primary economic driver of the system. However, n-propanol, produced in the second stage of the process, represents a strategically important product from an energy systems perspective due to its potential application as a renewable fuel and energy carrier.

The economic analysis carried out as part of the study identified the key economic parameters, in particular the selling price of glycolic acid and the cost of renewable electricity, which have the greatest impact on the profitability of the proposed installation. The results indicate that the stability of these parameters in the long term will be a decisive factor determining the commercialization potential of the technology. In the context of further development, it seems necessary to conduct detailed research on the optimization of technological processes, which may contribute to increasing the efficiency of the system and reducing operating costs. The integration of renewable energy sources is essential for improving both economic stability and environmental performance of the system. This highlights the importance of coupling waste valorization technologies with renewable energy systems to support both economic viability and energy transition goals.

The LCA shows that the conceptual model of proposed tandem reactor system holds a large potential for decarbonization. Compared with heavily fossil-dependant benchmarks, the system reduces the overall environmental impacts by roughly two-thirds and substantially lowers fossil energy demand. These benefits stem from its exclusive reliance on renewable electricity and the circular use of CO_2 as a feedstock. The results highlight the potential role of integrated electrochemical systems in reducing the environmental intensity of chemical production within a low-carbon energy system.

Comparison of the two electrochemical configurations reveals a clear environmental advantage of the PV-EC pathway. This advantage is primarily driven by the substantially lower ethylene glycol requirement and reduced electricity consumption per functional unit. The higher impacts associated with the PEC configuration originate from its lower conversion efficiency, which necessitates larger ethylene glycol throughput, and from elevated electrochemical overpotentials that increase electricity demand.

Across both reactor concepts, ethylene glycol supply dominates the life-cycle profile, accounting for roughly 85 % of total impacts after allocation, which reflects the large production volume and economic relevance of glycolic acid as the main product stream. Economic allocation indicates that glycolic acid receives 83.53 % of the total environmental burden, despite being originally treated as a co-product, because it combines the highest mass yield with the dominant contribution to revenue. Although glycolic acid dominates both the economic and environmental allocation of the system due to its high yield and revenue contribution, the system should be interpreted as a dual-purpose platform integrating chemical production with renewable fuel generation. In this context, n-propanol plays a key role as an energy vector, linking CO_2 utilization with fuel production pathways and enhancing the overall system relevance within a low-carbon energy framework.

The economic analysis and LCA identified the differences between the factors determining profitability and the environmental impact. The NPV analysis showed that the key economic determinants are the price of glycolic acid and electricity, while the LCA indicates that ethylene glycol generates the largest environmental footprint. This means that the economically relevant parameters do not coincide with those determining the environmental impact. From a commercialization perspective, it is necessary to reduce costs and stabilize the GA market, while from an environmental perspective, it is necessary to replace EG with recycled PET or a renewable equivalent.

8. Funding information

The PHOENIX project received funding from the European Union's Horizon Europe research and innovation program under grant agreement No. 101172764. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them. This work received funding from the Swiss State Secretariat for Education, Research and Innovation (SERI).

CRediT authorship contribution statement

Baszczeńska Oliwia: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Andretta Antonio:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Kotowicz Janusz:** Writing – review & editing, Supervision, Project administration, Methodology, Conceptualization. **Niesporek Kamil:** Writing – review & editing, Writing – original draft, Visualization, Formal analysis, Data curation. **Brzęczek Mateusz:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fuel.2026.141204.

Data availability

Data will be made available on request.

References

[1] Ang TZ, Salem M, Kamarol M, Das HS, Nazari MA, Prabaharan N. A comprehensive study of renewable energy sources: classifications, challenges and suggestions. Energ Strat Rev 2022;43:100939. https://doi.org/10.1016/j.esr.2022.100939.
[2] Vine E. Breaking down the silos: the integration of energy efficiency, renewable energy, demand response and climate change. Energy Efficiency 2008;1:49–63. https://doi.org/10.1007/s12053-008-9004-z.
[3] Ould Amrouche S, Rekioua D, Rekioua T, Bacha S. Comprehensive review of energy storage systems technologies, objectives, challenges, and future trends. Energ Strat Rev 2024;54:101482. https://doi.org/10.1016/j.ijhydene.2016.06.243.
[4] Zhang R, Zhang J, Wang S, Tan Z, Yang Y, Song Y, et al. Synthesis of n-Propanol from CO2 Electroreduction on Bicontinuous Cu2O/Cu Nanodomains. Angew Chem Int Ed 2024;63:e202405733. https://doi.org/10.1002/anie.202405733.
[5] Rahaman M, Kiran K, Montiel IZ, Grozovski V, Dutta A, Broekmann P. Selective n-propanol formation from CO2 over degradation-resistant activated PdCu alloy foam electrocatalysts. Green Chem 2020;22:6497–509. https://doi.org/10.1039/d0gc01636e.
[6] Plastics the Fast Facts 2025 • Plastics Europe n.d. https://plasticseurope.org/knowledge-hub/plastics-the-fast-facts-2025/ (accessed February 12, 2026).
[7] Geyer R, Jambeck JR, Law KL. Production, use, and fate of all plastics ever made. Sci Adv 2017;3. https://doi.org/10.1126/sciadv.1700782.
[8] Lamberts-Van Assche H, Lavrutich M, Compernolle T, Thomassen G, Thijssen JJJ, Kort PM. CO2 storage or utilization? A real options analysis under market and technological uncertainty. J Environ Econ Manage 2023;122:102902. https://doi.org/10.1016/j.jeem.2023.102902.
[9] Diao J, Hu Y, Tian Y, Carr R, Moon TS. Upcycling of poly(ethylene terephthalate) to produce high-value bio-products. Cell Rep 2023;42:111908. https://doi.org/10.1016/j.celrep.2022.111908.

[10] Chen J, Li J, Wei Z. Recent advances in the preparation of glycolic acid by selective electrocatalytic oxidation of ethylene glycol. Chin J Catal 2025;73:79–98. https://doi.org/10.1016/S1872-2067(25)64710-3.
[11] Glycolic Acid Market | Global Market Analysis Report - 2035 n.d. https://www.futuremarketinsights.com/reports/glycolic-acid-market (accessed March 3, 2026).
[12] Al Mesfer MK, Parthasarthy V, Danish M, Shah M, Ansari KB, Ammendola P, et al. A critical review on current progress and challenges in post-combustion CO2 separation from flue gas. Sep Sci Technol (Philadelphia) 2024;59:1454–76. https://doi.org/10.1080/01496395.2024.2377585.
[13] Peres CB, Resende PMR, Nunes LJR, Morais LC de. Advances in carbon capture and use (CCU) technologies: a comprehensive review and CO2 mitigation potential analysis. Clean Technologies 2022;4:1193–207. https://doi.org/10.3390/cleantechnol4040073.
[14] Wu G, Song Y, Zheng Q, Long C, Fan T, Yang Z, et al. Selective electroreduction of CO2 to n-propanol in two-step tandem catalytic system. Adv Energy Mater 2022;12. https://doi.org/10.1002/aenm.202202054.
[15] Çelebi Y, Cengiz M, Aydın H. Propanol and its blend in diesel engines: an extensive review. J Energy Inst 2025;120:102047. https://doi.org/10.1016/j.joei.2025.102047.
[16] Overa S, Ko BH, Zhao Y, Jiao F. Electrochemical approaches for CO2 conversion to chemicals: a journey toward practical applications. Acc Chem Res 2022;55:638–48. https://doi.org/10.1021/ACS.ACCOUNTS.1C00674.
[17] Liu Y, Wang L, Zhang Y, Xie J, Li J, Wei J, et al. From ethylene glycol to glycolic acid: electrocatalytic conversion on Pt-group metal surfaces. Inorg Chem 2024;63:14794–803. https://doi.org/10.1021/ACS.INORGCHEM.4C02799.
[18] Niu W, Chen Z, Guo W, Mao W, Liu Y, Guo Y, et al. Pb-rich Cu grain boundary sites for selective CO-to-n-propanol electroconversion. Nature Communications 2023;14:4882. https://doi.org/10.1038/s41467-023-40689-w.
[19] Oliwia B, Janusz K, Antonio A, Kamil N, Mateusz B. Economic analysis and life cycle assessment of an electrochemical reactor for CO2 and ethylene glycol conversion. Energies (Basel) 2025;18:5125. https://doi.org/10.3390/EN18195125/S1.
[20] Bareiß K, de la Rua C, Möckl M, Hamacher T. Life cycle assessment of hydrogen from proton exchange membrane water electrolysis in future energy systems. Appl Energy 2019;237:862–72. https://doi.org/10.1016/J.APENERGY.2019.01.001.
[21] Personal income tax rates (SDG) n.d. https://podatki-arch.mf.gov.pl/en/residents/personal-income-tax-rates/ (accessed July 7, 2026).
[22] Kredyt obrotowy dla firm – na czym polega i kiedy z niego skorzystać? | KPR Restrukturyzacja n.d. https://kpr-restrukturyzacja.pl/kredyt-obrotowy-dla-firm-na-czym-polega-i-kiedy-warto-z-niego-skorzystac/ (accessed July 7, 2026).
[23] Roczne stawki amortyzacyjne n.d. https://wskazniki.gofin.pl/wskaznik/210/roczne-stawki-amortyzacyjne (accessed July 7, 2026).
[24] Mapping the cost of carbon capture and storage in Europe – Clean Air Task Force n.d. https://www.catf.us/2023/02/mapping-cost-carbon-capture-storage-europe/ (accessed January 11, 2026).
[25] nPropanol (1-propanol) price index - businessanalytiq n.d. https://businessanalytiq.com/procurementanalytics/index/npropanol-price-index/ (accessed January 11, 2026).
[26] Acetic Acid price index - businessanalytiq n.d. https://businessanalytiq.com/procurementanalytics/index/acetic-acid-price-index/ (accessed January 11, 2026).
[27] Ethanol price index - businessanalytiq n.d. https://businessanalytiq.com/procurementanalytics/index/ethanol-price-index/ (accessed January 11, 2026).
[28] Ethylene price index - businessanalytiq n.d. https://businessanalytiq.com/procurementanalytics/index/ethylene-price-index/ (accessed January 11, 2026).
[29] Green hydrogen price index - businessanalytiq n.d. https://businessanalytiq.com/procurementanalytics/index/green-hydrogen-price-index/ (accessed April 10, 2026).
[30] Curcio E. Techno-economic analysis of hydrogen production: costs, policies, and scalability in the transition to net-zero. Int J Hydrogen Energy 2025;128:473–87. https://doi.org/10.1016/J.IJHYDENE.2025.04.013.
[31] Woda destylowana cena - Woda demineralizowana cena Czysta Woda Śląsk n.d. https://czystawoda.slask.pl/cennik-wody-demineralizowanej/ (accessed January 11, 2026).
[32] Kumar B, Muchharla B, Dikshit M, Dongare S, Kumar K, Gurkan B, et al. Electrochemical CO2 conversion commercialization pathways: a concise review on experimental frontiers and technoeconomic analysis. Environ Sci Technol Lett 2024;11:1161–74. https://doi.org/10.1021/ACS.ESTLETT.4C00564.
[33] Zhou X, Zha M, Cao J, Yan H, Feng X, Chen D, et al. Glycolic acid production from ethylene glycol via sustainable biomass energy: integrated conceptual process design and comparative techno-economic–society–environment analysis. ACS Sustain Chem Eng 2021;9:10948–62. https://doi.org/10.1021/ACSSUSCHEMENG.1C03717.
[34] Formic Acid price index - businessanalytiq n.d. https://businessanalytiq.com/procurementanalytics/index/formic-acid-price-index/ (accessed January 11, 2026).
[35] Oxygen price index - businessanalytiq n.d. https://businessanalytiq.com/procurementanalytics/index/oxygen-price-index/ (accessed January 11, 2026).
[36] Ethylene Glycol price index - businessanalytiq n.d. https://businessanalytiq.com/procurementanalytics/index/ethylene-glycol-price-index/ (accessed January 11, 2026).
[37] Cena energii elektrycznej 2025. Ile kosztuje 1 kwh (Tauron, PGE, Enea) n.d. https://corab.pl/aktualnosci/ile-kosztuje-1-kwh-energii-elektrycznej-w-2025-roku-z-czego-wynika-cena (accessed January 11, 2026).
[38] Gawel A, Jaster T, Siegmund D, Holzmann J, Lohmann H, Klemm E, et al. Electrochemical CO2 reduction - the macroscopic world of electrode design, reactor concepts & economic aspects. IScience 2022;25:104011. https://doi.org/10.1016/J.ISCI.2022.104011.
[39] Hu XM, Liang HQ, Rosas-Hernández A, Daasbjerg K. Electrochemical valorization of captured CO2: recent advances and future perspectives. Chem Soc Rev 2025;54:1216–50. https://doi.org/10.1039/D4CS00480A.
[40] Monis Ayyub M, Kormányos A, Endrődi B, Janáky C. Electrochemical carbon monoxide reduction at high current density: cell configuration matters. Chem Eng J 2024;490:151698. https://doi.org/10.1016/J.CEJ.2024.151698.
[41] Lee J, Lee W, Ryu KH, Park J, Lee H, Lee JH, et al. Catholyte-free electroreduction of CO2 for sustainable production of CO: concept, process development, techno-economic analysis, and CO2 reduction assessment. Green Chem 2021;23:2397–410. https://doi.org/10.1039/D0GC02969F.
[42] ISO 14040:2006 - Environmental management — Life cycle assessment — Principles and framework n.d. https://www.iso.org/standard/37456.html (accessed September 25, 2025).
[43] ISO 14044:2006 - Environmental management — Life cycle assessment — Requirements and guidelines n.d. https://www.iso.org/standard/38498.html (accessed September 25, 2025).
[44] Directive - EU - 2023/2413 - EN - Renewable Energy Directive - EUR-Lex n.d. https://eur-lex.europa.eu/eli/dir/2023/2413/oj/eng (accessed April 13, 2026).
[45] Iturrondobeitia M, Alonso L, Lizundia E. Prospective life cycle assessment of poly (ethylene terephthalate) upcycling via chemoselective depolymerization. Resour Conserv Recycl 2023;198:107182. https://doi.org/10.1016/J.RESCONREC.2023.107182.