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Feasibility study (techno-economic evaluation) of a biogas-fed SOFC system

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1. Plant Description: Wastewater treatment plant in Novara

Wastewater treatment plant in Novara with a population of 102000 inhabitants was chosen as a case study for the techno-economic evaluation of a biogas-fed SOFC system. The schematic of a Wastewater treatment plant integrated with Biogas-fed SOFC plant is shown on the Figure 1.

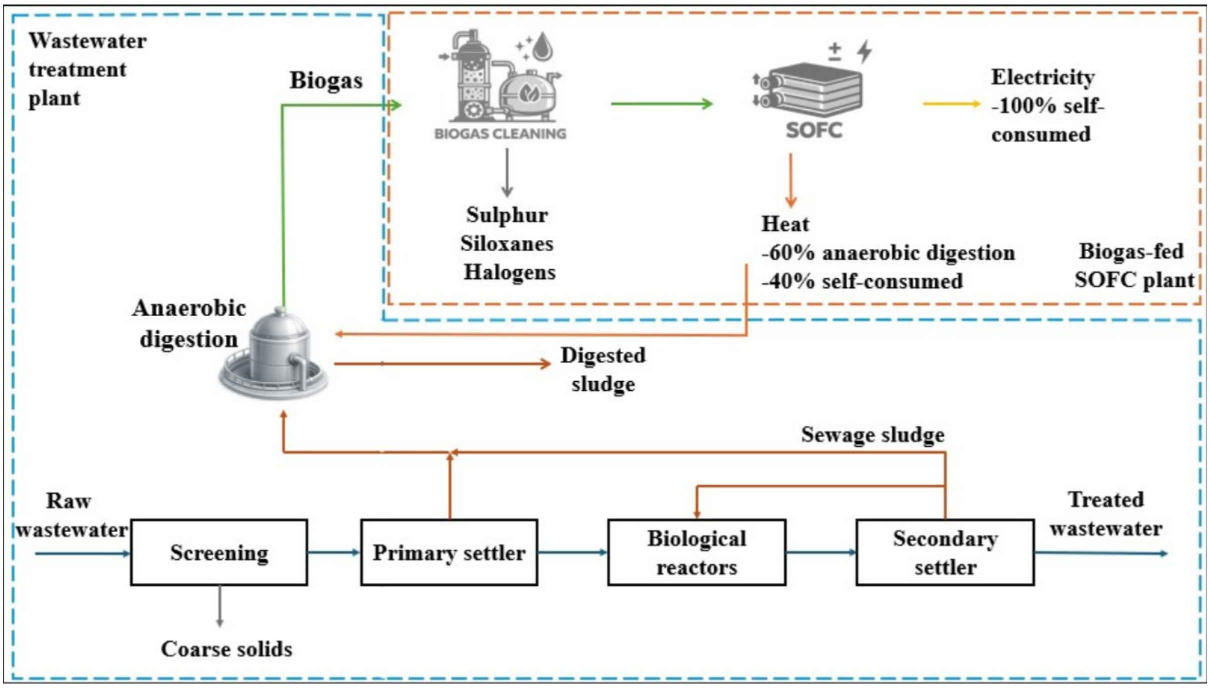

Figure 1. Schematic illustration of a WWTP integrated with Biogas-fed SOFC plant [1]

The process has three main stages: Wastewater Treatment, Biogas Production and Energy Conversion. For the Biogas Production the sewage sludge from primary and secondary water treatment is sent to the Anaerobic Digester. Before entering the digester, sewage sludge can be optionally processed through screening and thickening to increase solid fraction concentration to approximately 7% dry solids to optimize the efficiency. For the digestion step, the sludge is pumped into anaerobic continuously stirred tank reactor. With a temperature of 35-39 C, during a period of around 20 days, microorganisms produce biogas which is composed of methane, carbon dioxide and trace gases[1].

1.1 Rationale: Why Biogas with SOFC?

Biogas with Solid Oxide Fuel Cells (SOFC) integration offers a higher efficiency, sustainable solution for decentralised power generation due to several reasons:

- Superior electrical efficiency: SOFC systems achieve electrical efficiencies of 50-60%[2]. This is significantly higher than traditional internal combustion engines, which typically operate between 28-37% [3]
- Modular technology: Unlike large-scale power plants, SOFC performance remains constant event at small sizes. This makes them ideal for small-to-medium-sized biogas plants (farms. WWTPs) where traditional engines might lose efficiency [4].

- Environmental impact: Because the electrochemical reactions does not involve combustion, it produces zero atmospheric emissions of NO_x, SO_x, particulate matter (PM), or Volatile organic compounds (VOCs).

1.2 Biogas plant input data

The data for WWTP is presented in the Table 1.

Table 1. Input data for WWTP

Production	Value	Unit
Waste water	22440000	l/day
Sludge feed	51000	$m^3/year$
Biogas	267240	$Nm^3/year$

The capacity factor of the plant was chosen as 0.913. The amount of biogas produced is used as the Input for the ASPEN PLUS simulation V_{fuel} =33.41385 $Nm^3/hour$ and with the following composition of the gas 0.6 of CH_4 and 0.4 CO_2 . It is assumed that the inlet biogas has been cleaned from sulfur, siloxane trap, halogen scrubber, etc. The anaerobic digester and biogas cleaning system is not considered in the modulation. The main components for the biogas preparation before entering SOFC module are presented in Table 2.

1.3 Biogas -fed SOFC System description

The integrated plant is modeled as a continuous thermochemical process designed to convert raw biogas from the Novara WWTP into high-grade energy through three distinct stages, as illustrated in Figure 2. The cycle begins with the fuel and air preparation blocks, where low-pressure gases are compressed and pre-heated using recycled thermal energy. A central feature is the anode recirculation loop, which mixes fresh biogas with steam-rich exhaust to enable the endothermic reforming reaction. This prepared fuel then enters the SOFC electrochemical core, where it reacts with oxygen ions extracted from the cathode air stream to generate DC electricity. Finally, unreacted species are oxidized in an after-burner, producing a high-temperature exhaust stream routed through a Heat Recovery Unit (HRU) to provide thermal power for both internal pre-heating and external heating of the anaerobic digester.

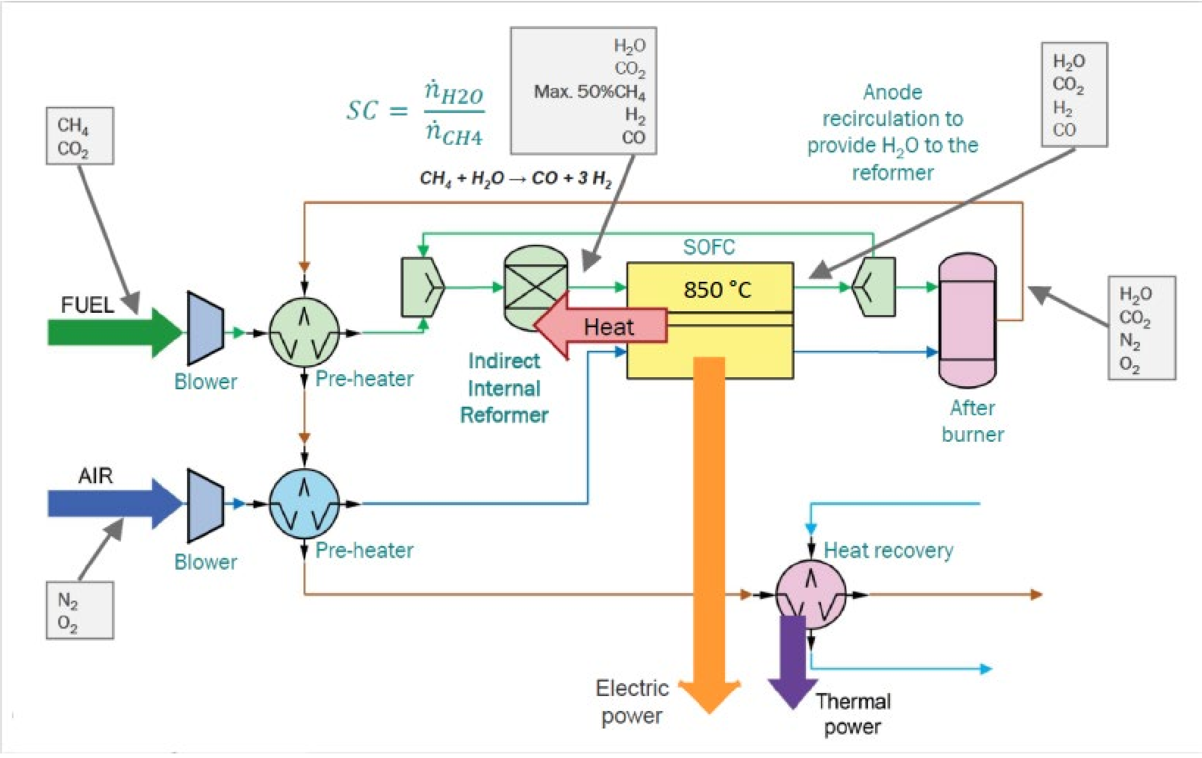

Figure 2. Working Principle of a Biogas-Fed SOFC System

a, Biogas preparation (Pre-anode)

Before entering the fuel cell stack, the biogas must be pressurized, heated, and reformed to ensure it is chemically compatible with the SOFC anode. The component modelled in Aspen Plus and preparation stage are detailed in Table 2

Table 2. Plant component specification for the biogas preparation

Unit	Operating conditions	Function	Output
Biogas Blower	$T_{inlet} = 15°C$ $P_{inlet} = 1$ bar	Performing isentropic compression of the fuel for the pressure drop compensation in the system	$P_{outlet} = 1.2$ bar
Biogas Pre-Heater	$T_{inlet} = 15°C$ $P_{operating} = 1.2$ bar	Pre-heating the fuel for the reaction using waste heat from after-burner exhaust	$T_{outlet} = 800°C$
Anode Recirculation Mixer	$T_{operating} = 800°C$ $P_{operating} = 1.2$ bar	To mix biogas with recirculated steam from SOFC anode exhaust	Mixture of Biogas and H_2O for reformer inlet
Reformer	$T_{operating} = 800°C$ $P_{operating} = 1.2$ bar	Reformer is modelled as Gibbs Equilibrium Reactor. Converts methane to hydrogen via steam methane reforming endothermic reaction: $CH_4 + H_2O \rightarrow CO + 3H_2$ Reaction requires water as reforming agent. Steam to carbon ratio is defined as SC=2.5[5]	H_2 rich SOFC fuel
Air Blower	$T_{inlet} = 15°C$ $P_{inlet} = 1$ bar	Performing isentropic compression of the air for the pressure drop compensation in the cathode side	$P_{outlet} = 1.2$ bar

Air Pre-Heater	$T_{inlet} = 15°C$ $P_{inlet} = 1.2$ bar	Pre-heating cathode using waste heat	$T_{output} = 700°C$

The system integration aspects, including full SOFC description, recirculation loops, after-burner operation and complete energy balances are presented in Chapter 2.

b, The SOFC system

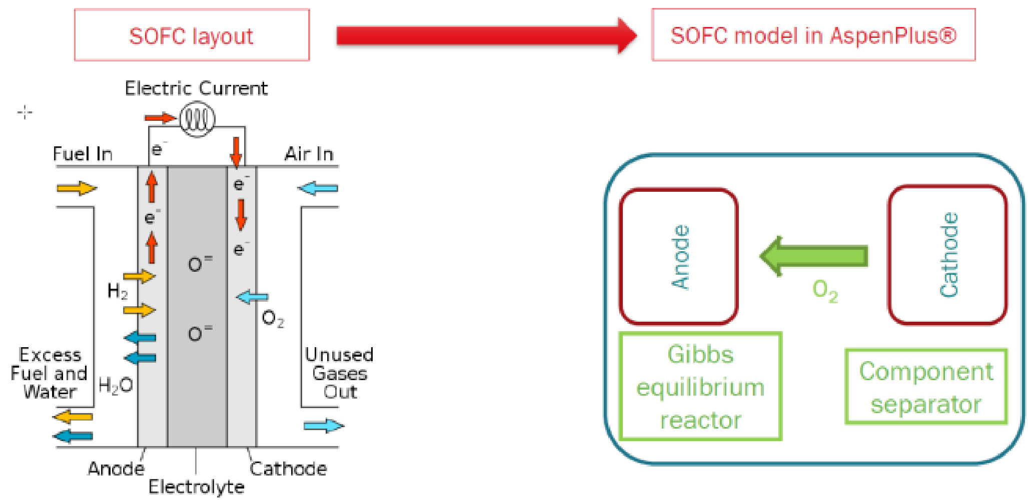

Figure 3. SOFC model simulation in Aspen Plus

In ASPEN Plus, the SOFC stack is simulated using a split-block approach to model the physical separation of the fuel and air by the electrolyte (Figure 3). Since a single "Fuel Cell" block does not exist in the software, the following components are linked:

- Anode Simulation (`SOFC-AN`): An RGibbs reactor that calculates the chemical equilibrium of the fuel at high temperature (700–850°C). It represents the site where hydrogen is oxidized.
- Cathode Simulation (`SOFC-CAT`): A Separator (`SEP`) block. Its primary function is to "extract" the necessary oxygen from the incoming air stream.
- The Calculator Bridge (`C-OXY`): This block uses Fortran code to link the chemical species to electrical variables via Faraday's Law.

Simulation formulas:

+ Total stack current (I_{tot}): Calculated based on the molar flow of methane ($\dot{n}_{CH_4}$) and the fuel utilisation (FU):

$$I_{tot} = \dot{n}_{CH_4}.z.F.FU \quad (1)$$

Where z = 8 electrons per molecule of CH_4 and F = 96485 C/mol

+ Oxygen ion transfer ($\dot{n}_{O_2}$): The amount of oxygen the simulation must move from the cathode to anode:

$$\dot{n}_{O_2} = \frac{I_{tot}}{4F} \quad (2)$$

c, Electricity generation and heat recovery

This stage captures the outputs of the simulation to determine the plant's overall efficiency.

Eletrical power:

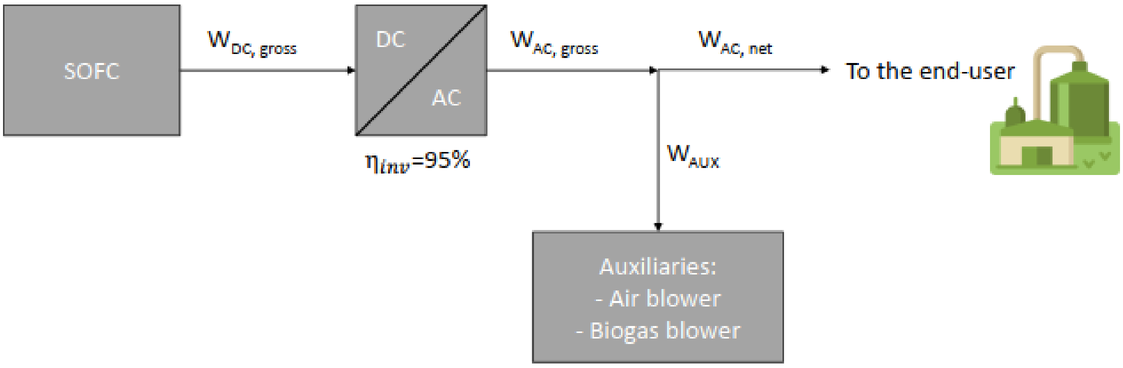

Figure 4. SOFC power output distribution

- Gross DC power: produced directly by electrochemical reactions: $W_{DC,gross} = V_{cell}. I_{tot}$
- Net AC power: the final power delivered after inverter losses and blower power consumption

$$W_{AC}, net = W_{AC,gross} - W_{aux} = W_{DC,gross} * \eta_{inv} - W_{aux} \quad (3)$$

+ Heat recovery unit

- After-burner: An Rgibss reactor that burns the unreacted fuel from the anode (1- FU portion) with the depleted cathode air.
- Thermal ouput: the resulting high-temperature exhaust is used to calculate the available thermal output (Q_{th}) for pre-heating the plant and heating the WWTP anaerobic digester (35-39 °C).

Upon completing the simulation in Aspen, the results are summarized in Table 3.

Table 3: SOFC performance output

Total Work Out	119.868	kW
Electrical consumption of biogas blower	0.249682	kW
Electrical consumption of air bolwer	2.73532	kW
Total heat out	66.6532	kW
Outlet temperature	90	$°C$
Net electricity available for consumption	116.882998	kW
Net heat available for consumption	26.66128	kW

2. Techno-Economic Analysis of the Novara WWTP

2.1 Scope and Framing of the Economic Analysis

In this section, the techno-economic of the biogas-fed SOFC system integrated into the Novara WWTP was analysed over a 20-year operational lifetime using discounted cash flow methodology. The analysis evaluates capital expenditure (CAPEX), operational expenditure (OPEX), and key performance indicators including net present value (NPV), internal rate of return (IRR), and payback period.

The system boundaries include the energy conversion components: the SOFC modules, balance-of-plant equipment, and biogas clean up units. However, the existing wastewater treatment infrastructure and anaerobic digestion system are excluded from the economic assessment, as these represent pre-existing facilities.

2.2 Cost analysis

In this section, all investment (CAPEX) and operational costs (O&M cost) related to SOFC system implementation are presented.

2.2.1 CAPEX

CAPEX includes the initial investment required for system installation and commissioning. The total investment is calculated as:

$$\mathrm{CAPEX_{total}} = \mathrm{C_{SOFC}} + \mathrm{C_{clean\ up}} + \mathrm{C_{thermal}} + \mathrm{C_{construction}} \tag{4}$$

a, SOFC system cost

The SOFC modules represents the largest capital cost component. For a 120-kW installed capacity (2 x 60 kW Convion C60 modules). In 2022, the state-of-the art SOFC system CAPEX around 7000 – 10000 €/kW of which stack is the single most expensive opponent. Targets is aiming for under €2,000-€3,500/kW for larger systems by 2030 through automation and mass production [6], [7].

In this project, we estimate CAPEX around 6000 €/kW in 2026, consistent with current market values for stationary biogas-fed SOFC system:

$$\mathrm{C_{SOFC}} = 6000\ \times 120 = 720000\ €$$

This includes all fuel cell stacks, balance of plant (air/biogas, reformer auxiliaries, pre-heater), power electronics (DC/AC inverter), and control systems.

b, Biogas clean-up system

The clean-up system removes contaminants (H_2S, siloxanes, halogens) to levels below 1 ppm. In [8], the authors ranged the clean-up system cost around 1500 €/kWe, and estimated it will reduce to 500 €/kWe in long term. Therefore, based on referenced values, we assumed a specific cost is 800 €/kW

c, Thermal recovery system cost

Heat recovery component is sized using a scaling equation:

$$C_{\text{thermal}} = C_0 \left(\frac{S_1}{S_0}\right)^n \quad (5)$$

Where:

- C_0 = 50,000 € (reference cost for heat recovery system)
- S_0 = 90 (reference thermal capacity)
- n = 0.6 (scaling factor for heat exchangers)
- S_1 = 66.65 (actual thermal output (kW))

d, Plant Preparation, Integration and Construction

This category includes engineering design, installation, commissioning, civil works, and electrical/control infrastructure. A fixed cost of 122400 € is assumed (approximately 17% of total CAPEX), consistent with systems of this capacity

2.2.2 OPEX

Annual OPEX includes recurring costs over the system lifetime (general O&M, reformer catalyst replacement, SOFC stack replacement, and labour cost), excluding fuel costs as biogas is a waste-derived product.

a, Annual maintenance cost for the cleaning unit

Biogas cleaning is essential for SOFC applications due to fuel cell sensitivity to sulfur and other contaminants that can cause performance degradation.

In 2014, authors in [8]that long term annual clean-up cost can be around 0.5 c€/kWhe (operating expense in euro cents per kilowatt-hour of electricity produced). Therefore, for our system, we assumed $C_{\text{OPEX,clean\_up}} = 4434€$ annually.

b, General O&M

General O&M in this project, we assume that it includes plant general maintenance and annual maintenance cost for the reformer.

Calculated as 5% of total CAPEX annually:

$$C_{\text{O\&M}} = 0.05 \times \text{CAPEX}_{\text{total}} = 47146.0257\ €/\text{year} \quad (6)$$

c, Reformer catalyst replacement

Annual replacement cost, scaled from reference values:

$$C_{\text{catalyst}} = C_0 \left(\frac{S_1}{S_0}\right)^n \quad (7)$$

Where $C_0 = 500$ € (reference cost at $S_0 = 60\ \text{Nm}^3/\text{h}$ biogas), $S_1 = 33.41\ \text{Nm}^3/\text{h}$ (actual flow), and n = 1, yielding:

$$C_{catalyst} = 278 \text{ €/year}$$

d, SOFC stack replacement

Stack replacement occurs every 5 years, costing 35% of initial SOFC investment:

$$C_{stack} = 0.35 \times C_{SOFC} = 210000 \text{ € (every 5 years)} \tag{8}$$

e, Labour cost

From ERI (Economic Research Institute) [9], one specialised operator working 20 hours/week at 24 €/hour:

$$C_{labour} = 20 \times 24 = 480 \text{ €/year} \tag{9}$$

2.2.3 Consolidated cost summary

Table 3 presents complet cost structure

Table 4: Complete cost structure

Cost Category	Component	Value	Frequency	Formula/Basis
CAPEX				
	SOFC System	720000 €	One-time	6,000 €/kW × 120 kW
	Biogas Clean-up	60000 €	One-time	500 €/kW × 120 kW
	Thermal Recovery	41755 €	One-time	Scaling equation (n=0.6)
	Plant Preparation & Construction	122400 €	One-time	~17% of total CAPEX
	Total CAPEX	944155 €		~ 7868 €/kW
OPEX				
	Annual maintenance cost for the Clearning unit	4434€	Annual	0.5 c€/kWhe
	General O&M	47208 €	Annual	5% × CAPEX
	Reformer Catalyst	278 €	Annual	Scaling equation (n=1)
	SOFC Stack Replacement	252000 €	Every 5 years	35% × SOFC cost

Cost Category	Component	Value	Frequency	Formula/Basis
	Labour	23040 €	Annual	20 h/week × 30 €/h
	Total Annual OPEX	120926 €		(excluding stack years)

2.3 Economic performance indicators

This section describes the methodology for calculating key financial metrics used to assess investment viability.

2.3.1 Depreciation rate

Depreciation is a method used to distribute the purchase price of an asset over the years it is actually used. Because machinery and tools lose value as they age or become outdated, this process allows businesses to record the expense gradually rather than all at once:

- reduces taxable income,
- represents the annual economic consumption of the asset,
- does not represent a cash outflow (it's a non-cash cost).

For this analysis, a depreciation period of 10 years (Depreciation applies only during years 1-10) is assumed:

$$\mathrm{Dep.\,rate} = \frac{\mathrm{CAPEX}\ [€]}{\mathrm{Dep.\,time}} = \frac{944155}{10} = 94415.5\ €/\mathrm{year} \tag{10}$$

2.3.2 Tax rate

If the sum of incomes and costs is positive (positive cashflow before taxes) the plant need to pay taxes, according to the national taxation rate t (in Italy, the imposta sul reddito delle società - IRES), assumed $\mathrm{t} = 24\%$. The general equation is:

$$\mathrm{Taxes_n} = \mathrm{t}\ \times (\mathrm{Incomes_n} - \mathrm{Costs_n} - \mathrm{Dep.\,rate}) \tag{11}$$

Case 1: The depreciation rate, which is a reduction in the taxes, should be applied only during depreciation time (if $\mathrm{n} \leq \mathrm{Dep.\,time}$)

After this period (if $\mathrm{n} \leq \mathrm{Dep.\,time}$), the tax rate is applied only to the $(\mathrm{Incomes_n} - \mathrm{costs_n})$

Case 2: If $\mathrm{dep.\,rate} > (\mathrm{Incomes_n} - \mathrm{cost_n})$, the terms $(\mathrm{Incomes_n} - \mathrm{Costs_n} - \mathrm{Dep.\,rate})$ would be negative. In this case no taxes will be paid.

2.3.3 Discount rate (WACC)

The WACC (weighted average cost of capital) represents the minimum acceptable return:

$$\mathrm{WACC} = \mathrm{r_e}\ \times \mathrm{E} + \mathrm{r_d}\ \times (1 - \mathrm{t}) \times \mathrm{D} = 5.06\% \tag{12}$$

Where:

- E = 30% (Equity financing share)

- D = 70% (Debt financing share)
- $r_e = 8\%$ (Cost of equity-required return for equity investors)
- $r_d = 5\%$ (Interest rate on debt)
- $t = 24\%$ (coporate tax rate)

2.3.4 Cash flow analysis

Annual cash flow represents the acutal monetary movement:

Year 0 (Construction):

$$\text{Cash Flow}_0 = -\text{CAPEX}_{\text{total}} \tag{13}$$

Years 1-20 (Operation):

$$\text{Cash Flow}_n = \text{Cashflow}_n = \text{Incomes}_n - \text{Cost}_n - \text{Taxes}_n \tag{14}$$

After the construction year, the cost component is calculated in the following way:

$$\text{Cost}_n = \text{Cost}_{\text{SOFC,rep}} + \text{Cost}_{\text{OPEX,clean-up}} + \text{CF} \cdot \left(\text{Cost}_{\text{OPEX,general}} + \text{Cost}_{\text{labour}}\right) \tag{15}$$

Where the income is defined by:

$$\text{Incomes}_n = \text{Incomes}_{\text{Elect}} + \text{Incomes}_{\text{Therm}} + \text{Savings}_{\text{Elect}} + \text{Savings}_{\text{Therm}} \tag{16}$$

Considering only for this case, the electricity and heat costs savings.

Finally, the cumulative cashflow is obtained:

$$\text{Cumulative cashflow} = \Sigma_{n=0}^{20} \text{Discounted cashflow}_n = \Sigma_{n=0}^{20} \frac{\text{Incomes}_n - \text{Cost}_n - \text{Taxes}_n}{(1+\text{WACC})^n} \tag{17}$$

2.3.5 Internal Rate of Return (IRR)

The Internal Rate of Return (IRR, r) is the discount rate that makes the Net Present Value (NPV) equal to zero. It represents the average annual rate of return that the investment generates over its lifetime. IRR is the discount rate at which the project breaks even (NPV = 0, PBT =lifetime) in present-value terms.

$$\Sigma_{n=0}^{20} \frac{\text{Incomes}_n - \text{Cost}_n - \text{Taxes}_n}{(1+\text{IRR})^n} = 0 \tag{18}$$

If the IRR is greater than the required return (e.g., WACC), the investment is considered economically attractive.

2.3.6 Payback time (PBT)

The payback period identifies when cumulative cash flow becomes positive:

$$\text{PBT} = n_y + \frac{\left|\text{CCF}_{n_y}\right|}{\text{CF}_{n_y=1}} \tag{19}$$

Where n_y is the last year with negative cummulative cash flow

2.4 Senstivity analysis

Sensitivity analysis evaluates how variations in key parameters affect economic performance. Three critical variables are examined

- Stack replacement: -50% to 100% variatons
- Lifetime of stack cost: 5,6,7,8,9,10 years
- Energy prices: -20% to 100% variations

For each scenario, NPV, IRR, and PBT are recalculated to identify which parameters most significantly influence project viability.

3. Results and Discussion

3.1 Base Case

Figure 5 illustrate cumulative cash flow diagram. In the first year, the project requires a substantial investment of €944155, resulting in a negative cumulative cash flow for the first 16 years of operation. Additionally, every five years, the system requires €252000 stack replacement cost, which create a tremendous “dip” in the cash position. Break-even is finally achieved in year 17 which is very risky, leading to a final project NPV of €80559 and 16.33-year PBT, 6.27% IRR.

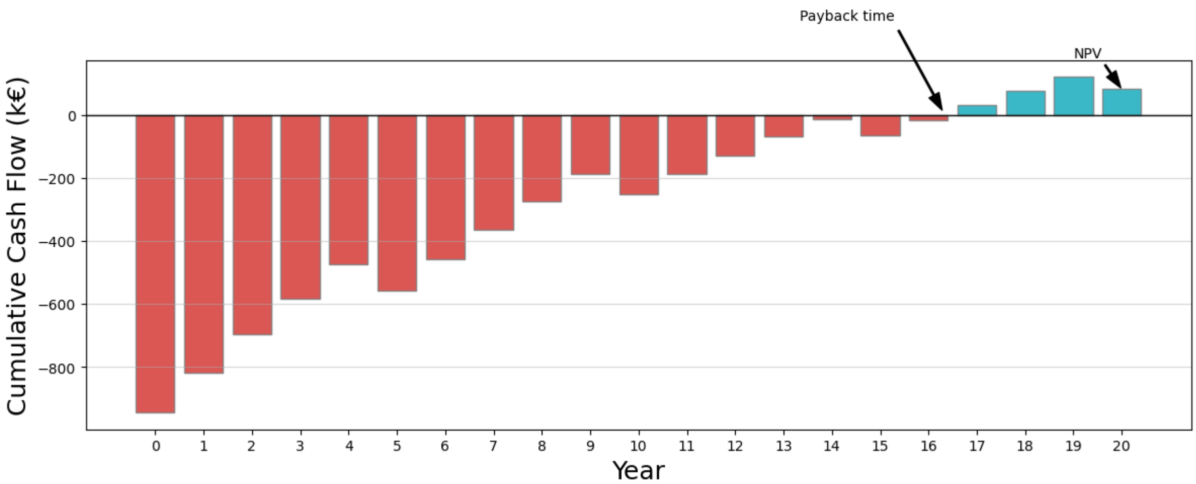

Figure 5. Cumulative cash flow diagram

3.2 Sensitivity analysis

Figure 6 and Figure 7 present the sensitivity analysis for NPV and payback period, examining three key parameters affecting project economics. Energy prices are the most critical factor: a 50% price drop pushes NPV to more than -1000 k€ and extends payback beyond 20 years, while a 100% increase yields NPV above +2500 k€ with payback of just 3-4 years. This steep sensitivity makes long-term power purchase agreements essential for project viability.

Stack replacement costs show moderate influence, with $\pm$ 50-100% variations shifting NPV by (-5-year PBT, + 1000k€) and (over 20-year PBT, + 2000k€). The project tolerates cost increases up to 30-40% before becoming unviable, indicating reasonable resilience. Negotiating favorable contracts and exploring refurbishment options could meaningfully improve economics.

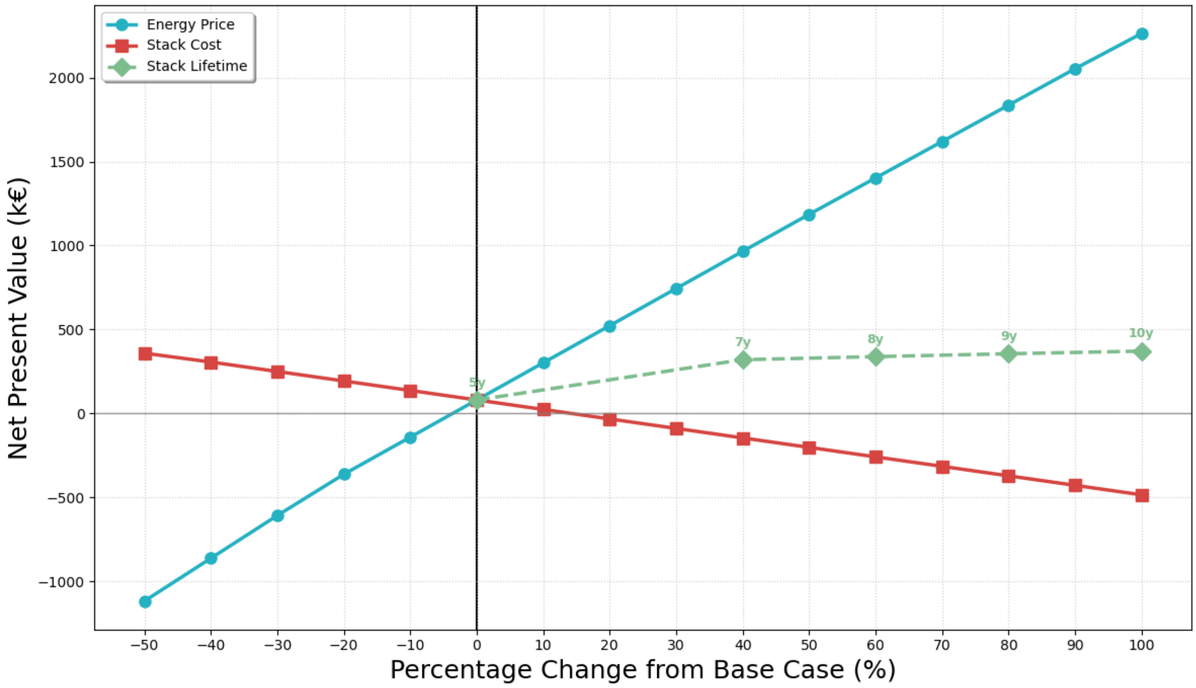

Figure 6. Sensitivity analysis key parameters on NPV

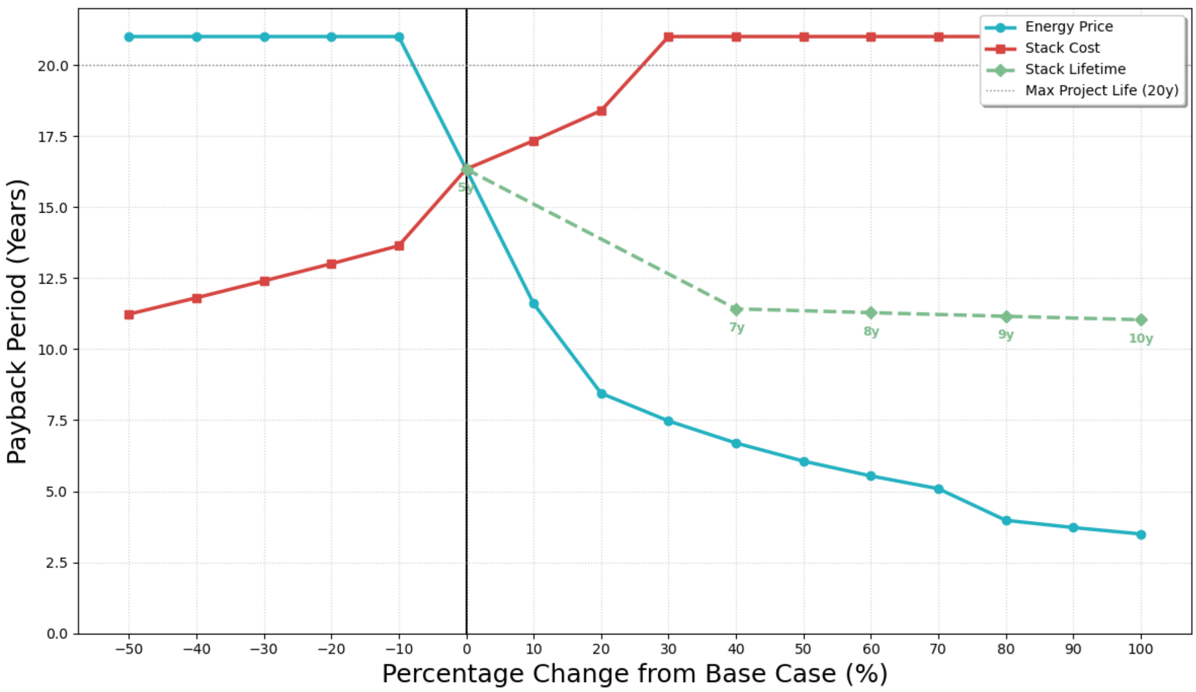

Figure 7. Sensitivity analysis parameters on PBT

Stack lifetime has the smallest impact, with extending life from 5 to 10 years improving NPV and reducing payback time. All scenarios maintain positive NPV and achieve payback within project lifetime.

4. Conclusion

This feasibility study evaluated a 120-kW biogas-fed SOFC system integrated into the Novara wastewater treatment plant serving 102,000 inhabitants. The Aspen Plus simulation demonstrated net electrical output of 116.88 kW and thermal recovery of 26.66 kW at 90°C, achieving superior performance compared to conventional combustion technologies. The techno-economic analysis over a 20-year lifetime revealed a total CAPEX of €944,155 (€7,868/kW) and annual OPEX of €120,926, with stack replacement every 5 years representing a significant recurring cost of €252,000.

The base case yielded an NPV of €80,559, IRR of 6.27%, and payback period of 16.33 years, indicating marginal economic viability under current assumptions. Sensitivity analysis identified energy prices as the most critical parameter, where a 50% price reduction renders the project unviable (NPV < -1,000 k€, PBT > 20 years), while a 100% increase produces NPV exceeding +2,500 k€ with 3–4-year payback. Stack replacement costs show moderate sensitivity, with the project tolerating up to 30-40% cost increases before becoming uneconomical. Stack lifetime extension from 5 to 10 years provides modest improvements but does not fundamentally alter project economics.

The project demonstrates technical feasibility but operates within a narrow economic margin, making long-term power purchase agreements and stack cost optimization essential for commercial viability. Future improvements in SOFC technology, particularly extended stack lifetimes and reduced capital costs, would significantly enhance economic attractiveness for similar wastewater treatment applications

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