POLITECNICO DI TORINO

ENERGY ENGINEERING (Master's Degree)

Polygeneration and advanced energy systems

Technical Reports

Feasibility study of a biogas-fed SOFC system

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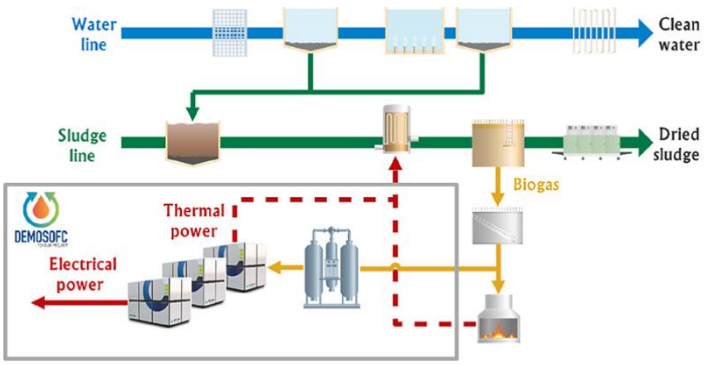
Introduction



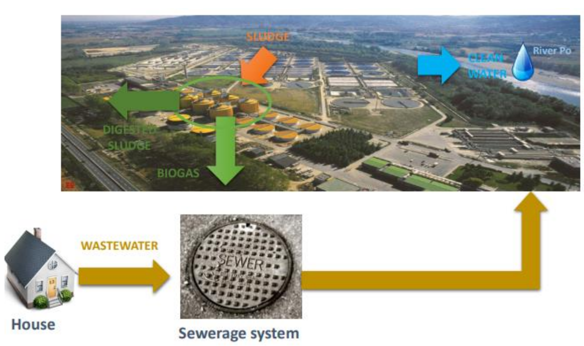
DEMOSOFC plant layout [1]

Nowadays, as a population gathering place, cities are constantly consuming energy and producing waste. Sewage treatment in a city is no longer just a pure financial consumption. Combining sewage treatment with SOFC can ensure both energy self-sufficiency and sewage treatment.

The integrated biogas-SOFC plant includes three main units: 1) the biogas cleaning and compression section, 2) the three SOFC power modules, and 3) the heat recovery loop. Main advantages of the proposed layout are the net electric efficiency of the SOFC, which is in the range 50-55%, and the near-zero emissions.

We will use ASPEN PLUS for SOFC modeling and economic analysis and try to combine with Steam Power Plant to achieve maximum economic benefits.

Waste Water Treatment Plant (WWTP)



We don't care about how the Wastewater Treatment Plant treats sewage, we only focus on how much fuel WWTP will provide us. We selected the factory in Bologna and designated the target of wastewater treatment as the population in the city.

Bologna is an important road and rail transportation hub and an important mechanical, electronic and food industry location in northern Italy. Therefore, the population in the urban area will inevitably undergo seasonal movement (students return to their hometowns during holidays;

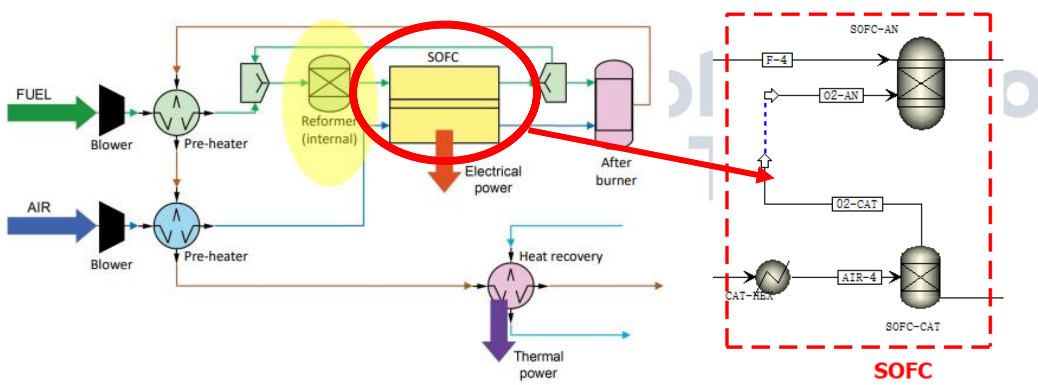
company employees take a holiday in August; tourist population flows...). Up to now, it is impossible to accurately count the specific population movements, so the wastewater produced cannot be accurately calculated. We can use a simple model to estimate the amount of biogas produced, so as to carry out a preliminary simulation of SOFC.

Production	Value	Unit
Waste water	220	l/day/capita
Sludge feed	0.50	m³/year/capita
Biogas	2.62	Nm³/year/capita

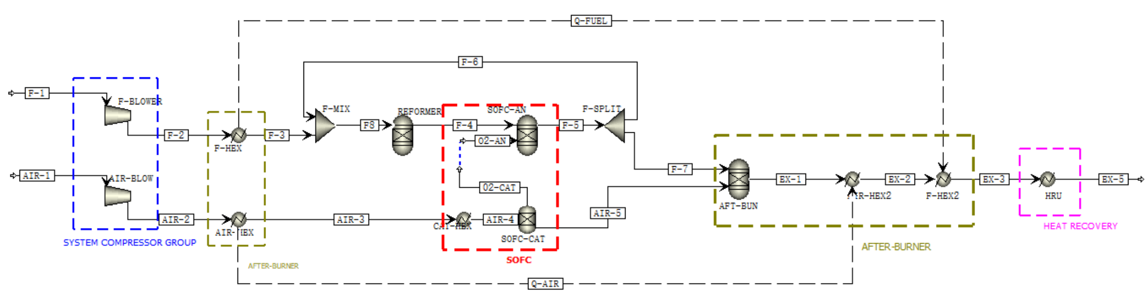
Bologna has 394,843 residents [2], so we know that the biogas production is 117.333 Nm^3/h
For input biogas, we consider it contain 60% of CH_4 and 40% of CO_2(Mole fraction).

SOFC Model

Model



Unfortunately, there is no SOFC model in Aspen, so we can only use Reformer and Separates to simulate SOFC's anode and cathode.



Carbon deposition

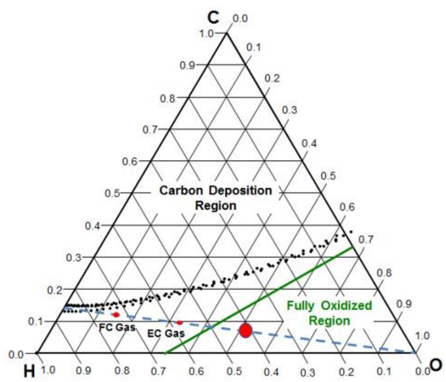
We must be careful about solid carbon deposition. Cause it will block the pore and catalyst will be oxidized. This is a very serious issue; we must ensure that avoid the thermodynamic condition to have carbon separation in from of solid.

So we have set $SC = {\dot{n}_{H_2O}}/{\dot{n}_{CH_4}} = 3$, the reformer before the anode of SOFC consider as Steam-methane reforming reaction:

$$CH_4 + H_2O(+heat) \rightarrow CO + 3H_2$$

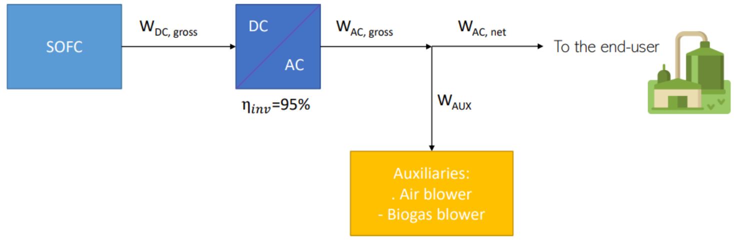
+ Mole Flows	mol/sec	9.83512
− Mole Fractions		
CH4		5.98259e-06
CO2		0.301549
N2		0
O2		2.03101e-17
H2		0.174242
CO		0.152988
H2O		0.371216
+ Mass Flows	kg/sec	0.241897

The composition after the reaction is shown in the figure.



As shown in the figure, we ensured that the reaction is in the safety region.

Result



$$\dot{m}_{CH_4} = 0.0134\, {}^{Kg}/_{S}\ ; LHV_{CH4} = 50\ MJ/kg$$

For the auxiliary system of the SOFC model:
It contains two compressors (for fuel and air), in the simulation results is following:

For the auxiliary system:

$$Lc_{fuel} = 863\ W \quad ; \quad Lc_{air} = 4879\ W$$
$$Q_{fuel} = 57432\ W \quad ; \quad Q_{air} = 161286\ W$$

For the SOFC model:

$$W_{el,DC,SOFC} = 362330\ W \sim 362\ KW \quad ; Q = 491638\ W \sim 492\ KW \quad ; Q_{rev} = 272920\ W \sim 273\ KW$$

$$W_{el,AC,SOFC} = W_{el,DC.SOFC} \times 95\% - Lc_{fuel} - Lc_{air} = 338471.5\ W \sim 338KW$$

Consider the efficiency of DC inverter is 95%.

$$\eta_{el,DC,SOFC} = \frac{W_{el,DC,SOFC}}{\dot{m}_{CH_4} \times LHV_{CH4}} = 53.9\%$$

$$\eta_{el,AC,SOFC} = \frac{W_{el,AC,SOFC}}{\dot{m}_{CH_4} \times LHV_{CH4}} = 50.5\%$$

$$\eta_{th,SOFC} = \frac{Q_{rev}}{\dot{m}_{CH_4} \times LHV_{CH4}} = 40.6\%$$

$$\eta_{tot,SOFC} = \eta_{el,AC,SOFC} + \eta_{th,SOFC} = 91.1\%$$

SOFC system sizing

Convion C60

Electric power output	60	kW net-AC*
Electrical efficiency	60	% (LHV)*
Thermal output**	24	kW (LHV, exhaust cooled to 55°C)*
Total efficiency	83	% (LHV) (exhaust cooled to 55°C)*
Range of electric output	60 - 30	kW
Electrical efficiency at 50% output	60	% (LHV)*
Standard installation requirements for rated performance	Elevation <1000 m, temperature -20...+40°C, outdoor installatio installation optional.	
Electrical connection, capability	3 x 380-500V AC, 50/60Hz, in accordance with local grid code	
Noise level	< 70	dB(A) at 1 m
Water consumption	None	
Nominal fuel intake	11.5 Nm3/h (natural gas)	
Exhaust gas	200°C, 575 kg/h, dew point 37°C	
EXHAUST EMISSIONS		
Nitrogen oxides, NO_x	≤ 2.6 ppm-v/ ≤0.05 g/kWh (below detection limit)	
Sulphur dioxide, SO_2	≤ 3 ppm-v/ ≤0.07 g/kWh (below detection limit), sulphur remov fuel before use	
Carbon monoxide, CO	≤ 1.7 ppm-v/ ≤0.02 g/kWh (below detection limit)	
Particulates (PM)	Negligible	
Volatile organic compounds	Negligible	
Carbon dioxide, CO_2	330 kg/MWh$_e$	
SYSTEM DIMENSIONS		
H * L * W	2330 * 2780 * 2090 mm	

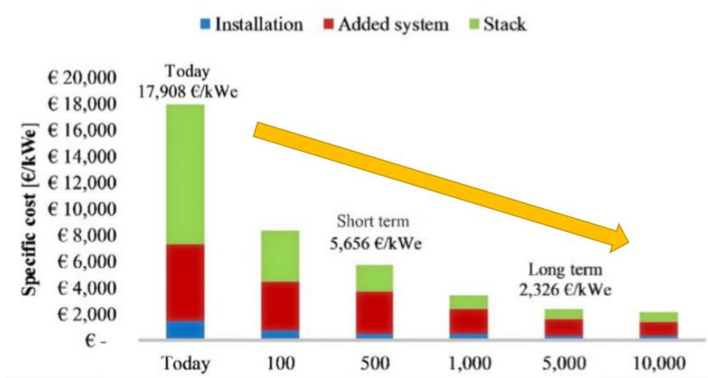
$$n = {W_{el,DC,SOFC} \times 95\%}/{60\ KW} = 5.73$$

In my opinion, we can use 6 stacks of Convion C60. Although the actual power generation of SOFC is 343.9 KW, the utilization rate of fuel cell has reached 95.5%, so it is feasible to choose six stacks.

Economic analysis.

The capital expenditure

CAPEX 1



As one of the city's important infrastructures, WWTP can be regarded as a long-term investment, and its project operation time should be regarded as a long-term operation.

$$Capex_{SOFC} = 360\ KW\ \times 2326\ ^{€}/_{KW} = 837{,}360\ €$$

CAPEX 2

Item	Today	Short term	Long term
Clean-up system CAPEX (€/kWe)	1500	1000	500

$$Capex_{clean-up} = 360\ KW\ \times 500\ ^{€}/_{KW} = 180{,}000\ €$$

CAPEX 3

$$Capex_{HRU} = C_0 \times (\frac{S_1}{S_0})^{0.7} = 108{,}721.2\ €$$
$$where\ C_0 = 50000€, \mathrm{S}_0 = 90\ KW \text{ and } \mathrm{S}_1 = Q_{rev} = \ 272920\ W$$

CAPEX 4

Consider 150,000€ for the plants in the range 100-500 KW.

$$Capex_{other} = 150{,}000\ €$$

Operating Expenditure

OPEX 1

Item	Today	Short term	Long term
Clean-up system OPEX (c€/kWhe)	1	1	0.5

Under standard condition, $S_1 = 117.333\ m^3/h$

$$Opex_{reformer} = C_0 \times (\frac{S_1}{S_0})^{0.5} = 977.775\ € \quad every\ year$$

$$Opex_{\text{adsorbent}} = W_{el,DC} \times 0.005 \times 1\ year\ = 15{,}855\ € \quad \text{every year}$$

The cost of clean-up of adsorbent should based on the SOFC system real power generation without any auxiliary consumption.

OPEX 2

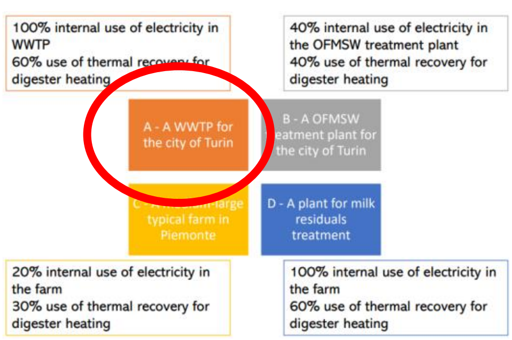
$$Opex_{replace} = 0.35 \times Capex_{sofc} = 293{,}076\ € \quad \text{every 5 years}$$

$$Opex_{SOFC,labour\ cost} = 52\ weeks \times 20\frac{\text{h}}{week} \times 30\frac{€}{\text{h}} = 31{,}200\ € \quad \text{every year}$$

However, it is difficult for us to estimate how many labors are required, so we assume that two part-time laborers are required to operate alternately.

$$Opex_{maintenance,SOFC} = 5\% \times \left(Capex_{SOFC} + Capex_{clean-up} + Capex_{HRU} + Capex_{other}\right)$$
$$= 63{,}804\ € \quad every\ year$$

OPEX 3



The most convenient option could also be to sell all the electricity to the grid and re-buy what's required for internal use.

Fonte rinnovabile	Tipologia	Potenza (kW)	VITA UTILE degli IMPIANTI (years)	TARIFFA (€MWh)
		kW	anni	€/MWh
Gas di discarica (Landfill gas)		1<P≤1000	20	99
		1000<P≤5000	20	94
		P>5000	-	-
Gas residuati dai processi di depurazione (WWTP)		1<P≤1000	20	111
		1000<P≤5000	20	88
		P>5000	-	-
Biogas	a) prodotti di origine biologica di cui alla Tabella 1-B (Crops)	1<P≤300	20	170
		300<P≤600	20	140
		600<P≤1000	20	120
		1000<P≤5000	20	97
		P>5000	20	85
	b) sottoprodotti di … alla Tabella 1 –A; … da raccolta differen… cui alla lettera c) (Milk serum, Livestock effluents, OFMSW)	1<P≤300	20	233
		300<P≤600	20	180
		600<P≤1000	20	160
		1000<P≤5000	20	112
		P>5000	-	-

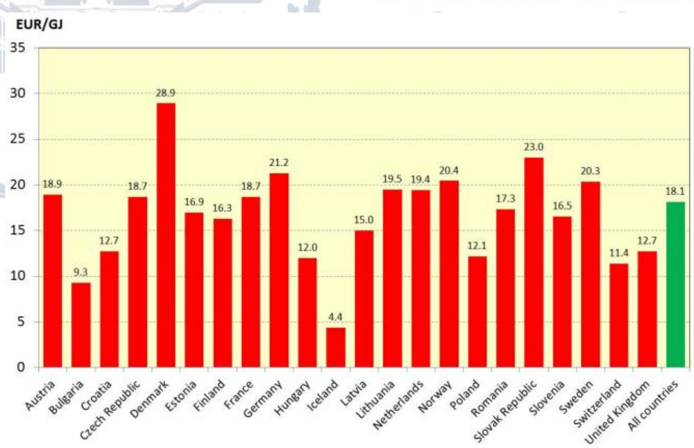
$$Opex_{el,SOFC} = 0.111 \times W_{el,DC} \times 95\% \times 1\ year = 334{,}699\ € \qquad \text{every year}$$

Based on the guidance of WWTP, we believe that the power required by the factory is

$$W_{demaind} = W_{el,DC} \times 95\% + Lc_{fuel} + Lc_{air} = 349955.5\ W$$

According to online data [5], "Il costo da sostenere, in ogni caso, dipenderà dalla fascia oraria di riferimento in cui l'energia viene maggiormente sfruttata: se in F1 (giorno), il prezzo energia sarà 0,03206 €/kWh, mentre per le F2 e F3 (sera e weekend), il prezzo energia si aggira attorno ai 0,02890 €/kWh.", so we can consider the annual average electricity price to be 0.0312 €/kWh

$$Cost_{el} = 0.0312 \times W_{demaind} \times 1\ year = 95{,}647\ € \qquad \text{every year}$$



National average district heating prices for 22 European countries in 2013 [4]

According to the online reference [4], the cost of district heating is about 0.0655 Euro/KWh, so we can consider this price as the saving equal to the price of heat for that plant.
Consider the 60% of Q_{rev} is self-consumption, other 40% of Q_{rev} can be sold to the market but only valid from November 15th to April 15th.

$$Opex_{th} = 0.0655 \times (40\% \times Q_{rev}) \times 24\ h \times 5 \times 30\ days = 25{,}963\ €$$

$$Q_{saving} = 0.6 \times Q_{rev} = 164\ KW$$

$$Saving_{th} = Q_{saving} \times 0.0655 \times 1\ year = 93{,}469\ € \quad every\ year$$

Cash Flow

Assumptions:

$$capacity\ factor(CF, \%) = \frac{working\ hours}{total\ hours\ per\ year}$$

Generally speaking, SOFC continues to work uninterrupted until stack replacement or retirement, so we can consider $capacity\ factor = 1$ and lifetime of the plant/the horizon of the economic analysis consider as 20 years.

First year investment cost:

$$Cost_{year,0} = Capex_{SOFC} + Capex_{clean-up} + Capex_{HRU} + Capex_{other} = 1{,}276{,}081\ €$$

The total yearly cost from the second year to the end of the analysis (20 years) can be evaluated as:

$$Cost_{year,i=6,11,16} = Opex_{replace} + Opex_{\text{adsorbent}} + CF \times (Opex_{reformer} + Opex_{labour\ cost} + Opex_{maintenance}) = 404{,}912\ €$$

$$Cost_{year,i\neq 6,11,16} = Opex_{\text{adsorbent}} + CF \times (Opex_{reformer} + Opex_{labour\ cost} + Opex_{maintenance}) = 111{,}836\ €$$

The incomes are evaluated as function of the savings/revenues and on the price of energy/subsidies, it can be computed as ($Opex_{th}$ have uncertainty, so it is not included in the calculation):

$$income = Opex_{el} + Saving_{th} - Cost_{el} = 358{,}486\ €$$

The depreciation rate can be determined as:

$$Dep.Rate_{i<11} = \frac{\text{Total investment cost}}{\text{Depreciation Time } (10\ years)} = 127{,}608\ €$$

$$Dep.Rate_{i\geq 11} = \frac{\text{Total investment cost}}{\text{Depreciation Time } (10\ years)} = 0\ €$$

The depreciation rate only valid on first 10 years.

Parameter	Value
Equity percentage (%e)	50%
Debt percentage (%d)	50%
Cost of equity (Ce)	3%
Cost of debt (Cd)	5%
Depreciation time	10-15 years

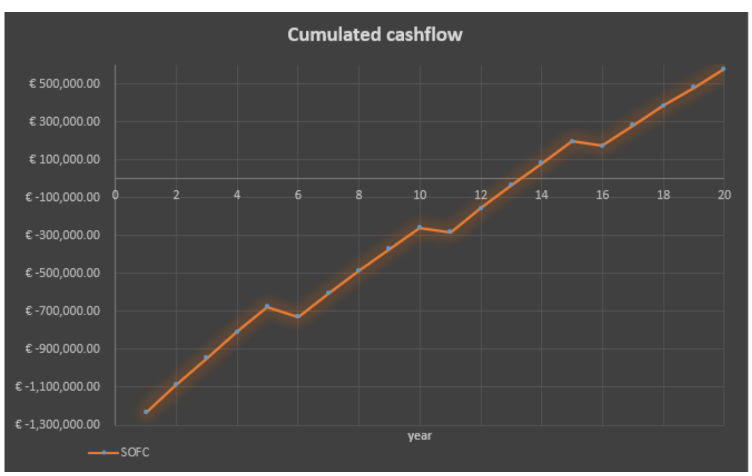
We assume that the financial structure is shown in the figure, and we can calculate the WACC (Weight Average Cost of Capital).

$$\text{WACC (Weight Average Cost of Capital)} = 0.034$$

Result

Cash Flow Analysis													
						(before taxes)				(after taxes)			
Years	CAPEX	Stack Replacement	Annual cost	Total cost	Income	Present Cash Flow	Depreciation rate	Income-Cost	Taxes	Present Cash Flow	Discount factor	Discount cashflow	Cumulated cashflow
1	€ -1,276,081		€ -	€ -1,276,081		€ -1,276,081	€ -127,608.12	€ -1,276,081		€ -1,276,081	0.97	€ -1,234,121	€ -1,234,121
2			€ -111,837	€ -111,837	€ 358,486	€ 246,649	€ -127,608	€ 246,649	€ 89,822	€ 156,828	0.94	€ 146,684	€ -1,087,438
3			€ -111,837	€ -111,837	€ 358,486	€ 246,649	€ -127,608	€ 246,649	€ 89,822	€ 156,828	0.90	€ 141,860	€ -945,577
4			€ -111,837	€ -111,837	€ 358,486	€ 246,649	€ -127,608	€ 246,649	€ 89,822	€ 156,828	0.87	€ 137,196	€ -808,382
5			€ -111,837	€ -111,837	€ 358,486	€ 246,649	€ -127,608	€ 246,649	€ 89,822	€ 156,828	0.85	€ 132,684	€ -675,697
6		€ -293,076	€ -111,837	€ -404,913	€ 358,486	€ -46,427	€ -127,608	€ -46,427	€ 19,484	€ -65,910	0.82	€ -53,930	€ -729,627
7			€ -111,837	€ -111,837	€ 358,486	€ 246,649	€ -127,608	€ 246,649	€ 89,822	€ 156,828	0.79	€ 124,102	€ -605,525
8			€ -111,837	€ -111,837	€ 358,486	€ 246,649	€ -127,608	€ 246,649	€ 89,822	€ 156,828	0.77	€ 120,021	€ -485,504
9			€ -111,837	€ -111,837	€ 358,486	€ 246,649	€ -127,608	€ 246,649	€ 89,822	€ 156,828	0.74	€ 116,075	€ -369,429
10			€ -111,837	€ -111,837	€ 358,486	€ 246,649	€ -127,608	€ 246,649	€ 89,822	€ 156,828	0.72	€ 112,258	€ -257,171
11		€ -293,076	€ -111,837	€ -404,913	€ 358,486	€ -46,427		€ -46,427	€ -11,142	€ -35,284	0.69	€ -24,426	€ -281,598
12			€ -111,837	€ -111,837	€ 358,486	€ 246,649		€ 246,649	€ 59,196	€ 187,453	0.67	€ 125,501	€ -156,097
13			€ -111,837	€ -111,837	€ 358,486	€ 246,649		€ 246,649	€ 59,196	€ 187,453	0.65	€ 121,374	€ -34,722
14			€ -111,837	€ -111,837	€ 358,486	€ 246,649		€ 246,649	€ 59,196	€ 187,453	0.63	€ 117,383	€ 82,661
15			€ -111,837	€ -111,837	€ 358,486	€ 246,649		€ 246,649	€ 59,196	€ 187,453	0.61	€ 113,523	€ 196,184
16		€ -293,076	€ -111,837	€ -404,913	€ 358,486	€ -46,427		€ -46,427	€ -11,142	€ -35,284	0.59	€ -20,666	€ 175,518
17			€ -111,837	€ -111,837	€ 358,486	€ 246,649		€ 246,649	€ 59,196	€ 187,453	0.57	€ 106,180	€ 281,699
18			€ -111,837	€ -111,837	€ 358,486	€ 246,649		€ 246,649	€ 59,196	€ 187,453	0.55	€ 102,689	€ 384,388
19			€ -111,837	€ -111,837	€ 358,486	€ 246,649		€ 246,649	€ 59,196	€ 187,453	0.53	€ 99,312	€ 483,700
20			€ -111,837	€ -111,837	€ 358,486	€ 246,649		€ 246,649	€ 59,196	€ 187,453	0.51	€ 96,047	€ 579,747

We can see from the cash flow chart that the system has started to make a profit in the 14th year, and the profit reached the maximum in the 20th year. From the final profit situation, the return on investment reached 45%.



$$PBT = 13.82$$

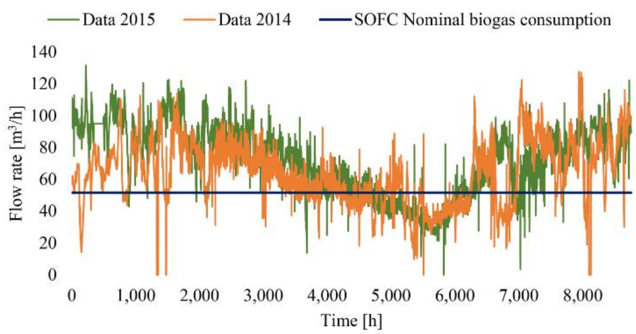
$$NPV = 579{,}747\ €$$

$$IRR = 8.08\%$$

Discussion

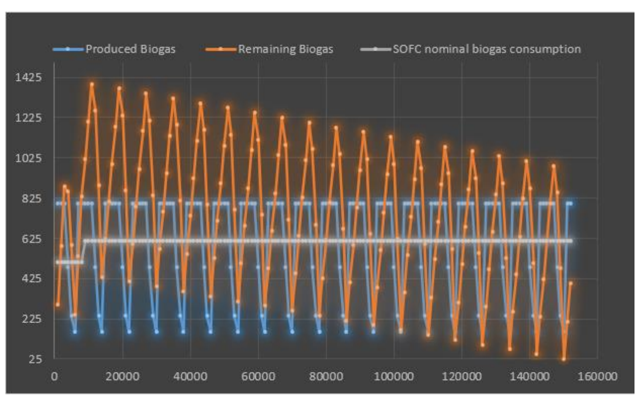
Actual biogas production

DEMOSOFC is in Collegno. The population of Collegno is 49674, which is almost 1/8 times different from Bologna. If we assume that the seasonal mobility of the two cities is the same, we can find a more accurate one from Dr. Marta Gandiglio's research.



Biogas flow rate in 2014, 2015 and SOFC nominal biogas consumption in the DEMOSOFC project [1]

According to the research of Dr. Marta Gandiglio, the sludge anaerobic digestion process produces biogas that is stored in the gas holder and the digester operates continuously during the year. Therefore, with storage facilities, we can effectively control the fuel input of SOFC. Therefore, with storage facilities, we can effectively control the fuel input of SOFC.



In our design, the basic principle is that the remaining biogas will be lower than $1400\ m^3$ (consider maximum the storage is $1400\ m^3$), so the conclusion is: the daily consumption of biogas is

$$506\, Nm^3/h \qquad time(0-8000\ hour)$$
$$613.7\, Nm^3/h \qquad time(8000-152000\ hour)$$

Result

For $0-8000\ hour$:

$$\dot{m_{CH4}} = 0.0595\, {}^{Kg}/_{S}\ ; LHV_{CH4} = 50\ MJ/kg$$

$$Lc_{fuel} = 3.8\ KW \quad ; \quad Lc_{air} = 21.6KW$$
$$Q_{fuel} = 254\ KW \quad ; \quad Q_{air} = 713\ KW$$

$$W_{el,DC} \sim 1.6\ MW \quad ; \quad Q \sim 2.17MW \quad ; \quad Q_{rev} \sim 1.2\ MW$$

$$\eta_{el,DC} = \frac{W_{el,DC}}{\dot{m}_{CH_4} \times LHV_{CH4}} = 52.9\%$$

$$\eta_{el,AC} = \frac{(W_{el,DC} \times 95\% - Lc_{fuel} - Lc_{air})}{\dot{m}_{CH_4} \times LHV_{CH4}} = 50.2\%$$

$$\eta_{th} = \frac{Q - Q_{fuel} - Q_{air}}{\dot{m}_{CH_4} \times LHV_{CH4}} = 40.3\%$$

$$\eta_{tot} = \eta_{el,AC} + \eta_{th} = 90.5\%$$

For $8000-152000\ hour$:

$$\dot{m_{CH4}} = 0.0722\, {}^{Kg}/_{S}\ ; LHV_{CH4} = 50\ MJ/kg$$

$$Lc_{fuel} = 4.63\ KW \quad ; \quad Lc_{air} = 26.2KW$$
$$Q_{fuel} = 308\ KW \quad ; \quad Q_{air} = 865.9\ KW$$

$$W_{el,DC} \sim 1.95\ MW \quad ; \quad Q \sim 2.64MW \quad ; \quad Q_{rev} \sim 1.47\ MW$$

$$\eta_{el,DC} = \frac{W_{el,DC}}{\dot{m}_{CH_4} \times LHV_{CH4}} = 54.0\%$$

$$\eta_{el,AC} = \frac{(W_{el,DC} \times 95\% - Lc_{fuel} - Lc_{air})}{\dot{m}_{CH_4} \times LHV_{CH4}} = 50.5\%$$

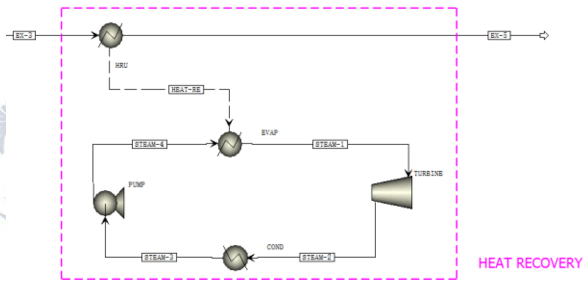
$$\eta_{th} = \frac{Q - Q_{fuel} - Q_{air}}{\dot{m}_{CH_4} \times LHV_{CH4}} = 40.7\%$$

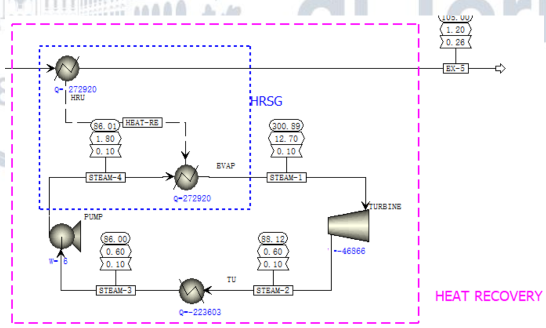
$$\eta_{tot} = \eta_{el,AC} + \eta_{th} = 91.2\%$$

Of course, the above-mentioned two kinds of biogas are only based on the simple analysis of the data, and the real FC system should use the dynamic control system. The capacity of the storage facility is fixed, and we need to be careful to maintain a certain baseline. This means that we need to install more stacks, and each stack is not running at full capacity. From an economic point of view, that means more investment and a later pay back.

Combined with Steam turbine

Regarding the heat generated, we use part of it to heat fuel and air, besides that can use HRSG combined with small size turbine (30-50 KW) to generate electricity.
Since the available heat energy is only about 273KW, the output of the entire steam power plant is only about 50KW within the predictable range (by assuming that the efficiency of the entire steam power plant is 20%).





型号 Model	功率 Capacity (KW)	转速 Speed (r/min)	进汽参数 Inlet 压力 Pressure (MPa)	温度 Temp (℃)	汽量 Flow (t/h)	汽耗 Consumption (kg/kw.h)	排汽压力 Exhaust Pressure (MPa)	本体重量 Weight (t)	外型尺寸 Overall Dimensions LxWxH(mm)
NO.05-1.27	30-50	1500	1.27	300	0.31	6.2	0.06	0.33	506x211x621
NO.07-1.27	50-70	1500	1.27	300	0.45	6.42	0.06	0.43	560x251x652
NO.03-1.27	1-30	1500	1.27	300	0.20	6.67	0.06	0.16	322x211x351
NO.1-1.27	70-100	1500	1.27	300	0.64	6.36	0.06	0.55	706x403x666
NO.15-1.27	150	1500	1.27	300	0.95	6.35	0.05	0.62	735x432x701

The characteristics of the 30-50KW steam turbine we found on the market are shown in the figure. In general, the steam turbine is directly connected to the generator, so there is no need to consider the

loss of the inverter. The thermal user will recovery the heat which can apply to Anaerobic digestion process.
Through modeling in ASPEN, the output power can be obtained as:

$$\dot{m}_{steam} = 0.098\ {}^{kg}/_{s} = 0.35\ {}^{t}/_{h}$$

$$W_{el,turbine} = 46866\ W \sim 47\ KW$$

All auxiliary losses on steam power plant have been deducted from turbine output.

$$W_{el,SOFC+SP,AC} = W_{el,AC} + W_{el,turbine} = 382994.2\ W \sim 383\ KW$$

$$Q_{tu} = 227045\ W \sim 227\ KW$$

$$\eta_{el,AC,SOFC+SP} = \frac{W_{el,SOFC+SP,AC}}{\dot{m}_{CH_4} \times LHV_{CH4}} = 57\%$$

$$\eta_{th,SOFC+SP} = \frac{Q_{tu}}{\dot{m}_{CH_4} \times LHV_{CH4}} = 33.8\%$$

$$\eta_{tot,SOFC+SP} = \eta_{el,AC,SOFC+SP} + \eta_{th,SOFC+SP} = 90.8\%$$

Economic analysis result (combined with steam turbine)

$$Capex_{steam\ plant} = 50\ KW \times 1005 \frac{€}{\text{KW}} = 50{,}250\ € \quad [3]$$

The cost of steam plant (with HRSG part and auxiliary system) includes the installation and balancing. However, it is difficult for us to estimate how many labors are required, so we assume that another one part-time laborers are required to operate alternately.

$$Opex_{SOFC+SP,labour\ cost} = 2 \times Opex_{SOFC,labour\ cost} = 62{,}400\ €$$

Steam power generation is known for having relatively low O&M costs when compared to other generation methods Power plants equipped with simple-cycle turbines, the cost has reached an average annual O&M cost of just 17.7 €/kW, making this technology the cheapest O&M option in the industry [6].

$$Opex_{maintenance,SOFC+SP} = 5\% \times \left(Capex_{SOFC} + Capex_{clean-up} + Capex_{HRU} + Capex_{other}\right) \\ +50\ KW \times 17.7\ €/\text{kW} = 63{,}848€$$

For the thermal energy recovered by the thermal user, it is sufficient to meet the needs of Anaerobic digestion (For mesophilic digestion, the temperature must theoretically be maintained between

30 °C to 38 °C [7]). Therefore, the operation strategy does not need to be changed, that is, 60% of Q_{rev} is used for self-consumption, and the rest is sold to the market.

$$Opex_{th} = 0.0655 \times (Q_{tu} - 60\% \times Q_{rev}) \times 24\ h \times 5 \times 30\ days = 14{,}924\ €$$

However, since this is low-grade waste heat, I personally think it is very difficult to sell, so I think this part of thermal energy is wasted.

$$Q_{saving} = 0.6 \times Q_{rev} = 164\ KW$$

$$Saving_{th} = Q_{saving} \times 0.0655 \times 1\ year = 93{,}469.9\ € \quad every\ year$$

$$Opex_{el,SOFC} = 0.111 \times (W_{el,DC} \times 95\% + W_{el,turbine}) \times 1\ year = 334{,}699\ € \quad \text{every year}$$

Based on the guidance of WWTP, we believe that the power required by the factory is

$$W_{demaind} = W_{el,DC} \times 95\% + Lc_{fuel} + Lc_{air} = 349955.5\ W$$

$$Cost_{el} = 0.0312 \times W_{demaind} \times 1\ year = 95{,}647€ \quad \text{every year}$$

$$Cost_{year,0} = Capex_{SOFC} + Capex_{steam\ plant} + Capex_{clean-up} + Capex_{HRU} + Capex_{other} = 1{,}326{,}331\ €$$

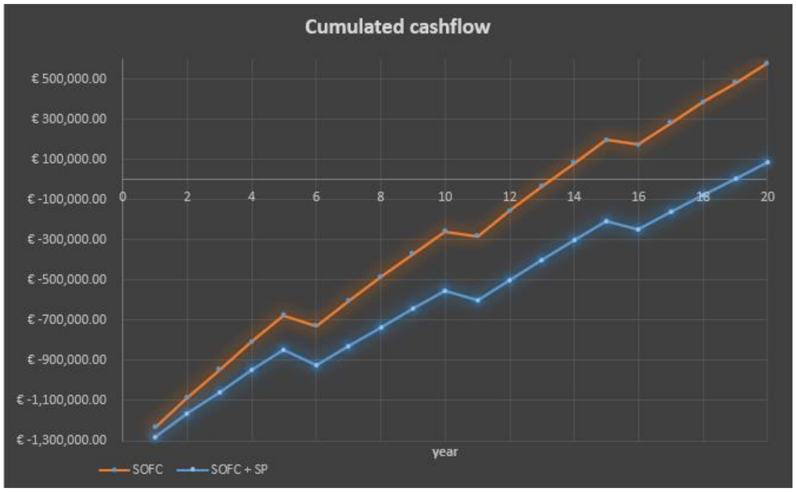
$$Cost_{year,i=6,11,16} = Opex_{replace} + Opex_{\text{adsorbent}} + CF \times (Opex_{reformer} + Opex_{labour\ cost} + Opex_{maintenance}) = 467357\ €$$

$$Cost_{year,i\neq6,11,16} = Opex_{\text{adsorbent}} + CF \times (Opex_{reformer} + Opex_{labour\ cost} + Opex_{maintenance}) = 174{,}281\ €$$

The incomes are evaluated as function of the savings/revenues and on the price of energy/subsidies, it can be computed as ($Opex_{th}$ have uncertainty, so it is not included in the calculation):

$$income = Opex_{el} + Saving_{th} - Cost_{el} = 378{,}093\ €$$

Cash Flow Analysis													
						(before taxes)				(after taxes)			
Years	CAPEX	Stack Replacement	Annual cost	Total cost	Income	resent Cash Flov	Depreciation rate	Income-Cost	Taxes	Present Cash Flow	iscount factc	Discount cashflow	Cumulated cashflow
1	€ -1,326,331		€ -	########		€ -1,326,331	€ -132,633.12	€ -1,326,331		€ -1,326,331	0.97	€ -1,282,719	€ -1,282,719
2			€ -174,281	€ -174,281	€ 378,093	€ 203,812	€ -132,633	€ 203,812	€ 80,747	€ 123,065	0.94	€ 115,105	€ -1,167,614
3			€ -174,281	€ -174,281	€ 378,093	€ 203,812	€ -132,633	€ 203,812	€ 80,747	€ 123,065	0.90	€ 111,320	€ -1,056,294
4			€ -174,281	€ -174,281	€ 378,093	€ 203,812	€ -132,633	€ 203,812	€ 80,747	€ 123,065	0.87	€ 107,660	€ -948,634
5			€ -174,281	€ -174,281	€ 378,093	€ 203,812	€ -132,633	€ 203,812	€ 80,747	€ 123,065	0.85	€ 104,119	€ -844,515
6		€ -293,076	€ -174,281	€ -467,357	€ 378,093	€ -89,264	€ -132,633	€ -89,264	€ 10,409	€ -99,673	0.82	€ -81,555	€ -926,070
7			€ -174,281	€ -174,281	€ 378,093	€ 203,812	€ -132,633	€ 203,812	€ 80,747	€ 123,065	0.79	€ 97,385	€ -828,686
8			€ -174,281	€ -174,281	€ 378,093	€ 203,812	€ -132,633	€ 203,812	€ 80,747	€ 123,065	0.77	€ 94,183	€ -734,503
9			€ -174,281	€ -174,281	€ 378,093	€ 203,812	€ -132,633	€ 203,812	€ 80,747	€ 123,065	0.74	€ 91,086	€ -643,417
10			€ -174,281	€ -174,281	€ 378,093	€ 203,812	€ -132,633	€ 203,812	€ 80,747	€ 123,065	0.72	€ 88,091	€ -555,327
11		€ -293,076	€ -174,281	€ -467,357	€ 378,093	€ -89,264		€ -89,264	€ -21,423	€ -67,841	0.69	€ -46,964	€ -602,291
12			€ -174,281	€ -174,281	€ 378,093	€ 203,812		€ 203,812	€ 48,915	€ 154,897	0.67	€ 103,704	€ -498,587
13			€ -174,281	€ -174,281	€ 378,093	€ 203,812		€ 203,812	€ 48,915	€ 154,897	0.65	€ 100,294	€ -398,292
14			€ -174,281	€ -174,281	€ 378,093	€ 203,812		€ 203,812	€ 48,915	€ 154,897	0.63	€ 96,996	€ -301,296
15			€ -174,281	€ -174,281	€ 378,093	€ 203,812		€ 203,812	€ 48,915	€ 154,897	0.61	€ 93,807	€ -207,489
16		€ -293,076	€ -174,281	€ -467,357	€ 378,093	€ -89,264		€ -89,264	€ -21,423	€ -67,841	0.59	€ -39,734	€ -247,223
17			€ -174,281	€ -174,281	€ 378,093	€ 203,812		€ 203,812	€ 48,915	€ 154,897	0.57	€ 87,739	€ -159,484
18			€ -174,281	€ -174,281	€ 378,093	€ 203,812		€ 203,812	€ 48,915	€ 154,897	0.55	€ 84,854	€ -74,630
19			€ -174,281	€ -174,281	€ 378,093	€ 203,812		€ 203,812	€ 48,915	€ 154,897	0.53	€ 82,064	€ 7,435
20			€ -174,281	€ -174,281	€ 378,093	€ 203,812		€ 203,812	€ 48,915	€ 154,897	0.51	€ 79,366	€ 86,800



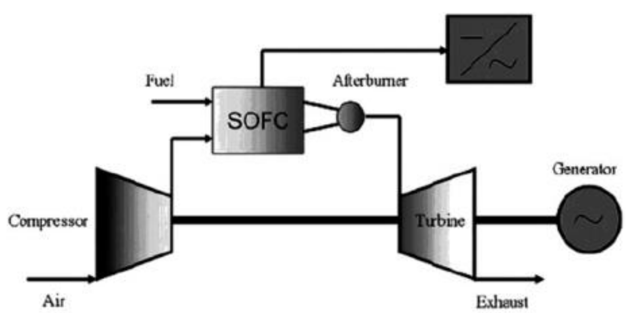
$$PBT = 18.52$$

$$NPV = 86{,}800\ €$$

$$IRR = 4.12\%$$

Although the power generation increased by 13.2% (44522.7 W) after we combined the SOFC system with the Steam power plant, the initial investment cost increased by 3.94% (50,250 €), and the annual expenditure soared by 55.8% (62,444 €). Combining SOFC system with steam power plant in WWTP for mid-sized cities is not feasible from an economic point of view.

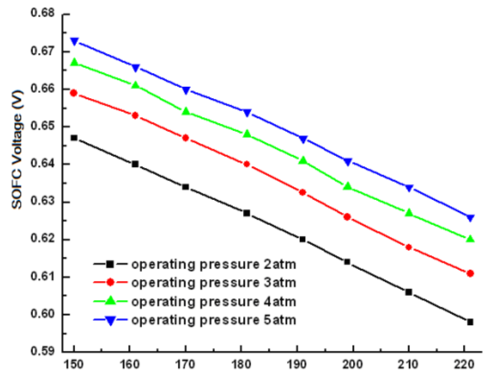
Combined with Gas turbine



Gas turbine engine as a bottoming cycle in a SOFCgas turbine system. [8]

SOFC converts the hydrogen, reformed from the natural gas, electrochemically producing both electrical power and high-grade waste heat for combined heat and power (CHP) system. It has been demonstrated that SOFC can achieve 50% net electrical efficiencies and have already been considered feasible for integration with multi-MW gas turbine engines to achieve higher electrical efficiency.

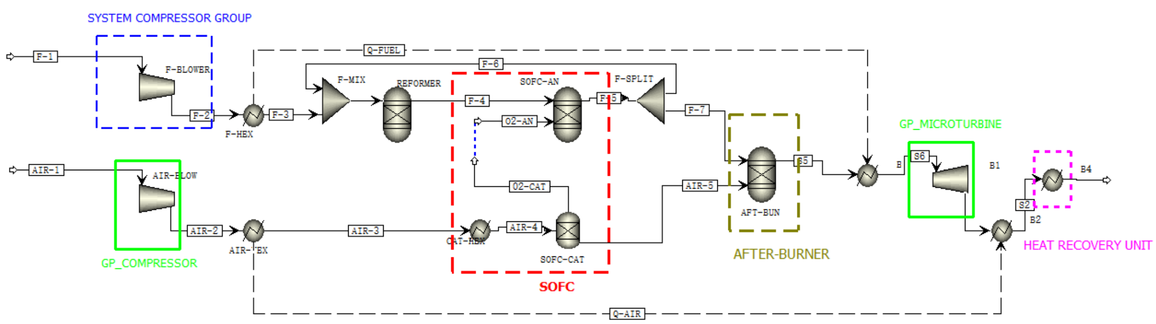
Adding a gas turbine to a SOFC system means that the incoming air and fuel needs to be pressurized, which is a good thing for the reaction in the SOFC but the high-pressure operation of SOFC stack causes large pressure gradients between anode and cathode. This pressure imbalance needs to be avoided, due to the brittleness of the SOFC materials, and good sealants are required to stop leakages.

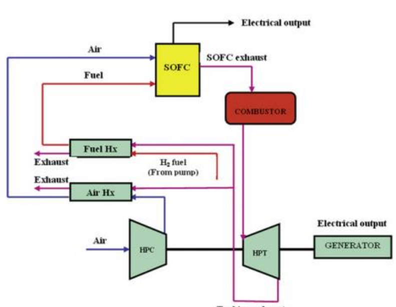


Pressure effect SOFC [9]

Since the model established in Aspen is based on VOC=0.8, there is no need to change the base model. According to reference [10], In the pressurized SOFC test rig SOFC short stacks can be characterized at pressures of 1 to 8 bar. So, it is reasonable to set the operating pressure of our chosen SOFC system (Convion's C60) to 2.9 bar.

According to the model mentioned in the literature [8], we need to increase the total mass flow rate to at least 0.4kg/s to adapt to the working standard of micro-turbine. Since the production of biogas is fixed, we need to increase the input of air.





Schematic of SOFC+GT [8]

Table 1 – Comparative result for the two configurations.

	Configuration 1	Configuration 2
Fuel flow (g/s)	9.62	9.62
Air flow (g/s)	400	400
SOFC Temperature (°C)	944	832
Turbine Inlet Temp (°C)	1136	1166
SOFC power (kW)	359	319
HPT (kW)	104	108
Total power (kW)	463	427
Cycle efficiency (%)	58	53.5
Exhaust Temp (°C) (Air HE)	617	605

operating condition of two configurations [8]

Since the mass flow rate of air is 1.4 times of the base model, the heat exchanger for the air can only be placed after the microturbine. To avoid the temperature of turbine inlet higher than 1400 degrees Celsius, we need to reduce the temperature by manage the heat to the fuel first.
Through modeling in ASPEN, the output power can be obtained as:

$$Lc_{fuel} = 5572\ W$$

$$W_{el,DC,SOFC} = 362330\ W \sim 362\ KW$$

$$W_{el,AC,SOFC} = W_{el,DC.SOFC} \times 95\% - Lc_{fuel} = 338641.5\ W \sim 338KW$$

$$W_{el,TURBINE} = 122155W \sim 122\ KW\ \ turbine$$

$$W_{el,COMPRESSOR} = 58017 \sim 58\ KW\ \ compressor$$

All auxiliary losses on gas power plant have been deducted from turbine output.

$$W_{el,SOFC+GT,AC} = W_{el,AC,SOFC} + W_{el,TURBINE} - W_{el,COMPRESSOR} = 402779.5\ W \sim 403\ KW$$

$$Q_{tu} = 196764\ W \sim 197\ KW$$

$$\eta_{el,AC,SOFC+GT} = \frac{W_{el,SOFC+SP,AC}}{\dot{m}_{CH_4} \times LHV_{CH4}} = 59.9\%$$

$$\eta_{th,SOFC+GT} = \frac{Q_{tu}}{\dot{m}_{CH_4} \times LHV_{CH4}} = 29.3\%$$

$$\eta_{tot,SOFC+GT} = \eta_{el,AC,SOFC+GT} + \eta_{th,SOFC+GT} = 89.2\%$$

Economic analysis result (combined with gas turbine)

$$Capex_{GT} = 100\ KW \times 1283\frac{€}{\text{KW}} = 128{,}300\ € \quad [11]$$

The cost of gas turbine group (with thermal exchange group) includes the installation and balancing. However, it is difficult for us to estimate how many labors are required, so we assume that another one part-time laborers are required to operate alternately.

$$Opex_{SOFC+GT,labour\ cost} = 2 \times Opex_{SOFC,labour\ cost} = 62{,}400\ €$$

$$Opex_{th} = 0.0655 \times (Q_{tu} - 60\% \times Q_{rev}) \times 24\ h \times 5 \times 30\ days = 3{,}140\ €$$

$$Q_{saving} = 0.6 \times Q_{rev} = 164\ KW$$

$$Saving_{th} = Q_{saving} \times 0.0655 \times 1\ year = 93{,}469\ € \quad every\ year$$

$$Opex_{el,SOFC+GT} = 0.111 \times (W_{el,DC} \times 95\% + W_{el,TURBINE} - W_{el,COMPRESSOR}) \times 1\ year = 397{,}064\ €$$

$$Opex_{maintenance,SOFC+GT} = 5\% \times \left(Capex_{SOFC} + Capex_{clean-up} + Capex_{HRU} + Capex_{other}\right) + 100\ KW \times 17.7\ €/\text{kW} = 63{,}892\ €$$

Based on the guidance of WWTP, we believe that the power required by the factory is

$$W_{demaind} = W_{el,DC} \times 95\% + Lc_{fuel} = 344{,}312.5\ W$$

$$Cost_{el} = 0.0312 \times W_{demaind} \times 1\ year = 94{,}104\ € \quad \text{every year}$$

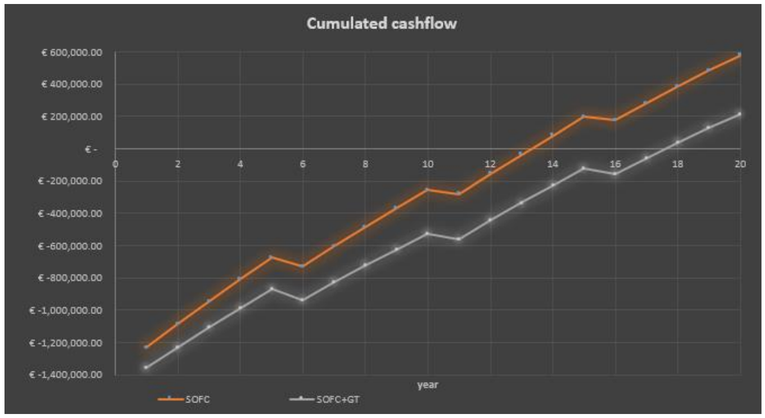
$$Cost_{year,0} = Capex_{SOFC} + Capex_{GT} + Capex_{clean-up} + Capex_{HRU} + Capex_{other} = 1{,}404{,}381\ €$$

$$Cost_{year,i=6,11,16} = Opex_{replace} + Opex_{\text{adsorbent}} + CF \times (Opex_{reformer} + Opex_{labour\ cost} + Opex_{maintenance}) = 467{,}401\ €$$

$$Cost_{year,i\neq 6,11,16} = Opex_{\text{adsorbent}} + CF \times (Opex_{reformer} + Opex_{labour\ cost} + Opex_{maintenance}) = 174{,}325\ €$$

$$income = Opex_{el} + Saving_{th} - Cost_{el} = 399{,}570\ €$$

Cash Flow Analysis												
						(before taxes)				(after taxes)			
Years	CAPEX	Stack Replacement	Annual cost	Total cost	Income	resent Cash Flow	Depreciation rate	Income-Cost	Taxes	Present Cash Flow	iscount facto	Discount cashflow	Cumulated cashflow
1	€ -1,404,381		€ -	€ -1,404,381		€ -1,404,381	€ -140,438	€ -1,404,381		€ -1,404,381	0.97	€ -1,358,202	€ -1,358,202
2			€ -174,325	€ -174,325	€ 399,570	€ 225,245	€ -140,438	€ 225,245	€ 87,764	€ 137,481	0.94	€ 128,588	€ -1,229,614
3			€ -174,325	€ -174,325	€ 399,570	€ 225,245	€ -140,438	€ 225,245	€ 87,764	€ 137,481	0.90	€ 124,360	€ -1,105,254
4			€ -174,325	€ -174,325	€ 399,570	€ 225,245	€ -140,438	€ 225,245	€ 87,764	€ 137,481	0.87	€ 120,271	€ -984,983
5			€ -174,325	€ -174,325	€ 399,570	€ 225,245	€ -140,438	€ 225,245	€ 87,764	€ 137,481	0.85	€ 116,316	€ -868,666
6		€ -293,076	€ -174,325	€ -467,401	€ 399,570	€ -67,831	€ -140,438	€ -67,831	€ 17,426	€ -85,257	0.82	€ -69,760	€ -938,426
7			€ -174,325	€ -174,325	€ 399,570	€ 225,245	€ -140,438	€ 225,245	€ 87,764	€ 137,481	0.79	€ 108,793	€ -829,634
8			€ -174,325	€ -174,325	€ 399,570	€ 225,245	€ -140,438	€ 225,245	€ 87,764	€ 137,481	0.77	€ 105,215	€ -724,418
9			€ -174,325	€ -174,325	€ 399,570	€ 225,245	€ -140,438	€ 225,245	€ 87,764	€ 137,481	0.74	€ 101,756	€ -622,663
10			€ -174,325	€ -174,325	€ 399,570	€ 225,245	€ -140,438	€ 225,245	€ 87,764	€ 137,481	0.72	€ 98,410	€ -524,253
11		€ -293,076	€ -174,325	€ -467,401	€ 399,570	€ -67,831		€ -67,831	€ -16,279	€ -51,552	0.69	€ -35,687	€ -559,941
12			€ -174,325	€ -174,325	€ 399,570	€ 225,245		€ 225,245	€ 54,059	€ 171,186	0.67	€ 114,610	€ -445,331
13			€ -174,325	€ -174,325	€ 399,570	€ 225,245		€ 225,245	€ 54,059	€ 171,186	0.65	€ 110,841	€ -334,489
14			€ -174,325	€ -174,325	€ 399,570	€ 225,245		€ 225,245	€ 54,059	€ 171,186	0.63	€ 107,197	€ -227,293
15			€ -174,325	€ -174,325	€ 399,570	€ 225,245		€ 225,245	€ 54,059	€ 171,186	0.61	€ 103,672	€ -123,621
16		€ -293,076	€ -174,325	€ -467,401	€ 399,570	€ -67,831		€ -67,831	€ -16,279	€ -51,552	0.59	€ -30,193	€ -153,814
17			€ -174,325	€ -174,325	€ 399,570	€ 225,245		€ 225,245	€ 54,059	€ 171,186	0.57	€ 96,966	€ -56,848
18			€ -174,325	€ -174,325	€ 399,570	€ 225,245		€ 225,245	€ 54,059	€ 171,186	0.55	€ 93,778	€ 36,929
19			€ -174,325	€ -174,325	€ 399,570	€ 225,245		€ 225,245	€ 54,059	€ 171,186	0.53	€ 90,694	€ 127,623
20			€ -174,325	€ -174,325	€ 399,570	€ 225,245		€ 225,245	€ 54,059	€ 171,186	0.51	€ 87,712	€ 215,335



$$PBT = 17.67$$

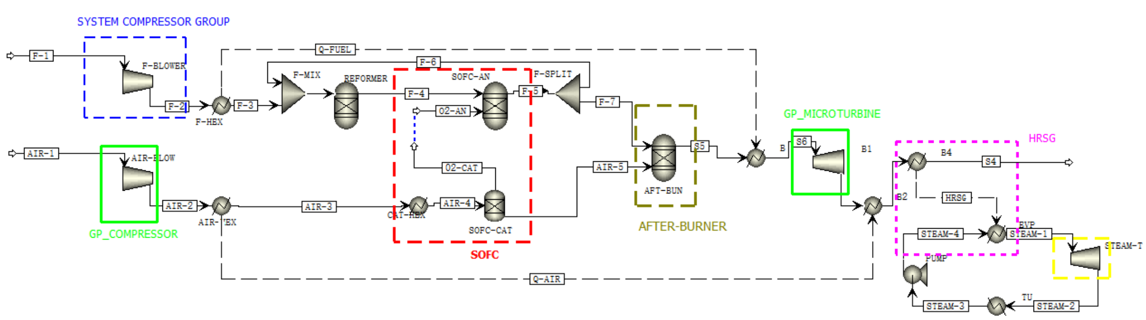
$$NPV = 215{,}335\ €$$

$$IRR = 5.05\%$$

The power generation increased by 19% (64308 W) after we combined the SOFC system with the Gas turbine, the initial investment cost increased by 10.1% (128,300 €), and the annual expenditure soared by 55.9% (62,488 €).

Combined with Gas turbine +Steam turbine

After the above selection, it can be seen that after combining with the gas turbine, although the overall efficiency will be reduced, the power output will increase considerably. Therefore, we further study the feasibility of converting residual thermal energy into electrical energy.



All parts work the same as our options above. But since the heat available for conversion to electricity is reduced for the steam power plant, the mass flow rate of vapor for the steam power plant is also reduced.

$$\dot{m}_{steam} = 0.071\ {}^{kg}/_{s} = 0.26\ {}^{t}/_{h}$$

$$W_{el,ST+GT} = 93493\sim 94\ KW$$

$$W_{el,AC,SOFC+GT+ST} = W_{el,DC.SOFC} \times 95\% - Lc_{fuel} + W_{el,ST+GT} = 432134.5\ W\sim 432KW$$

$$Q_{tu} = 165861\ W\sim 166\ KW$$

$$\eta_{el,AC,SOFC+GT+ST} = \frac{W_{el,SOFC+GT+ST,AC}}{\dot{m}_{CH_4} \times LHV_{CH4}} = 64.3\%$$

$$\eta_{th,SOFC+GT+SP} = \frac{Q_{tu}}{\dot{m}_{CH_4} \times LHV_{CH4}} = 24.6\%$$

$$\eta_{tot,SOFC+GT+ST} = \eta_{el,AC,SOFC+GT+ST} + \eta_{th,SOFC+GT+ST} = 88.9\%$$

Economic analysis result (combined with gas turbine +steam turbine)

$$Capex_{GT} = 100\ KW \times 1283 \frac{€}{\mathrm{KW}} = 128{,}300\ € \quad [11]$$

$$Capex_{ST} = 30\ KW \times 1005 \frac{€}{\mathrm{KW}} = 30{,}150\ € \quad [3]$$

The cost of gas turbine group and steam turbine group (with thermal exchange group) includes the installation and balancing.

$$Opex_{SOFC+GT+ST,labour\ cost} = 2 \times Opex_{SOFC,labour\ cost} = 62{,}400\ €$$

$$Q_{saving} = 0.6 \times Q_{rev,sofc} = 164\ KW$$

$$Saving_{th} = Q_{saving} \times 0.0655 \times 1\ year = 93{,}469\ € \quad every\ year$$

$$Q_{wasted} = Q_{tu} - Q_{saving} = 2109\ W$$

This past of thermal energy is totally wasted because they are low-grade energy.

$$Opex_{el,SOFC+GT+ST} = 0.111 \times (W_{el,DC} \times 95\% + W_{el,ST+GT}) \times 1\ year = 425{,}606\ €$$

$$Opex_{maintenance,SOFC+GT} = 5\% \times \left(Capex_{SOFC} + Capex_{clean-up} + Capex_{HRU} + Capex_{other}\right) \\ +130\ KW \times 17.7\ €/\mathrm{kW} = 63{,}919\ €$$

Based on the guidance of WWTP, we believe that the power required by the factory is

$$W_{demaind} = W_{el,DC} \times 95\% + Lc_{fuel} = 344{,}312.5\ W$$

$$Cost_{el} = 0.0312 \times W_{demaind} \times 1\ year = 94{,}104\ € \qquad \text{every year}$$

$$Cost_{year,0} = Capex_{SOFC} + Capex_{GT+ST} + Capex_{clean-up} + Capex_{HRU} + Capex_{other} = 1{,}434{,}531\ €$$

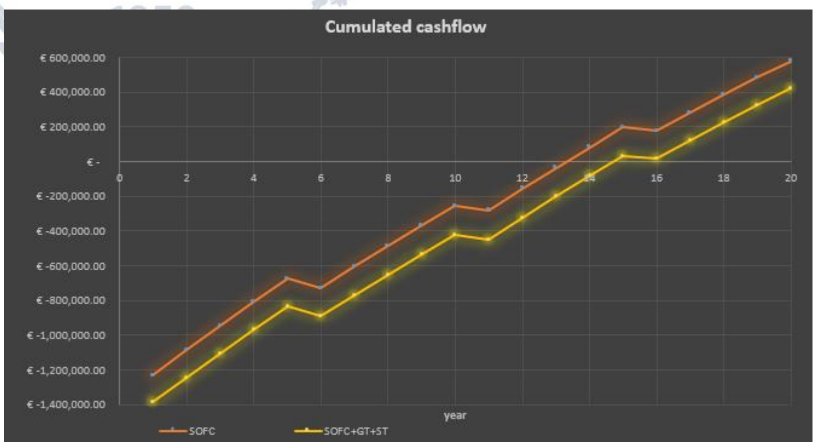
$$Cost_{year,i=6,11,16} = Opex_{replace} + Opex_{\text{adsorbent}} + CF \times (Opex_{reformer} + Opex_{labour\ cost} + Opex_{maintenance}) = 467{,}401\ €$$

$$Cost_{year,i\neq 6,11,16} = Opex_{\text{adsorbent}} + CF \times (Opex_{reformer} + Opex_{labour\ cost} + Opex_{maintenance}) = 174{,}325\ €$$

$$income = Opex_{el} + Saving_{th} - Cost_{el} = 423{,}429\ €$$

Cash Flow Analysis

Years	CAPEX	Stack Replacement	Annual cost	Total cost	Income	(before taxes) Present Cash Flow	Depreciation rate	Income-Cost	Taxes	(after taxes) Present Cash Flow	Discount facto	Discount cashflow	Cumulated cashflow
1	€ -1,434,531		€ -	€ -1,434,531		€ -1,434,531	€ -143,453	€ -1,434,531		€ -1,434,531	0.97	€ -1,387,361	€ -1,387,361
2			€ -174,325	€ -174,325	€ 423,429	€ 249,104	€ -143,453	€ 249,104	€ 94,214	€ 154,890	0.94	€ 144,871	€ -1,242,489
3			€ -174,325	€ -174,325	€ 423,429	€ 249,104	€ -143,453	€ 249,104	€ 94,214	€ 154,890	0.90	€ 140,108	€ -1,102,382
4			€ -174,325	€ -174,325	€ 423,429	€ 249,104	€ -143,453	€ 249,104	€ 94,214	€ 154,890	0.87	€ 135,501	€ -966,881
5			€ -174,325	€ -174,325	€ 423,429	€ 249,104	€ -143,453	€ 249,104	€ 94,214	€ 154,890	0.85	€ 131,045	€ -835,836
6		€ -293,076	€ -174,325	€ -467,401	€ 423,429	€ -43,972	€ -143,453	€ -43,972	€ 23,875	€ -67,848	0.82	€ -55,515	€ -891,351
7			€ -174,325	€ -174,325	€ 423,429	€ 249,104	€ -143,453	€ 249,104	€ 94,214	€ 154,890	0.79	€ 122,569	€ -768,782
8			€ -174,325	€ -174,325	€ 423,429	€ 249,104	€ -143,453	€ 249,104	€ 94,214	€ 154,890	0.77	€ 118,539	€ -650,243
9			€ -174,325	€ -174,325	€ 423,429	€ 249,104	€ -143,453	€ 249,104	€ 94,214	€ 154,890	0.74	€ 114,641	€ -535,602
10			€ -174,325	€ -174,325	€ 423,429	€ 249,104	€ -143,453	€ 249,104	€ 94,214	€ 154,890	0.72	€ 110,871	€ -424,731
11		€ -293,076	€ -174,325	€ -467,401	€ 423,429	€ -43,972		€ -43,972	€ -10,553	€ -33,419	0.69	€ -23,135	€ -447,866
12			€ -174,325	€ -174,325	€ 423,429	€ 249,104		€ 249,104	€ 59,785	€ 189,319	0.67	€ 126,750	€ -321,116
13			€ -174,325	€ -174,325	€ 423,429	€ 249,104		€ 249,104	€ 59,785	€ 189,319	0.65	€ 122,582	€ -198,534
14			€ -174,325	€ -174,325	€ 423,429	€ 249,104		€ 249,104	€ 59,785	€ 189,319	0.63	€ 118,551	€ -79,983
15			€ -174,325	€ -174,325	€ 423,429	€ 249,104		€ 249,104	€ 59,785	€ 189,319	0.61	€ 114,653	€ 34,670
16		€ -293,076	€ -174,325	€ -467,401	€ 423,429	€ -43,972		€ -43,972	€ -10,553	€ -33,419	0.59	€ -19,573	€ 15,097
17			€ -174,325	€ -174,325	€ 423,429	€ 249,104		€ 249,104	€ 59,785	€ 189,319	0.57	€ 107,237	€ 122,334
18			€ -174,325	€ -174,325	€ 423,429	€ 249,104		€ 249,104	€ 59,785	€ 189,319	0.55	€ 103,711	€ 226,045
19			€ -174,325	€ -174,325	€ 423,429	€ 249,104		€ 249,104	€ 59,785	€ 189,319	0.53	€ 100,301	€ 326,346
20			€ -174,325	€ -174,325	€ 423,429	€ 249,104		€ 249,104	€ 59,785	€ 189,319	0.51	€ 97,003	€ 423,348



$$PBT = 14.58$$

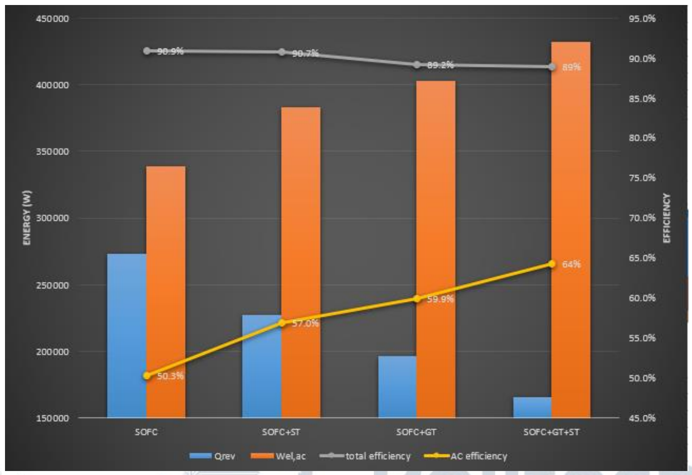
$$NPV = 423{,}348\ €$$

$$IRR = 6.51\%$$

The power generation increased by 27.7% (93663 W) after we combined the SOFC system with the

Gas turbine and steam turbine, the initial investment cost increased by 12.4% (158,450 €), and the annual expenditure soared by 55.9% (62,488 €). The SOFC+GT+ST system is feasible in terms of economic analysis, but compared with the sorely SOFC system, the initial investment is too high, and the payback period is too long, but it can generate more electricity. So, the final choice is whether we need a high amount of power output.

Conclusions



SOFC system have very high efficiency, from compressed biogas to AC power, the efficiency can reach to 50%. However, the utilization of the heat recovered by the HRU still to be developed. The ideal situation is to convert as much thermal energy as possible into electricity, so as to maximize profits.

For WWTP in a medium-sized city (Bologna), if combined with SOFC system, the power generation scale can reach 360KW, and the operation can be profitable in the twelfth year under ideal conditions. From the economic analysis, SOFC system has the problems of high initial investment, slower payback and high technology requirement.

In terms of the scale of power generation, this system is not outstanding, but WWTP is an infrastructure, and the original intention of its establishment is not for profit. From this point of view, this project can not only subsidize the operation of WWTP, but also generate profits. By comparing with different configuration, we find that gas turbine + steam turbine has more power output, but the initial investment and annual expenditure will higher than SOFC system. In terms of total efficiency, SOFC system can have unparalleled advantages. Adding more systems will reduce the overall efficiency, but it is still higher than CHP.

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