



**Politecnico  
di Torino**

# *Feasibility study of a biogas-fed SOFC system*

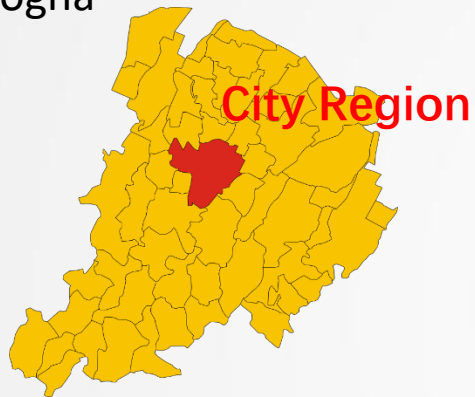
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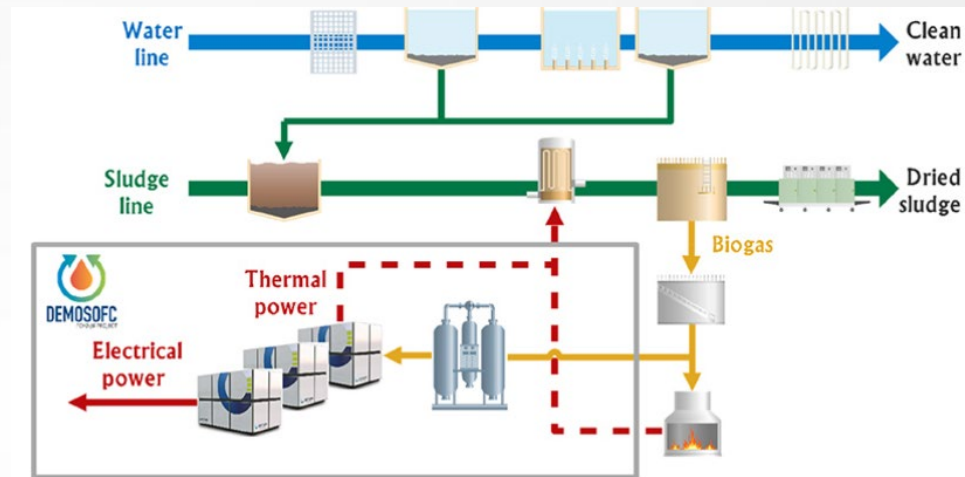
# Wastewater Treatment Plant (WWTP)

Bologna



394,843 residents

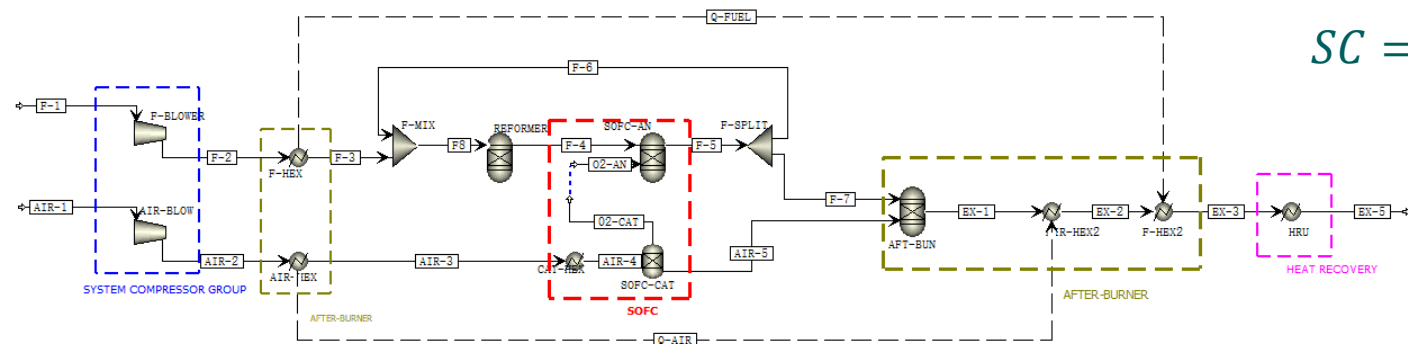
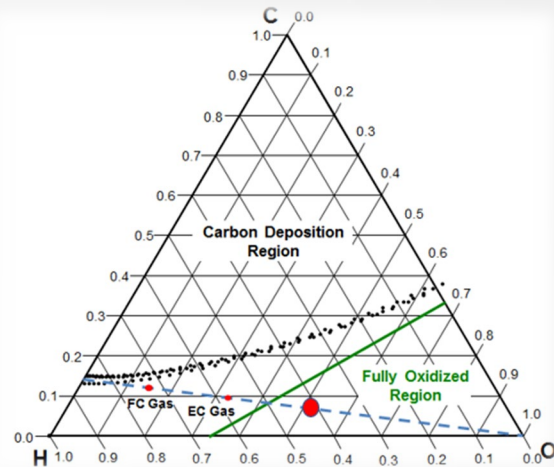
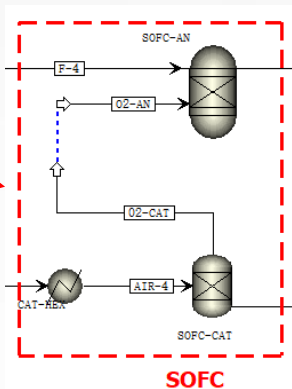
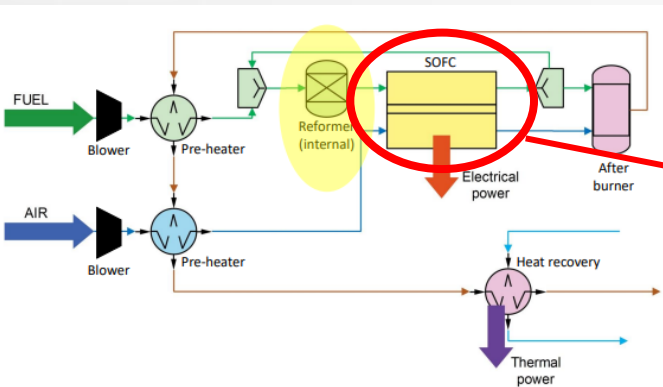
Biogas production is  $117.333 \text{ Nm}^3/\text{h}$



DEMOSOFC plant layout [1]

60% of  $\text{CH}_4$  and 40% of  $\text{CO}_2$  (Mole fraction)

# SOFC Model



$$SC = \frac{\dot{n}_{H_2O}}{\dot{n}_{CH_4}} = 3$$

# SOFC Model-----Result

$$\dot{m}_{CH_4} = 0.0134 \text{ Kg/s} ; LHV_{CH_4} = 50 \text{ MJ/kg}$$

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

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

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

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

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

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

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

# SOFC system-----Sizing

$$n = \frac{W_{el,FC}}{60 \text{ KW}} = 5.73$$



6 stack



$$W_{el,tot} \sim 343.9 \text{ KW}$$

utilization of fuel cell ~95.5%

## 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 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 <sub>x</sub>	≤ 2.6 ppm-v/ ≤0.05 g/kWh (below detection limit)	
Sulphur dioxide, SO <sub>2</sub>	≤ 3 ppm-v/ ≤0.07 g/kWh (below detection limit), sulphur removal 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 <sub>2</sub>	330 kg/MWh <sub>e</sub>	
SYSTEM DIMENSIONS		
H * L * W	2330 * 2780 * 2090 mm	

# Economic analysis-----The capital expenditure

01

$Capex_{sofc}$

837,360 €



02

$Capex_{clean-up}$

180.000 €



03

$Capex_{HRU}$

10,8721.2 €



04

$Capex_{other}$

150,000 €



# Economic analysis-----Operating Expenditure

01

$Opex_{reformer}$

977.775 €

$Opex_{adsorbent}$

15,855 €

*every year*

02

$Opex_{replace}$

293,076 €

*every 5 year*

$Opex_{labour\ cost}$

31,200 €

*every year*

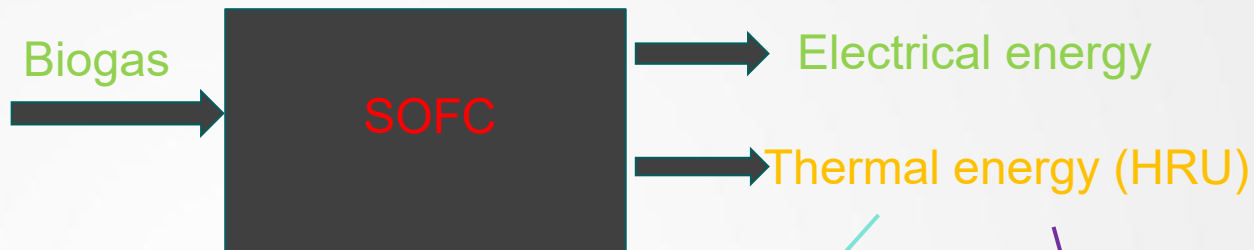
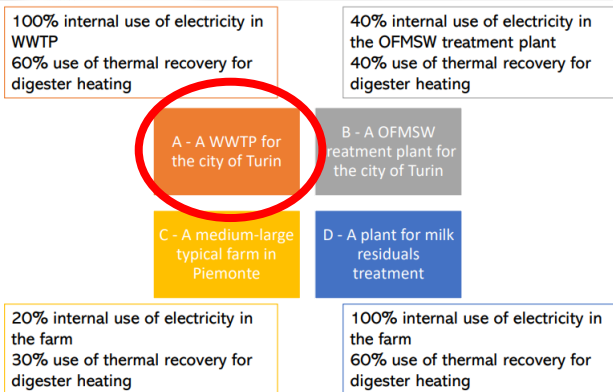
03

$Opex_{maintenance}$

63,804.06 €

*every year*

# Economic analysis-----Operating Expenditure



Sell  
(60% of HRU)

Digester Heating  
(60% of HRU)

$$Opex_{el} = 0.111 \times W_{el,DC} \times 95\% \times 1 \text{ year} = 334,699.44\text{€}$$

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

$$Cost_{el} = 0.0312 \times W_{demandd} \times 1 \text{ year} = 95,647.4 \text{ €}$$

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

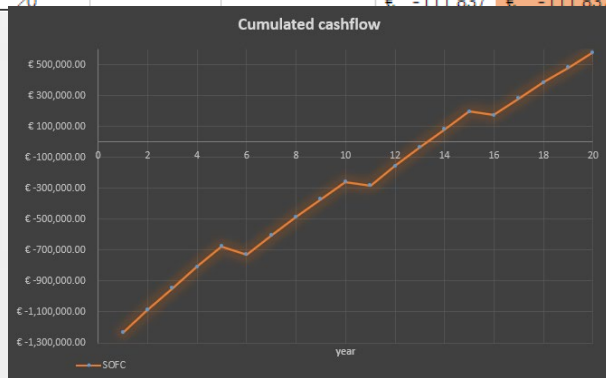
$$Opex_{th} = 0.0655 \times (60\% \times Q_{rev}) \times 24 \text{ h} \times 5 \text{ month} \times 30 \text{ days} = 25,963.86 \text{ €} \quad \text{District heating}$$

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



# Economic analysis-----Cash flow

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 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

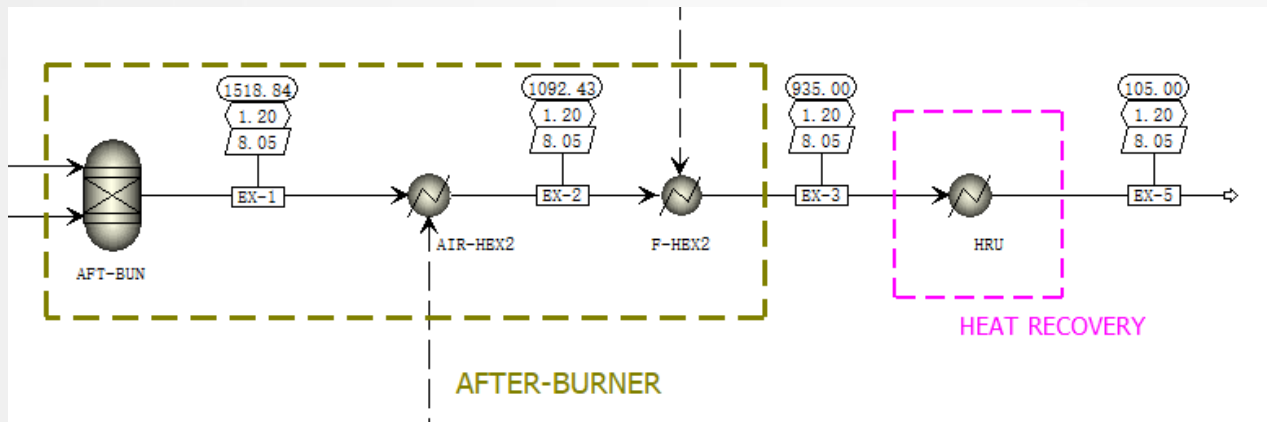


$$PBT = 13.82$$

$$NPV = 579,747€$$

$$IRR = 8.08 \%$$

# SOFC system-----Discussion



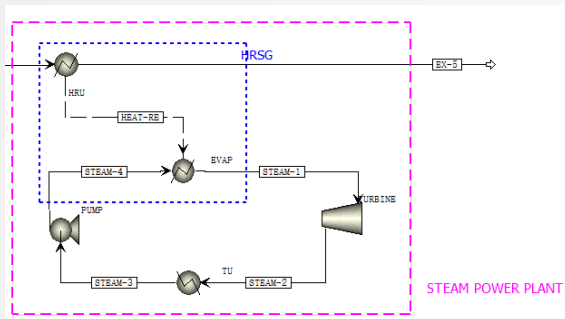
$T_{\text{exhaust}} = 935^{\circ}\text{C}$  high grade heat

$Q_{\text{rev}} = 272920 \text{ W} \sim 273 \text{ KW}$



*Electrical energy*

# SOFC system-----Combined with Steam Plant



1

$$W_{el,turbine} \sim 47 \text{ KW}$$

2

$$W_{el,SOFC+SP,AC} \sim 383 \text{ KW}$$

3

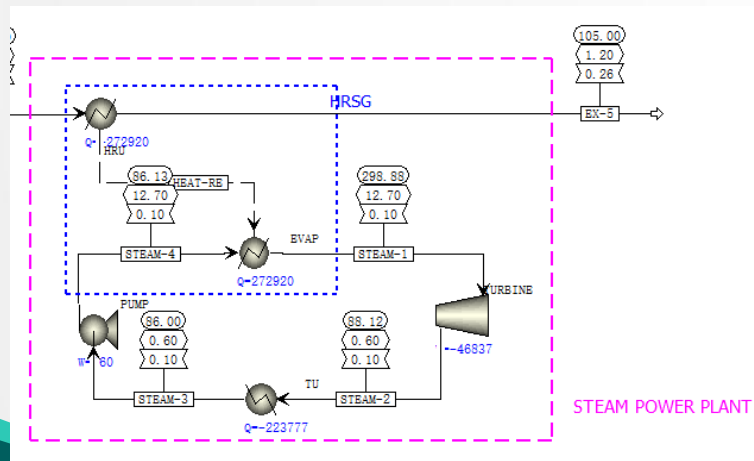
$$Q_{tu} \sim 227 \text{ KW}$$

4

$$\eta_{el,AC} = 57\% ; \eta_{th} = 33.8\%$$

5

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



# Economic analysis-----Cash flow

Cash Flow Analysis													
Years	CAPEX	Stack Replacement	Annual cost	Total cost	Income	(before taxes)					(after taxes)		
						Present Cash Flow	Depreciation rate	Income-Cost	Taxes	Present Cash Flow	Discount factor	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



$$PBT = 18.52$$

power generation increased by 13.2%  
(44522.7 W)

$$NPV = 86,747\text{€}$$

the initial investment cost increased by 3.94%  
(50,250 €)

$$IRR = 4.12 \%$$

the annual expenditure soared by 55.8%  
(62,444 €)

# SOFC system-----Combined with Gas Turbine

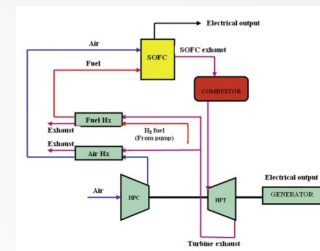
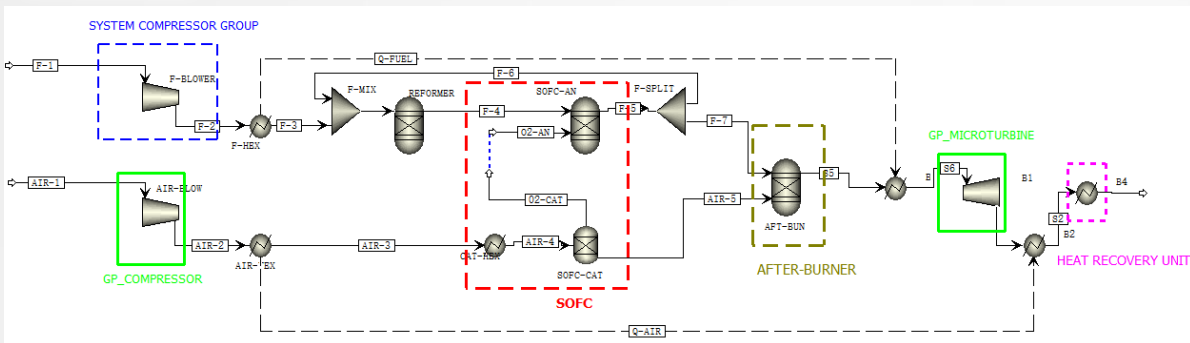


Table 1 – Comparative result for the two configurations.

	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

1

$$W_{el,turbine} \sim 71 \text{ KW}$$

2

$$W_{el,SOFC+GT,AC} \sim 403 \text{ KW}$$

3

$$Q_{tu} \sim 197 \text{ KW}$$

4

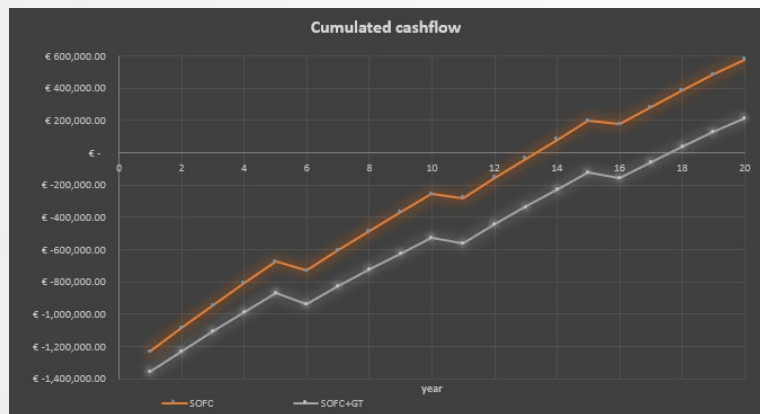
$$\eta_{el,AC} = 59.9\% ; \eta_{th} = 29.3\%$$

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



# Economic analysis-----Cash flow

Cash Flow Analysis													
Years	CAPEX	Stack Replacement	Annual cost	Total cost	Income	Present Cash Flow (before taxes)	Depreciation rate	Income-Cost	Taxes	Present Cash Flow (after taxes)	Discount factor	Discount cashflow	Cumulated cashflow
1	€ -1,404,381		€ -	€ -1,404,381		€ -1,404,381	€ -140,438	€ -1,404,381	€ 87,764	€ -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



$$PBT = 17.67$$

power generation increased by 19%  
(64308 W)

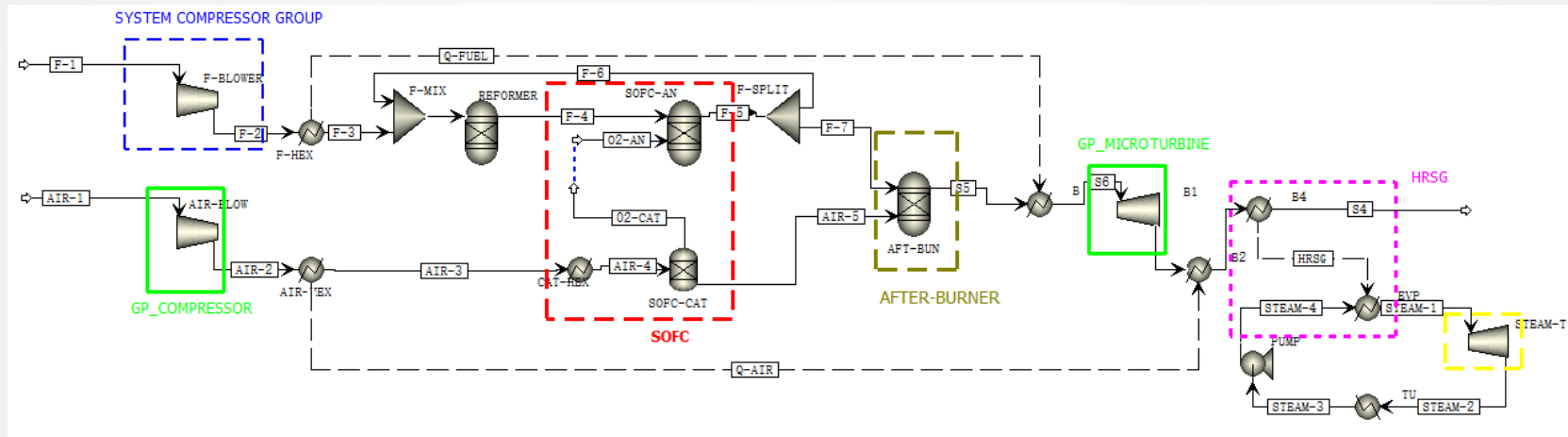
$$NPV = 215,335€$$

the initial investment cost increased by 10.1%  
(128,300 €)

$$IRR = 5.05 \%$$

the annual expenditure soared by 55.9%  
(62,489 €)

## SOFC system-----Combined with GT+ST



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

$$W_{el,AC,SOFC+GT+ST} \sim 432KW$$

$$Q_{tu} \sim 166 \text{ KW}$$

$$\eta_{el,AC} = 64.3\% ; \eta_{th} = 24.6\%$$

*low grade heat*

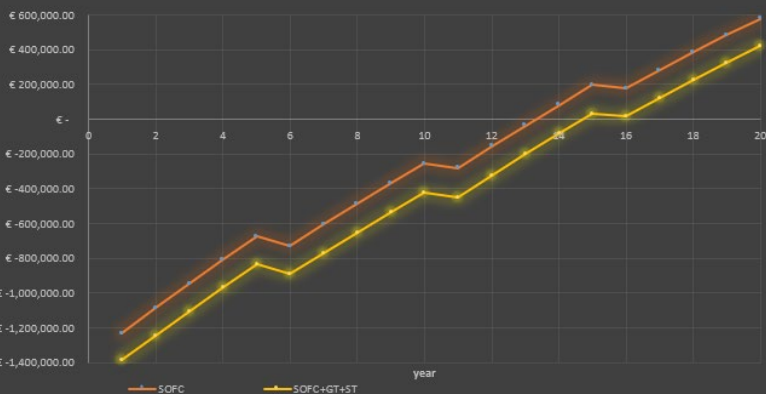
$$T_{exhaust} = 86\text{ }^{\circ}\text{C}$$

$$\eta_{tot} = 88.9\%$$

# Economic analysis-----Cash flow

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 factor	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	€ 423.420	€ 240.104	€ -143.453	€ 240.104	€ 94.214	€ 154.890	0.94	€ 144.871	€ -1.242.489	
3			€ -174.325	€ -174.325	€ 423.420	€ 240.104	€ -143.453	€ 240.104	€ 94.214	€ 154.890	0.90	€ 140.108	€ -1.102.382	
4			€ -174.325	€ -174.325	€ 423.420	€ 240.104	€ -143.453	€ 240.104	€ 94.214	€ 154.890	0.87	€ 135.501	€ -966.881	
5			€ -174.325	€ -174.325	€ 423.420	€ 240.104	€ -143.453	€ 240.104	€ 94.214	€ 154.890	0.85	€ 131.045	€ -835.836	
6		€ -293.076	€ -174.325	€ -467.401	€ 423.420	€ -43.972	€ -143.453	€ -43.972	€ 23.875	€ -67.848	0.82	€ -55.515	€ -891.351	
7			€ -174.325	€ -174.325	€ 423.420	€ 240.104	€ -143.453	€ 240.104	€ 94.214	€ 154.890	0.79	€ 122.569	€ -768.782	
8			€ -174.325	€ -174.325	€ 423.420	€ 240.104	€ -143.453	€ 240.104	€ 94.214	€ 154.890	0.77	€ 118.539	€ -650.243	
9			€ -174.325	€ -174.325	€ 423.420	€ 240.104	€ -143.453	€ 240.104	€ 94.214	€ 154.890	0.74	€ 114.641	€ -535.602	
10			€ -174.325	€ -174.325	€ 423.420	€ 240.104	€ -143.453	€ 240.104	€ 94.214	€ 154.890	0.72	€ 110.871	€ -424.731	
11		€ -293.076	€ -174.325	€ -467.401	€ 423.420	€ -43.972		€ -43.972	€ -10.553	€ -33.419	0.69	€ -23.135	€ -447.866	
12			€ -174.325	€ -174.325	€ 423.420	€ 240.104		€ 240.104	€ 59.785	€ 189.319	0.67	€ 126.750	€ -321.116	
13			€ -174.325	€ -174.325	€ 423.420	€ 240.104		€ 240.104	€ 59.785	€ 189.319	0.65	€ 122.582	€ -198.534	
14			€ -174.325	€ -174.325	€ 423.420	€ 240.104		€ 240.104	€ 59.785	€ 189.319	0.63	€ 118.551	€ -79.983	
15			€ -174.325	€ -174.325	€ 423.420	€ 240.104		€ 240.104	€ 59.785	€ 189.319	0.61	€ 114.653	€ 34.670	
16		€ -293.076	€ -174.325	€ -467.401	€ 423.420	€ -43.972		€ -43.972	€ -10.553	€ -33.419	0.59	€ -19.573	€ 15.097	
17			€ -174.325	€ -174.325	€ 423.420	€ 240.104		€ 240.104	€ 59.785	€ 189.319	0.57	€ 107.237	€ 122.334	
18			€ -174.325	€ -174.325	€ 423.420	€ 240.104		€ 240.104	€ 59.785	€ 189.319	0.55	€ 103.711	€ 226.045	
19			€ -174.325	€ -174.325	€ 423.420	€ 240.104		€ 240.104	€ 59.785	€ 189.319	0.53	€ 100.301	€ 326.346	
20			€ -174.325	€ -174.325	€ 423.420	€ 240.104		€ 240.104	€ 59.785	€ 189.319	0.51	€ 97.003	€ 423.346	

Cumulated cashflow



$$PBT = 14.58$$

power generation increased by 27.7%  
(93663 W)

$$NPV = 423.384€$$

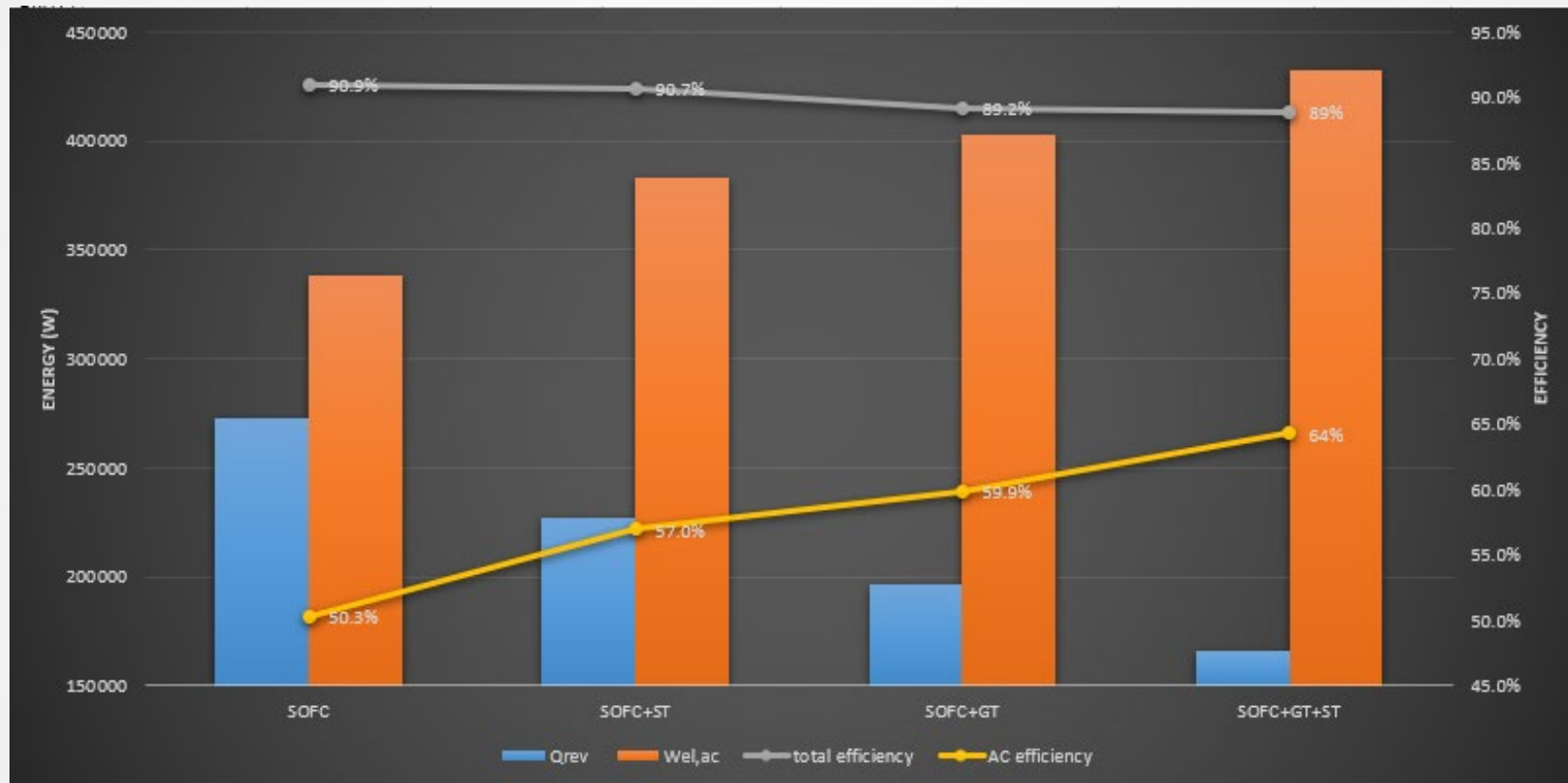
the initial investment cost increased by 12.4%  
(158,450 €)

$$IRR = 6.51 \%$$

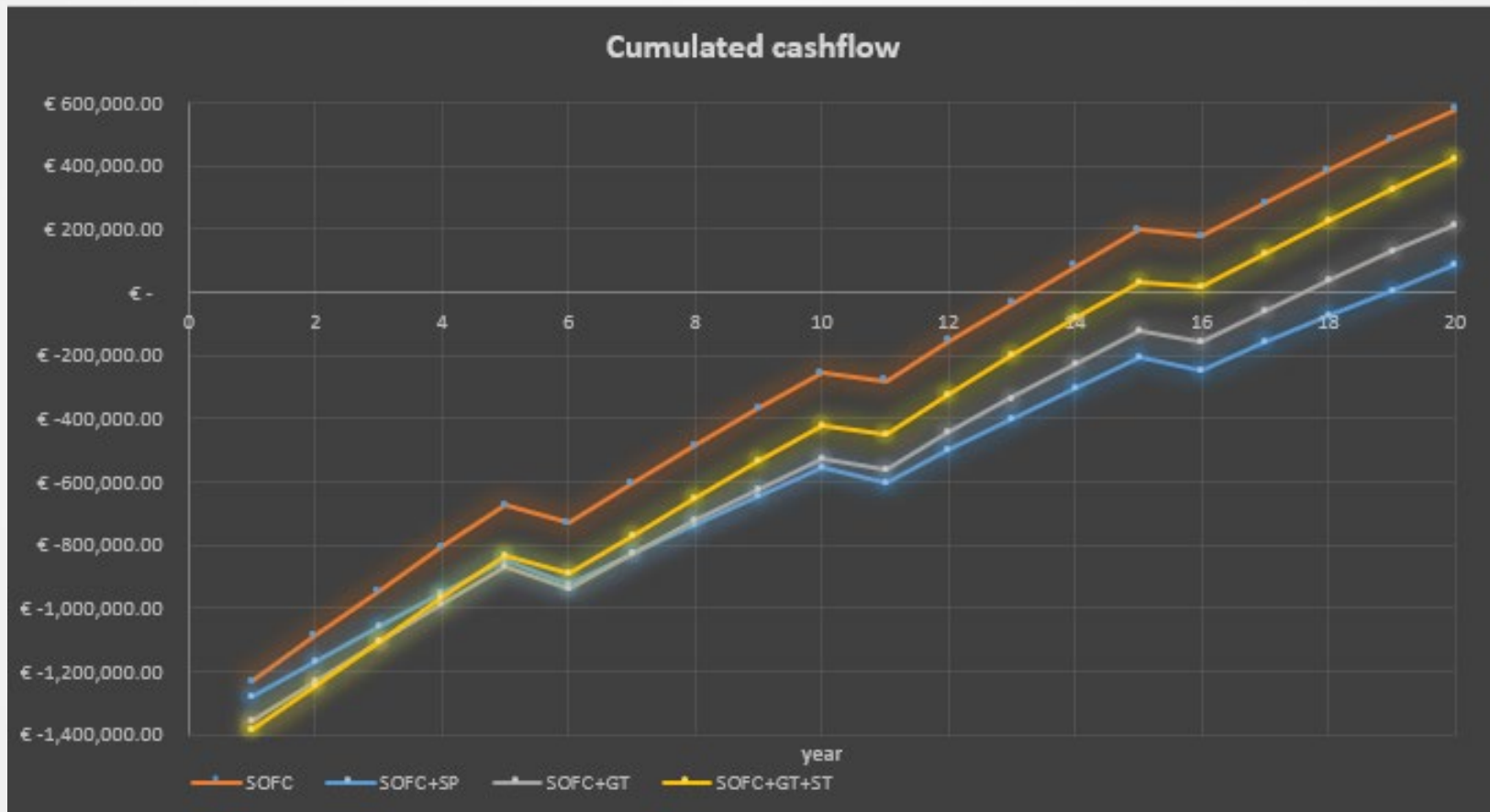
the annual expenditure soared by 55.9%  
(62,488 €)



# Conclusions



# Conclusions



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