Thermodynamic, ecological, and economic analysis of negative CO_2 emission power plant using gasified sewage sludge

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Abstract - Currently, sewage sludge is considered as a biomass, according to the Polish act on renewable energy sources from 20th of February 2015 and its novel version from 19th of July 2019. Possibility to utilize sewage sludge in gasification process is an additional advantage of the negative CO_2 emissions power plant (nCO_2PP). The work presents results of thermodynamic, ecological, and economical analysis using a zero-dimensional mathematical models of a negative CO_2 emission novel structure power plant. Parameters of thermodynamic cycles such as output power, efficiency, combustion gas composition, exhaust temperature, avoided emission of carbon dioxide, as well Specific Primary Energy Consumption for Carbone Avoided (SPECCA), Discounted cash-flows, NPV, IRR etc., will be taken into account. Precise thermodynamic models are particularly important for Carbon Capture and Storage (CCS) and CCU (Carbon Capture and Utilization) energy system, where quite new devices mutually cooperate and their thermodynamic parameters affect those devices. Proposed negative CO_2 emission novel power plant includes wet combustion chamber, spray-ejector condenser, gas-steam turbine, sewage sludge gasifier, separator of CO_2, to determine the effect of cycle into environment. First of all, the possibility of a negative CO_2 emission power plant and the positive environmental impact of the proposed solution has been demonstrated. Secondly, the technical-economic analysis made for presented feasibility study showed the high profitability of the installation which allows to: 1) gasification and vitrification of the sludge, 2) energy generation and 3) CO_2 capture. All these activities are the basis of revenues or avoided costs. According to the performed analysis, the real return period for assumed commercial scale installation is 4 years. Internal rate of return is also high (IRR=24.11%). The main conclusion is that the investment in the analysed installation is profitable.

1 Introduction

Nowadays, mankind is facing threats of its own making, namely global warming [1] and the huge production of waste [2]. Of course, various efforts are being made to reduce greenhouse gases [3-7], but more determined steps are required, among which Bioenergy with Carbon Capture and Storage (BECCS) could be one [8]. It should be added that, sewage sludge utilization by plasma use is one of the main interests of the waste treatment industry. High-temperature decomposition of sludge (by using a plasma torch) enables safe waste recovery and excludes contamination by heavy metals of the resulting P-rich product. The plasma technology has the benefit that besides a P-rich product, which can be practically free of heavy metals, it also offers very interesting co-products. The produced tar-free rich in hydrogen synthesis gas (syngas) can be used in the next cycle of the waste treatment as a fuel for energy production (e.g. CHP). In spite of the required electricity, which is needed to generate plasma and can be considered a downside of this technology, the advantages of that technology prevail applied to sewage sludge utilization. Among advantages, one should mention that such technology is easily controllable, with a much simpler start-up [2].

Considering the above-mentioned issues, it can be concluded that the research carried out in the grant dedicated to the negative CO_2 emissions power plant with carbon dioxide capture and integrated with gasification process is of the greatest possible environmental benefit [9]. However, this effect needs to be confirmed on concrete values and analyses need to be carried out to further determine thermodynamic parameters and economic balances. So far, this circuit has been analysed from an energy perspective using three calculation codes [10]. Also, the parameters necessary for sewage sludge gasification were determined based on a steam converter experiment, which was finally validated in a paper [11].

Techno-economic analyses of the process of syngas production from sewage sludge are becoming increasingly common and provide opportunities to determine the profitability of gasification [12]. Also, economic-environmental analyses e.g. for the integration of biomass gasification with electricity production cycles are becoming a decisive indicator for industrial investments [13]. Analyses using oxyfuel combustion are also becoming more and more widespread, as starting from basic techno-economic analyses [14,15], it is possible to move on to whole strategies that ensure beneficial CO_2 capture [16]. These analyses can be further extended obtaining a combined determination of technical, environmental and economic benefits [17]. Finally, the use of CO_2 in methanol production can also be considered [18].

Thus, the main objective of this paper is first to gather the results of thermodynamic and ecological analyses and, on their basis, to carry out an economic analysis which will indicate whether the investment of an nCO_2PP power plant pays off and at what level such an installation can be profitable.

2 Process flow diagram of nCO_2 cycle for sewage sludge utilization

In Figure 1 is presented process flow diagram of the nCO_2PP cycle with gasification of sewage sludge, where can be indicated three essential parts of power plant, as the first area of fuel preparation (sewage sludge gasification), the second area of combustion of the previously created fuel and electricity generation, and the third area of carbon dioxide separation and capture. These areas are interconnected in a way that ensures a full flow of streams from the area of electricity generation to the area of gasification, which is shown among other things by the dimensionless coefficient mass of dry syngas produced per 1 kg of dried sewage sludge ($b^{(d)}_{\frac{gas}{fuel}}$).

It is also important that part of the carbon dioxide stream can be added as gasifying agents in the reactor or as an inert agent in the wet combustion chamber. Computational Fluid Dynamics (CFD) calculations are currently being carried out in the project, of key elements of the system, but the focus of this paper is on zero-dimensional calculations referred to as design calculations.

Process flow diagram of nCO_2PP cycle consists of sewage sludge utilization with fuel preparation, energy generation and CO_2 capture in spray-ejector condenser (SEC) and Carbon Capture Storage (CCS) units. Fuel comes out from Gasifier (R) as the product of the thermochemical process transformation of supplied dry sewage sludge in the presence of gasifying agent. The gasifying agent is released after GT with optional release from Carbon Capture Unit (CCU) at ambient pressure and consists of a mixture of steam and CO_2. The gasifying agent properties such as content of CO_2, steam and its temperature or pressure can be controlled as required. Oxygen Compressor (C_{O2}) is supplied from Air Separation Unit (ASU).

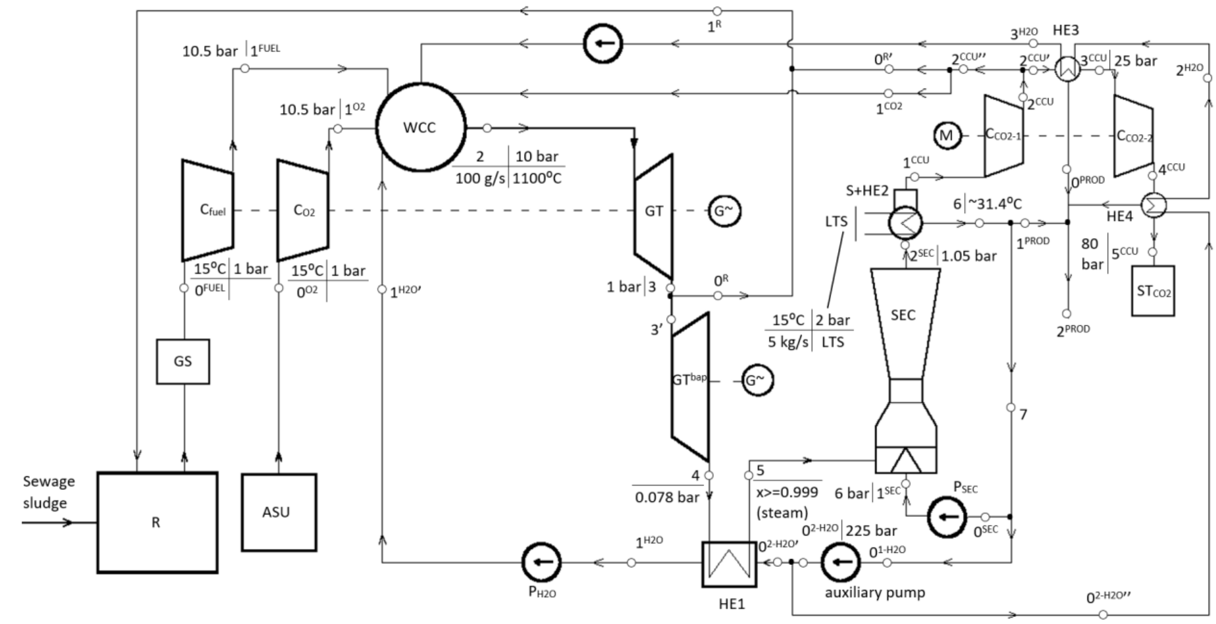

Figure 1: Process flow diagram of the nCO2 cycle for sewage sludge utilization with spray ejector condenser, where: WCC – Wet Combustion Chamber, SEC – Spray-Ejector Condenser, R –Gasifier (Reactor), GT – Gas-steam Turbine, GT^{bap} – Gas-steam Turbine - below ambient pressure, C_{fuel} – Fuel Compressor, C_{O2} – Oxygen Compressor, $C_{CO2\text{-}1,2}$ – CO_2 capture unit compressors 1 and 2, P_{H2O} – Water Pump supplying supercritical water, P_{SEC} – Water Pump supplying SEC, S+HE2 – Separator with Heat Exchanger 2, HE1,3,4 – Heat Exchanger 1, 3 and 4, ASU – Air Separation Unit, GS – Gas Scrubber, G~ – Power Generators, M – Motor, LTS – Low-temperature source, ST_{CO2} – CO_2 Storage Tank.

SEC sucks the exhaust from the Heat Exchanger 1 (HE1), while the motive fluid is supplied to SEC through dedicated Pump (P_{SEC}). The outlet mixture of condensed steam and moist CO_2 vapour from SEC is directed to Separator with Heat Exchanger 2 (S+HE2) where Low Temperature Source (LTS) is supplied, and separation of CO_2 takes place. Water from HE2 is directed to P_{H2O} and P_{SEC}, while excess water is discharged out of the plant. Humid gas, namely CO_2+H_2O from Separator is directed to the CCU in which after each CO_2 Compressor

1 and 2 (C_{CO2-1} and C_{CO2-2}) there are intercoolers Heat Exchangers 3 and 4 (HE3 and HE4) with decantation which are supplied with water supplied from P_{SEC}. Water after heating in CCU is directed to WCC where it reaches supercritical conditions. Partial release of CO_2 gas can be used as gasifying agent to Gasifier (R) or to WCC to manipulate in order to obtain desired chemical reactions pathway. CO_2 is directed to CO_2 Storage Tank (ST_{CO2}) or it can be used for other processes like methanol production.

Taking the above into account in Figure 1 we can distinguish such islands of devices with corresponding nodal points as:

- general thermodynamic cycle: 0^{FUEL}, 0^{O2}, 1^{FUEL}, 1^{O2}, 2, 3, 3', 4, 5, 6, 7, optional: 2',
- CO_2 capture unit: 1^{CCU}, 2^{CCU}, 3^{CCU}, 4^{CCU}, 5^{CCU}, optional: $2^{CCU'}$, $2^{CCU''}$,
- SEC: 0^{SEC}, 1^{SEC}, 2^{SEC},
- gasifying agent supply: 0^{R}, optional: $0^{R'}$,1^{R},
- water production: 0^{PROD}, $1^{PROD'}$, 2^{PROD},
- optional CO_2 injection to WCC: 1^{CO2},
- water supply: 0^{1-H2O}, 0^{2-H2O}, $0^{2-H2O'}$, $0^{2-H2O''}$,1^{H2O}, 2^{H2O}, 3^{H2O}, optional: $1^{H2O'}$, $1^{H2O''}$, $3^{H2O'}$, $3^{H2O''}$.

In the nCO2PP the motive fluid has to be $H_2O_{(l)}$ (1^{SEC}) while the entrained fluid (5) is the mixture of $CO_{2(g)}$ and $H_2O_{(l)}$ or $H_2O_{(g)}$. Both $CO_{2(g)}$ and $H_2O_{(g)}$ vapours occupies large volume causing decrease of efficiency. For the optimum case with novel approach steam $H_2O_{(g)}$ would immediately be condensed in mixing chamber of SEC contributing to efficiency will obtain higher efficiency than in the less favourable case, in which steam would be partially condensed in SEC resulting in decrease of efficiency due to increase of required motive fluid mass flow.

3 Analysis of the negative CO_2 emission power plant using gasified sewage sludge

The basic assumptions for proper modelling of the cycle described above in terms of thermodynamic and ecological analyses have been presented in previous articles by the authors [10-11]. The thermodynamic analyses presented in this paper have been achieved using Aspen Plus, and definitions of the efficiencies used have been presented in previous work [10,11].

3.1 Thermodynamics analysis

The zero-emission cycle as well as the nCO2PP system have a carbon dioxide capture facility and the main difference results from a different type of fuel. In zero emission gas power plants, natural gas (methane) is usually used as a fuel, whereas in carbon negative systems, i.e. also in nCO2PP, fuel coming from a renewable energy source. Fuel compositions for the analysed cycle can be found in [10].

Table 1 shows different systems for nCO2PP and one zero-emission unit. The Table 1 highlights:

1) a demonstration (demo) plant being developed in the articles [10];

2) a commercial one achievable in the near future, which would operate at a sewage treatment plant supplying 10,000 tonnes per year (Mg/year) of dry sewage sludge;

3) great power output - which could replace conventional power plants in the future

4) zero-emission unit being developed in the articles [19].

The net system efficiency of the system was calculated according to the formula:

$$\eta_{net} = \frac{N_t - N_{C-fuel} - N_{C-O2} - N_{P-H2O} - N_{CCU} - N_{p-SEC}}{\dot{Q}_{CC}} \tag{1}$$

where:

N_t – combined turbine power on the shaft in [kW],
N_{C-fuel} – power for fuel compressor in [kW],
N_{C-O2} – power for oxygen compressor in [kW],
N_{P-H2O} – power for water pump P_{H2O} in [kW],
N_{P-SEC} – power for water pump $P_{SEC\ supplying}$ SEC in [kW],
N_{CCU} – combined power for CO_2 capture unit compressors [kW],
$\dot{Q}_{CC}$ – chemical energy rate of combustion in [kW].

Optimistic performance of SEC represents situation, in which pump power consumption can be obtain for water vapor quality *x*=0 in mixing part of SEC. However, the gross efficiency of the cycle was described by the equation as follows:

$$\eta_g = \frac{N_t}{\dot{Q}_{CC}}\ [-] \tag{2}$$

Power for own needs:

$$N_{CP} = N_{C-fuel} + N_{C-O2} + N_{P-H2O} + N_{P-SEC} + N_{CCU} \tag{3}$$

Chemical energy rate of combustion in WCC:

$$\dot{Q}_{CC} = \dot{m}_{fuel} \cdot LHV\ [kW] \tag{4}$$

where:

$\dot{m}_{fuel}$ – mass fuel flow in [g/s],
LHV – lower heating value in [MJ/kg],

The Peng-Robinson gas model has been used for calculations. Other details of the cycle model can be found in the work [10]. Mass of dry gas obtained from 1 kg of feedstock gasification, formula including CO_2 from the gasifying agent is the following form [11]:

$$b^{(d)}_{\frac{gas}{fuel}} = \frac{M_{gas} \cdot \left(1 - x_{H_2O}\right)}{\left(x_{CO_2} + x_{CO} + x_{CH_4} + x_{COS} - n_{con} \cdot x^{con}_{CO_2}\right)} \cdot \frac{C}{M_C} \left[\frac{\text{kg gas}}{\text{kg fuel}}\right] \tag{5}$$

where:

C – mass fractions of carbon in the feedstock,
M_C – molar masses of carbon,
M_{gas} – molar masses of produced gases,

n_{con} – required mole amount of converter per 1 kmole of syngas,
$x_{CO_2}^{con}$ – molar fraction of CO_2 in gasifying agent in [%mol].
$x_{CO_2}, x_{H_2O}, x_{CO}, x_{CH_4}, x_{COS}$ – molar fractions of ingredients in [%mol].

Additionally, it is worth mentioning that the table adjusts the flue gases mass flow rates in the GT turbine for a great power output solution, which could constitute a utility power plant analogous to the system studied in the article [19]. In order to achieve the possibilities of a commercial solution or even a great power output solution for an nCO_2PP power plant, it is worthwhile to first refer to a zero-emission power plant. The high-power turbine was designed for the power that is used for power units in Poland. Its gross and net efficiencies are close to those specified for the system under consideration in this paper (nCO_2PP).

Table 1: Thermodynamic analysis results of negative CO_2 emission power plant using gasified sewage sludge vs methane for zero-emission.

Parameter	Symbol	Unit	Value			
Fuel type	–	-	Produced gas – nCO_2PP			Methane
Purpose of the nCO_2PP installation			Demo [10]	Commercial	Great power output	Zero-emission Great power output [19]
Exhaust mass flow in GT	$\dot{m}_2$	g/s	100	1463.89	182300	182300
Dried Sewage Sludge mass flow annually	$\dot{m}_{SS}$	Mg/year	683.1	10000	1245300	---
Mass of dry syngas produced per 1 kg of dried sewage sludge	$b_{\frac{gas}{fuel}}^{(d)}$	kg	0.77			---
Syngas mass flow produced annually	$\dot{m}_{fuel}$	Mg/year	525.0	7700	958881	---
Fuel mass flow	$\dot{m}_{1-fuel}$	g/s	16.68	244.17	30406.49	12830
Oxygen mass flow	$\dot{m}_{1-O2}$	g/s	21.21	310.44	38659.09	51800
Water mass flow	$\dot{m}_{1-H2O}$	g/s	62.11	909.29	113233.9	117700
CO_2 mass flow in exhaust	$\dot{m}_{2-CO2}$	g/s	22.68	331.98	41341.47	35238.59
Water mass flow in exhaust	$\dot{m}_{2-H2O}$	g/s	76.50	1119.83	139452.4	146514.5
Water production	$\dot{m}_{p-H2O}$	g/s	14.38	210.55	26219.79	28200
Combined turbines gross power	N_t	kW	155.9	2282.8	284277.1	410570.1
Chemical energy rate of combustion	$\dot{Q}_{CC}$	kW	284.86	4170.07	519298.8	784578.8
Net efficiency with optimistic SEC	η_{net}	%	39.43	39.43	39.43	37.78
Gross efficiency	η_g	%	54.74	54.74	54.74	52.33

Table 1 also includes the parameters for the mass flow rates of the individual components as well as the chemical energy rate delivered in the combustion chamber. The basic conclusion that emerges after analysing this table and the result of the thermodynamic analysis is that we can use the models developed for the analysis of classical thermodynamic cycles in the analysis of BECCS systems.

3.2 Ecological analysis

The ecological analysis was based on carbon dioxide emissions per net electrical power output. A comparison of the emissivity of the systems for the different options is summarised in Table 2. Of the parameters which determine carbon dioxide emissions are especially noteworthy:

$$e_{CO_2} = \frac{\dot{m}_{2-CO2}}{N_t - N_{cp}} 3600 \tag{6}$$

$$\eta_{net} \cdot e_{CO_2} = \frac{N_t - N_{cp}}{\dot{Q}_{CC}} \frac{\dot{m}_{2-CO2}}{N_t - N_{cp}} 3600 = \frac{\dot{m}_{2-CO2}}{\dot{Q}_{CC}} 3600 \tag{7}$$

where:
$\dot{m}_{2-CO2}$ – mass flow rate of CO_2 in exhaust in [g/s]. Ecological analysis was determined for different exhaust mass flow rate $\dot{m}_2 = variable$, however both equations (6-7) express quantities not dependent on amount of working medium.

Specific primary energy consumption for CO_2 avoided (SPECCA) can be defined as follows [20]:

$$SPECCA = 3600 \frac{\frac{1}{(\eta_{net})_{with\,retr.}} - \frac{1}{(\eta_{net})_{wo.retr.}}}{e_{CO_2,wo.retr.} - e_{CO_2,with\,retr.}} \quad \left[\frac{MJ}{kg_{CO_2}}\right] \tag{8}$$

where:
$(\eta_{net})_{wo.retr.}$ – efficiency of methane conventional power plant;
$(\eta_{net})_{with\,retr.}$ – efficiency of power plant taking into account retrofit;
$e_{CO_2,wo.retr.}$ – emissivity of the systems burning methane in conventional power plant;
$e_{CO_2,wo.retr.}$ – emissivity of the systems after retrofit.

In the traditional view, both parameters show the emissions of the unit, but in the case of nCO_2PP they are an indicator of the negative emissions related to the electrical energy obtained from the cycle or to the chemical energy supplied to the cycle, respectively.

As shown in Table 2 in the conventional cycle where methane is burnt the emissivity related to the electrical energy e_{CO_2} is 418.78 kg/MWh_{el} and in case of emissivity related to the chemical energy $\eta_{net} \cdot e_{CO_2}$ is 197.42 kg/MW_{ch} and we have to use an additional set of equipment to avoid carbon dioxide emissions.

In the zero-emission power plant, on the other hand, we capture carbon dioxide and thus avoid emissivity related to the electrical energy at the level $e_{CO_2} = 475.33$ kg/MWh_{el} and in case of emissivity related to the chemical energy we avoid $\eta_{net} \cdot e_{CO_2} = 197.45$kg/$MW_{ch}$, respectively. In the case of nCO_2PP the indicated coefficients are much more favourable. Both parameters show that the avoided emissivity of the block after carbon dioxide capture is equal to twice the absolute value of the previously determined numbers. Specific primary energy consumption for CO_2 avoided has been introduced to compare different solutions [20]. The SPECCA value reaches 0.999 and 0.822 for zero-emission and negative emission power plant [10], respectively. However, for research in article [20], MEA is classified at the level 4.16.

Table 2: Ecological analysis results of negative CO_2 emission power plant using gasified sewage sludge vs methane for zero-emission [10].

Parameter	Symbol	Unit	Methane conventional power plant	Methane zero-emission power plant	Syngas negative CO_2 power plant
Net efficiency	η_{net}	%	47.1	41.5	39.4
Emission of carbon dioxide	e_{CO_2}	kg/MWh	418.78	0.0	-727.12
Relative emissivity of carbon dioxide	$\eta_{net} \cdot e_{CO_2}$	%kg/MWh	197.42	0.0	-286.70
Avoided emission of carbon dioxide	Avoid e_{CO_2}	kg/MWh	0.00	475.33	1454.23
Avoided relative emissivity of carbon dioxide	Avoid $\eta_{net} \cdot e_{CO_2}$	%kg/MWh	0.00	197.45	573.40

3.3 Economic analysis

The economic analysis was elaborated for a commercial scale installation of capacity 10 000 Mg/year mass flow rate of sewage sludge (see Table 1). The technical scale installation is designed based on commercial components (like pumps, oxygen generating station, heat exchanger etc.) and their operational reliability is high (they have guarantee of their producers). The turbine with WCC and SEC, sludge drying system and gasifier with plasmatron remain prototypes so far, although they will be tested in smaller scale firstly. In order to perform the economic analysis of sludge gasification for energetic purposes the following cost assumptions were made:

1. The heat produced in the installation will be consumed for drying the sludge (installation self-consumption).
2. The prices were taken from polish market (prices of components, and for energy or emissions or disposal as well).
3. Prices are in EUR.
4. Exchange rate 4.7 PLN/EUR.
5. Discount rate: 5.6 %, based on WIBOR index (Mai 2022).
6. Considered period of exploitation: 10 years.
7. Price of the sewage slug disposal: 85.11EUR/Mg.
8. Price of the electrical energy: 145.5 EUR/MWh.
9. Avoided cost of CO_2 emission: 88.31 EUR/Mg (basing on [21]).

These assumptions apply to the Mai, year 2022. In the last half year electricity prices have risen recently,and are as follows: in Poland 145.5 EUR/MWh (March 2022), globally 128

EUR/MWh, Germany 317 EUR/MWh. Recently, higher prices for avoided CO_2 emissions have also been quoted, namely 88.31 EUR/Mg (as of 13.05.2022).

The results were shown as *NPV* ratio (Net Present Value) described by formula (9), *IRR* (Internal Rate of Return) formula (10) and return period.

Net present value (*NPV*) is a standard method for the financial appraisal of long-term projects. Used for capital budgeting, and widely throughout economics, it measures the excess or shortfall of cash flows, in present value (PV) terms, once financing charges are met.

$$NPV = \sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} - I_0 \tag{9}$$

where:

NPV, CF_t and r are Net Present Value, the net cash flow (the amount of cash) at time t, and discount rate (the rate of return that could be earned on an investment in the financial markets with similar risk), respectively.

I_0 is initial expenditures,

t represents time of the cash flow and

n refers to number of years.

From economic point of view, the most profitable undertaking generates the highest cumulated cash flow in the considered exploitation period of a negative CO_2 gas power plant.

The internal rate of return (*IRR*) is a capital budgeting metric used by companies to estimate whether they should make investments. It is an indicator of the efficiency of an investment, as opposed to net present value (*NPV*), which indicates value or magnitude.

The *IRR* is the annualized effective compounded return rate, which can be earned on the invested capital, i.e., the yield on the investment. A project is a good investment proposition if its *IRR* is greater than the rate of return that could be earned by alternate investments (investing in other projects, buying bonds, even putting the money in a bank account). Thus, the IRR should be compared to any alternate costs of capital including an appropriate risk premium. In general, if the *IRR* is greater than the project's cost of capital, or hurdle rate, the project will add value for the company.

Mathematically the *IRR* is defined as any discount rate that results in a net present value of zero of a series of cash flows. To find the internal rate of return, the value of r should be found, that satisfies the following equation:

$$\sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} - I_o = 0 \tag{10}$$

where:
IRR – Internal Rate of Return,
CF_t – net cash flow (the amount of cash) at time t,
r – discount rate (the rate of return that could be earned on an investment in the financial markets with similar risk),
I_0 – initial expenditures,

t – time of the cash flow, and
n – number of years.

For the purpose of *IRR* calculation, the new cash flows were created. The cash-flows were generated basing on investment costs, exploitation costs and technical data. The most important data taken to the economic analysis were shown in the Table 3. Investment costs were estimated by market analyses and by project partners as well. The main cost components were shown in the Table 4.

Table 3: Main technical data for economic analysis

No.	Description	Unit	Value
1.	The annual stream of sewage sludge in working condition	Mg/year	10 000
2.	Amount of CO_2 captured in the installation	Mg/year	10 469.5
3.	Amount of electricity generated in the installation	MWh/year	19 997.6
4.	Amount of electricity for own needs	MWh/year	5 592.9
5.	Net electrical energy	MWh/year	14 404.7

Table 4: Investment costs

No.	Description	Cost, EUR
1.	Gas turbine with a special combustion chamber	9 000 000
2.	Heat exchanger	12 300
3.	Spray-ejector condenser	330 000
4.	CO_2 compression system	40 000
5.	O_2 generating station	900 000
6.	Pumps	41 910
7.	Plasma gasifier	310 000
8.	Pre-treatment	980 000
9.	Syngas cleaning system	600 000
	TOTAL	12 214 210

Other expenditures shown above are costs of estimated costs of installation and commissioning of the installation.

The incomes or avoided costs (i.e. sludge disposal or CO_2 emission cost) were presented in Table 5. They were calculated on the basis of prices given in assumptions and technical data from Tables 1 -3.

Table 5: Yearly incomes/avoided costs for the installation

Description	EUR/year
Avoided cost of sewage sludge disposal	851 100
Avoided cost of CO_2 emissions	924 562
Electricity produced (netto)	2 095 884
TOTAL	3 871 545

Additionally from the third year of analysis the yearly cost of servicing and maintenance of the turbine 900 000 EUR was added to cash-flows.

All data showed in the tables above were used for calculating cash-flows showed in the Figure 2.

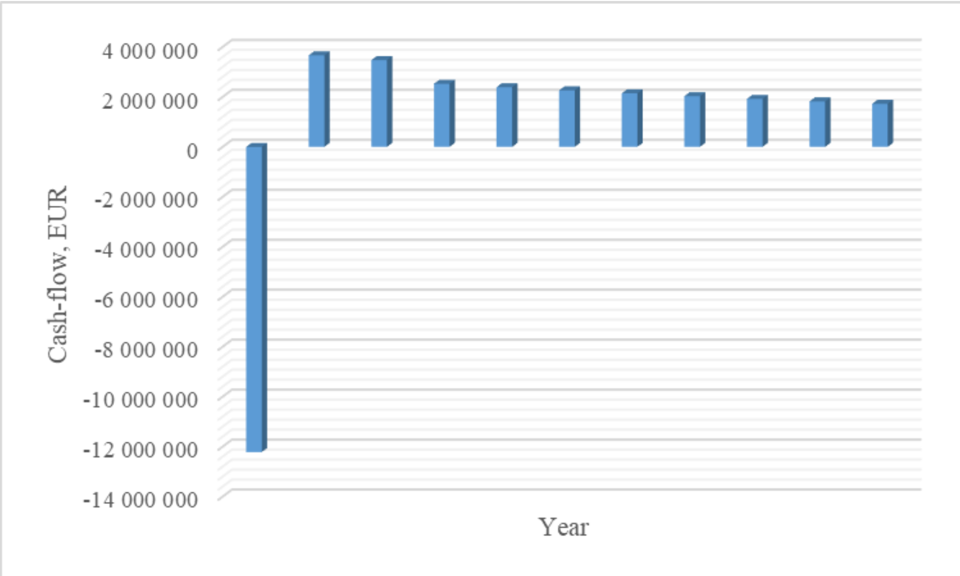

Figure 2: Discounted cash-flows of the analysed installation

The first cash-flow concerns period 0, where investment expenditures are made. Consecutive positive flows show incomes of the installation. They are lower from the third year when servicing and maintenance costs were added.

From the economic point of view the most important are cumulated discounted cash-flows, shown in the Figure 3.

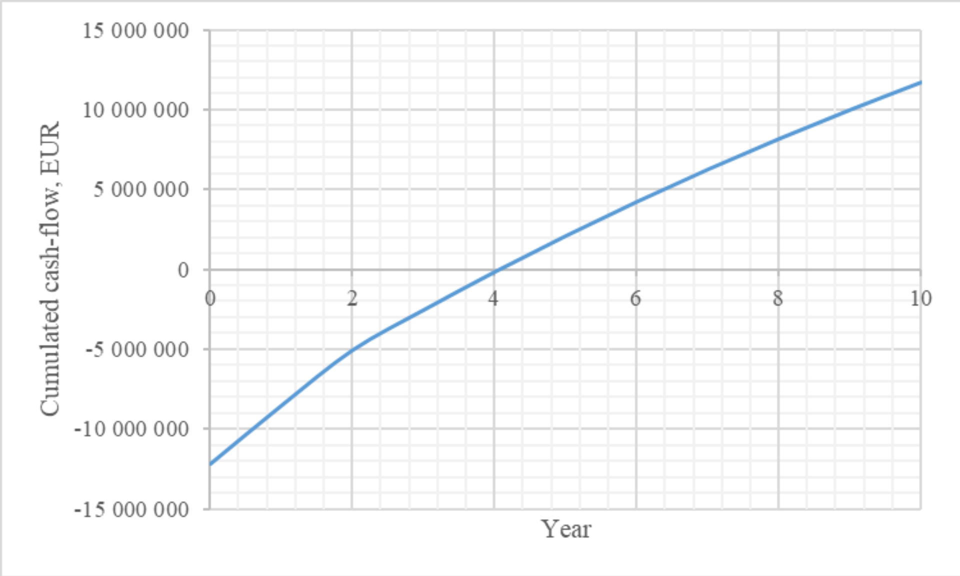

Figure 3: Discounted cumulated cash-flows of the analysed installation

The analysis showed high profitability of analysed installation in commercial scale. The real return period (when the plot crosses the X axis) is 4 years.

Other parameters calculated for the feasibility study: *NPV* = 11 114 100 EUR and *IRR* = 24.11%.

4 Conclusions

The technical-economic analysis made for the developed negative CO_2 emission power plant, including vitrification the inorganic fraction of sludge, energy generation, and CO_2 capture, showed high profitability of the analysed installation. All these activities are the basis of revenues or avoided costs. The commercial scale installation will return investments after 4 years. Internal rate of return is also high (IRR=24.11%). The main conclusion is that the investment in the analysed installation is profitable. It should be also mentioned that it will bring positive environmental and social effects as well.

Performed analysis shows that all three assumed revenue streams are important, in terms of the profitability of the installation, and efforts should be undertaken to maximise each of them, namely: 1) gasification and vitrification of the sludge, 2) energy generation and 3) CO_2 capture. It should not be overlooked, that vitrified residue was assumed to be given away at no cost.

Further commercial efforts, leading to assuring the customers of the safety of this alternative construction material (aggregate), are expected to lead to acceptance among the customers, bringing the fourth revenue stream as a consequence. This would improve profitability of the installation and should be takin into consideration in the future works. Therefore, the project nCO_2PP will develop technologies for the management of syngas arising from the gasification of sewage sludge and a dedicated wet combustion chamber plant using oxy-combustion for the developed fuel type.

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