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An economic analysis of three operational co-digestion biogas plants in Germany

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ABSTRACT
As for other renewable energies in Germany, biogas production has rapidly expanded in recent years, such that the current installed capacity in this country accounts for around half of the European total. Against this background, and recognising the actual research need in the profitability analysis of along the whole supply chains for biogas, this paper carries out an economic analysis of three operational German co-digestion biogas plants, which employ biowaste, sewage sludge and energy crops for electricity production as well as for injection of biomethane into the natural gas grid. The profitability of the considered plants is assessed using the static Profit Comparison and the dynamic Net Present Value methods. From the analysis of each of the plants based on several technical and economic assumptions, the production costs for electricity and biomethane have been derived. Investment-related costs and substrate prices represent the most important financial variables of the considered plants. The electricity production from energy crops appears to be the most lucrative option, with a dynamic pay-back period of 6.7 years. Hence, subsidies and incentive schemes for biogas play a key role for the plants using energy crops as well as for plants using biowaste and sewage sludge. Furthermore, process failures under mesophilic conditions are here briefly described and could affect the biogas yield and thus have an influence on the profitability of the plants. The obtained results represent the foundation for a forthcoming comprehensive energy system analysis of the integration of biogas into the German energy system.

Keywords Co-digestion; Techno-economic analysis; Biomethane; Production costs

1. Introduction

Processes aiming at biomethanegas production can be divided into two main categories: biochemical (anaerobic digestion) and thermo-chemical (e.g. gasification, see Fig. 1). In Germany, about 5800 biogas plants based on anaerobic digestion processes, corresponding to a total installed electrical capacity of 2,300 MW_{el}, were operating in the year 2010 [1], meeting the electrical needs of around ten million households. By comparison, about 1000 similar plants were counted in the year 2000, which demonstrates the recent rapid growth within this sector.

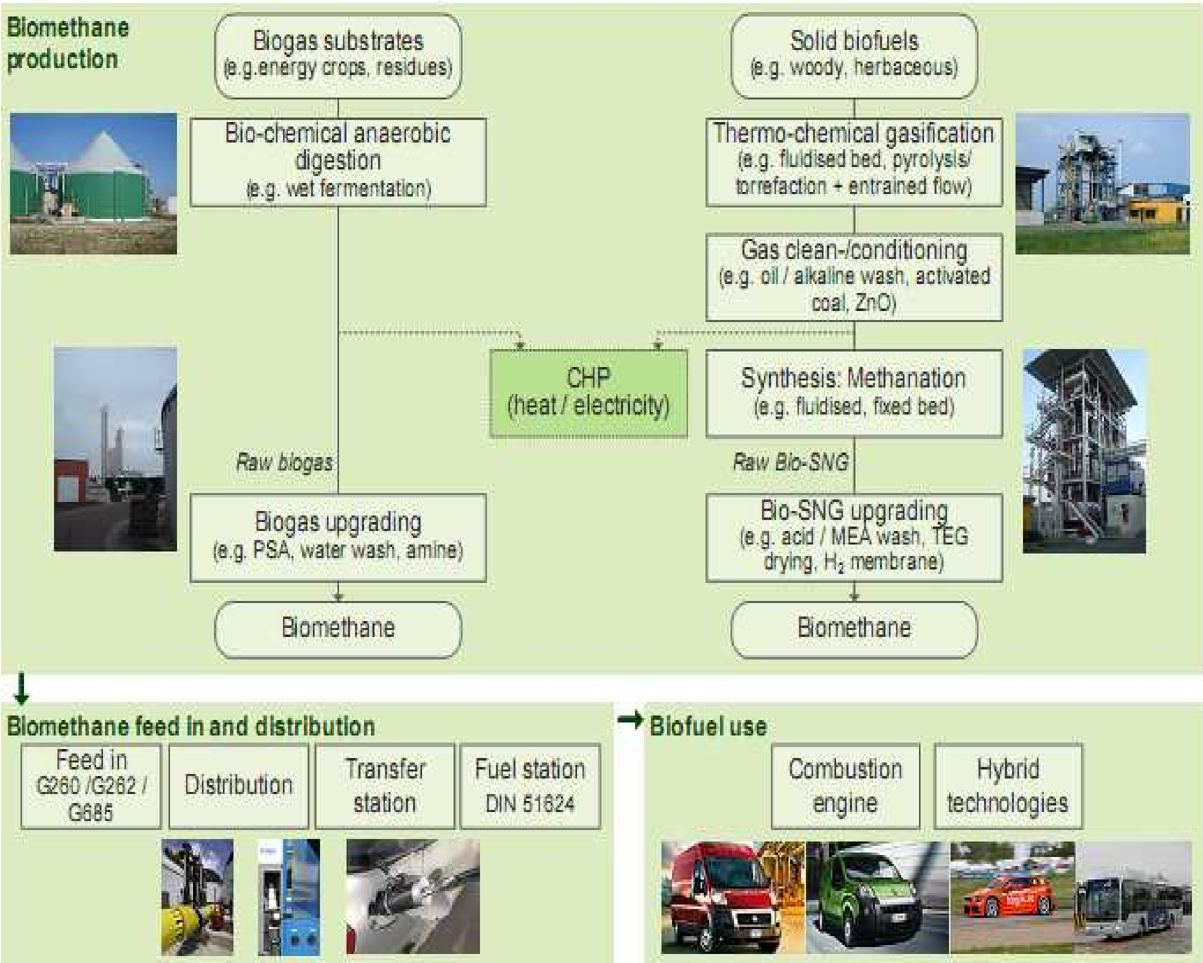

Fig.1. Energetic biomass valorization pathways [2]

There is an important research need in the techno-economic assessment and optimization of existing biogas plants and valorization routes. The maximization of the biogas yield and consequently of the operating profit are crucial tasks for plant operators. In this respect, subsidies play a very important role: in Germany compensation from renewable electricity production is determined by the German Renewable Energies Act 2009 [3]. The EEG guarantees the plant operators fixed tariffs for electricity fed into the grid (i.e. feed-in tariffs) for a period of 20 years plus the year it was taken into operation.

The present paper analyses three operative co-digestion plants valorizing, through biochemical anaerobic digestion, biowaste and sewage sludge for electricity production on the one hand and several energy crops (maize silage and wheat) both for electricity and biomethane generation on the other. The whole supply chain is considered, from the substrate transportation to the plants, through the biogas production and finally up to the energy production and distribution through the German gas and electricity grids (see Table.1.).

Table.1. Overview of the investigated pathways, corresponding to Plants A, B and C.

Application	Substrates used for co-digestion	
	Biowaste and sewage sludge	**Energy crops (maize silage and wheat)**
Heat and electricity	Plant A: Combined Heat and Power (CHP): 2 x 380 kW_{el}	Plant B: Combined Heat and Power (CHP): 1 x 500 kW_{el}
Biogas upgrading and biomethane feed-in	*Not considered in this paper*	Plant C: Biomethane feed-in (260 Nm^3/h) after biogas upgrading

This paper is structured as follows. Firstly an overview of biogas use and potential in Europe is given. The second part of the literature review focuses on the assessment of production costs for electricity from biogas and biomethane. The methodology used for the economic assessment of Plants A, B and C, namely a static Profit Comparison method and a dynamic Net-Present-Value method, is presented in section 3. The main general assumptions used for the techno-economic evaluation are also described. For each of the three plant types a brief technical description of the involved process is then given, followed by a capital investment estimate based on plant operators' data as well as on the authors' assumptions. An assessment of investment-related and operating costs as well as an estimation of resulting revenues are finally carried out (sections 4, 5 and 6).

Production costs for electricity and for biomethane are then derived and compared with literature values. The results obtained in sections 4, 5 and 6 are compared and critically discussed in section 7, which identifies promising valorization pathways for the biogas produced from co-digestion processes, under several "What-If" scenarios. Sensitivity analysis of critical parameters, such as the amount of electricity fed into the grid, local subsidies for bio-wastes and sewage sludge and energy crops prices, on the operating results are carried out. The use of a potential composting-unit to treat the digestate of plant A is economically analysed and compared with other treatment concepts (co-firing). Then, the effects of process failures such as over-acidification, scum formation, and floating/sinking layers, are briefly described and suggestions for further work are presented. The paper concludes in section 8, by presenting some perspectives for policy and decision makers for the integration of biogas into the German energy system.

2. Literature Review

2.1. Biogas in Europe

This subsection gives an overview of biogas potential and use in Europe, whereas the focus in subsection 2.2 is on the situation in Germany. Across Europe diverse substrate types are employed for biogas production. According to [4], Italy was the fourth largest biogas producer in 2009 with 18.6 PJ, as primary energy production increased in 2009. The Italian government expects least 2,000 MW_{el} of plant to be constructed in the next 5 years. About 200 installations with combined capacity of about 200 MW_{el} were operating in 2009, due to the implementation of highly pro-active legislation geared towards agricultural biogas.

On the other hand, the UK strongly focuses on landfill-based biogas production. According to the DECC (Department of Energy and Climate Change), the UK produced 72.18 PJ of biogas in 2009, of which 61.73 PJ (85.5%) was landfill biogas [4]. The development of biogas on dairy farms in the UK was analysed by Butler et al [5], who concluded that the average dairy farm in the UK is at an early stage of development (only 30 plants valorizing biowaste according to the National Non Food Crops Centre) and not of sufficient size to allow profitable biogas production. Indeed, farm size needs to be scaled up by three to four times for a biogas enterprise to reach the break-even point. In order to reach a profitable situation, some farms may use additional energy (food and non-food) crops as well as other high energy sources such as biodiesel residues, etc. The engagement of neighboring farmers appears to be another solution: they could be involved in the management of a biogas installation in order to valorize manures from pigs and energy crops, which would increase the scale of an on-farm plant.In France, most of the energy produced (22.03 PJ in 2009) comes from biogas generated by the anaerobic digestion of non-hazardous waste (84% of the total). In 2009, there were also 74 urban wastewater plants and 90 effluent treatment stations, valorizing sludge primarily to produce heat and a small amount of electricity. Farm installations are under-represented with about 20 plants producing almost 100 GWh of biogas [4].

The case of Denmark should also be mentioned, where 20 centralised plant and over 35 farmscale plants, are treating manure and organic waste. However, no new centralised plants have been established since 1998 and the development of farm-scale plants has slowed down [6].

Finally, current Swedish biogas production amounts to approximately 5 PJ, equivalent to 0.3% of the total annual end energy use [7]. Ten percent of this produced biogas is currently upgraded and used as vehicle fuel in buses, distribution trucks and passenger cars [7] and the remaining is mainly used for heat or in combined heat and power plants. Estimates of the biogas potential in Sweden indicate approximately 50 PJ/year, implying the possibility of a 10-fold increase of the present production [8, 9]. A global overview of the primary biogas energy output (in PJ) in the European Union for the year 2009 is given in Table 2.

Table 2. Primary biogas energy output in the European Union in 2009

	Landfill gas (PJ)	Sewage and sludge gas (PJ)	Other biogas sources (energy crops and municipal solid waste, PJ)	Total (PJ)
Germany	11.11	16.19	149.1	176.4
United Kingdom	61.73	10.45	0.43 *	72.18
France	18.52	1.89	1.62	22.03
Italy	15.15	0,21	3.24	18.6
Netherlands	1.64	2.05	7.53	11.22
Spain	5.9	0.42	1.38	7.69
Sweden	1.44	2.51	0.62	4.57
Denmark	0.26	0.84	3.08	4.18
Poland	1.49	2.43	0.19	4.11
Finland [10]	1.28	0.45	0.16	1.89
European Union 25	125.67	42.1	181.74	349.48

* No concrete information about the primary biogas energy output (in PJ) from biowaste and energy crops in the United Kingdom was available. We have here assumed that from the existing 30 plants valorizing biowaste (information from the National Non Food Crops Centre), 0.33 PJ biogas were produced This amount corresponds to the biogas energy output generated by 30 biogas plants with a middle size of 378 kWel (running 8000 h/a). This middle size was obtained from 5 existing biogas plants valorizing energy crops according to the study of the ANDERSONS Centre "A detailed economic assessment of anaerobic digestion technology and its sustainability to UK farming and waste systems" (2nd edition)

2.2. Biogas in Germany

For several years now, Germany has developed agricultural biogas plants by encouraging the planting of energy crops. The value of investments relating to Germany was about 2.3 billion euros in 2010. andthe sector created 17,000 jobs in 2010. Furthermore, the use of biowaste in Germany in co-digestion with sewage sludge, aiming at biogas production for electricity generation in combined heat and power units (CHP) has been analysed in several studies [11, 12]. For this pathway, production costs of electricity were estimated at 42 ct/kWh$_{el}$ [11] and 32 ct/kWh$_{el}$ [12] respectively, for a 500 kW$_{el}$ plant in both cases using comparable quantities of biowaste and sewage sludge as in Plant A. The pathway "biomethane from biowaste" is at an early stage of development in Germany, but the case of a plant using 51,000 t/a biowaste for the production of 500 m^3/h raw biogas, to be upgraded to biomethane through high pressure wet scrubbing, is worth mentioning [13]. In that case, specific biomethane production costs of 13.5 ct/kWh$_{i,N}$ have been estimated. Urban [14] determined values for biomethane production costs from energy crops (mainly maize silage) of about 8.4 ct/kWh$_{i,N}$ for the treatment of

Table.3. Electricity and biomethane production costs reference values (literature values).

Study	Electricity from biowaste (Plant A type): production costs in ct/kWh_{el}	Electricity from energy crops (Plant B type): production costs in ct/kWh_{el}	Biomethane from energy crops (Plant C type): production costs in ct/$kWh_{i,N}$
Urban [14]			7.8
Thrän [1]	32.0	19.4	
FNR [16]		17.5	
Strahl [17]			8.0
FNR [16]	19.0	24.0	
ZSW [18]		17.0	
König, [19]		18.5	
Hessen Energie [20]		18.4	
Koch [15]	61.0	18.0	
Arlt [12]	42.0		
Schinnerl [21]			7.9

500 m^3/h crude biogas, and about 7.9 ct/$kWh_{i,N}$ for the treatment of 1,000 m^3/h[1]. Finally, for case of using energy crops to produce electricity from biogas combustion in CHPs, Koch [15] mentioned production costs of electricity of about 18 ct/kWh_{el} (co-digestion with 75% maize silage and 25% cattle manure). Table.3. sums up values of electricity and biomethane production costs for the three investigated pathways (Plant A type, Plant B type, Plant C type), based on a brief literature review. These values are quite independent of the types of energy crops employed, for electricity as well for biomethane generation. However, important variations of production costs for electricity production from bio-wastes can be observed, which is highly dependent on the substrate pre-treatment process, as discussed further in section 4.

3. General assumptions, methodology and plant's specifications

3.1. General assumptions and methodology

As a first step for each of the three analysed plants, the main technical design data are described, characterizing the whole supply chain, from the amount of valorized substrates, through the main process parameters, and finally up to the quantity of produced energy. For each plant, a capital investment estimate follows, based on several general assumptions as well as from plant operator information. From these derived capital investment estimates, investment-related costs are then calculated. The main assumptions concerning investment-related costs, energy requirements, substrates and utilities prices, transportation costs, revenues, process costs as well as grid assessment are summarised in Table.4. Furthermore, and for each of the three plants, equipment stand for 60% of the investment whereas the remaining 40% are associated to the construction part. Insurance costs represent 0.5% of the global capital investment estimates and the discount rate is set at 6%. Operation and maintenance, personnel, energy related, transportation, utilities and process costs are furthermore obtained from calculations based on plant owner's and operator's information. The revenues are estimated following several incentive schemes like the German Renewable Energies Act [3] for electricity production, as well as local subsidies for biowaste and sewage sludge energetic valorization. Revenues are primarily derived from the sale of

[1] These values refer to the lower calorific value for the gas and a CO_2-removal through a pressurized wet scrubbing process from the company Malmberg.

Table.4. General assumptions for the techno-economic assessment of Plants A, B and C

	Plant A	**Plant B**	**Plant C**
Energy requirements	Costs for energy requirements based on a fixed tariff for electricity production from sewage gas	Fixed diesel price (for transportation): 1.2 €/L (requirements: 0.5 L/t transported biomass) On site electricity demand represents 8% of the electricity production Fixed electricity price: 8 ct/kWh_{el} 70% of the heat produced by the CHP is used in a fertilizer production plant.	Fixed diesel price (for transportation): 1.2 €/L (requirements: 0.5 L/t transported biomass) Average electricity price of 8 ct/kWh 30 kWh_{el}/h are required for mixing in the digesters
Substrate and utilities prices	Anti-foaming agent: 3 €/kg Water: 1,88 €/ m^3 Chemical agent: 2.50 €/kg	30€/t maize silage and 120 €/t for wheat	30 €/t for maize silage and 120 €/t for wheat
Transportation costs	Transportation costs (over 20 km): fixed: 1.75 €/t, variable: 18 cent/(kmt)	Specific transportation cost of 5.5 €/t for maize silage, 6 €/t for wheat and 5.5 €/t for the digestate	Transport cost of 6 €/t for maize silage, and 6 €/t wheat Price for water: 1,81 €/m^3
Revenues	Revenues for Electricity fed into the grid (sewage gas): 6.16 ct/kWh_{el} Heat's sale: 5 ct/kWh_{th} 25.4 €/t: biowaste valorisation 19.4 €/t: sludge's valorisation	Revenues according to the German Renewable energies Act (EEG 2009): see section 4. Revenues from the digestate sale as a fertilizer: 6 €/t	Benefits 6 €/t for digestate sale
Operating costs (process costs)	26 €/t: co-firing of digestate		CO2-removal: 9.26 ct/m^3 biogas Desulphurization : 0.46 ct/m^3 biogas
Grid assessment (costs and avoided fees)			Fees associated with the natural gas grid use for plant operators : 0.6 $ct/kWh_{i,N}$ Specific costs for the connection to the natural gas grid: 0,15 $ct/kWh_{i,N}$ Specific subsidies for avoided network fees (GasNZV): 0.78 $ct/kWh_{i,N}$

electricity and heat or biomethane. The revenues from electricity production are calculated on the basis of the German Renewable Energies Act 2009 [3]. The applicable base tariffs for electricity from biomass vary with the electrical power of the considered plant and can be increased by taking into account several additional boni [3], as shown in Table.5. Furthermore, revenues of 5 $cent/kWh_{th}$ associated with the heat sale have been fixed [15]. Other revenues are linked to the biowaste and sewage sludge use into Plant A (see section 4.3).

Table.5. Base tariffs and boni for electricity from biogas feed-in to the grid in ct/kWh$_{el}$ (EEG 2009)

Electrical output range	**0 to 150 kW$_{el}$**	**150 to 500 kW$_{el}$**	**500 kW$_{el}$ to 5 MW$_{el}$**
Base tariffs for electricity fed into the grid	11.67	9.18	8.25
Energy crops bonus	7.00	7.00	4.00
Formaldehyde bonus	1.00	1.00	-
Manure bonus	4.00	1.00	-
Landscape maintenance grass bonus	2.00	2.00	-
Technology bonus (with injection from biomethane into the natural gas grid)	2.00 (for the treatment of 350 m^3/h raw biogas) 1.00 (for the treatment of 700 m^3/h raw biogas)		
Technology bonus (without injection)	2.00	2.00	2.00
CHP-Bonus	3.00	3.00	3.00

Finally, for Plants A, B and C, a comparison of the costs and revenues is carried out in each case, aiming at the calculation of the operating profits, defined as the difference between revenues and costs. Specific operating profits per unit of output (electricity and biomethane, with respect to the lower calorific value of the gas) are then determined. The profitability of each of the biogas plants is further assessed with the Net Present Value method. The lifetimes of the plants are assumed to be 20 years, the project's Net Present Value (NPV) is then determined [22] and the calculation of the dynamic payback period t_{eq} (defined as the amount of time required to recover the cost of an investment and associated interest repayments) is derived from the cash flows.

3.2. Specifications of the analysed co-digestion plants

3.3.1. Specification of Plant A

Plant A processes 15,000 m^3/a biowaste (mixed waste vegetables transported by trucks to the Plant) and 41,000 t/a sewage sludge (from an onsite existing waste water treatment plant) to produce heat and electricity in two cogeneration units of 380 kW$_{el}$ each. The considered biogas plant can be divided into zones: the biowaste pre-treatment zone, the anaerobic digestion operation, the energy production zone with the valorisation of biogas in Otto gas engines and finally the digestate treatment through centrifugal decanters. The biowaste is firstly stocked in silage for 20 days. Then a shredding operation follows, aiming at increasing the substrate's homogeneity. Furthermore, the substrates contain varying amounts of metallic components (e.g. iron), which could cause disturbances along the anaerobic digestion process and should be removed by an electromagnetic iron separator. The substrates are then cooled by a heat exchanger to 37°C before their entrance into the digesters. The fermentation process consists of the anaerobic digestion of the biomass at 37°C and 22 mbar in two digestion units operating 7,950 h/a at a pH of 7.3, and with a nominal retention time of 20 days. The energy production zone consists of one gasometer with a nominal volume of 780 m^3 and the two CHP-units.

Each gas engine has an electrical efficiency of 36% and a thermal efficiency of 53% (thermal power: 550 kW$_{th}$). About 15% of the produced biogas volume is burned in a gas flare and 90% of the produced electricity is fed into the German electricity grid, the remaining 10% being used to cover the electrical consumption of the plant. Of the produced heat, around 70% is used to heat a public building located within a few kilometres of the plant and the remaining 30% are used to cover the thermal loads of the plant. The thermal and electrical loads of the biogas plant investigated here are fully covered by the energy generated by the cogeneration units: the plant is energy auto-sufficient. Using some less refined fuel, like wood chips for heating the plant would not be economically profitable, as heat is here a by-product from the cogeneration unit. At the digester output, the digestate is pumped to be further treated in two decanters (separation of liquid and solid phases). This step aims to increase the dry matter content in the co-products. The digestate is further transported to a coal co-firing plant located 40 km from the plant. The composting of the digestate in order to obtain fertilizers to be further sold is not envisaged by Plant A's operator, as it does not appear lucrative (see section 7.4. for a comparison between a potential composting step and the existing co-firing step for the digestate treatment).

3.3.2. Specification of Plant B

Plant B currently processes around 9.16kt/a of energy crops: 95% maize silage and 5% wheat so as to generate 500 kW_{el} of electricity in a CHP-unit. The substrates are transported to the plant in agricultural trucks and are then fed into an adiabatic mix-container and homogenized. The process is mesophilic (37°C), with a one-level fermentation stage. The organic loading rate is 3.5 kg(VS).$m^{-3}d^{-1}$ and the pH varies between 7.2 and 7.5. Each digester has a working volume of 2,570 m^3 with a hydraulic residence time of 71 days. The CHP-unit consists of an Otto-engine (500 kW_{el}) with an electrical efficiency of 38% and a thermal efficiency of 52%. Approximately 8 kt/a of digestate are issued from the co-digestion process and then further treated. The fermentation byproduct (digestate) is first mechanically separated into solid and liquid substances. The liquid phase is, in a further step, concentrated in a thermal vacuum evaporator at low pressure and high temperature. The solid fertilizers (press cake) are particularly rich in nutrients and are returned the field in order to insure and improve the humus balance (use as a fertilizer). The process water is reused in the fermentation process for the substrates.

3.3.3. Specification of Plant C

The third investigated plant (Plant C) produces about 500 Nm^3/h crude biogas from 19 kt/a energy crops feedstock, namely 88% maize silage and 12% wheat silage, and upgrades the produced biogas to biomethane: an annual volume of 2.3 million Nm^3/a biomethane is thus fed into the natural gas grid. The substrates are transported to the plant in agricultural trucks and are then fed into an adiabatic mix-container and homogenized. Each digester has a working volume of 4,300 m^3 with a nominal biomass-residence time of 60 days. The organic loading rate amounts to 4.2 kg(VS)m^{-3} d^{-1} and the pH is around 7.5. The produced biogas is treated in a desulphurization unit, a high pressure wet scrubbing operation (from the company Flotech) then removes the CO_2 from the crude biogas.
Fermentation residues (digestate) are reemployed in a fertilizer plant located nearby. The digestate is firstly pressed, and the remaining liquids are concentrated in a complex filtration system into liquid fertilizer. Plant C has a nearly closed fuel cycle with nutrients and humus forming carbon being returned to the arable land. The remaining water is used in the fermenter or is directed into a nearby sewage treatment plant. Finally, in the case of plant C the specific values of biomethane production costs related to the energy content (in kWh) are linked to the low calorific value under normal conditions ($H_{i,N}$ at 101.325 kPa and 0°C), supposed to be equal to 10 $kWh_{i,N}/Nm^3$ biomethane.

4. Economic analysis of a co-digestion plant valorising biowaste and sewage sludge for electricity generation (Plant A, type "Biowaste/Electricity")

4.1. Capital investment estimates

The total capital investment for equipment and construction according to Plant A operators is about €6.02 million (see Table.6.). This includes a total fee for project management and authorization of €0.5 million.

Table.6. Capital Investment Estimates for Plant A (in €million)

Construction		Equipment	
Biogas plant	0.19	Substrate pre-treatment	0.10
CHP units	0.60	Digesters	0.67
Infrastructure	0.60	Pumps and pipes	0.06
Heating network	0.20	CHP-unit	0.57
Valves and accessories	0.54	Automation and control	0.50
Buildings	0.13	Connection to the electricity grid	0.05
		Dehydration unit	0.50
		Gas storage	0.18
		Gas treatment	0.38
		Heat exchangers	0.25
Total construction	2.26	Total equipment	3.26
Additional fee for engineering and authorization			0.50
Grand total capital investment estimates			**6.02**

4.2. Operating and investment-related costs

Investment-related costs consist of depreciation, interest and insurance costs. Depreciation is assumed to be linear over the lifetime of the investment: 10 years for technical components, 20 years for additional fees (project management and authorization) and 7 years for the CHP units. For the first year, interest costs have been calculated with a rate of 8% and derived from the global capital investment estimates. A corresponding annual amount of €0.25 million/a is thus obtained. Insurance costs stand for 0.5 % from the capital investment estimates [16]. Depreciation costs are evaluated at €0.45 million. Thus, investment-related (set up from amortization ,interests and insurance costs) costs can be estimated at €0.73 million. The costs for energy requirements are based on the fixed tariffs for electricity from sewage gas, corresponding to 6.16 ct/kWh$_{el}$ [3] and stand here for 40,000 €/a. Further assumptions concerning specific digestate treatment cost, fixed and variable transport costs, price for antifoaming and chemical conditioning agents as well for water are obtained from the dissertation of Koch [15]. Annual miscellaneous operating costs are estimated by the plant operator at €0.1 million. Finally 9,516 t/a digestates from the biogas plants are co-fired in a coal power plant at a price of 26 €/t (plant operator information). Maintenance costs are set at 180,000 €/a (126,000 €/a for the biogas plant, 50,000 €/a for the gas CHP engines and 4,000 €/a for the heat network). Personnel costs are provided by the plant's operator corresponding to a global amount of €0.26 million/a. These assumptions lead to the following investment-related and operating costs (Table.7.).

Table.7. Investment related and operation costs for plant A (in €million/a)

Investment-related costs	0.73
Energy related costs	0.04
Digestate treatment costs	0.29
Personnel costs	0.26
Maintenance costs	0.18
Miscellaneous production costs	0.18
Transportation costs of the digestate	0.12
Total costs Plant A	**1.81**

4.3. Revenues

The revenues (sum of income and subsidies) for Plant A are primarily derived from the sale of electricity and heat (income). The annual generated heat and electricity result from the combustion of about 3 Mm^3/a biogas in two Otto engines. Considering the German Renewable Energies Act from 2009, a base tariff for the valorisation

of sewage gas in CHP-units is fixed at 6.16 ct/kWh$_{el}$. The effective electricity quantity fed into the grid is 5.2 GWh$_{el}$/a, which allows the revenue from the electricity generation to be determined as €0.32 million/a. Furthermore, the global amount of heat production is estimated in the case of Plant A at 10 GWh$_{th}$/a. It is also assumed that 30% of the heat production is used to cover the sewage treatment plant's needs. A revenue of 5 ct/kWh$_{th}$ associated with the heat sale is fixed [15], and thus leads to a total annual revenue for heat valorisation of €0.15 million/a.
Furthermore, subsidies are linked to the valorization biowaste and sewage sludges into the biogas plant. These subsidies are associated with the gate fees for the waste water treatment plant located on the same site as Plant A, as well as for the domestic landfill site. Specific local subsidies of 19.4 €/t for sewage sludge and 25.4 €/t for biowaste are considered here (information from the plant operator). 15,000 t/a biowaste (solids and liquids) are valorised as input, which correspond to a revenue of €0.38 million/a, whereas a revenue of €0.95million/a is associated with the sewage sludge valorisation. Miscellaneous incomes of 6750 €/a are finally to be added. The total annual revenues for Plant A are consequently about €1.807 million/a.

4.4. Profitability analysis of Plant A

The operating profit for Plant A stands for the difference between the annual total revenues and total costs, and can be derived from the preceding data as 1,099 € for the first year. A comparison between costs and revenues is discussed below and shown in Fig.2. Electricity production costs are estimated at 34.57ct/kWh$_{el}$.

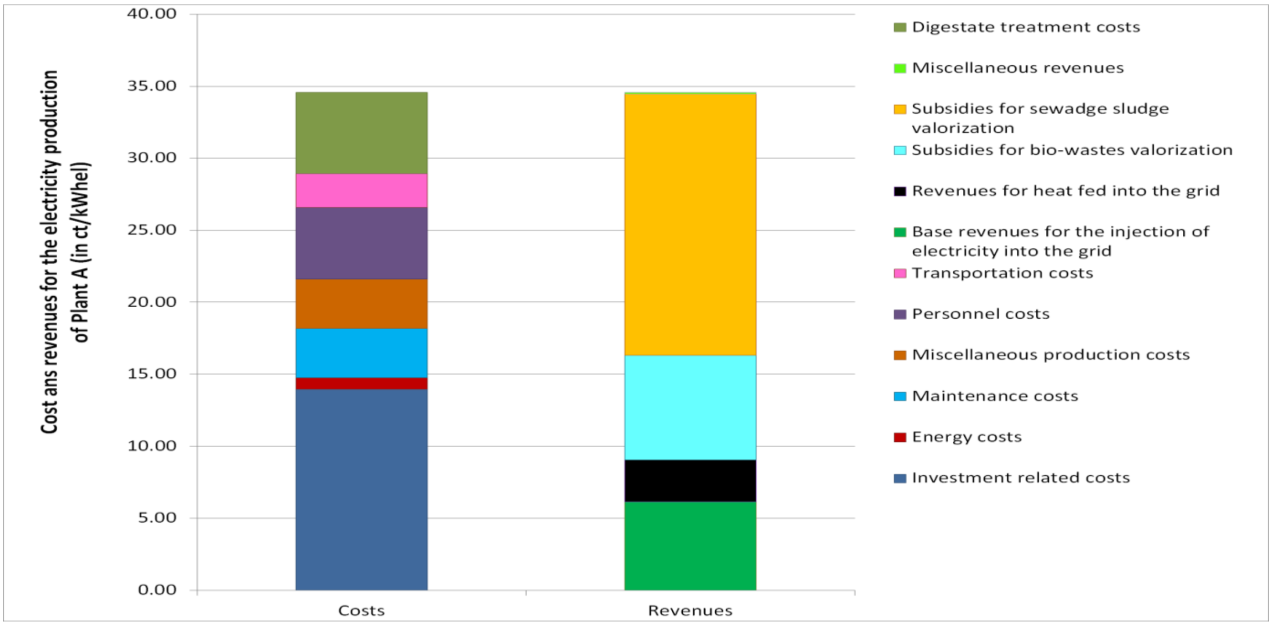

Fig.2. Costs and revenues comparison for Plant A (type "Biowaste/Electricity")

Finally, the dynamic payback period obtained is 11.56 years and the NPV is about €2.4 million, as shown in Fig.3.

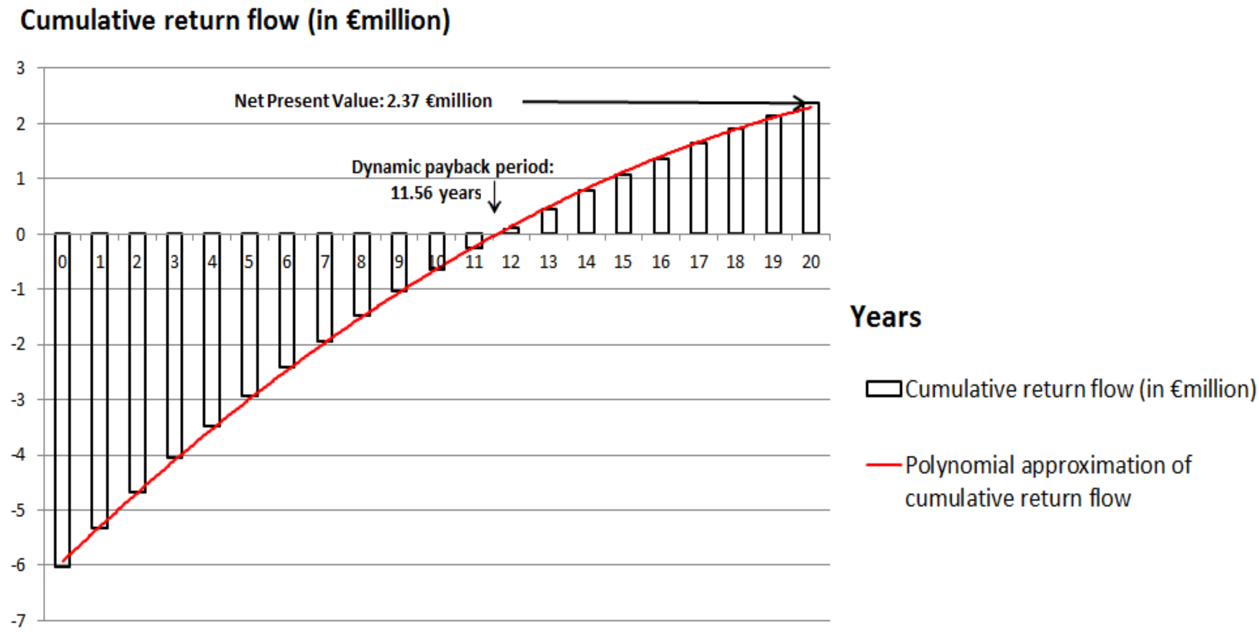

Fig.3. Cumulative return flow (in €million), payback period and NPV for Plant A

5. Economic analysis of a co-digestion plant valorising energy crops for electricity generation (Plant B, type "Energy crops/Electricity"

5.1. Capital Investment Estimates

The total capital investment for the plant according to the operator is €2 million, which corresponds to a specific investment of 4,000 €/kW$_{el}$. Table.8. sums up the investment estimates for Plant B.

Table.8. Capital Investment Estimates for Plant B (in €million)

Construction		**Equipment**	
Biogas plant and miscellaneous (CHP-units, infrastructure)	1.20	CHP-units with Gas-Otto engines (see ASUE [4])	0.29
		Other equipment: fermenters, pumps and pipes	0.51
Total construction	1.20	Total equipment	0.80
Grand total capital investment estimates			**2.00**

5.2. Operating and investment-related costs

Investment-related costs are provided by the plant's operator and correspond here to 14% of the capital investment estimates, i.e. €0.275 million/a. The energy costs for the plant are derived from the onsite requirements for electricity and heat. The onsite requirements in electricity account for 8% of the total electricity production, according to the plant operator. Assuming an annual electricity production of 4.2 GWh$_{el}$ (derived from calculations based on a yearly biogas production of 2.12 Mm^3/a), 0.34 GWh$_{el}$ is obtained for the plant's own consumption. The average specific cost of electricity (for energy requirements) is set at 8 ct/kWh$_{el}$ (plant operator's information), which corresponds to an annual electricity cost of 27 k€/a. Costs for diesel use during

the transport of the biomass are set at 1.2 €/l diesel [15]. Assuming a requirement of 0.5 l/t of diesel for the valorised biomass input (9.2 kt/a), an amount of 5.5 k€/a is thus obtained. The heat requirements of the whole plant are met by the produced thermal energy, whereby about 70% of the produced heat is used in a fertilizer production plant, and the rest of the produced heat is used for the heating of the digester. The maintenance costs are provided by the plant operator as 18 k€/a and personnel costs are set at 28 k€/a.
Substrate costs are derived from maize silage and wheat prices which are set at 30 €/t and 120 €/t respectively (information from the plant's operator). Considering an annual valorised quantity of 8.7 kt/a of maize silage and 0.46 kt/a of wheat, a cost for the substrate of €0.32 million/a is obtained. About 1.8 t of conditioning product are used every year in the fermenters, standing for a total cost of 1,000 €/a. Additionally 8,250 €/a have to be considered for several material requirements. Furthermore, specific transportation cost of 5.5 €/t for maize silage, 6 €/t for wheat and 5.5 €/t for the digestate are furnished by the plant operator, leading to a total amount of 95 k€/a for transportation costs. Finally, miscellaneous costs consist of taxes and expenditures for oils, cooling and emission measurements, and are set at 18 k€/a (data from the plant's operator). The total costs are summed up in Table.9.

Table.9. Operating and investment related costs for Plant B (in €million/a)

Investment related costs	0.28
Energy costs	0.03
Maintenance costs	0.02
Personnel costs	0.03
Substrate costs	0.32
Utilities process costs	0.01
Miscellaneous production costs	0.02
Transportation costs	0.09
Total annual costs	**0.80**

5.3. Revenues

Revenues for Plant B are primarily derived from the sale of electricity and heat. The annual generated heat and electricity derive from the combustion of 2.12 Mm^3/a biogas in gas-Otto engines. The revenues from electricity production are calculated on the basis of the German Renewable Energies Act 2009 (see Table 4. and [3]). The produced digestate is sold as a fertilizer at a price of 6 €/t. Furthermore, all the heat is used in the fertilizer plant, which will thus neither generate any revenue from the sale of the heat nor receive the CHP-Bonus. Table.10. sums up all the revenues for Plant B.

Table.10. Revenues for Plant B in (€million/a)

Basis feed-in tariff for electricity into the grid (electrical power up to 500 kWel)	0.42
Energy crops bonus	0.30
Formaldehyde bonus	0.04
Technology bonus	0.09
Benefit related to the valorisation of the digestate as a fertilizer	0.05
Total annual revenues	**0.90**

5.4. Profitability analysis of Plant B

The operating profit for Plant B can thus be derived from the previous calculations as €0.1 million/a for the first year. Furthermore, the specific electricity production costs are evaluated as 18.77 ct/kWh$_{el}$. A comparison between costs and revenues is shown in Fig.4. Finally, a calculated payback period of 6.7years and a Net Present Value of €2.27 million are obtained for Plant B.

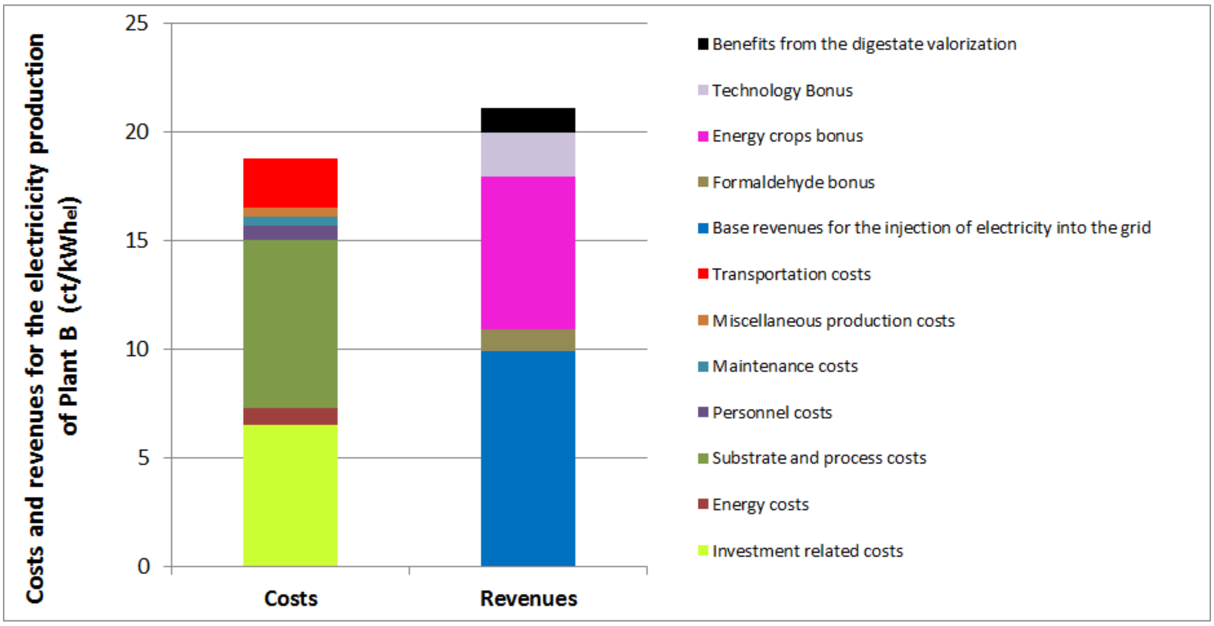

Fig.4. Costs and revenues comparison for Plant B (type “Energy crops/Electricity”)

6. Economic analysis of a co-digestion plant valorising energy crops for the biomethane production (Plant C, type “Energy crops/Biomethane”)

6.1. Capital investment estimates for Plant C

An amount for the total capital investment of €4.17 million linked to the biogas plant (construction and equipment, without crude biogas treatment), the connection to the natural gas grid and the pressurized water scrubbing process is provided by the plant operator. A detailed capital investment could not be provided and has thus to be estimated for the present study. Investments for the crude biogas desulphurization (investment for dosing and storage) are thus neglected [14] and those for the CO_2-removal from crude biogas are set at €1.32 million (plant operator information). Finally, investments for the connection to the gas grid are estimated by the plant operator at €0.6 million. Table.11. sums up the investment estimates for Plant C.

Table.11. Capital investment estimates for Plant C (in €million)

Construction		Equipment	
Biogas plant	1.35	Digesters and periphery	0.90
Investment for the connection to the natural gas grid	0.60	Investment for CO_2-removal from crude biogas (pressurized water scrubbing)	1.32
Total construction	1.95	Total equipment	2.22
Grand total capital investment estimates			**4.17**

6.2. Operating and investment-related costs

According to the assumed lifetimes of 10 years for technical components and 20 years for the construction, a total amount of €0.16 million/a for depreciation should be considered. Insurance costs stand for 0.5% from the total capital investment estimates [16], with a value of 12.5 k€/a. The energy costs of the plants are derived from the onsite requirements for electricity, heat and diesel: 30 kWh_{el}/h are required by the mixers in the digester. Assuming, as for Plant B, an average cost of electricity (for energy requirements) of 8 ct/kWh_{el} and that the plant is running 8,300 h/a, an amount linked to the electrical consumption for the plant of 20 k€/a is obtained. The specific price for diesel (for biomass transportation) is set, as in the case of Plant B, to 1.2 €/l, leading to a cost for diesel of 11.4 k€/a. Maintenance costs are provided by the plant operator and stand at €0.06 million/a. Personnel costs are set at about €0.05 million/a. About 5,533 m^3/a of process water, at a price estimate of 1.81 €/m^3 [23], is used to mash the maize silage. Considering an annual valorised quantity of 16.7 kt/a maize silage and 2.3 kt/a of wheat, a cost for the substrate of €0.78 million/a is obtained. Furthermore, conditioning products are used in the fermenter at a total cost of 1,000 €/a.

A specific transport cost of 6 €/t for maize silage, and 6 €/t wheat is assumed. With these values, a total amount of €0.11 million/a for the transportation costs is obtained. Finally, miscellaneous costs are made include taxes, and expenditures for oils, cooling and emission measurements, and are set at 25,500 €/a (data from the plant's operator). Specific costs for crude biogas treatment are composed of costs for desulphurization, CO_2-removal (through pressurized-water scrubbing) as well as costs for injection of biomethane into the natural gas grid. Specific costs for desulphurization are set at 0.46 ct/Nm^3 biogas [14] standing for an annual amount of 19 k€/a. Specific costs for CO_2-removal corresponds to 9.26 ct/Nm^3 following data taken from the company Flotech [14]. In the case of Plant C, an amount of 500 m^3/h of crude biogas is treated and upgraded to biomethane during 8,300 h/a, leading to CO_2-removal costs at about €0.38 million/a. Fees associated with the natural gas grid use for plant operators are thus to be considered with a specific amount of 0.6 ct/$kWh_{i,N}$ [14]. A total amount of 23.4 $GWh_{i,N}$ of energy is fed into the grid, which leads to a cost of 140 k€/a for the use of biomethane through the natural gas grid. Specific costs for the connection to the natural gas grid are set at 0.15 ct/$kWh_{i,N}$ [14], which corresponds to 35.1 k€/a. The total costs related to investment are summed up in Table.12.

Table.12. Operating and investment related costs for Plant C **(in €million/a)**

Investment-related costs for the biogas plant	0.23
Energy costs	0.03
Maintenance costs	0.06
Personnel	0.06
Substrate costs	0.78
Utilities process costs	0.01
Miscellaneous production costs	0.02
Transportation costs	0.11
Costs for desulphurization	0.02
Costs for CO2-removal	0.38
Fees for the use of the natural gas grid	0.14
Costs for the connection to the natural gas grid	0.03
Total annual costs	1.87

6.2. Revenues

Revenues for Plant C result from the sale of biomethane, for which a total price of €1.95 million/a is given by the plant operator. The sold biomethane can be used as a fuel in a decentral CHP-unit or used as a gaseous transport fuel after treatment (bio-CNG: compressed natural gas from a biogenous source). Furthermore, the revenues from the sale of digestate are set at 6 €/t (plant operator information) for an annual quantity of 17 kt/a digestate, providing a total amount of €0.1 million/a. Furthermore, specific subsidies of 0.78 ct/kWh$_{i,N}$ are received [14], following the GasNZV (German Act for the access to the natural gas grid [24]) for avoided network fees. A corresponding revenue of €0.18 million/a is also calculated, so that the total revenue therefore stands at €2.23 million/a.

6.3. Profitability analysis of plant C

As for Plants A and B, an operating profit is determined, corresponding to the difference between revenues and total costs (a comparison between costs and revenues follows in Fig.5.). An operating profit of about €0.36 million/a is obtained and the specific biomethane production costs are thus evaluated at 8.13ct/kWh$_{i,N}$ (referring to the low calorific value for the gas). kWh. Finally, a calculated pay-back period of 9.4 years and a net present value of €2.56 million for Plant C are determined.

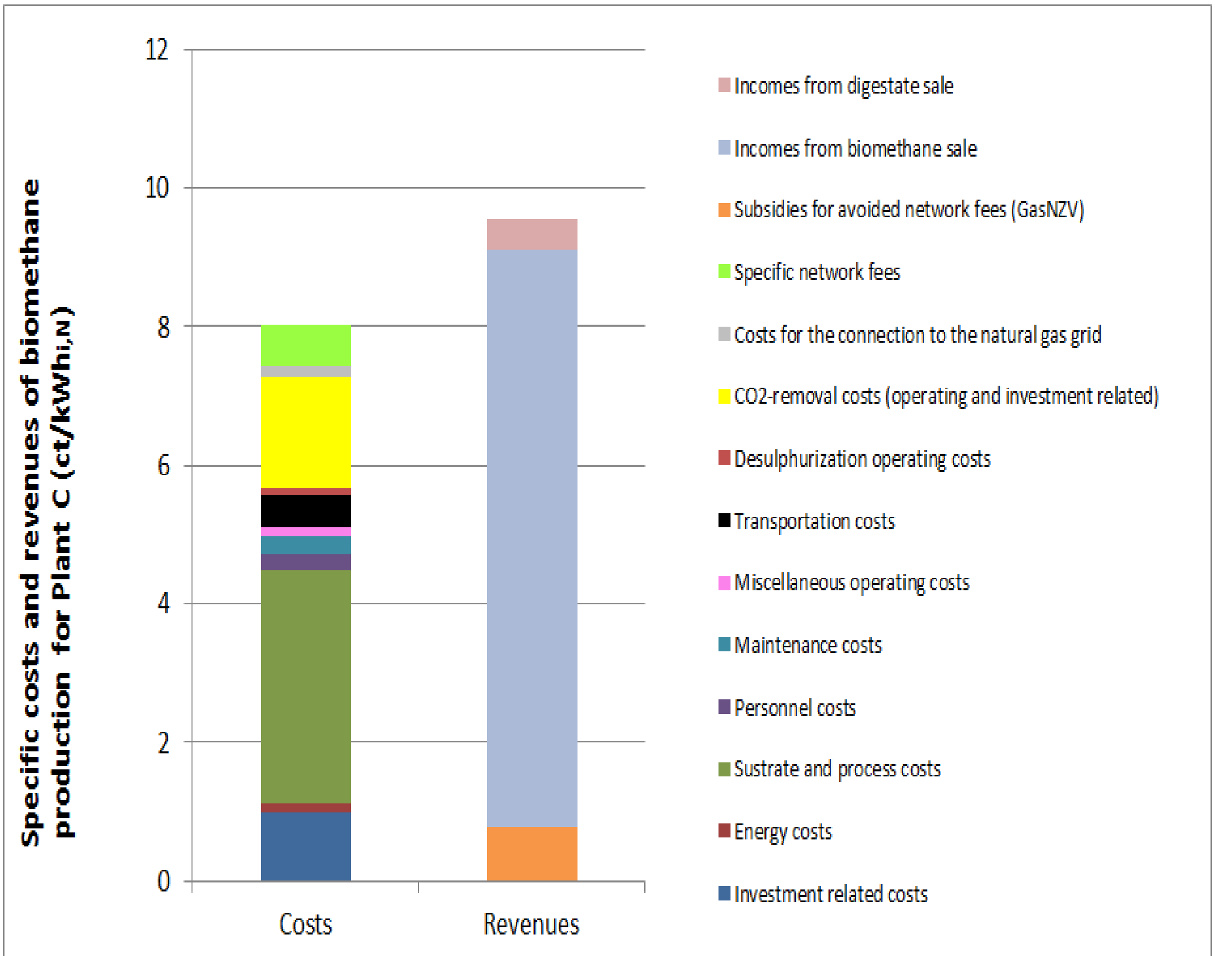

Fig.5. Costs and revenues comparison for plant C (type "Energy crops/Biomethane"

7. Discussion of results

7.1. Comparison of the three cases

Regarding the calculated dynamic payback periods, it appears that the generation of electricity from the co-digestion of energy crops is the most lucrative option (case of Plant B with a payback period of 6.7 years), followed by biomethane production (Plant C with a pay-back period of 9.4 years) and finally the production of energy from the co-digestion of bio-wastes and sewage sludge (Plant A with a pay-back period of 11.6 years). For comparison, the biogas Plant in Kirchstockach [25] uses around 30,500 t/a biowaste to produce electricity in CHP-units from biogas, and for this plant a pay-back period of 12 years has been calculated. Refered to Plant A, Artl [12] and Thrän [1] provides comparable values for the production costs of electricity in the case of a co-digestion of biowaste and sewage sludge at 42 ct/kWh$_{el}$ and 32 ct/kWh$_{el}$ respectively. A pay-back period of 8.0 years has been calculated for a biogas plant quite similar to Plant B (3000 m^3 fermenter volume, production in CHP-units of 500 kW$_{el,}$ valorizing 93.7% maize silage, 2.9% wheat and 3.4% cattle manure [16]). Furthermore, Koch [14] mentioned production costs of electricity of about 18 ct/kWh$_{el}$ for a co-digestion biogas plant with 75% maize silage and 25% cattle manure.
Concerning the biomethane production costs in Plant C, Urban [14] found similar values (referring to the low calorific value for the gas and with a CO_2-removal through pressurized-water scrubbing process form the company Flotech) of about 8.2 ct/kWh$_{i,N}$. However, these results are strongly dependent upon the assumptions made in this study, as well as the combination of and market conditions for substrates employed, so that caution should be exercised when making such generalisations.

7.2. The significance of subsidies

The importance of the framework conditions and incentive schemes on the profitability of the analysed biogas plants will be briefly discussed in this section. For Plant A, incomes (sale of heat and electricity and miscellaneous) stand for 27% of revenues and subsidies (linked to the valorization of sewage sludges and biowaste) represents 73% . If no local subsidies were assigned (scenario 0), Plant A would be unprofitable by far, with a negative specific operating profit of – 25.39 ct/kWh$_{el}$. This emphasizes the high importance of suitable local political framework conditions for a profitable operation of German co-digestion plants. In the case of plant B, incomes (sale of the produced electricity as well as the digestate as a fertilizer) and subsidies (technology, energy crops and Formaldehyde bonuses) are equal, at around 50%. If no subsidies (i.e. no bonuses) were assigned, Plant B would be unprofitable with a negative specific operation profit of – 7.70 ct/kWh$_{el}$. Finally, for Plant C, incomes (from biomethane and digestate sale) stand for 72% of all revenues whereas subsidies (avoided network fees) represent 28%. If no subsidies (for avoided network fees) were assigned, Plant C would be still profitable with a positive specific operation profit of 0.75 ct/kWh$_{i,N}$.
Furtherrmore, several exemplary scenarios have been determined regarding the German Renewable energy Act and the associated subsidies based on Plant B, which valorizes crops to produce biogas, so that an energy crops bonus of 7 ct/kWh$_{el}$ should be systematically allocated to the revenues. However, the bonuses for digestate valorisation, as well as technology and emissions bonuses are not always relevant to plants valorizing energy crops. Thus several "What-If Scenarios" can be analysed, starting with a scenario in which no bonuses for the digestate valorization and for innovative technologies are received**.** In this scenario ("What-If" scenario 1), the plant is no longer profitable, with a negative operating profit of -0.84 ct/kWh$_{el}$. Considering now a second scenario ("What-If" scenario 2) where no emission bonus (Formaldehyde Bonus) and no technology bonus are attributed, a non- profitable state for Plant B is again observed, with a negative specific operating profit of -0.71 ct/kWh$_{el}$. Finally, the last considered scenario ("What-If" scenario 3) corresponds to the case where Plant B neither receives the emission bonus nor revenue from the digestate valorisation. In that case, Plant B still appears to be profitable with a positive specific operating profit of 0.16 ct/kWh$_{el}$.
The comparison of these three different scenarios thus emphasizes the fact that the profitability of biogas plant is highly dependent on current energy-political framework conditions. In particular, the role played by the technology bonus on Plant B profitability appears to be essential. Strongly varying incentive schemes (a new

German Renewable Energies Act is published every three or four years) constrain plant operators to adapt their technological configurations, so as to maintain to an optimized process and maximise operating profits. The critical influence of communal subsidies for bio-wastes and sewage sludge valorisation raises the question of the optimal location of these plant types. Plant operators are therefore constantly striving for locations associated with the most lucrative revenues for their employed substrates.

Table.13. Influence of several incentives schemes (subsidies and bonuses) on the plants profitability

	Scenario 0: No subsidiees (sewage sludge and biowaste valorization, bonuses or avoided network fees) for all the plants	**“What-If” Scenario 1: No bonuses for digestate valorization and for innovative technologies (Plant B case)**	**“What-If” Scenario 2: No emission bonus and no technology bonus (Plant B case)**	**“What-If” scenario 3: No emission bonus and no bonus for the digestate’s valorization (Plant B case)**
Plant A’s operating result	-25.39 ct/kWh$_{el}$	-	-	-
Plant B’s operating result	-7.70 ct/kWh$_{el}$	- 0.84 ct/kWh$_{el}$	- 0.71 ct/kWh$_{el}$	0.16 ct/kWh$_{el}$
Plant C’s operating result	0.75 ct/kWh$_{i,N}$	-	-	-

Table 13. sums up the here analysed scenarios for Plants A, B and C:

7.3. Biogasification potential of substrates.

Schievano [26] analysed the potential of several biomass types to substitute for energy crops: industrial and agro-industrial by-products and residues, animal manures, and various types of organic wastes. Substrate prices and anaerobic biogasification potential obtained in batch reactors under optimized methanogenic conditions were taken into account to analyse the feedstock mix. In Schievano [26], an average biogasification potential of 177 Nm^3 biogas/t was measured for biowaste. In Koch, a biogasification potential of 10.4 Nm^3 biogas/t sewage sludge is mentioned [15]. In the case of Plant A, about 2.9 Mio Nm^3 biogas are yearly produced from 56 kt/a feedstocks (15k t/a biowaste and 41 kt/a sewage sludge). This also stands for a biogasification potential of 51.79 Nm^3 biogas/t feedstock. If the considered biowaste and sewage sludge types in Koch and Schievano studies where employed in plant A (instead of the existing feedstocks), this would lead to a yearly biogas production of 3.08 Mio Nm^3/a (55.03 Nm^3 biogas/t feedstock), standing for an improvement of 6.26 %.

Furthermore, in Schievano [26], an average biogasification potential of 235.3 Nm^3 biogas/t was measured for mixed maize flour and 316.9 Nm^3 biogas/t for wheat. In the case of Plant B, about 2.116 Mio Nm^3 biogas are yearly produced from 9,167 kt/a feedstocks (8708.33 t/a maize silage and 458.33 t/a wheat). This also stands for a biogasification potential of 230.91 Nm^3 biogas/t feedstock. If the considered maize silage and wheat in Schievano’s study were employed in plant B (instead of the existing feedstocks), this would lead to a yearly biogas production of 2.194 Mio Nm^3/a (239.38 Nm^3 biogas/t feedstock), standing for an improvement of 3.67%.

7.4. Assessment and comparison of several digestate’s treatment concepts: composting and co-firing

Another important point regarding the plant’s profitability is the further digestate treatment concepts that are employed. The application of composting units to treat the digestate coming from biowaste and other organic wastes aims at reducing the presence of organic volatile compounds, ammonia and other chemicals (responsible for bad odours), as well as correcting an insufficient level of digestate stability (e.g. with the objective of the application to soils as fertilizer). Costs for composting are made of capital costs (building costs including land area occupation and equipment), fixed costs (construction and equipment purchase, insurance, depreciation, repairs and maintenance of fixed assets), operating costs (labour costs for daily operation, cost of bulking agent, maintenance and operating costs for the relevant equipment, charges for energy, as well as contingency). The main operating costs are bulking agents polyacrylamide at a standard price of 2.5 € per kg of polymer [27]. As an example, Wei [28] analysed the cost structure of a Chinese sewage sludge composting unit for small and mid-scale municipal wastewater treatment plants: composting costs ranged there from US$55.31 to US$173.66 per dry tonne, depending on the type of system considered (windrow, aerated static pile and horizontal agitated solid bed) as well as the moisture content of sewage sludge (70%, 75% or 80%).

The economic aspects of composting processes in France are highlighted in a study by ADEME [29], which assesses the costs for biowaste composting units in two French municipalities. For the first municipality (where 6024 t/a biowaste are yearly collected), the global costs of composting are about 59 €/t biowaste. In the case of the second municipality (where 4752 t/a biowaste are yearly collected) global costs for composting were estimated at 70€/t. One should be careful, however, in making comparisons between French and German cases: several technical configurations, different technical maturity levels and load factors should be considered.

Costs for composting are highly dependent on the component mass input as well as the associated plant technology. For example, in Germany and according to [30] costs for composting vary between 30 €/t and 100 €/t biowaste, according to the considered city or rural district. For the district of Hessen, an average cost for biowaste composting of 75 €/t applies, which represents quite a high treatment cost. At the national scale, actual prices are more in the range from 30 to 50 €/t with minimal values of 20 €/t in the new German federal states. Composting treatment costs are lower for green wastes than for biowaste, principally due to a simpler technology [30]: average composting treatment costs at the national level vary from 15 to 30 €/t. Thus, several concepts for the digestate treatment in the case of Plant A (biowaste and sewage sludge valorization) can be assessed as shown in Table.14. If a composting concept for Plant A's digestate were implemented, an unprofitability for plant operators would occur: the operating profit of Plant A be would be in that case negative, at about -2.54 ct/kWh_{el}.

Table 14. Digestate treatment concept assessment for Plant A

Digestate treatment concepts	Amount of treated digestate (t/a)	Specific costs for the digestate (€/t)	Cost for the digestate treatment in Plant A (€)	Specific costs of digestate treatment per kWh_{el}
1.Existing concept: Digestate co-firing in a coal power plant	9,516	26	247,416	4.76
2. Composting concept for the digestate	9,516	40	380,640	7.32

7.5. Sustainability of biogas production

A last issue to mention in the discussion is the sustainability of the analysed plant's concept, especially in terms of social benefits as well as environmental impacts. Concerning the social added value, biogas production creates local employment, provides diversification for a rural business (farming systems, especially in the case of Plant B and Plant C) and can treat wastes (sewage sludge and biowaste in the case of Plant A) close to their source (proximity principle). The positive environmental impacts of biogas production mainly concern the contribution to the reduction in greenhouse gas emissions, the pollution and odour control of organic putrescible wastes, as well as the use as natural (instead of artificial) fertilizers in the case of Plant B and Plant C.

A last important aspect is the valorization of manure from pigs: the energetic use of pig manure to produce biogas (e.g. in co-digestion plants with energy crops) would be a source of profitability for the plants operators. Indeed, manure could be used in biogas plants for free and is associated with subsidies ("manure bonus" form the German Renewable Energies Act 2009) of 4 ct/kWh_{el} for a biogas plant with an electrical power range from 0 to 150 kW_{el} and 1 ct/kWh_{el} for an electrical power range from 150 to 500 kW_{el}. However, in the case of the three considered biogas plants in this paper, no farms are located at the proximity of such an installation. The specific transportation costs of manure for a potential energetic valorization would be thus higher than the specific manure bonus and would not be attractive with respect to the plant's profitability.

7.6. Sensitivity analysis

The influence of several input parameters on the three biogas plants' operating profits can be quantified through a sensitivity analysis. The varied parameters for each plant are described in Table.14. The variation step for each parameter was assigned at 25% and the crosses in Table 15. stands for the influence of the selected parameters on the operation profit associated to each plant. . One cross (+) stands for a variation between 0 and 10% of the whole variation domain for the operation profit (0 to 70 k€) in reaction to the varied parameter of one step (25%). Two crosses (++) stand for a variation between 10 and 20% (70 k€ to 140 k€) whereas three crosses (+++) correspond to a variation between 20 and 30% (140 k€ to 210 k€). A detailed quantitative sensitivity analysis is further furnished, through the case of Plant A.

Table.15. Key-parameters having an influence on the operation profit of Plants A, B and C

	Plant A	Plant B	Plant C
Subsidies for sewage sludge valorization	+++		
Subsidies for biowaste valorization	++		
Annual amount of heat fed into the grid	+		
Annual amount of electricity fed into the grid	+	+++	
Amount of biomethane fed into the natural gas grid			+++
Specific transportation costs of substrates	+	+	+
Specific transportation costs of digestate (plant B)	+	+	+
Specific wheat price		+	+
Specific maize silage price		+	+
Digestate treatment costs	++		
Investment related costs	++	+	+

In case of Plant A, the most important parameters influencing the operating profit are the investment-dependent costs and the communal specific revenues allocated to sewage sludge and bio-wastes. Furthermore, an optimization of the energy requirements associated with the pre-treatment steps appears to be critical for the minimisation of the production costs. As an example, Fig.6. shows a detailed sensitivity analysis for Plant A. The x-axis stands for the domain of variation (with a step of +/- 25%) for the analysed parameters (e.g investment related costs or incomes for sewage sludge valorization), influencing the operation profit of Plant A (in €/a).

For Plant B, the most sensitive parameter is the amount of electricity fed into the grid. Unprofitability appears with a reduction in the amount of electricity fed into the grid of 12.5%. Finally, the most sensitive parameter related to Plant C's operating profit is the amount of biomethane fed into the grid. The plant becomes unprofitable with a reduction in the amount of biomethane fed into the natural gas grid of 25% or more.

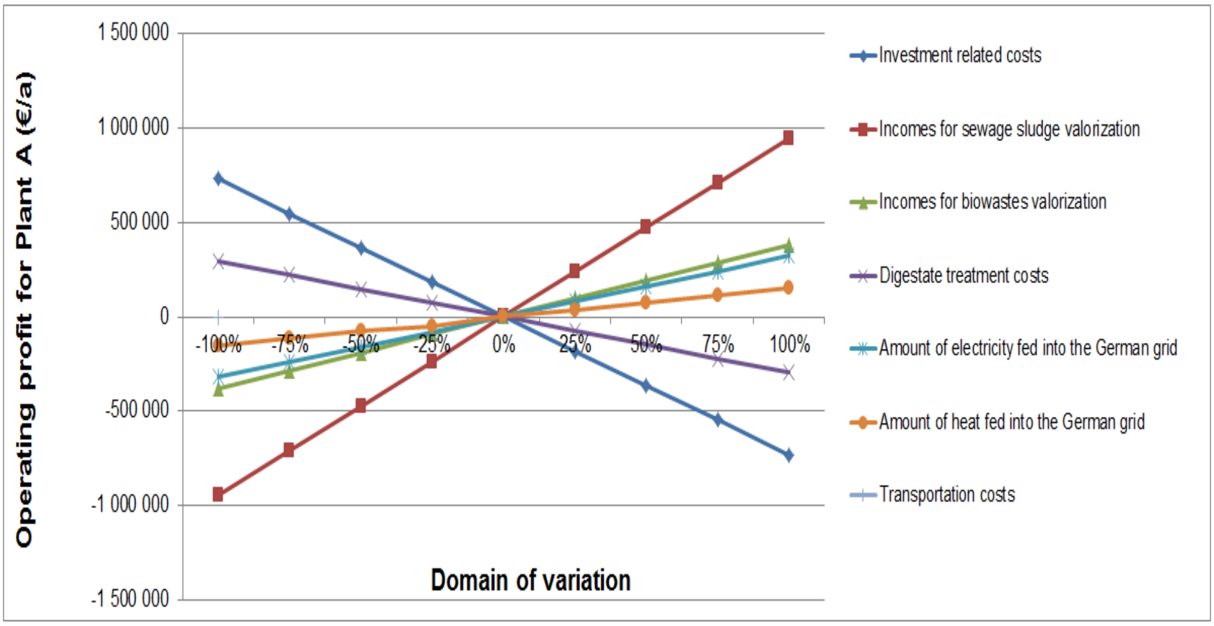

Fig.6. Sensitivity analysis of key-parameters on Plant A's operating profit

7.7. Influence of process inhibitions on the operating profit

Process failures strongly affect the biogas yield and can thus dramatically reduce the profitability of the plant. Besides process failures such as over-acidification, scum formation, and floating/sinking layers, short-circuits due to inadequate mixing conditions can cause high losses in the biogas yield. In the case of commercial waste digesters the operator depends on the markets for substrates. Therefore the operator needs to cope with a variable substrate matrix. New substrates are rarely investigated in terms of their effects on the microbial community. Consequently it is unknown whether the new substrate is suitable for the digestion process and/or in which amounts it is applicable. Usually the operator does not have enough time to investigate the substrate before employing it. Therefore many operators "investigate" it in a large scale experiment, by taking the risk of a process failure. Due to inadequate monitoring of the digestion process, the operator only notices a process failure after the biogas production rate and/or the electricity production has already decreased ([31], [32]).
Furthermore, toxic inhibitors can also cause over-acidification. The methanogenic microorganisms are usually inhibited, so that the hydrogen partial pressure and the acetic acid concentration increase. The accumulation of hydrogen inhibits the acetogenic microorganisms which consume propionic acid and long chain fatty acids. The increasing concentration of propionic acid and long chain fatty acids inhibits the methanogenic microorganisms as well, so that the biogas production decreases [33]. Investigations at a large-scale waste digester have shown that the methane yield of the biogas plant was reduced to about 80 % for around 6 weeks due to a toxic inhibitor [34]. It is likely that cresols inhibited the microorganisms, as their concentration was 6000-fold higher than legally permitted.
The inhibitor was carried by the sewage sludge into the reactor. In another case, the operator of a large scale biogas plant used an unknown substrate for the digestion process and caused an over-acidification. The methane yield was reduced to about 60 % and it took around three weeks to stabilize the biogas formation process with proper countermeasures [35]. In addition, the formation of scum and/or floating layers leads to a reduction in the biogas yield due to a more difficult release of the biogas from the liquid phase into the gas phase of the reactor [36]. Floating layer formation occurs easily, if fatty and/or fibrous material is used as a substrate. Especially organic waste contains this kind of material; therefore commercial waste digesters are predestined for floating layers [37]. The formation of floating layers depends highly on the mixing conditions; as soon as the mixing device mixes inefficiently or does not work at all, the reactor content becomes separated into different phases/layers. Especially fatty substrates need a minimum residence time of around 25 to 30 days in order that they can be completely degraded [38], [39]. Investigations of the residence time distribution at three large scale biogas reactors revealed that inadequate mixing conditions lead to a methane loss of around 20 % to 30 % [40].

This would for example correspond to an operating profit decrease of €0.2million in the case of Plant B for the first year and would then lead to a negative operating profit, standing for €-0.1 million.

7.5. Suggestions for further work

The case of biomethane production from biowaste and sewage sludge has not been treated in the present paper: only a few plants are currently valorising these types of substrates, mainly for application in the transportation sector (biomethane filling stations) and detailed data for calculations are thus difficult to acquire. Given the flexibility required for biogas plant operators in terms of the available substrates, there is a need to investigate the optimal combination of different substrates for a given plant under varying market conditions (especially prices). In this perspective, a non-linear optimization of the biogas yield (and thus also of the derived operating profit) by simultaneous variation of the input substrates could be a fruitful area for further research.
Furthermore, the volatility of the substrate price as well as biomethane and power prices have not been taken into account in this study; prices have instead been assumed constant for the profitability assessment of the three plants. The modelling (e.g. via stochastic processes) of uncertainties regarding power and substrate prices applied to bio-energy systems could stand for another interesting and useful next step. The framework of the analysed system described in Fig.2 could and should be enlarged to account for the end users (e.g. Combined Heat and Power systems for residential use, biomethane filling stations), which would enable the determination of specific generation costs along the whole supply chain, a fairer comparison of the three systems here investigated and finally the integration of increasing amounts of biogas into the German energy system.

8. Summary and outlook

This paper presents an overview of the techno-economic parameters influencing the profitability of three different biogas plant types, using biowaste and sewage sludge in co-digestion for electricity production (Plant A) as well as energy crops for electricity production (Plant B) and for injection of biomethane into the natural gas grid (Plant C) in Germany. The status quo regarding the European biogas situation is firstly given, emphasizing the high diversity of the employed substrates in the different countries (eg. energy crops in Germany and sewage sludges and landfill in the UK). The context for biogas development in Germany, the European leader in terms of primary energy from biogas production and installed plants, is further analysed through a comparative literature review of electricity and biomethane production costs.
As an important result of the economic ananlysis, the communal subsidies for the energetic valorisation of biowaste and sewage sludge appear to be a key parameter for the profitability of the associated biogas plant. For this plant type (Plant A), high specific electricity production costs of about 35 ct/kWh were determined, which are mainly dependent on the investment for substrate pre-treatment operations. A comparison of two biogas valorisation pathways, namely electricity and heat generation by burning the biogas in CHP-units (Plant B) or upgrading and then injecting the biomethane into the natural gas grid (Plant C), was also carried out, based in both cases on the energetic use of maize silage and wheat through co-digestion processes. Referring to a calculated dynamic payback period of 6.7 years, the production of electricity from biogas combustion in gas engines appears as the most lucrative option. Several “What-If” scenarios have shown that incentives schemes, in particular the German Renewable Energies Act, are crucial for the profitability of the assessed plants. Furthermore, the volatility of the substrate prices as well as of biomethane and electricity has not been considered in the present paper but their influence on the operating profit should also be analysed in future work. Several end-use options for the biomethane utilization (Plant C) should also be examined, by contrasting the case of a biomethane valorization in a decentralized CHP-unit with a direct and local combustion of biogas into gas engines. Finally, the use of a potential composting unit to treat the digestate (instead of a co-firing step in the case of Plant A) does not appear economically profitable in the German context.
To extend the present analysis and to provide a solid foundation for decision makers regarding a sustainable bio-energy strategy, a systemic evaluation of all the relevant bio-energy pathways into the coming decades is required. As a main objective, the German Act for Access to the Natural Gas Grid (GasNZV) formulates the aim

in §31 to substitute 6 billion m^3 of natural gas by biomethane by 2020 and 10 billion m^3 by 2030 [24]. The actual natural gas consumption for Germany in 2011 is around 100 billion m^3. The competitiveness of biogas in comparison with other bio-energy carriers therefore needs to be further investigated in the system context. As a next step, the economically, energetically and ecologically optimal application of biogas will be determined based upon possible scenarios relating to the evolution of biogas use in Germany. A comparison with other valorization routes aiming at bio-energy production (e.g. biomethane for transportation, or upgraded Bio-SNG) should also be realized in order to identify the most promising options for a future cost effective and rational use of biomass resources.

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