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Economic analysis of renewable heat and electricity production by sewage sludge digestion—a case study

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SUMMARY

In this paper, we assess the total cost of energy recovery from sewage sludge through anaerobic digestion with biogas utilization in combined heat and power (CHP) system. The important advantage of anaerobic digestion process is the production of biogas, which can be used to generate electricity and heat as a source of renewable energy. From this study, it can be retained that the generated thermal energy from the anaerobic digestion process meets the needs of the wastewater treatment plant (WWTP) and guarantees its self-sufficiency in heat. The surplus of renewable heat produced by CHP is not a primary factor to improve the economic viability of the process. Moreover, the sales of electricity output represent about 76% of the operating costs of anaerobic digestion process. Renewable energy production is not economically viable by its own, without considering the wastewater treatment function and the associated incomes. Nevertheless, sludge digestion helps to reduce the wastewater treatment costs mainly by giving a good source of revenue via electricity production. Copyright © 2014 John Wiley & Sons, Ltd.

KEY WORDS
economics; anaerobic digestion; combined heat and power; renewable energy; sewage sludge; biogas; sensitivity analysis

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1. INTRODUCTION

Sewage sludge is among the unwanted residual solid waste generated in wastewater treatment, and its management is one of the environmental challenges [1].The fate of urban wastewater sludge remains an ongoing challenge as long as its quantity increases over the years [2]. The classical disposal routes (landfilling, landspreading, incineration, etc.) represent disadvantages in terms of environmental impacts, which contribute to a higher investment cost. Technological change has contributed to the emergence of new processes such as anaerobic digestion and gasification. These processes have a double advantage that may be justified by reducing the waste volume and producing a renewable and marketable energy. There is a significant push to develop viable renewable energy technologies [3,4]. Anaerobic digestion of sewage sludge generates biogas as a renewable energy. This energy can be used from different ways, such as heat, combined heat and power or as a vehicle fuel [5]. Energy recovery from sewage sludge is considered as a new approach of recycling that contributes to global warming mitigation [1]. Therefore, several studies have been conducted in the literature to analyze sludge treatment processes. Houillon and Jolliet [2] have carried out a life cycle assessment (LCA) on sludge treatment processes where they have compared six scenarios (agricultural landspreading, cement production, wet oxidation, incineration, melting of dried sludge and landfilling) focused on energy and emissions contributing to global warming potential, but they have not analyzed the anaerobic digestion process. Hong *et al.* [6] have reported an LCA for sewage sludge treatment to estimate the environmental and economic impacts of the processes used most commonly in Japan: dewatering, composting, drying, incineration, incinerated ash melting and dewatered sludge melting, each with and without digestion. This study has quantified in detail the environmental and economic impacts of equipment, construction, energy, operation and transport of these processes. Nevertheless, the reuse of heat and electricity generated from a cogeneration process has not taken into account. Evangelisti *et al.* [7] have performed an LCA of anaerobic digestion with energy and organic fertilizer production over two approaches: incineration with energy production by combined heat and power (CHP) process and landfill with electricity production. However, they have only considered the environmental impact of processes; they have not qualified it in monetary terms. Cao and Pawłowski [8] have evaluated and compared the energy conversion efficiency of two technology configurations (anaerobic digestion and pyrolysis) in the application to bioenergy production from sewage sludge but have not followed a life cycle approach. Mills *et al.* [9] have carried out an environmental and economic LCA on sludge treatment processes in the UK. However, related to the energy recovery in monetary terms, economic analysis information is limited and hardly detailed.

Similarly, available data about costs of sewage sludge treatment by anaerobic digestion are very restricted and do not allow thorough analysis. The study of Merlin [10] has estimated that the cost of sludge treatment by anaerobic digestion has been between €300 and 400/t DM, including depreciation. The work undertaken by Solagro's agency [11] has indicated that digestion costs extend from €56 to 160/ t DM depending on the size of the plant, including depreciation. The scope of Merlin's study is wider than that of Solagro because it includes, in particular, the pretreatment of the sludge. These studies have not been LCA based. A market study of the anaerobic digestion with biogas recovery from sewage sludge has been carried out by Ernst and Young [12]. It has referred to the results of Merlin's and Solagro studies without presenting an expanded analysis. There are still few economic studies that cover all the life cycle stages of sludge management inside and outside the wastewater treatment plant (WWTP). This kind of research is often studied by chemists and engineers and hardly by economists. The present work focuses on the economic study of a project for energy recovery by CHP from sewage sludge. An important goal of energy policy is to ensure a high level of security of electricity supply [13]. Nevertheless, the production of electrical energy from fossil fuels has a significant impact on the environment. Many experts have tried to quantify the real cost of this impact by evaluating the external cost (i.e. indirect cost) [14]. Consciousness over the environmental crisis raises the level of the R&D for alternative energy sources instead of the fossil fuel [15]. Hence, this project sets high environmental objectives including (i) sustainable sewage sludge management, (ii) production of renewable energy and (iii) energy independency of the WWTP. This study is based on LCA approach in order to take into consideration the whole process of anaerobic digestion of sewage sludge with cogeneration of biogas and composting of digested matter. An advantage of LCA is that the method is well established and standardized [16]. In addition, many authors have used this methodology to evaluate the environmental impact of sewage sludge treatment processes [2,6,9]. In this study, the energy balance of sewage sludge digestion with heat and electricity production is evaluated in monetary terms. This is done by combining the approach of economic LCA with a benefit-cost analysis (BCA).

Apart from the introduction, this paper is structured into four sections. Section 2 provides a short overview of the economic theory related to the waste recovery. The methodology and data are presented in Section 3. Section 4 illustrates the results and discussion of the economic analysis of sewage sludge to energy conversion through anaerobic digestion with CHP. Section 5 contains concluding remarks.

2. THE ECONOMICS OF WASTE[1]

Although waste is an important aspect of our economies, economists have not enough taken into consideration these specific goods, potentially recoverable, especially through recycling and energy recovery.

Several economists talked about the kind of goods including those of a negative value [17]. Despite this work, in the literature, there is little interest regarding the field of waste economics. Waste management has long been considered in the literature as a field of application of existing theories, particularly in the context of microeconomics, public and environmental economics [18].

The pioneering work on the economics of waste has been carried out by Bertolini [19] entitled "*Le marché des ordures*" (i.e. 'The Garbage Market'). Bertolini has introduced microeconomic elements to express a supply of waste at a negative price. The work of Porter [20] is also an international benchmark for the economics of waste. Furthermore, the Organisation for Economic Co-operation and Development (OECD) has presented the policy instruments implemented in different countries to reduce negative externalities of waste [21].

O'Brien [22] has studied the economic and social benefits of waste while considering the optimistic view of the engineering from Talbot [23] and Kershaw [24].

Finally, Lupton [18] has analyzed the particularity of waste in economics and cited all the references that have marked the study of waste in economics.

2.1. Waste and creating value

Waste can play a key role in industry. Many of these can be injected into the production process. Therefore, the integration of waste in the production process requires an intense coordination between research and industry. Scientific progress, particularly in chemistry, has helped to highlight the usefulness of such waste.

Marx [25] has indicated the importance of the use of waste, particularly, by the chemical industry. The latter uses not only its own waste but also those of many other industries. As noted by Marsh [26], "The utilization, …, of waste from metallurgical, chemical, and manufacturing establishments, is among the most important results of the application of science to industrial purposes" (Marsh, 1864, p.37). This is the case, for example, of anaerobic

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[1] This section draws considerably from Lupton [18] and Popp *et al.* [28].

digestion system that uses the sludge to produce biogas. This one will be converted into heat and electricity through cogeneration technology. The welfare of an economy is determined by the amount and the environmental quality of its energy consumption, beside other factors. Thus, to make sure that an economy can attain its maximum level of welfare, it should ensure the supply and demand of sustainable energy quantities [27]. Therefore, waste can be a source of sustainable energy.

2.2. Waste and emerging technologies

Environmental technologies are those that reduce pollution. They also include changes in the production process, such as energy efficiency, which leads to reduce environmental impacts. Because the benefits of the environmental technologies tend to return to the society, market forces alone cannot encourage the development of environmental technologies. Environmental regulation and public funding of research and development (R&D) are often the first impulses for the development of emerging environmental technologies [28]. Furthermore, technological risks could be reduced by strengthening the cooperation between industry and universities in applied research projects [29].

Understanding the interactions between environmental policies and technologies can have important consequences in the context of the BCAs of these policies. The capacity of technology to reduce remediation costs has greatly influenced research in environmental economics [28]. The cost of adaptation of new technologies should be lower than the cost of the regulation [30].

The production of knowledge through the process of innovation opposes to the negative externalities of waste. A company that invests in new technology creates benefits for others. In general, users will feel better if others use the same technology [28].

In addition, the private investor and policy decision-makers must take into consideration that the new power plants that are able to produce energy from waste in electric and thermal forms represent innovative projects, with strategic, social and environmental gains that hardly may be addressed by a pure financial analysis [31].

3. METHODOLOGY

This economic study is performed in the A3i Innovation[2] Company located in Valence (France) for a French WWTP (A). The evaluation is based on LCA of sewage sludge treatment of WWTP (A) performed by A3i Innovation Company. LCA is a method that quantifies inputs and outputs as well as the potential environmental impacts associated with a product all over its whole life cycle [32–36]. However, in spite of the advantages of an LCA methodology, there are some important limitations that must be overcome. A potential failing of an LCA is the huge amount of data involved the availability of such data and the time intensities of an LCA [37].

In this study, the LCA covers the whole processing chain of urban wastewater, namely the lifting of water to obtain a recovery product (energy and compost). The WWTP (A) receives the effluents of 128 190 equivalent inhabitant (eq. Inh.). This capacity is equivalent to a sludge production of about 93 495 t/year.

The database used to determine the quantity of substances emitted and the energy consumed in the process of anaerobic digestion of sewage sludge is derived from reference documents and the life cycle inventory ecoinvent database version 2.2. Data evaluation is performed according to cumulative energy demand (CED) method. The analysis of flow material is provided with the LCA software Umberto®. The calculations in this study are performed using the Microsoft Excel 2010.

3.1. System description

This diagram shows the boundaries of the studied system, as shown in Figure 1. The process chain is evaluated in monetary terms. It is composed of the following: (i) pumps, (ii) aeration tank, (iii) clarifier, (iv) thickener, (v) digester, (vi) CHP system, (vii) dehydration and (viii) composting process. It is assumed that all of the thermal consumed energy arises from the one produced during the combustion of the biogas. Its cost is estimated to be equal to zero.

The thermal energy surplus (54%) is potentially recoverable. Because many factors can affect the overall recoverability of heat (losses in pipes, reduced demand in summer, only partial valorization, etc.), two scenarios of heat recovery are evaluated (30 or 50% of surplus heat is recovered) leading to an income of €20 043 to 33 405/yr. It is assumed that all of the generated electricity will be fed into the electricity network. The cost of electricity mobilized is about €151 714/yr. The chemical consumption in this process has a monetary cost equal to €33 772/yr. The non-renewable energy mobilized in the anaerobic digestion process is about 1394 MWh (91.7% of the 1520 MWh). Cogeneration allows producing 2044 MWh of heat and 1431 MWh of electricity per year, generating an income of €193 526/yr (based on Figure 1 and Table I).

3.2. Economic analysis

Alternative energy must be, not only environmentally beneficial, but also, economically competitive in order to attract investors [31,38]. The positive impacts of renewable energy on the climate change mitigation are incontestable [3,39]. However, renewable energy projects suffer from high cost of heat and electricity generation [40,41]. This is a strategic challenge to maintain economies running under a sustainable model [27]. An economic analysis of the use of the sewage sludge for the production of electricity and heat must consider factors such as the following: the characteristics of the residue, its geographical distribution,

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[2] http://www.a3i-inno.fr/

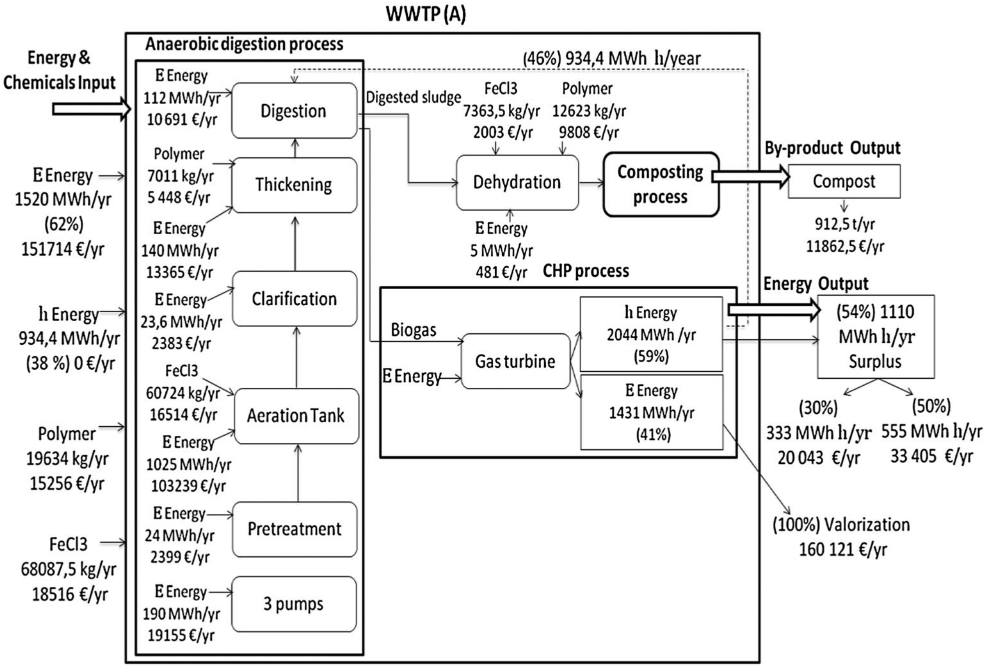

Figure 1. Overview of system boundaries.

Table I. Data used for the economic evaluation of the project.

Parameter	Value	Reference
Economic lifetime	20 years	Industrial partner
Discount rate	4%	[44]
Damping ratio	6%	[10]
Treatment capacity of WWTP (A)	128 190 eq. Inh. 0.0219 t DM/eq. Inh./yr	Industrial partner
Incoming t DM in the digester	2804 t DM/yr	Industrial partner
Incoming dehydrated sludge in composting process	6935 t/yr	Industrial partner
NFU 44-095 compost by-product	912.5 t/yr	Industrial partner
Electricity cost	€0.0953/kWh	[46]
Sold electricity	€0.1119/kWh	[47]
Sold heat	€60.2/MWh	[48]
$FeCl_3$ cost	€271.95/t	[49]
Diesel cost	€1.369/l	[50]
Wood chips	€15/m^3	Industrial partner
NFU 44-095 compost selling price	€13/t	[51]
Cost of treatment of dehydrated sludge to produce NFU 44-095 compost	€45/t	[52,53]

the recovery technology and the economy of scale of the transformation plant [42]. The assessment of the life cycle cost of energy projects in the future will allow a fair competition in the energy market and expand opportunities for a broaden participation in renewable energy. An extra effort must be made by the private sector to develop innovative technologies and their implementation to achieve economies of scale [43].

In this work, we have developed an economic analysis that incorporates all these factors. The total cost of this project is based on the capital expenditure (CapEx) and the operational expenditure (OpEx). The net present value (NPV) is computed based on a discounted cash flow over 20 years (lifetime of the plant) at a rate of 4%[3] [44]. The cash flows are compacted from OpEx and income (the sales of energy recovered). The damping ratio is assumed to be 6% [10]. The subsidies are not taken into account in the calculation. A BCA shows that if a project has a

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[3] Average interest rate of long-term French financial market calculated on the basis of a series from 1999 until 2012.

positive NPV, the project will be welfare improving. The BCA of the project becomes increasingly used to inform and improve decisions [45].

The collection of reliable economic data related to the investment cost of the digestion is difficult because this is only one step of sludge treatment on the whole of the sewage plant. The data collected in the studies are limited, incomplete and disparate. According to the study of Solagro [11], for a treatment capacity of 100 000 eq. Inh., which corresponds to 0.018 t DM/eq. Inh./year, the cost of the investment is €2 916 000 or 81/t DM/yr. For a WWTP of 100 000 eq. Inh., the investment cost is usually between €33 and 67/t DM/yr [10,12]. The operating costs represent about 33% of the total investment cost [11].

4. PROJECT EVALUATION

4.1. Anaerobic digestion cost

- OpEx

OpEx for the 20-year period are shown in Table II. The costs of maintenance, conduct and digester maintenance are based on the data from the study of Solagro [11] and Chabrier [54].Electricity is considered the biggest contributor to OpEx, 73% (can be seen in Table II). There is a strong correlation between electricity consumption and the investment cost (electricity contributed to 24% to the investment cost). For this reason, it is proposed that electricity consumption should be used as a crude financial indicator for the performance of a biogas plant. Chemicals (polymer and $FeCl_3$) also contribute to a significant portion of the total, 16%. The OPEX corresponds to €75/yr/t DM. It is higher than the amount found in Solagro's study [11], that is €27/yr/t DM. The same reference has shown that electricity varies between €3 and 12/yr/ t DM. Indeed, the system boundaries are different from one study to another, and as it is mentioned, our study is based on LCA.

- CapEx

As mentioned previously, the operating costs represent about 33% of the total investment cost. This allows us to calculate a total investment in the WWTP (A) with anaerobic digestion of sludge of about €12 667 811 or 226/yr/t DM, as shown in Tables III and V.

Table II. OpEx of WWTP (A) with anaerobic digestion of sludge.

OPEX costs	€/yr	€/yr/t DM	€/20 year	%
Electricity	151 714	54	3 034 273	73
Maintenance	12 500	4	250 000	6
$FeCl_3$	18 516	7	370 329	9
Conduct (DM, pH, °C)	7065	3	141 304	3
Polymer	15 256	5	305 125	7
Digestion maintenance	1630	1	32 609	1
Transport	2337	1	46 738	1
Total	209 019	75	4 180 378	100

Table III. Total investment in the WWTP with anaerobic digestion of sludge.

OpEx (20 years)	%	OpEx/yr	OpEx/yr/t DM
€4 180 378	33	€209 019	€75
CapEx	%	CapEx/yr	CapEx/yr/t DM
€8 487 433	67	€424 372	€151
Total cost (TC)	%	TC/yr	TC/yr/t DM
€12 667 811	100	€633 391	€226

4.2. Cogeneration cost

The efficiency of the cogeneration of electrical energy is 35%. The installed capacity of cogeneration is 2 MW. Based on the unit cost of investment in small-scale cogeneration corresponding to €1500/kW [55], the cogeneration cost is nearly €52 500/yr, as seen in Table IV.

4.3. Composting cost

According to Solagro's [11] study, composting cost ranges from €50 to 80/yr/t of raw sludge. The French standard NFU 44-095 covers sludge-based compost. This was validated in May 2002. In 2004, the implementation of this standard became mandatory [56]. It gives the standardized compost the status of 'product' that can be distributed in the same way as an organic fertilizer, which increases the cost of composting.

From our study, the net cost of producing compost is equal to 300 212, €5 or 43/yr/t of dehydrated sludge. Composting is not profitable because the cost of production exceeds the profit that can be achieved with the marketing of the compost. It should be noted that the selling price of the compost may range from €0 to 13/t of compost [51].

4.4. The total investment cost

The total investment cost of the sewage sludge to energy conversion based on anaerobic digestion with CHP and composting of digested matter is around €19 722 061 (refer to Table V, Sections 4.1, 4.2 and 4.3). Few economic studies, which have been conducted in the field of anaerobic digestion of sewage sludge, take into account the stage of cogeneration of biogas and composting of digestate that are based on LCA methodology. Our findings imply that anaerobic digestion process contributes to 64% to the total

Table IV. Cogeneration cost.

€/kW	€1500
Thermal power output	1 MW
Heat efficiency of cogeneration	50%
Input power	2 MW
Electric efficiency of cogeneration	35%
Electric power output	0.7 MW
Cogeneration cost for 20 years	€1 050 000
Cogeneration cost/yr	€52 500

Table V. The total investment includes cogeneration and composting costs.

Investment cost	€ for 20 years	%
WWTP with anaerobic digestion	12 667 811	64
Cogeneration	1 050 000	5
Composting	6 004 250	30
Total	19 722 061	100

project cost. 30% is related to the composting process while 5% is related to CHP system; it can be seen in Table V.

4.5. Net present value

The economic profitability of each plant is calculated through the NPV with Eqn 1 [42].

$$NPV = \sum_{t=1}^{N} \frac{\left[R_{E,h} - TOC\right]_t}{(1+i)^t} - CI \qquad (1)$$

where N is the life of the installation (taken as 20 years), $R_{E,h}$ (€/yr) is the annual income from the selling of generated electricity and heat, TOC are the operating costs (i.e. OpEx), i is the discount rate (assumed as 4%) and CI (€) is the capital investment (i.e. CapEx). The net cash flow (NCF) is given by $[R_{E,h} - TOC]_t$, as in Eqn 1.

NPV and NCF are important indices to evaluate the economic performance of a project. The NPV is a financial index, which plays a key role in the decision-making for investment projects in the long term. A positive NPV indicates that net profits will be high and will come with very soon [57]. This economic analysis is developed on the basis of three scenarios:

- Scenario 1(S1): sale of electricity output without heat recovery;
- Scenario 2 (S2): sale of electricity output and heat recovery of 30% of the surplus;
- Scenario 3 (S3): sale of electricity output and heat recovery of 50% of the surplus.

From Table VI, the NCF is negative because the operating costs are much higher than the incomes.

From Table VII, the NPV is negative. This means that the investment is not profitable, even in scenario 3. That is partly because of the assumptions whereas the prices and quantities produced remain unchanged throughout the lifetime of the installation. Also, the annual operating costs remain the same. The subsidies and bonuses granted by the state have not been considered. For a positive NPV, the cash flows must be positive and growing significantly each year, and the internal rate of return must be higher than the discount rate of capital.

Table VI. Net cash flow.

$R_{E,h}$ (S1)	€160 121
TOC (S1)	€209 019
NCF (S1)	−€48 898
$R_{E,h}$ (S2)	€180 164
TOC (S2)	€209 019
NCF (S2)	−€28 855
$R_{E,h}$ (S3)	€193 526
TOC (S3)	€209 019
NCF (S3)	−€15 493

Table VII. Net present value (NPV).

Year	Cash flows (S1)	NPV (S1)	Year	Cash flows (S2)	NPV (S2)	Year	Cash flows (S3)	NPV (S3)
1	−€47 017		1	−€27 745		1	−€14 897	
2	−€45 209		2	−€26 678		2	−€14 324	
3	−€43 470		3	−€25 652		3	−€13 773	
4	−€41 798		4	−€24 665		4	−€13 243	
5	−€40 190		5	−€23 716		5	−€12 734	
6	−€38 644		6	−€22 804		6	−€12 244	
7	−€37 158		7	−€21 927		7	−€11 773	
8	−€35 729		8	−€21 084		8	−€11 320	
9	−€34 355		9	−20 273		9	−€10 885	
10	−€33 033		10	−€19 493		10	−€10 466	
11	−€31 763		11	−€18 743		11	−€10 064	
12	−€30 541		12	−€18 023		12	−€9677	
13	−€29 367		13	−17 329		13	−€9305	
14	−€28 237		14	−€16 663		14	−€8947	
15	−€27 151		15	−€16 022		15	−€8603	
16	−€26 107		16	−€15 406		16	−€8272	
17	−€25 103		17	−€14 813		17	−€7954	
18	−€24 137		18	−€14 244		18	−€7648	
19	−€23 209		19	−€13 696		19	−€7354	
20	−€22 316		20	−€13 169		20	−€7071	
Total	−€664 533	−€9 151 966	Total	−€392 145	−€8 879 578	Total	−€210 553	−8 697 986

Table VIII. Sensitivity of the income related to the variation of the heat recovery.

	€/yr	€/t DM/yr	€/eq. Inh./yr	€/m^3/yr	€/kWh/yr					
OpEx	€209 019	€74.53	€2	€8	€0.08					
Income (three scenarios)							Scenarios	Δ h	Sensitivity	R/Δ h
R (S1)	€160 121	€57	€1	€6	€0.06	ΔR	S1	0%	–	–
R (S2)	€180 164	€64	€1	€7	€0.07	13%	S2	30%	0.42	€668
R (S3)	€193 526	€69	€2	€7	€0.08	21%	S3	50%	0.42	€668
Net cash flow (three scenarios)							Scenarios	Δ h	Sensitivity	R/Δ h
Deficit S1	−€48 898	−€17	€0	−€2	−€0.02	Δ CF	S1	0%		
Deficit S2	−€28 855	−€10	€0	−€1	−€0.01	−41%	S2	30%	−1.37	−€668
Deficit S3	−€15 493	−€6	€0	−€1	−€0.01	−68%	S3	50%	−1.37	−€668
Cost saving	€111 505	€40	€1	€4	€0.04					
NPV (S1)	−€9 151 966	−€3263	−€71	−€346	−€4					
NPV (S2)	−€8 879 578	−€3166	−€69	−€336	−€4					
NPV (S3)	−€8 697 986	−€3101	−€68	−€329	−€3					

Table IX. Sensitivity of the income related to the variation of the electricity price.

	€/yr	€/t DM/yr	€/eq. Inh. /yr	€/m^3/yr	€/kWh/yr					
Income (3 scenarios)						ΔR	Scenarios	Δ Ep	Sensitivity	R/Δ h
S1 + Δ Ep	€168 127	€59.95	€1	€6	€0.07	5%	S1	5%	1.00	
S2 + Δ Ep	€188 170	€67	€1	€7	€0.07	4.4%	S2	5%	0.89	€4009
S3 + Δ Ep	€201 532	€72	€2	€8	€0.08	4.1%	S3	5%	0.83	€6681
Net cash flow (three scenarios)						ΔCF	Scenarios	Δ Ep	Sensitivity	R/Δ h
S1 + Δ Ep	−€40 891	−€15	€0	−€2	−0.02	−16.4%	S1	5%	−3.27	
S2 + Δ Ep	−€20 849	−€7	€0	−€1	−€0.01	−27.7%	S2	5%	−5.55	€4009
S3+ ΔEp	−€7487	−€3	€0	€0	€0.00	−51.7%	S3	5%	−10.34	€6681

Moreover, investment in renewable energy is dependent on the subsidy system or other support systems implemented by the government. In the case of France, the state guarantees of up to 70% of the amounts of loans [43,58]. Without subsidies, renewable energy projects risk to become non-profitable.

4.6. Sensitivity analysis

The sensitivity analysis is related to the annual income from the selling of generated electricity and heat based on three scenarios. The objective is to test the sensitivity of the income to (i) the heat recovery and (ii) the price of the sold electricity (increase at 5%) in order to identify the key parameter of the system that contributes most to the increased income.

4.6.1. Sensitivity of the income to the heat recovery

Income increase depends on the heat recovery, as shown in Table VIII. A heat recovery at 50% allows a surplus of €193 526/yr, but this increase is modest and has an average sensitivity (0.42). Although it is improved slightly, the NPV remains largely negative in the three scenarios. This means that investment is not profitable, even if heat is recovered at 50%.

4.6.2. Sensitivity of the income to the electricity prices

The income is very sensitive to changes in the price of electricity. An increase in electricity price by 5% leads to an increase in sales by 5% (scenario 1), as shown in Table IX. The sale price of electricity is a key parameter in the decision-making.

5. CONCLUSIONS

This study shows the results of an economic analysis of anaerobic digestion of sewage sludge with CHP and composting of digested matter based on the LCA approach. Sludge to energy represents a source of renewable energy. Mobilized in the anaerobic digestion process, 2.4 MWh of renewable generation results from 1 MWh of non-renewable energy. This indicates that energy balance of the anaerobic digestion of sewage sludge is positive. Cogeneration can produce 2044 thermal MWh and 1431 electric MWh per year. The production of electrical and thermal energy by cogeneration of biogas replaces the energy requirements of the process of anaerobic digestion. The produced electricity can be fed into the electricity grid. In this study, our results show that total investment in the WWTP (A) with anaerobic digestion of sludge, cogeneration of biogas and composting of digested matter is about €19 722 061. Electricity consumption contributes with 24% of the investment cost of anaerobic digestion process. An electricity index is a sensitive factor and recommended to be applied for the performance of the treatment processes of WWTP.

The NCF is negative in this project as a result of the fact that the operating costs are higher than the income in the three scenarios. The sensitivity analysis shows that income is very sensitive to the increase in electricity prices. An increase in the price of the sold electricity improves the NCF. In the three scenarios, we record a negative NPV. To achieve a positive NPV, the cash flows must be positive and increase significantly each year. Two parameters need to be considered in the development of future anaerobic digestion plants: maximizing the electricity produced by the CHP process and optimizing the system to reduce the operational costs.

It is, however, necessary to keep in mind that the primary function of the WWTP is the treatment of wastewater. It is then necessary to take into account, in the economic analysis, the payment of companies and individuals for this service, which significantly improves the NPV. The cost saving, which replaces the energy requirements of the process of anaerobic digestion, is about €111 505/yr.

Renewable energy projects suffer from high initial capital requirements. They represent a high economic risk. The private investor is rarely willing to take risk in this kind of project. In this way, governments should adopt laws and regulations to support private investment.

This study is only a first step to analyze the direct costs of such a project. It should be coupled with a monetization of external costs with a life cycle impact assessment approach. It will be the second part of this study.

NOMENCLATURE

BCA = Benefit-cost analysis
CapEx = Capital expenditure
CED = Cumulative energy demand
eq. Inh. = Equivalent inhabitant
$FeCl_3$ = Iron(III) chloride
LCA = Life cycle assessment
NCF = Net cash flow
NFU 44-095 = Standard for soil improvers after a composting treatment
NPV = Net present value
OpEx = Operational expenditure
t DM = Ton of dry matter
TC = Total costs
WWTP = Wastewater treatment plant

Subscripts

$R_{E,h}$ = Annual income from the selling of generated electricity and heat
Δ Ep = Variation of the price of the sold electricity
Δ h = Variation of the heat recovery
E = Electricity
h = Heat
i = Discount rate
N = Life of the installation
R = Annual income
S1 = Scenario 1
S2 = Scenario 2
S3 = Scenario 3
TOC = Total operating costs
yr = Year
Δ R = Variation of the annual income
Δ CF = Variation of the annual cash flows

Units of measure

€ = Euro
€/eq. Inh./yr = Euro per equivalent inhabitant per year
€/kWh/yr = Euro per kilo watt hour per year
€/m^3/yr = Euro per cubic metre per year
€/yr/t DM = Euro per year per ton of dry matter
CapEx/yr/t DM = Capital expenditure per year per ton of dry matter
kWh = Kilo watt hour
l = Litre
m^3 = Cubic metre
MW = Megawatt
MWh = Megawatt hour
OpEx/yr/t DM = Operational expenditure per year per ton of dry matter
t = Tonne
TC/yr/t DM = Total costs per year per ton of dry matter

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REFERENCES

1. Li XR, Lim WS, Iwata Y, Koseki H. Safety evaluation of sewage-sludge-derived fuels by comparison with other fuels. *Fire and Materials* 2009; **33**:187–200.
2. Houillon G, Jolliet O. Life cycle assessment of processes for the treatment of wastewater urban sludge: energy and global warming analysis. *Journal of Cleaner Production* 2005; **13**:287–299.
3. Akhgari PA, Kamalan H. Economical-environmental evaluation of natural gas and renewable energy

systems. *International Journal of Energy Research* 2013; **37**(12):1550–1561.

4. Cingarapu S, Singh D, Timofeeva EV, Moravek MR. Nanofluids with encapsulated tin nanoparticles for advanced heat transfer and thermal energy storage. *International Journal of Energy Research* 2014; **38**:51–59.
5. Zhang HJ. Sludge treatment to increase biogas production. Trita-LWR Degree Project 10-20 2010.
6. Hong J, Hong J, Otaki M, Jolliet O. Environmental and economic life cycle assessment for sewage sludge treatment processes in Japan. *Waste Management* 2009; **29**:696–703.
7. Evangelisti S, Lettieri P, Borello D, Clift R. Life cycle assessment of energy from waste via anaerobic digestion: A UK case study. *Waste Management* 2014; **34**:226–237.
8. Cao Y, Pawłowskia A. Sewage sludge-to-energy approaches based on anaerobic digestion and pyrolysis: Brief overview and energy efficiency assessment. *Renewable and Sustainable Energy Reviews* 2012; **16**:1657–1665.
9. Mills N, Pearce P, Farrow J, Thorpe RB, Kirkby NF. Environmental & economic life cycle assessment of current & future sewage sludge to energy technologies. *Waste Management* 2014; **34**:185–195.
10. Merlin/EREP. Réalisation d'un référentiel technique et économique d'unités de traitement de déchets organiques par méthanisation avec et sans valorisation du biogaz. Synthèse Rapport d'étude, 2003.
11. Solagro, AEAG. *La digestion anaérobie des boues urbaines, état des lieux, état de l'art* 2001. Available at: http://www.solagro.org/site/430.html. Accessed on August 02, 2012.
12. Ernst & Young. Etude de marché de la méthanisation et des valorisations du biogaz. Etude réalisée pour le compte de l'ADEME et GrDF, Rapport final, Septembre, 2010.
13. Eisgruber L. The resource curse: Analysis of the applicability to the large-scale export of electricity from renewable resources. *Energy Policy* 2013; **57**:429–440.
14. Coiante D, Barra L. A practical method for evaluating the real cost of electrical energy. *International Journal of Energy Research* 1995; **19**(2):159–168.
15. Jang YS, Lee DJ, Oh HS. Evaluation of new and renewable energy technologies in Korea using real options. *International Journal of Energy Research* 2013; **37**(13):1645–1656.
16. Ghazy MR, Dockhorn T, Dichtl N. Economic and environmental assessment of sewage sludge treatment processes application in Egypt. *15th International Water Technology Conference*, IWTC-15, Alexandria, Egypt, 2011.
17. Jevons WS. *The Theory of Political Economy*. Edition Macmillan and Co.: London, 1871. Available at: http://www.econlib.org/library/YPDBooks/Jevons/jvnPE3.html#Chapter 3. Accessed on December 12 2013.
18. Lupton S. *Economie des déchets : Une approche institutionnaliste*. Ouvertures Economiques, Groupe De Boech, 1re édition, Groupe De Boeck s.a., Bruxelles, ISBN 978-2-8041-6301-3, 2011.
19. Bertolini G. *Le marché des ordures : Economie et gestion des déchets ménagers*. L'Harmattan, Collection Environnement: Paris, 1990.
20. Porter RC. *The Economics of Waste. Resources for the Future*. RFF Press: Washington DC, 2002.
21. OECD. *Addressing the Economics of Waste*. OECD: Paris, 2004.
22. O'Brien M. *A crisis of waste? Understanding the Rubbish Society*. Routledge: New York, 2008.
23. Talbot F. *Millions from Waste*. J.B. Lippincott Company: Philadelphie, 1920.
24. Kershaw J. *The Recovery and Use of Industrial and Other Waste*. Ernest Benn Limited: Londres, 1928.
25. Marx K. *Capital, Vol. III. The Processus of Capitalist Production as Whole*. Progress Publishers: Moscow, 1978 (first published 1894).
26. Marsh G. *Man and nature; or, Physical geography as modified by human action*. Charles Scribner: New York, 1864. Available at: http://books.google.fr/books?id=MtZ-AAAAMAAJ&printsec=frontcover&hl=fr&source=gbs_ge_summary_r&cad=0#v=onepage&q&f=false. Accessed on April 17, 2014.
27. Blum H, Legey LFL. The challenging economics of energy security: Ensuring energy benefits in support to sustainable development. *Energy Economics* 2012; **34**:1982–1989.
28. Popp D, Newell RG, Jaffe AB. Energy, the Environment, and Technological Change. *Working Paper 14832*, National Bureau of Economic Research (NBER), 2009.
29. Ekman A, Campos M, Lindahl S, Co M, Börjesson P, Karlsson EN, Turner C. Bioresource utilisation by sustainable technologies in new value added biorefinery concepts-two case studies from food and forest industry. *Journal of Cleaner Production* 2013; **57**:46–58.
30. Harrington W, Morgenstern RD, Nelson P. On the accuracy of regulatory cost estimates. *Journal of Policy Analysis and Management* 2000; **19**(2):297–322.
31. Carneiro P, Ferreira P. The economic, environmental and strategic value of biomass. *Renewable Energy* 2012; **44**:17–22.
32. ISO. ISO 14040: Environmental Management- Life Cycle Assessment-Principles and Framework, 2006. Available at: http://www.iso.org/iso/catalogue_detail?csnumber=37456. Accessed on September 14, 2012.
33. Elcock D. Life-cycle thinking for the oil and gas exploration and production industry. ANL/EVS/R-07/5,

prepared by the Environmental Science Division, Argonne National Laboratory, September 2007.
34. Rebitzer G, Ekvall T, Frischknecht R, Hunkeler D, Norris G, Rydberg T, Schmidt WP, Suh S, Weidema BP, Pennington DW. Review life cycle assessment, part 1: framework, goal and scope definition, inventory analysis, and applications. *Environment International* 2004; **30**(5):701–720.
35. Garcia GR, Senante MM, Hospido A, Sancho FH, Moreira MT, Feijoo G. Environmental and economic profile of six typologies of wastewater treatment plants. *Water Research* 2011; **45**(18):5997–6010.
36. Lansche J, Müller J. Life cycle assessment of energy generation of biogas fed combined heat and power plants: Environmental impact of different agricultural substrates. *International Journal of Energy Research* 2012; **12**(3):313–320.
37. Cucek L, Klemes JJ, Kravanja Z. A Review of Footprint analysis tools for monitoring impacts on sustainability. *Journal of Cleaner Production* 2012; **34**:9–20.
38. Fersi S, Chtourou N, Bazin D. Energy analysis and potentials of biodiesel production from Jatropha Curcas in Tunisia. *International Journal of Global Energy Issues* 2012; **35**(6):441–455.
39. Smyth BM, Smyth H, Murphy JD. Can grass biomethane be an economically viable biofuel for the farmer and the consumer? *International Journal of Energy Research* 2010; **4**(5):519–537.
40. Lehr U, Lutz C, Edler D. Green jobs? Economic impacts of renewable energy in Germany. *Energy Policy* 2012; **47**:358–364.
41. Wittmann N, Yildiz Ö. A microeconomic analysis of decentralized small scale biomass based CHP plants-The case of Germany. *Energy Policy* 2013; **63**:123–129. DOI: 10.1016/j.enpol.2013.05.069.
42. Gómez A, Zubizarreta J, Rodrigues M, Dopazo C, Fueyo N. An estimation of the energy potential of agro-industrial residues in Spain. Resources. *Conservation and Recycling* 2010; **54**(11):972–984.
43. World Energy Council. *Renewable Energy Projects Handbook*. World Energy Council, London, 2004. ISBN:0-946121-12-5.
44. INSEE. Taux d'intérêt à court et à long terme par pays en 2012. Available at: http://www.insee.fr/fr/themes/tableau.asp?ref_id=CMPTEF08205. Accessed on September 22, 2012.
45. Dietz S, Hepburn C. Benefit–cost analysis of non-marginal climate and energy projects. *Energy Economics* 2013; **40**:61–71.
46. EDF. Prix d'électricité : Option de base, Les prix métropole. Available at: http://edfpro.edf.com/abonnement-et-contrat/les-prix/les-prix-de-l-electricite/electricite-pro-49194.html#acc52647. Accessed April 01, 2012.
47. EurObserv'ER. Etats des Energies Renouvelables en Europe, Edition 2011.
48. AMORCE, ADEME. *Prix de vente de la chaleur en 2009*. Séries Economiques RCE. AMORCE, Lyon, France, 2010; 3–40.
49. SODIM. Évaluation d'un procédé de coagulation-floculation au chitosane pour l'enlèvement du phosphore dans les effluents piscicoles, Rapport n° 710.149, 2008.
50. Portail de l'économie. Le prix des carburants. Available at: http://www.prix-carburants.gouv.fr/index.php?module=dbgestion&action=fsearch. Accessed August 02, 2012.
51. SIGO. Les principales caractéristiques techniques. Available at: http://www.fontaine-etoupefour.fr/spip.php?article45. Accessed on December 15, 2012.
52. Chambre d'Agriculture de l'Yonne. Recycler des boues d'épuration de collectivités autrement, Bulletin n°8, 2012. Available at: http://www.yonne.chambagri.fr/fileadmin/templates/images/internet/Environnement/MCEA/bulletin8_fili%E8res%20alternatives.pdf. Accessed on December 15, 2012.
53. AEAG. Le retour du sol des boues d'épuration domestique. *Revue de mars de l'Agence de l'Eau Adour Garonne*. File March 2010; **109**:16–22.
54. Chabrier JP. La digestion anaérobie des boues d'épuration. Journée technique GRESE, ENVIRO-CONSULT, YVERDON, septembre 23, 2004. Available at: http://www.grese.ch/Doc/Epuration/dig_boue.pdf. Accessed on October 11, 2014.
55. MEEDDM. Analyse du potentiel national pour l'application de la cogénération à haut Rendement, 2011. Available at: http://www.developpement-durable.gouv.fr/IMG/pdf/101015_Rapport_potentiel_coge_pour_UE-1.pdf. Accessed on September 12, 2012.
56. AERMC. La norme compost de boues NFU 44 095. Available at: http://www.eaurmc.fr/fileadmin/grands-dossiers/documents/Grands-dossiers-Assainissement/GD-Boues/Norme_NFU_44095_compost_de_boues.pdf. Accessed on April 16, 2014.
57. Yu S, Tao J. Economic, energy and environmental evaluations of biomass-based fuel ethanol projects based on life cycle assessment and simulation. *Applied Energy* 2009; **86**(1):178–188.
58. Voorspools KR, D'haeseleer WD. The evaluation of small cogeneration for residential heating. *International Journal of Energy Research* 2002; **26**(13):1175–1190.