SEWAGE SLUDGE SOLAR DRYING AND GASIFICATION AT PILOT SCALE FOR CHP

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ABSTRACT: LIFE-DRY4GAS is a demonstrative project that proposes an environmentally sustainable technology solution for the management of sewage sludge generated in a Waste Water Treatment Plant (WWTP). A prototype integrated by a solar dryer, a gasification plant, a gas burner and an Organic Rankine Cycle will be developed and demonstrated in a WWTP. This work aims at the study of solar drying and gasification of sewage sludge at a pilot plant scale in CEDER-CIEMAT's facilities in Soria (Spain). During the drying test, 8170 kg of sewage sludge with a moisture content of 80% were dried up to 12%, consuming a specific energy of 6474 kJ/kg of evaporated water. 95% of the whole amount of energy came from renewable energy sources (solar and hot air from a biomass burner). Ambient conditions were unfavorable for the drying test: temperature of 4.9ºC and ambient air humidity of 72.4%, but results were satisfactory. The gas produced during the gasification test had a composition of 5.1-6.2% H_2, 6.3-7.5% CO and 2.4-3.1% CH_4, with a low heating value of 2.5-2.9 MJ/Nm^3. The content of total tars of the gas was 5.4-6.4 g/Nm^3.
Keywords: drying, gasification, sewage sludge, wastewater treatment, CHP.

1 INTRODUCTION

The establishment of the Directive concerning urban waste water treatment in Europe [1] has originated an increase in the production of sewage sludge to be managed. The average annual production of sewage sludge per inhabitant in the EU-27 was 22.5 kg/inhabitant/year, expressed as dried matter, in 2014 [2]. These are considered as waste in Directive on waste [3] and a hierarchy should be used in their management: prevention, reutilization, recycling, valorization and removal. The elimination of sewage sludge in landfills is regulated by the Directive on landfill of waste [4] and it shall be reduced until it disappears.

The use of sewage sludge varies from one country to another, according to the existing policies. The use of them in agriculture is very extended in countries such as UK, France or Spain [5]. Taking into account data from National Sludge Register, in Spain the production of sewage sludge was approximately 1,200 kt/year, expressed as dried matter, in 2012 (69.7% in agriculture, 3.7% in incineration, 12.7% in other uses and 13.9% in landfill, according to Eurostat [6].

Nevertheless, these uses are changing due to the following reasons:

- Reduction of availability of landfills for biodegradable wastes.
- Disagreement to their agricultural use for local users.
- More severe standards for metals, organic micro-pollutants and hygienic parameters.
- Increasing costs associated to transport from the waste water treatment plant.

During the last years, experts in waste water treatment have agreed that sewage sludge is not a waste, but a source of valuable resources. The main reasons for this argument are environmental and sustainability issues, increasing costs of energy, stricter directives for sewage sludge elimination and social pressure for avoiding the use of it.

The alternative for recovery of resources through nutrients extraction, fuels production or energy recovery seems to be the more convenient options. The future efforts should imply the application of technical solutions for the conversion of sludge into resource at pilot or commercial scale (currently, most technologies are available at laboratory scale) [7].

Sewage sludge for WWTP in general is a mixture of:

- Water (variable content).
- Organic matter and nutrients.
- Inorganic matter (silicates, alumina, etc.)
- Pollutants (heavy metals, organic compounds, pathogenic, etc.).

Composition can vary depending on the applied technologies during the treatment and the tendency is the application of different stages until getting the production of stabilized sludge. Nevertheless, only treatments at high temperature assure the removal of major organic compounds. On the contrary, during thermal processes, heavy metals increase their concentration [8].

In this context, LIFE-DRY4GAS is a demonstrative project that proposes an environmentally sustainable technology solution for the management and reuse of sewage sludge generated in a Waste Water Treatment Plant (WWTP) (Figure 1).

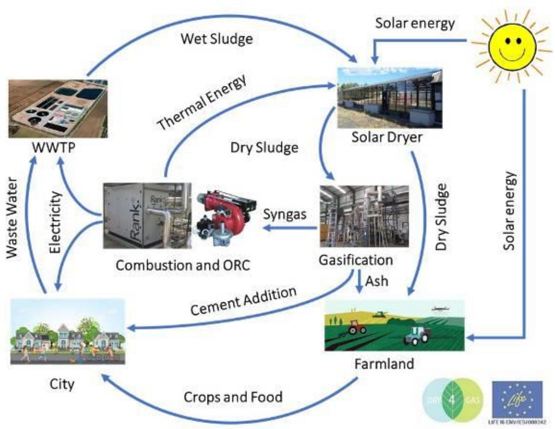

Figure 1: LIFE-DRY4GAS project concept

In the project framework, a prototype integrated by a solar dryer, a gasification plant, a gas burner and an Organic Rankine Cycle (ORC) will be developed, as energy valorization process with the production of 120 MWh/year. In addition, the project proposes an alternative agricultural valorization method of the sludge by evaluating the reuse of gasification ashes mixed with sewage sludge for improving sludge quality as an organic amendment and analyzing the associated effects on soil.

The main objective of the LIFE-DRY4GAS project is to reduce the environmental impact associated to the conventional management of sludge from a WWTP by implementing the proposed solution in an operating WWTP located in San Javier (Murcia, Spain). The results obtained during the project will demonstrate the feasibility of the proposed technology in a real operating WWTP. Furthermore, a replicability plan will be defined in order to applicate the project solution in other WWTPs or in other similar applications.

2 MATERIALS AND METHODS

2.1 Sewage sludge

Sewage sludge from a Waste Water Treatment Plant (WWTP) located in San Javier (Murcia, Spain) was received at CEDER-CIEMAT facilities with a moisture content of 80% (Figure 2). This sludge was dried at CEDER-CIEMAT up to a moisture content of 12%, in the drying pilot plant described below, before being gasified.

Figure 2: Wet sewage sludge received at CEDER-CIEMAT

2.2 Drying pilot plant

The hybrid drying pilot plant used for the test (CIEMAT's patent no. ES 2379932) is based on solar radiation energy and heat from biomass combustion and is located in CEDER-CIEMAT facilities in Soria (Spain) (Figure 3).

Figure 3: Hybrid drying pilot plant at CEDER-CIEMAT

This hybrid plant is specially designed to be able to dry automatically a wide range of types of biomass. The innovation of this facility lies on the integration of different sources of heat, mainly renewable, maximizing the contribution of solar energy, with a continuous processing of the material aiming at a humidity target.

The dryer size is 3.7 m wide and 19 m long. It is all covered by solar transparent walls, like a greenhouse. It also has a mechanism to distribute and move the biomass, forming a homogenous layer and increasing the heat transfer. The biomass processing capacity is between 15 and 60 kg/h, depending on factors such as product characteristics and meteorological conditions.

Biomass is fed into the dryer from a silo with a floor screw conveyor. A mechanical device tumbles and moves the biomass along the drying tunnel, forming a layer of material with a variable height, while measuring the moisture content and temperature of biomass. The dry biomass is removed from the process by a conveyor.

Heat from biomass combustion is provided by a boiler and a stove, both fed with different biomass such as wood chips, wood pellets and olive stones, among others. This flexibility contributes to the replicability of the plant. Hot water produced by the boiler is used in an underfloor heating, while hot air from the biomass stove is directly introduced into the dryer. There are fans along the drying tunnel in order to avoid stratification of hot air. Fresh and dry air is introduced by two fans, when the stove is not running, establishing a hot air flow which is counter-current to biomass movement.

The control of the whole process is performed automatically, ruled by the biomass humidity, which is the main target of the process.

With this technology, significant conventional energy savings can be achieved, estimated in a minimum value of 15%, when working continuously during the whole year. This percentage can be higher if the plant works only during solar radiation hours. In addition, the investment and maintenance outlays are low.

This drying pilot plant will be reproduced at a larger scale in the framework of the LIFE-DRY4GAS project, to demonstrate the technologies proposed by the project in a waste water treatment plant. The hybrid dryer prototype, with a treatment capacity of 175 kg/h of wet sludge with a moisture content of 80%, will be integrated in the whole sewage sludge treatment process. In this case, heat sources will be solar radiation hot air and hot water from an ORC cycle which produces electricity from the syngas obtained in the gasification of dried sewage sludge.

2.3 Gasifying pilot plant

The sewage sludge dried in the pilot plant described above was gasified in a bubbling fluidized bed gasification pilot plant located at CEDER-CIEMAT facilities in Soria (Spain) (Figure 4).

The gasifier has a thermal capacity of 150 kW_{th}. The system works at atmospheric pressure and in autothermal mode. The pilot plant is prepared to the introduction of different gasifying agents, such as air, water steam or oxygen.

The feeding system is airtight and consists of two hoppers and two screw conveyors. Moreover an additional hopper is connected to the gasifier for introducing inert material continuously during the process, if needed.

The ashes removal from the bed is carried out continuously by a refrigerated screw conveyor, when necessary.

Figure 4: Gasifying pilot plant at CEDER-CIEMAT

At the outlet of the gasifier, the gasification gas enters a cyclone which removes the coarse particles (cyclone cut size 80-100 μm). The gas without particles flows through a pipe with two sampling points, being finally burnt in a torch.

A centralized control system allows the online measurement and saving of all operating parameters, such as temperatures, pressures and flow of biomass, air and gas. An online measurement of O_2, CO, H_2, CO_2 and CH_4, among other gaseous components, is carried out in the exhaust gases. The tar sampling in the gas is performed based on the technical specification CEN/TS 15439:2006 and the concentrations of each component are determined in the laboratory [9].

This gasifying pilot plant will be used for the design of a prototype for the valorization of 65 kg/h of dried sewage sludge in the framework of LIFE-DRY4GAS project. The prototype will be integrated in a sewage sludge treatment plant in a WWTP for the demonstration of the technologies proposed by the project. The syngas obtained in the gasification of dried sewage sludge will be introduced into a burner and will produce electricity in an ORC. Residual heat will be used in the hybrid dryer.

2.4 Analytical methods

The characterization of sludge and ashes obtained during gasification process was carried out in the Biomass Characterization Laboratory at CEDER-CIEMAT, following the standards for biomass characterization shown in Table I.

Table I: Standards used in the characterization of sludge

Parameter	Standard
Moisture content	ISO 18134-2:2015
Ash content	ISO 18122:2015
Volatile matter	ISO 18123:2015
C, H, N	ISO 16948:2015
Cl, S	ISO 16994:2015
O	ISO 16993:2015
High heating value	EN 14918:2009
Chemical composition of ashes	ISO 16967:2015
Fusibility temperatures	CEN/TS 15370-1:2007

The quantity of gravimetric tars in the tar samples was determined using a rotary evaporator, following the technical specification CEN/TS 15439:2006 at CEDER-CIEMAT.

Regarding analytical method for determining tar content, Liquid Chromatography was used to determine 16 PAHs, benzene, toluene, and xylenes (BTEX) [10] [11].

Chromatographic conditions for PAH determination were adapted from previous methods using diode and fluorescence detection [12].

2.5 Experimental procedure

The drying procedure began feeding the wet sewage sludge by a screw conveyor. The amount fed was controlled according to the evaporating water capacity, which depends on the energy balance, between contribution and losses, and the ambient conditions of temperature and humidity.

The sewage sludge forward movement along the drying tunnel was achieved using a tumbler with adjustable travelling and rotatory speed. The residence time of the sludge was adjusted, controlling this system, depending also on the energy balance.

During the drying process, heat sources used were solar radiation and hot air, which contribute to heat up the greenhouse. Several fans help to avoid stratifying the air inside the greenhouse.

Once the dry sludge reached the end of the tunnel, with the required moisture content, was moved to a belt conveyor which transports the sludge to the storage facility.

The gasification tests were performed in the bubbling fluidized bed described before. First of all, air was introduced uniformly through the distribution plate by a blower. At the startup of the plant, the air was pre-heated with a propane burner until the temperature in the bed was around 400ºC. At this point, sewage sludge feeding started and when the systems reached a temperature around 550 ºC, the burner was off and the process continued working in autothermal mode, without any external heating source. The gasifier worked at atmospheric pressure and temperatures around 820 ºC. The inlet of dried sewage sludge was 36.6 kg/h. Silica sand was used as inert material for the fluidized bed. Bed ashes were collected from the bed using an overflow pipe.

The gas sampling was performed in two gas sampling points located in the pipeline after the cyclone, with the aim of evaluating the gas composition and the tar content.

3 RESULTS AND DISCUSSION

3.1 Sewage sludge characterization

A picture of dry sewage sludge is shown in Figure 5 and its characterization is included in Table II.

It can be highlighted the low volatile matter of sewage sludge (65.4%) and its high ash content (29.4%), associated to the presence of inert material.

Furthermore, carbon content is low and nitrogen, sulphur and chlorine are high, compared to the composition of typical biomass as pine wood chips. However, these values have been observed in the characterization of sewage sludge from other WWTP.

Finally, the low heating value is similar to that obtained for other biomass with the same moisture content, so that the energy use of sewage sludge appears to be a feasible possibility.

Figure 5: Dry sewage sludge used in the gasification test

Table II: Characterization of sewage sludge used in the gasification test

Parameter	Unit	Value
Moisture content	wt%, w.b.	12
Ash content	wt%, d.b.	29.4
Volatile matter	wt%, d.b.	65.4
Fixed carbon	wt%, d.b.	5.2
C	wt%, d.b.	37.0
H	wt%, d.b.	5.2
N	wt%, d.b.	5.8
S	wt%, d.b.	0.8
Cl	wt%, d.b.	0.3
O	wt%, d.b.	21.5
HHV	MJ/kg, d.b.	15.9
LHV	MJ/kg, d.b.	14.7

HHV: high heating value; LHV: low heating value; wt.%: weight %; w.b.: wet basis; d.b.: dry basis.

3.2 Drying results

Sewage sludge was dried in the hybrid dryer described during 408 hours under the conditions shown in Table III.

Table III: Operating conditions during the drying test

Parameter	Unit	Value
S.S. Initial moisture content	wt%, w.b.	80
S.S. Final moisture content	wt%, w.b.	12
Mean ambient temp.	ºC	4.9
Mean ambient rel. humidity	%	72.4
Mean greenhouse temp.	ºC	20.2
Mean greenhouse rel. humidity	%	41.6
Test duration	hours	408
Wet S.S. flow	kg/h	20
Specific evaporation ratio	kg e.w./h	15.5
Specific consumption	kJ/kg e.w.	6474
RES contribution	%	95

S.S.: sewage sludge; wt.%: weight %; w.b.: wet basis; temp.: temperature; rel.: relative; e.w.: evaporated water.

Figure 6 shows the evolution of temperatures and energy sources used during the test.

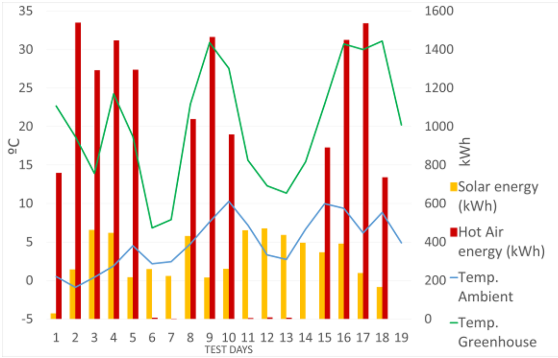

Figure 6: Temperatures and energy used in the drying test

The flow of sludge was 20 kg/h, with an initial moisture content of 80%, which was reduced to 12% along the drying tunnel. It could be remarked that the meteorological conditions during the drying test were unfavorable with an average ambient temperature of 4.9ºC and a relative air humidity of 72.4% and heat losses of 32% of the generated heat. Even so, the drying could be achieved as expected, with average conditions inside the dryer of 20.2ºC and 41.6% of relative air humidity, which means that this technology works successfully even at hard conditions.

The whole amount of sewage sludge processed by the dryer was 8170 kg, evaporating water at a ratio of 15.5 kg/h, obtaining 1860 kg of sludge with a moisture content of 12%.

For the design and replication of the prototype to be installed in a WWTP, the ratio of evaporated water per hour and square meter is a very useful information.

The amount of evaporated water was 6334.4 kg, which demanded a net power of 27.9 kW. This power came from different renewable energies, being the most relevant the hot air from combustion of biomass. The second resource in relevance was the solar radiation, which contributed with an average value of 424.9 W/m^2. Solar radiation is a clean and no cost energy, that contributes to reduce the consumption of other energy sources.

The 100% solar drying could be achievable during warmer seasons of the year, thanks to longer periods of solar radiation, drier ambient air and higher ambient temperatures.

With this way of operation, a share of 95% of RES was reached. The other 5% corresponds to electricity used to run the biomass stove, sewage sludge movement inside the dryer and different air fans.

Finally, all these data provided the specific consumption of energy for evaporating water from the sewage sludge up to the required value of moisture content: 6474 kJ/kg of evaporated water. This value is considerably high compared to the specific energy required for drying poplar or pine chips (from 1679 to 3125 kJ/ kg of evaporated water) [13].

A higher efficiency is expected in the prototype developed within LIFE-DRY4GAS project, mainly due to the higher solar radiation and the higher overall temperatures in Murcia compared to Soria. Additional energy supplied by the ORC will contribute to an increase in the efficiency of the overall system.

3.3 Gasification results

In the gasification test, a stable process was reached during more than ten hours of operation, as can be observed in Figure 7.

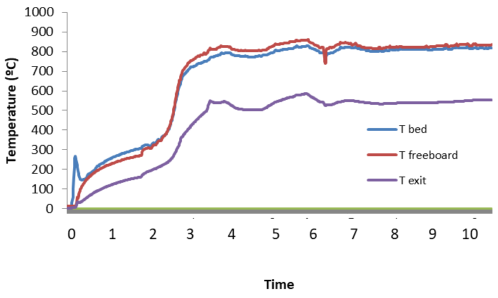

Figure 7: Temperature during the gasification test

Power was kept at 150 kW_{th} during the whole test with a constant fuel input of 36.6 kg/h and air flow between 25 and 28 Nm^3/h.

Good fluidization was performed for bed temperatures around 810-820ºC and equivalence ratio (ER) between 0.19-0.21. The equivalence ratio in gasification is defined as the actual air–fuel ratio to the stoichiometric air–fuel ratio.

Four different gasification regimens (1-4 in Tables IV, V and VI) were studied. Operating conditions reached in each one are included in Table IV.

Table IV: Operating conditions during gasification test

Parameter	1	2	3	4
Fuel (kg/h)	36.6	36.6	36.6	36.6
Air (Nm^3/h)	25.2	25.4	26.6	28.3
Power (kW_{th})	150	150	150	150
ER	0.190	0.191	0.200	0.213
Bed temperature (ºC)	810	812	817	812

The four regimens used have quite similar gasification conditions with only slight differences between ER and bed temperatures. The relationship between bed temperatures and ER can be seen in Figure 8. It can be observed that it was not totally linear, as it should be in an auto-thermal gasifier. This is due to a slight lack of stability in some conditions. Therefore, it is important to highlight that these are preliminary results and medium values or ranges of the whole process are going to be considered.

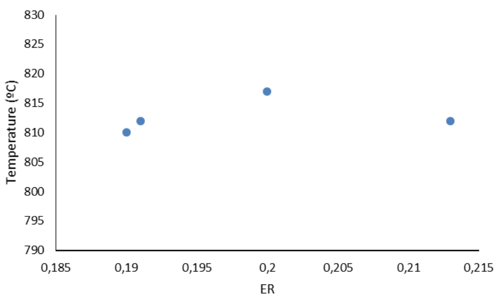

Figure 8: Temperature vs ER during gasifying test

Gas quality and tar composition was evaluated during the tests.

Results of gas characterization are included in Table V for each operating regimen. The produced gas is composed of 5.1-6.2% H_2, 6.3-7.5% CO and 2.4-3.1% CH_4, as the main components which contribute to its heating value. Furthermore, the low heating value (LHV) of the gas was calculated taking into account these three components, resulting in 2.5-2.9 MJ/Nm^3. If other compounds as ethane, ethylene and acetylene were considered, the heating value of the gas could be increased by around 20%.

Table V: Gas characterization

Parameter	1	2	3	4
H_2 (%), d.b.	6.08	6.24	6.02	5.19
CO (%), d.b.	7.34	7.49	6.28	7.17
CH_4 (%), d.b.	2.98	2.49	2.40	3.12
LHV (MJ/Nm^3)	2.88	2.51	2.30	2.58

LHV: low heating value; d.b.: dry basis.

The gasification conditions are quite similar; hence, there are not clear tendencies of the influence of the ER in the gas composition.

Results of tar composition are included in Table VI.

Table VI: Tar composition

Parameter	1	2	3	4
Total tar (g/Nm^3)	5.53	5.86	5.43	6.42
Gravimetric (g/Nm^3)	1.78	2.14	0.83	1.95
PAH (g/Nm^3)	1.62	1.52	2.63	2.18
BTEX* (g/Nm^3)	2.13	2.20	1.98	2.29
BTEX (g/Nm^3)	8.15	8.34	7.31	7.28

*excluding benzene

Gravimetric tars represented a concentration from 0.8 to 2.1 g/Nm^3 (semi-quantitative) and PAHs from 1.5 to 2.6 g/Nm^3. BTEX contents were between 7.3 and 8.3 g/Nm^3, including benzene. Nevertheless, benzene sometimes is not considered a tar in gasification tests, since benzene does not cause the tar common problems. Thus, excluding benzene, BTEX contents are in the range 1.9-2.3 g/Nm^3.

In the LIFE-DRY4GAS project, gas is burnt in a combustion chamber so that, tars will contribute also to the heating value of the gas.

The gasification conditions are quite similar; therefore, there are not clear tendencies of the influence of the ER in the tar contents.

4 CONCLUSIONS

Drying of sewage sludge from a WWTP in a solar-biomass dryer reduces its moisture content from 80% to 12%, with a specific energy consumed of 6474 kJ/kg of evaporated water, using 95% of renewable energy sources.

Gasification of dry sewage sludge in a bubbling fluidized bed reactor provides a gas with LHV of 2.5-2.9 MJ/Nm^3, considering only H_2, CO and CH_4, which will be higher if considering tars and other compounds of the gas.

The gasification conditions are quite similar, thus, there are not clear tendencies of the influence of the ER in the gas composition or in the tar content.

Solar drying and gasification of sewage sludge from WWTP is a technical and environmental sustainable solution for its treatment and management. Thus, LIFE-DRY4GAS project promotes the development of a circular economy with the installation of the technology in the place of the waste production.

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7 LOGO SPACE