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Plasma gasification of sewage sludge: Process development and energy optimization

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Abstract

The plasma gasification process has been demonstrated in many of the most recent studies as one of the most effective and environmentally friendly methods for solid waste treatment and energy utilization. This method is applied here to the treatment of sewage sludge. Results are presented for a case study concerning the Athens' Central Wastewater Treatment Plant, at Psittalia Island. An integrated process is proposed that includes also pre-drying of the sludge. By optimizing the process with the use of the GasifEq equilibrium model, it is demonstrated that plasma treatment of 250 ton/day sewage sludge with 68% moisture results in a net production of 2.85 MW electrical energy.

Keywords: Plasma gasification; Sewage sludge; Process; Electrical energy

1. Introduction

Plasma gasification is a technologically advanced and environmentally friendly process of disposing solid wastes and converting them to commercially usable products. It is a non-incineration thermal process that uses extremely high temperatures in an oxygen starved environment to decompose input waste material completely into very simple molecules [1]. The main product of the process is a gas, known as synthesis gas, which can be used, among others, for the production of energy and an inert vitreous by product material, known as slag. Furthermore, it consistently exhibits much lower environmental levels for both air emissions and slag leachate toxicity than competing technologies, e.g. incineration [2].

The majority of plasma technology units for waste management are located in Japan [3]. During the last decade, plasma technology has been applied for integrated waste treatment and energy production as the main part of modern waste to energy facilities. Many plasma gasification applications of such type, either pilot or full scale units, were developed during previous years or their development is in progress in Japan, the USA, Canada and Europe. Some examples of plasma gasification waste to energy facilities with great operational capacities are those in Minnesota, USA [4], Ottawa, Canada [5] and Malaysia [6]. However, the most known plasma gasification full scale facility is the one of Utashinai city, in Japan, that produce 7.9 MW gross electrical energy (4.1 MW net electrical energy) by treated 183 ton of municipal solid waste per day [4].

Standard gasification technologies operate the reactor in the 400–850 °C range. They do not use any external heat source and rely on the process itself to sustain the reactions [7]. Normal gasifiers are really "partial combustors", and a substantial portion of the carbon is combusted just to support the reaction. The gasification process produces a fuel gas similar to the gas produced by the plasma process, although it is much dirtier and contains char, tars and soot [8,9]. The lower temperatures involved cannot break down all the materials. As a result, in standard gasification, many materials must be sorted out of the waste stream before the

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reactor and landfilled or processed in other ways. Because of the low temperature used, the gas that is produced by a standard gasifier has tars that are difficult to remove and other contaminants that must be further cleaned. Char residue is up to 15% of the weight of the incoming material and must still be landfilled [10]. In addition to these drawbacks, most standard gasification systems cannot feed heterogeneous waste, e.g. municipal solid waste, directly from the truck.

Plasma gasification uses an external energy source, resulting, thus, in very little combustion of the waste material. As a result, most of the carbon is converted to fuel gas. Plasma gasification is the closest technology available to pure gasification, i.e. it is a "true gasification". Because of the high temperatures involved, all the tars, char and dioxins are broken down [11]. The exit gas from the reactor is cleaner, and there is no ash at the bottom of the reactor [12,13].

Since plasma gasification is an environmentally sound process that has a great potential to convert an organic content material to electricity more efficiently than conventional combustion, gasification or pyrolysis systems, it is examined here for the treatment of sewage sludge with a view of producing the highest possible amount of electrical energy. There are many indications obtained by many experimental [1,14] and modeling [15] studies that plasma gasification is not an energy consuming process for treatment of organic based waste materials. Although study of the energy efficiency issue concerning integrated plasma gasification processes is the main objective of many research and development (R&D) projects in progress, a thorough energy analysis of the process has not been presented in the international scientific literature. As a first step in this direction, Mountouris et al. [16] developed the GasifEq equilibrium thermodynamic model that describes thoroughly the plasma gasification process.

A detailed and well documented energy analysis is even more necessary for the cases where a subsystem of a plasma gasification integrated process is characterized as high energy consuming. Because of the fact that sewage sludge is a waste material with high initial moisture content, the proposed treatment process has to include a drying section that requires a thermal energy supply. The objective of this study is, thus, the development of an integrated treatment process for the case of sewage sludge, the demonstration of the energy performance of the integrated process by application of a reliable thermodynamic model and the selection of the operational parameters that result in the maximum net electrical energy production.

2. Sewage sludge from wastewater treatment facilities

2.1. The problem of sewage sludge management

Sewage sludge treatment and disposal represents one of the most important issues for environmental management in Europe [17]. The progressive implementation of the Urban Waste Water Treatment Directive 91/271/EEC in all Member States is increasing the quantities of sewage sludge requiring disposal. From an annual production of some 5.5 million ton of dry matter in 1992, the Community has reached nearly 9 million ton by the end of 2005. Today, dumping of sludge into the sea is forbidden, and its use a substitute for fertilizer on agricultural land is about to be prohibited as a result of legislation being planned by the European Community [18]. Similar argumentation and legislation development is in progress in the USA, as there are significant oppositions to land use of sewage sludge by the academic community and farmers [19,20]. Once such laws go into effect, the residue produced by sewage treatment plants will have to be thermally processed in the same way as normal waste.

Furthermore, there is a growing change in the perception of sludge from an unwanted waste to a beneficial resource, and it is important to develop a suitable technology or use an existing one in order to reduce the environmental problem and costs of sludge treatment while, at the same time, utilizing it as a source of energy. Plasma gasification technology can be applied to convert the sewage sludge into a usable energy and to reduce the waste volume. Additionally, it eliminates toxic organic compounds and fixes the heavy metals in the inert slag, while it produces synthesis gas that can be utilized in an energy and heat recovery system for electricity production.

In the case study considered here, sewage sludge from the main wastewater treatment plant (WWTP) of Athens at Psittalia Island is considered to be the waste material to be subjected to plasma gasification treatment. At Psittalia, after primary treatment of municipal wastewater mixed with industrial wastes, $\sim$250 ton per day of sludge are produced [21], an amount that will rise to 700–800 ton per day with commencement of secondary treatment [22].

2.2. Sewage sludge properties

Considering the fact that the sewage sludge is a waste material with a varying chemical composition and is not well defined, ultimate analysis of sewage sludge as well as experimental determination of its heating value is required. The sewage sludge that is produced at Psittalia Island passes through an anaerobic digestion section and, then, is mechanically dewatered prior to its final deposition. Because of this fact, the properties of two different samples of sewage sludge before and after anaerobic digestion are experimentally determined in this study.

The ultimate analysis results are shown in Table 1, where they are expressed in "as received – ar", "dry – dr" and "dry ash free – daf" base, as shown below:

ar (as received): C + H + O + N + S + ash + moisture
dr (dry): C + H + O + N + S + ash
daf (dry ash free): C + H + O + N + S

In most of the cases, the oxygen content is not measured but is calculated from the material balance.

Table 1
Ultimate analysis results of sewage sludge, Psittalia WWTP

Element (%w/w)	Sample 1 (before anaerobic digestion)			Sample 2 (after digestion and dewatering)		
Sampling	daf	dry	ar	daf	dry	ar
C	54.8	37.6	12.0	53.5	28.4	9.1
H	8.0	5.5	1.8	6.6	3.5	1.1
O	33.4	22.9	7.3	35.8	19.0	6.1
N	3.8	2.6	0.8	4.1	2.2	0.7
S	0.0	0.0	0.0	0.0	0.0	0.0
Moisture (%w/w)	–	–	68[a]	–	–	68
Ash (%w/w)	–	31.4	10.1	–	46.9	15.0
Sum	100.0	100.0	100.0	100.0	100.0	100.0
HHV (kJ/kg)	24,198	16,600	5312	19,586	10,400	3328

[a] Percentage expected after mechanical dewatering. Initial moisture content is about 90%.

As expected, the sewage sludge before the anaerobic digestion, due to the higher percent of carbon and hydrogen, contains a greater amount of chemical energy as indicated by the greater value of the higher heating value (HHV) in comparison to the sample after the anaerobic digestion and the production of methane gas, i.e. its chemical degradation. For the present work, as a case study, the sewage sludge before anaerobic digestion (sample 1 in Table 1) with moisture content equal to 68% w/w, a value that is expected after mechanical dewatering as in the case of sample 2, has been selected.

Apart from the experimentally determined HHV of the Psittalia sewage sludge (Table 1) and with a view to predict the HHV of other sewage sludges, eight equations from the literature, which were not developed specifically for sewage sludge material, have been applied here, and the results are presented in Table 2. It is worth mentioning that the original Dulong formula is an equation with a theoretical background, and the next two are two modified forms of Dulong's equation [23]. Additionally, the Milne's [24] as well as the Francis and Loyd equations [25] were developed by correlation of experimental data. Among the most recently developed equations are those of Meraz et al. [26], Channiwala and Parikh [27] and Sheng and Azevedo [28] that are applicable where a wide range of HHV values is involved. The predicted values of HHV are presented for evaluation purposes in Table 2 and indicate that the available equations predict fairly well the HHV of sewage sludge. It appears that the predicted values by the original Dulong formula, the Milne's formula and the correlation of Channiwala and Parikh are closer to the experimental value.

Table 2
Prediction of HHV for Psittalia sewage sludge

Equation	HHV_{dry} (kJ/kg)	% Error
Dulong	16,506	0.6
Scheuer and Kestner	18,892	13.8
Steuer	17,744	6.9
Milne	16,532	0.4
Francis and Loyd	16,895	1.8
Meraz et al.	17,686	6.5
Channiwala and Parikh	16,519	0.5
Sheng and Azevedo	15,083	9.1
Experimental value	16,600	±2

3. The plasma gasification process for the treatment of Psittalia sewage sludge

The block diagram of Fig. 1 presents the main sections of the proposed plasma treatment plant for the case of Psittalia sewage sludge.

3.1. Feed pre-treatment – drying system

The waste feed subsystem is used for pre-treatment of the waste in order to meet the inlet requirements of the plasma furnace. For sewage sludge, a waste material with high moisture content, a dryer for reducing the moisture content of the sludge will be required with air tight screw feeders being required to drive the sewage sludge into the furnace. Multiple ports ensure that the waste is evenly distributed within the furnace, and air tight operation ensures that the reducing atmosphere of the furnace can be fully controlled and no synthesis gas can escape from the furnace to the local surroundings.

3.2. Plasma furnace

The plasma furnace is the central component of the system where the gasification/vitrification process takes place. Two graphite electrodes, as a part of two transferred arc torches, extend into the plasma furnace. An electric current is passed through the electrodes, and an electric arc is generated between the tips of the electrodes and the conducting receiver, i.e. the slag in the furnace bottom. The gas introduced between the electrode and the slag that becomes plasma can be oxygen, helium or other, but use of air is very common due to its low cost.

At the temperatures maintained within the plasma furnace, the organic molecules contained in the sewage sludge begin to break down and react with the air to form carbon monoxide, hydrogen and carbon dioxide. Water contained in the sludge feed also dissociates and reacts with other organic molecules. As a result of these reactions, all organic constituents and water are transformed into a synthesis gas containing mostly hydrogen, carbon monoxide and nitrogen. The main reactions taking place in the plasma furnace are presented in the next paragraphs.

The inorganic components of the sewage sludge are mainly oxides, coming from the ash present in the sludge. When the oxides melt together, they form a type of glass that is extremely stable and inert [29,30]. The process is called vitrification and is an excellent method of permanently trapping many environmentally hazardous materials, mainly heavy metals, in an inert matrix. The molten vitrified oxides are called slag and are recovered from the furnace continuously and automatically in the form of fine gravel, perfectly suited for use as construction material [31,32].

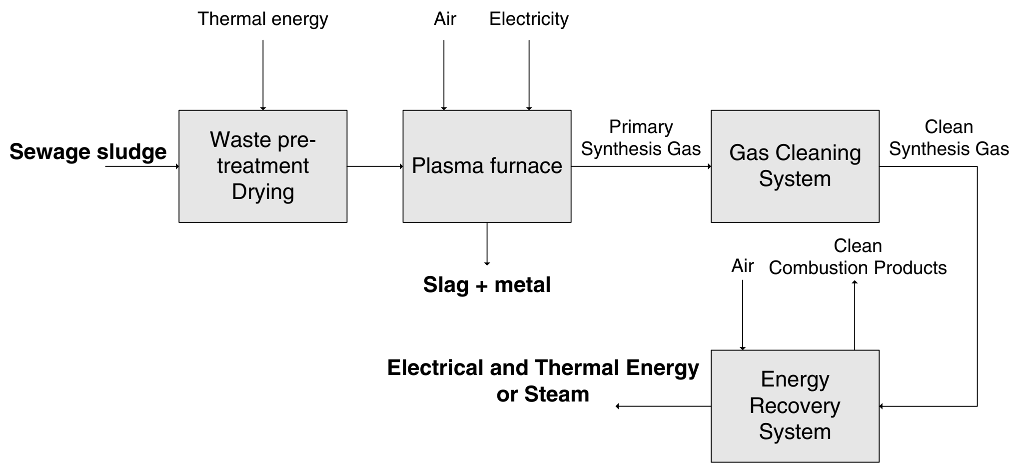

Fig. 1. Block diagram of plasma gasification process.

3.3. Gas cleaning subsystem

The gas cleaning subsystem has to achieve the elimination of acid gases (HCl, SO_x), suspended particulates, heavy metals and moisture from the synthesis gas prior to entering the energy recovery system. For that purpose, a typical gas cleaning system consists of

(a) A water quench for immediate cooling of the hot and dirty synthesis gas to avoid formation of complex molecules like dioxins. The quench is used to eliminate the possibility of formation of dioxins and furans. The quench is designed to cool the gases through the injected spray of water. Typical off gas outlet temperatures range from 70 °C to 90 °C.
(b) A packed bed tower scrubber using caustic solution to neutralize acid gases. Moreover, with the use of the cold scrubbing solution, the moisture in the gas is condensed in the solution.
(c) A venturi scrubber to remove particulates.
(d) A H_2S absorber used for removal of H_2S, which is then removed for sulphur recovery.
(e) Filters for entrapment of heavy metals and other fine particulates.

3.4. Energy recovery system

The energy recovery system can be based on a steam cycle, gas turbine cycle or a gas engine. Depending on the quality and the amount of the produced synthesis gas, the best option can be one of the above energy recovery scenarios.

4. Process development for the plasma treatment of sewage sludge

In the case of sewage sludge treatment with thermal processes, there are design difficulties due to the large amount of energy that is required for drying this waste material. Contrary to other thermal treatment options for sewage sludge, plasma gasification does not require a very low moisture content for the waste material, as moisture is essential for the chemical reactions of gasification [16].

The proposed process for sewage sludge plasma gasification is shown in Fig. 2. In this figure, the main modifications added to the general process block diagram of Fig. 1 refer to (a) the energy recovery section where a gas engine is proposed due to the relatively small amount of produced synthesis gas and (b) to the drying section.

Drying the sewage sludge is done by using part of the thermal energy from the hot synthesis gas produced in the plasma gasification section (Label 1 in Fig. 2) and part of the thermal energy produced in the energy recovery section (Label 2 in Fig. 2). It is noted that only part of the thermal energy of the hot synthesis gas produced in the plasma furnace is utilized because the temperature of the gas must not be reduced below 500 °C to avoid the possibility of dioxin reformation.

The necessary drying can be achieved by direct or indirect contact drying. In direct dryers, the energy is supplied by the heating medium (air) in direct contact with the sludge. Since the high temperature of the medium (usually 450 °C) is combined with the high oxygen content in the air flow, auto-ignition is often a problem in these dryers. With indirect contact drying systems, the heating medium is separated from the sludge by a wall.

Therefore, in this study, the use of an indirect dryer, with trays, is proposed. The necessary energy for the drying process is transferred by thermal oil that circulates through the hollow trays at a temperature range of 260–230 °C. The oil is heated by exchanging heat with two separate gas streams at elevated temperature (a) the hot synthesis gas produced in the plasma furnace and (b) the hot combustion gases produced in the gas engines used for production of electrical energy. The energy efficiency values that are used in the energy calculations of this study are presented below.

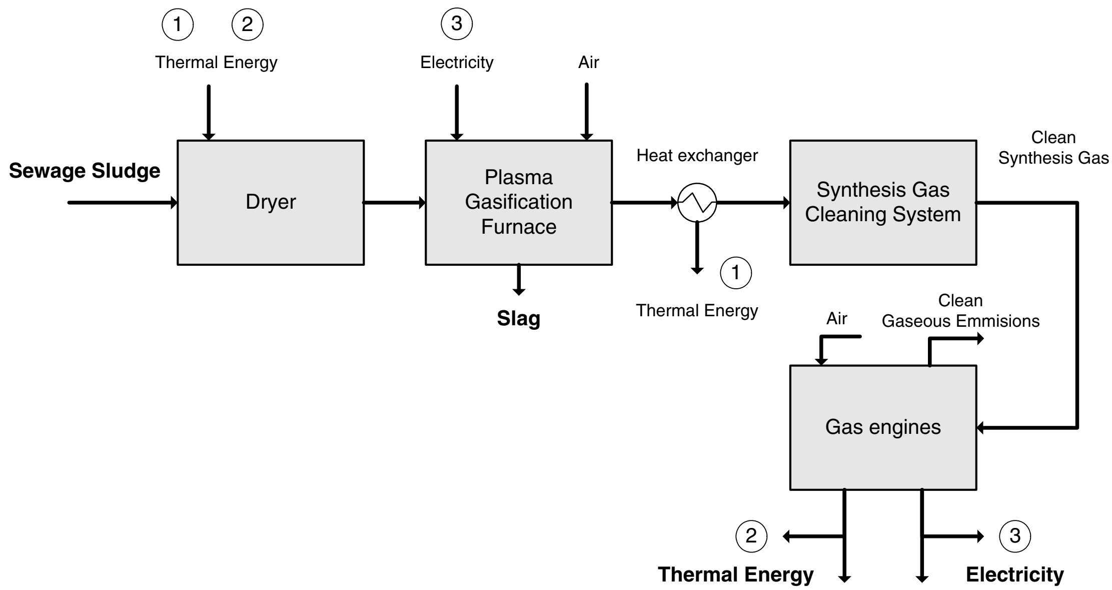

Fig. 2. Plasma gasification process for sewage sludge treatment.

5. Energy analysis of the process

5.1. Energy analysis system

The objective of the process analysis is to identify the conditions that optimize the production of electrical energy (net electricity), which is equal to the electrical energy produced from the gas engine minus the electrical energy consumed in the reactor. The net electrical energy production, in turn, depends on the following process variables:

1. The moisture content of the feed waste.
2. The amount of air/oxygen introduced to the reactor.
3. The gasification energy, i.e. the electrical energy needed for completion of the gasification reactions. It should be noted that the energy required for vitrification of the inorganic fraction of the waste is independent of the gasification procedure and will be discussed later.
4. The net thermal energy produced by the process, which is equal to the thermal energy recovered from the hot synthesis gas and the hot exhaust gases minus the thermal energy required for pre-drying the sewage sludge.
5. The quality, i.e. the heating value, of the produced synthesis gas, which, however, must be high enough to be used in a gas engine for electricity production, i.e. at least 1 kWh/Nm^3 [33,34].
6. The reactor temperature. This was set, in this study, equal to 1273 K due to the operation requirements and environmental limitations, e.g. cracking of hydrocarbons and organic volatiles [35,36]. This is also in agreement with other studies on gasification [37].

All these variables are not, of course, independent, and there are also three equations:

1. Material balance.
2. Energy balance.
3. Chemical equilibrium in the reactor.

There are, thus, five variables and three equations, which means that the electrical energy produced is a function of two independent variables.

5.2. GasifEq thermodynamic equilibrium model

The solutions to the energy analysis problem are obtained by application of the GasifEq model. The GasifEq thermodynamic equilibrium model was developed by Mountouris et al. [16] in order to describe the plasma gasification of solid waste. It includes the energy supplied to the main section of the plasma gasification process, i.e. electricity, the formation of the basic gasification gaseous products and the possibility of remaining solid carbon, i.e. soot particles.

GasifiEq uses the most recent thermodynamic data that are valid for the temperature range that is of special interest for high temperature thermal methods, e.g. plasma gasification. The model is based on the global gasification reaction of the waste material studied (input data: ultimate analysis results C, H and O fractions and HHV). The analysis of the system considered shows that simultaneous equilibrium is described by three independent reactions, three partial mass balances (for C, H and O) and one heat balance, which are incorporated in the GasifEq model. The specific heat and enthalpy changes of the gas products are expressed as a function of the gasification temperature, as well as the equilibrium constants of the chemical reactions.

The three main independent equilibrium reactions that are selected for the equilibrium calculations in GasifEq model are shown below:

1. $CH_4 + H_2O = CO + 3H_2$ (methane decomposition – endothermic)
2. $CO + H_2O = CO_2 + H_2$ (water gas shift – exothermic)
3. $C + H_2O = CO + H_2$ (primary water gas shift – endothermic)

The equilibrium calculations, as well as the analysis of the non-linear system of equations, involved in the development of the GasifEq model are presented in details elsewhere [16].

The GasifEq model has been validated by comparison to experimental and modeling results reported in the literature [38,39]. It appears that the GasifEq model results are satisfactorily close to the experimental values and the observed difference may be due to the fact that equilibrium is not attained in the experiments. Additionally, the results reported by other models agree closely with the GasifEq results [16]. All reported validation results refer to common organic waste material treated, i.e. waste wood, and they are representative of the majority of organic waste material of great importance, such as sewage sludge.

Use of the model in this study requires, however, a decision for some process energy efficiencies, which are incorporated in the GasifEq model.

5.2.1. Conversion factor of thermal energy to electricity in the heat engine

This factor is assumed to be equal to 0.40, an optimistic estimation based on the manufacturer's specifications [33] and taking into account the continual technological improvement in the field of electricity production with gas engines.

5.2.2. Heat transfer efficiency factors

These factors are required for the three sections where thermal energy utilization takes place. Firstly, it is the heat exchanger where a part of the thermal energy of the produced synthesis gas is recovered. An efficiency factor equal to 0.8 has already been assumed in the development of the GasifEq model. This value seems to be the best case of heat exchanger efficiency as presented by the Energy Systems Research Unit [40]. As a result, the use of 0.8 appears to be a realistic value for the heat exchanger, and this value is used in this study, too.

Secondly, it is the drying of sewage sludge. In this case, an energy consumption factor is required that will be used for calculation of the thermal energy consumed for drying a specific amount of sewage sludge. This is dependent on the selection of the drier's type. For an indirect drier, which is selected in this study, the specific thermal energy consumption is equal to 2800 kJ/kg evaporated water [41]. This value is also obtained by using experimental data for the case of the indirect drier installed in the Antwerp WWTP in Belgium by the Seghers Better Technology for air and solids NV company [41].

5.2.3. Thermal energy recovery from the hot exhaust gases produced in the synthesis gas engines

The specifications of the commonly used gas engines state that almost 40% of the heating value of the synthesis gas is converted into usable thermal energy [33]. In the proposed process, this thermal energy is used for drying the sewage sludge. The next question is, how much of the thermal energy can be utilized inside the drying section? A Japanese team report [42] presents experimental data from the Nitto Boseki Co. Ltd. and the Chiba plant where almost 26% of the exhaust gases thermal energy is recovered in the drying section. This value is taken as an assumption in this study for drying the sewage sludge.

It apparent that in order to meet the aforementioned quality requirement for the synthesis gas, i.e. to be at least equal to 1 kWh/Nm^3, there exist two options: (i) produce about 4 MW of electrical energy, from which about 1 MW will be used to cover the thermal energy requirements, as indicated by the results of Case I in Table 3; or (2) produce about 2.8 MW of electric energy with no need for thermal energy as indicated by the results of Case II in Table 4. The latter case has also the advantage over the former that it avoids the drying to a low moisture content and that it requires a significantly lower amount of air, reducing, thus, the equipment cost.

5.3. Results

In order to identify the conditions that optimize the production of electricity in the presence of two independent variables for the case of the 250 ton/day Psittalia sewage sludge described in Section 2.2, two cases are considered:

Table 3
Effect of feed moisture content on required oxygen amount, energy values and quality of synthesis gas for Case I: zero gasification energy

Moisture (%w/w)	Oxygen (mol/mol daf)	Net thermal (MW)	Net electrical (MW)	SynGas HV (kWh/Nm^3)
5.20	0.53	−1.07	4.17	1.12
10.23	0.55	−0.92	4.04	1.03
14.68	0.57	−0.77	3.90	0.96
20.50	0.60	−0.54	3.71	0.86
27.04	0.64	−0.25	3.45	0.74
29.88	0.66	−0.10	3.33	0.69
34.92	0.70	0.19	3.07	0.60

Table 4
Effect of feed moisture content on required oxygen amount, energy values and quality of synthesis gas for Case II: zero net thermal energy

Moisture (%w/w)	Oxygen (mol/mol daf)	Gasification energy (MW)	Net electrical (MW)	SynGas HV (kWh/Nm^3)
14.68	0.213	−3.92	2.12	2.14
20.50	0.348	−2.77	2.45	1.52
27.04	0.535	−1.18	2.90	0.95
29.88	0.613	−0.52	3.09	0.78

Table 5
Mass and energy values for the optimum scenario for energy production by plasma gasification of sewage sludge (zero net thermal energy)

		Synthesis gas (dry b.)	% v/v
Moisture (%w/w)	26.7	H_2	20.23
Oxygen (mol/mol daf)	0.515	CO	17.12
Gasification energy (MW)	1.35	CO_2	9.77
Net electrical (MW)	2.85	N_2	52.88
SynGas HV (kWh/Nm^3)	1.00		
Mass balance (250 ton ar waste)		Synthesis gas	(kg/s)
Oxygen (kg/s)	0.48	H_2	0.04
Water (kg/s) – after drying	0.34	CO	0.52
Waste daf (kg/s)	0.64	CO_2	0.46
Nitrogen (kg/s)	1.57	H_2O	0.40
Sum	3.02	N_2	1.60

Table 6
Thermodynamic equilibrium data

Equilibrium constants – K values		Heat of waste formation (kJ/K mol)	
Methane decomposition	8834.6	ΔH_C	−113,979
Water gas shift	0.56		
Primary water gas shift	94.7		

1. Case I: zero gasification energy; and
2. Case II: zero net thermal energy.

Under these requirements there is only one independent variable in each case, which we chose to be the moisture content, and the results are presented in Tables 3 and 4. The calculations involved are performed using the GasifEq thermodynamic equilibrium model [16], which is presented above.

6. The optimum scenario for energy production

On the basis of the aforementioned results, a detailed analysis of the process on the basis of zero thermal energy leads to the following optimum scenario for electrical energy production: the sewage sludge is dried prior to the plasma furnace to the moisture percent of 26.7% w/w. After drying of the sludge, it enters the plasma furnace along with the air supply, which corresponds to 0.515 mol oxygen per mol of dry ash free sewage sludge. All pertinent information, along with the composition of the resulting synthesis gas, is presented in Tables 5 and 6, and the process flow diagram, including the energy flows, in Fig. 3.

The energy required for vitrification is not included in the results above, as it is independent of the gasification procedure. The vitrification energy is the sum of the energies for heating the slag to temperatures around 1550 °C and for melting the slag. For the optimum scenario presented herein, the vitrification energy is calculated to be equal to 0.49 MW.

7. Conclusion

Plasma gasification offers an attractive and environmentally sound option for the treatment and energy utilization of solid wastes. This study demonstrates the energy utilization potential of sewage sludge treatment using an integrated process involving plasma gasification, pre-drying and electric energy production. Application in the case study involving the sludge from the Psittalia sewage treatment plant indicates that the proposed process is not only self sufficient from an energy point of view, but it leads to net production of 2.85 MW electrical energy.

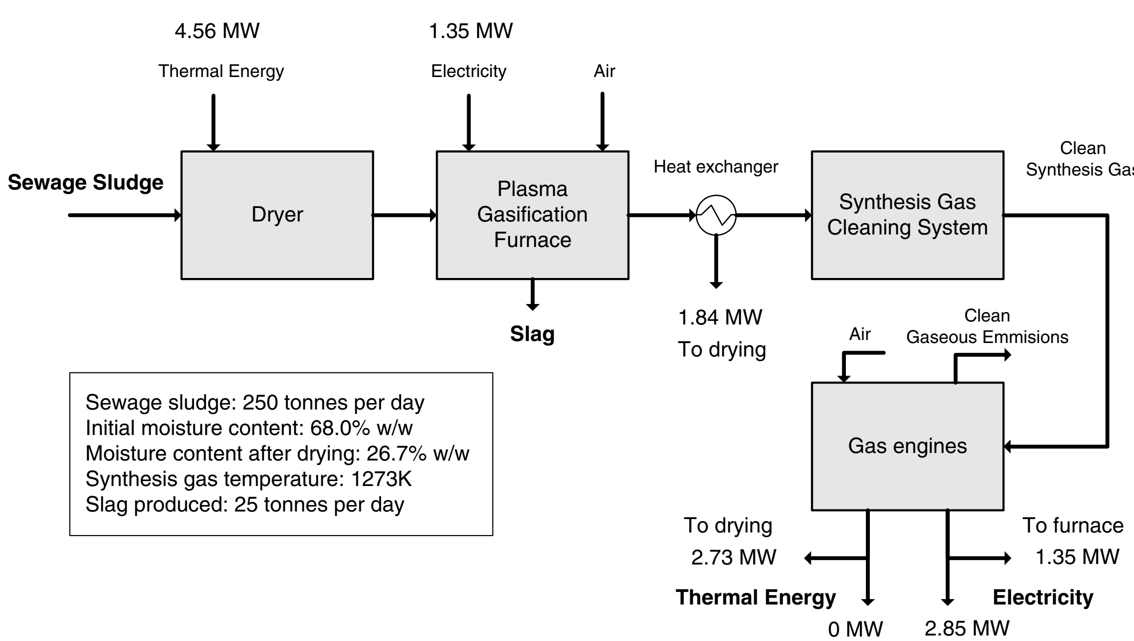

Fig. 3. Proposed integrated plasma gasification process for the sludge from the Psittalia sewage treatment plant.

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