# ELECTRICITY GENERATION USING HOT FLUE GAS FROM URBAN SOLID WASTE INCINERATION

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***Abstract.*** *The urban, industrial and hospital solid wastes are nowadays a great environmental and social problem since some of them are inappropriate for reuse or recycling. The incineration process enters as an option to reduce the amount of residues to the landfills and in cases of harmful wastes it is regulated as mandatory. Usually the solid waste incineration thermal energy is dissipated to the environment as well as its flue gas pollutants. This work objective is to analyze the potential of electricity generation using the rejected thermal energy from the solid waste incineration. The hot flue gas provides the energy for two Rankine Cycles: (i) using water and (ii) the organic HFC-245fa as working fluid. The flue gas emissions will be quantified as well as the heat losses through the unburned solid in the ashtray. The heat and mass balance analysis is developed for both systems using the Engineering Equation Solver software. Both configurations are compared in the use of the thermal energy. The remaining emissions are analyzed to complement the culture of microalgae in photobioreactors since these emissions are rich in $CO_2$. The microalgae are expected to absorb the pollutants needed to meet the environmental regulations for the flue gas emissions.*

***Keywords:*** *Urban solid waste; incineration; Rankine; power generation; photobioreactors.*

## 1. INTRODUCTION

The Brazilian legislation that governs on procedures and criteria for the operation of thermal waste treatment systems is the Conama Resolution No. 316, (MMA, 2002), in which Article 27 states that: “Any and all heat treatment system must have receiver units, storage, supply, gases and particulate emissions treatment, wastewater, ashes and slag treatment.”

Incineration is a thermal treatment that receives lots of criticism due to the potential emissions to the atmosphere. According to Jangsawang, *et al*., (2005), the optimized conditions for the complete decomposition ensures operation of volatile organic compounds into carbon dioxide, water, oxygen and nitrogen. However, it is needed to point out the potential of carbon dioxide ($CO_2$) as a global climate problem aggravating.

An incineration process cannot exist without being interconnected to a technologically advanced system of gas purification, treatment and recirculation of liquids in the process. The incinerator flue gas carry large amounts of substances in concentrations way above the legally permitted emission limits, (ABNT NBR 11175, 1990), and require physical and chemical treatment to remove and neutralize pollutants from the thermal process.

At this level, carbon sequestration mechanisms can be coupled to the waste incinerator projects as an attempt to obtain a clean design aiming to reduced or even zero emissions. Reforestation can be considered for this purpose; however, the cultivation of microalgae is potentially more attractive due to the high growth rate.

The microalgae biomass production on a large scale is performed in photobioreactors. These systems consist of tubular or helical reactors, made of transparent material. Since photobioreactors are closed systems they can be connected to the carbon dioxide emission lines of industries and waste incinerators (Silva, *et al*., 2015).

The photobioreactors installed at the Center of Research and Development of Self-Sustainable Energy - NPDEAS, located on the Polytechnic Center campus of the Federal University of Parana - UFPR, have large sun light receiving area with transparent tubes arranged compactly, as shown in Figure 1. It can be defined as a technologically advanced system for gas cleaning which can be connect to an incinerator or a furnace as an innovative engineering solution to environmental, social and financial problem.

The higher heat value of algal biomass suggests its use as a substitute for fossil energy sources. Several researchers have reported in the literature the possibility of biofuels production from microalgae since many strains have lipid content higher than 40% by dry mass (Andersson, et al., 2014; Venteris, et al., 2014; Quinn and Davis, 2015).

Microalgae grown in photobioreactors of NPDEAS - UFPR are the species Scenedesmus sp, which has several desirable characteristics for efficient and economical combination for fixing $CO_2$, wastewater treatment and synthesis of lipids for biofuel production. Currently the carbon sequestration is made only by the $CO_2$ present in the air, through the cycle of Calvin - Benson. The photobioreactors are a part of the NPDEAS layout, as shown in Figure 2.

Figure 1 - Compact tube photobioreactors developed by NPDEAS-UFPR

The microalgae photobioreactors are able to assimilate carbon dioxide emissions from waste incineration flue gas producing biomass with high energetic potential. However, there are few studies on the cultivation of microalgae supplemented with waste incineration gas, especially the ones related to the coupling of incinerator unit and photobioreactors.

The coupling between a solid waste incinerator and the compact photobioreactors and the technology needed for that will not be the focus of this paper, which should consider the solid waste management policies and environmental costs.

## 2. SOLID WASTE FIRED POWER PLANT

It is considered a power plant that operates with the thermal energy that comes from the incineration of university campus solid waste. This power plant is part of the NPDEAS layout, located at the Module 5, as shown in Figure 2. The solid wastes at university campi differ from the typical municipal solid wastes because it contains less food and other organic materials. It consists of residues such as wooden parts that come from old disposed furniture and infrastructure renovation, paper from cardboard and plastic packaging. It can also contain gardening wastes that comes from the campus cleaning. The residues that are expected to be sent to the furnaces are the ones that for some reason are rejected by the recycling processes. The university campi waste can also differ from typical municipal residues due to its lower humidity that can be achieved with a proper storage (Hla and Roberts, 2015).

Some non-combustible hazardous wastes have to be sent to the furnaces to undergo a sterilization process. This inert kind of residue contributes to the furnaces heat losses since it consume energy to have its temperature increased and leave the burning chamber with high sensible heat. Glass and metal have to be removed from the furnace similarly to the ash in the ashtray, decreasing the fuel heating value.

The waste acceptable content for ash (or inert materials) and humidity to keep a steady combustion without auxiliary fuel is up to 60% and 50%, respectively.

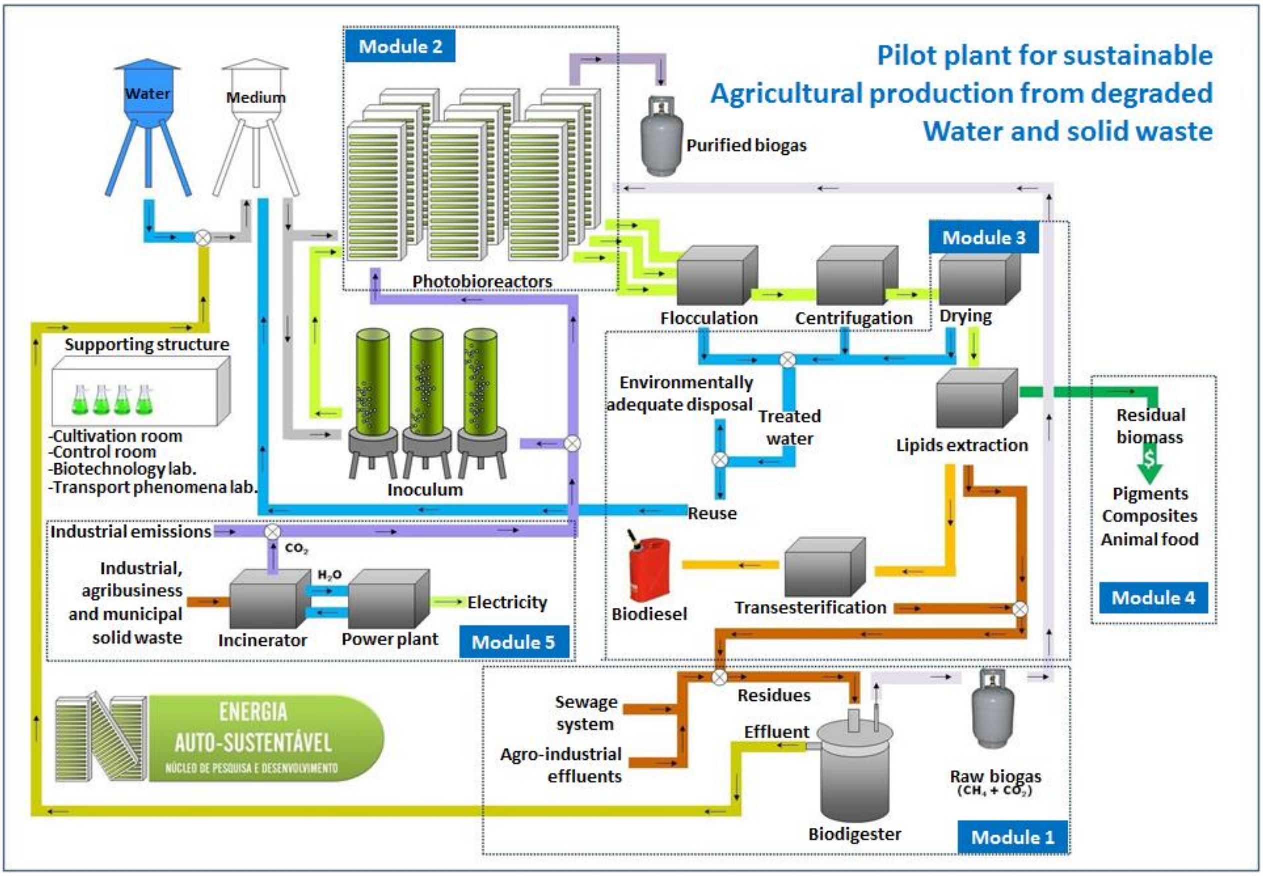


Figure 2 - NPDEAS layout

The solid waste chemical composition is modeled as describe in the Table 1. It is given the percentage of weight in the wet basis for the total moisture and the amount of ash, carbon, hydrogen, oxygen, nitrogen and sulfur in the dry basis for the gardening, paper, plastic and wood residues (Hla and Roberts, 2015). Three fuel mixtures are defined in the Table 2. The different fuel mixtures will give different Lower Heating Value (LHV) and different amounts of $CO_2$ that can be supplied to the photobioreactor. The mixtures LHV can also vary with the amount of inert material to be inserted.

Table 1 - Residues chemical composition.

| | Gardening | Paper | Plastic | Wood |
|---|---|---|---|---|
| Total moisture (% wb) | 59,9 | 25,0 | 25,6 | 11,9 |
| Ash (% db) | 8,3 | 12,2 | 3,9 | 1,0 |
| Carbon (% db) | 47,7 | 41,2 | 72,8 | 49,6 |
| Hydrogen (% db) | 5,7 | 5,2 | 9,4 | 6,1 |
| Oxygen (% db) | 36,3 | 41,0 | 11,5 | 43,0 |
| Nitrogen (% db) | 1,8 | 0,3 | 2,3 | 0,2 |
| Sulfur (% db) | 0,2 | 0,1 | 0,0 | 0,0 |

The Eq. (1) gives the amount of flue gas for each kg of fuel burned in the incinerator. This is a function of the stoichiometric mass of gas, $m^*_{gás}$ (Eq. 3), generated in the combustion, the stoichiometric mass of air of air, $m^*_{ar}$ (Eq. 2), needed to burn each kg of fuel, the excess of air ratio, $e$, and the air humidity, $W_{ar}$. In the Eq. (3) to Eq. (7) the quantities denoted by $m$, refers to the mass fraction of each component of the flue gas. The excess air ratio in this work is set equals to 1.

$$m_{gas/cb} = m^*_{gas} + (e-1)m^*_{ar} + e \cdot m^*_{ar} \cdot W_{ar} \tag{1}$$

$$m_{ar}^{*} = 138,23\left[\frac{C}{12}+\frac{H}{4}+\frac{S}{32}+\frac{O}{32}\right] \tag{2}$$

$$m_{gas}^{*} = m\left(CO_2\right)+m\left(SO_2\right)+m^{*}\left(H_2O\right)+m^{*}\left(N_2\right) \tag{3}$$

$$m\left(CO_2\right)=\frac{44}{12}\mathrm{C} \tag{4}$$

$$m\left(SO_2\right)=\frac{64}{32}S \tag{5}$$

$$m^{*}\left(H_2O\right)=W+9H \tag{6}$$

$$m^{*}\left(N_2\right)=0,7685m_{ar}^{*}+N \tag{7}$$

$$\dot{m}_{gas} = m_{gas/cb}\cdot m_{cb} \tag{8}$$

The HHV and LHV are given by the Eq. (9) and Eq. (10), where C, H, O, S, W are the fuel percentage by mass of carbon, hydrogen, oxygen, sulfur and moisture given by the Table 1 (Bazzo, 1995).

$$HHV = 33900C + 141800\left(H-\frac{O}{8}\right)+9200S \tag{9}$$

$$LHV = PCS - 2440\left(9H+W\right) \tag{10}$$

Table 2 - Fuel mixtures.

| | Gardening | Paper | Plastic | Wood |
|---|---|---|---|---|
| Fuel 1 (%) | 0 | 10 | 40 | 50 |
| Fuel 2 (%) | 25 | 25 | 25 | 25 |
| Fuel 3 (%) | 50 | 40 | 10 | 0 |

The mass fraction of $CO_2$ in the flue gas in the incineration process is given by the Eq. (11). The total amount of $CO_2$ in the flue gas is given by the multiplication of Eq. (11) by the Eq. (8).

$$F_{m(CO2)} = \frac{m(CO_2)}{m_{gas/cb}} \tag{11}$$

It is considered in this work that any flue gas that comes from the steam generator stack is cooled down as the feed working fluid is pre-heated. With the flue gas around 60ºC it is compressed and sent to the flue gas reservoir where it will be injected in the photobioreactors (Figure 2).

Two Rankine cycles power plants are considered for this work. Both are modeled with the configuration shown in the Figure 3 using the software Engineering Equation Solver (EES). It is considered a steam generator with a combustion efficiency of 85%, a steam turbine, a condenser set so operate at 50ºC and a condensate pump to increase the working fluid pressure. The design parameters for both systems are shown in the Table 3. The first cycle operates with water as working fluid and the second one uses the organic R245fa working fluid.

The first system is designed to be a simple and economic laboratory workbench equipment to generate up to 20 kW of shaft power burning 55 kg/h of solid waste. Due to the small scale for a water vapor power system, the isentropic turbine efficiency is equal to 60%. The steam generator combustion efficiency is set equals to 85% with a 10460 kJ/kg of fuel LHV. The steam generator, as described before, is designed to superheat the working fluid up to 250ºC and 700 kPa. Since the project does not aim many decades of operation and requires low cost and simplicity, it is designed without a deaerator. The condenser works at 50ºC and keeps the points 2 and 3 at its saturation pressure. The pump used in the cycle, between the points 3 and 4, is considered to have an isentropic efficiency of 85%. This first cycle is under construction as described.

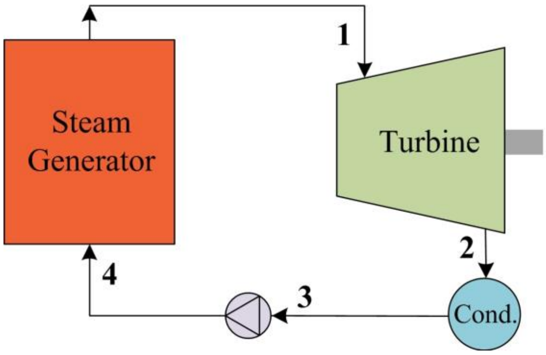


Figure 3 - 20 kW Rankine Cycle Power Plant.

The second power plant which operates with R245fa is modeled as the Figure 3 and its properties are shown in the Table 3. Since the systems that operate with this working fluid use to be of small scale, its turbine is considered to have a higher isentropic efficiency, equals to 80%. The systems with this working fluid are aimed to operate with lower temperature heat sources, so this is modeled with superheated vapor at 130ºC and 1500 kPa.

Table 3 - Design parameters for the water and the organic Rankine Cycles Power Plants.

| Design Parameters - Water | | | | | Design Parameters – R245fa | | | |
|---|---|---|---|---|---|---|---|---|
| # | Temperature | Pressure | Quality | | # | Temperature | Pressure | Quality |
| 1 | 250 ºC | 700 kPa | | | 1 | 130 ºC | 1500 kPa | |
| 2 | 50 ºC | Saturation | | | 2 | 50 ºC | Saturation | |
| 3 | 50 ºC | Saturation | 0 | | 3 | 50 ºC | Saturation | 0 |
| 4 | | 700 kPa | | | 4 | | 1500 kPa | |
| Turbine efficiency | | 60% | | | Turbine efficiency | | 83% | |

The overall system efficiency is the ration between the useful work and the inlet fuel energy given by the Eq. (11).

$$\eta_{sys} = \frac{\dot{W}_{net}}{Energy\,inlet} = \frac{\dot{W}_{turbine} - \dot{W}_{pump}}{\dot{m}_{fuel} \cdot LHV} \qquad (12)$$

## 3. RESULTS AND DISCUSSION

Using the LHV considered in its design condition (10460 kJ/kg) the first cycle requires 54.8 kg/h of fuel to supply 20 kW of power with an overall system efficiency of 12.5%. The organic Rankine cycle requires 79.5 kg of fuel with the same conditions to supply the same 20 kW of power with an overall system efficiency of 8.3 %. It was expected that the second cycle would have a lower efficiency since it operates at a much lower vapor temperature compared to the first cycle.

The efficiency for the water cycle is also considered low compared to the efficiencies usually found in water cycles in the industries and in the literature. The low efficiency is a result of the projects requirements that aimed low cost and simplicity. The vapor temperature and pressure could be higher to increase the overall efficiency. In addition, a proper vapor turbine for lower power would result in better isentropic efficiencies.

Since the second cycle showed a very low efficiency, it will not be considered in the further analysis because it would involve a furnace with a higher capacity and higher costs.

The water cycle is then tested burning gardening residues, paper, plastic and wood waste. Each of these materials has its particular LHV, which are shown in Table 4. The LHV of each fuel mixture is shown in Table 5 without any extra inert material and with 30% of ground glass, representing the possible inert materials.

Table 4 - HHV and LHV for each kind of solid waste.

| Solid residues | HHV [kJ/kg] | LHV [kJ/kg] |
|---|---|---|
| Gardening | 7148.1 | 5184.6 |
| Paper | 10549.5 | 9083.1 |
| Plastic | 26757.7 | 24597.3 |
| Wood | 15712.9 | 14242.4 |

Table 5 - LHV for each fuel mixture with and without inert material.

| | Gardening | Paper | Plastic | Wood | LHV [kJ/kg] | LHV (30% Glass) [kJ/kg] |
|---|---|---|---|---|---|---|
| Fuel 1 (%) | 0 | 10 | 40 | 50 | 17868 | 12508 |
| Fuel 2 (%) | 25 | 25 | 25 | 25 | 13277 | 9294 |
| Fuel 3 (%) | 50 | 40 | 10 | 0 | 8685 | 6080 |

The power generated in the water cycle for burning 50 kg/h of each of the 3 fuel mixtures with 30% of inert material is shown in the Table 6. As expected, the fuel mixture 1 which has the higher fuel LHV is the mixture that resulted in the higher net power generation. As the mixture 1 has the higher heating value it requires a higher amount of stoichiometric air to burn the fuel, leading to a higher amount of total flue gas. The higher heating value is associated with the higher ratio of carbon in the fuel composition, so the mixture 1 has also the higher amount of $CO_2$ in the flue gas. The amount of $CO_2$ in the flue gas is important for the dimensioning of the photobioreactors in which the flue gas will be inserted.

Table 6 - Water cycle: Net power, total flue gas and $CO_2$ in the flue gas.

| Fuel Mixture | Net Power [kW] | Total flue gas [kg/h] | $CO_2$ in flue gas [kg/h] |
|---|---|---|---|
| Fuel 1 (%) | 23.9 | 282.2 | 65.8 |
| Fuel 2 (%) | 17.8 | 226.1 | 52.2 |
| Fuel 3 (%) | 11.6 | 170.0 | 38.6 |

Considering only the decrease of the LHV, the addition of glass will reduce the power plant net power as shown in the Figure 4. It happens due to the effect over the LHV with the addition of inert material.

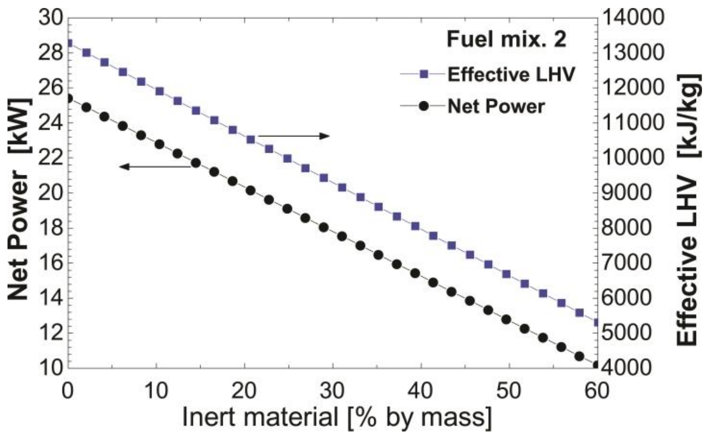


Figure 4 - Net Power and effective LHV with the addition of inert material in the fuel mixture.

## 4. ACKNOWLEDGEMENTS

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## 5. REFERENCES

Andersson, V., Viklund, S.B., Hackl, R., Karlsson, M., Berntsson, T., 2014. "Algae-based biofuel production as part of an industrial cluster". Biomass and Bioenergy. Vol. 71, p. 113- 124.
Bazzo, E., 1995. Geração de vapor. Editora da UFSC, Florianópolis, 2nd edition.
Hla, S.S. and Roberts, D., 2015. "Characterisation of chemical composition and energy content of green waste and municipal solid waste from Greater Brisbane, Australia". Waste Management. Vol. 41, p. 12–19.

Jangsawang, W., Fungtammasan, B., Kerdsuwan, S., 2015. "Effects of operating parameters on the combustion of the medical waste in a controlled air incinerator". Energy Conversion and Management Vol. 46, p. 3137.
MMA, 2002. “Conama Resolution No 316”. 29 May 2015.
<http://www.mma.gov.br/port/conama/legiabre.cfm?codlegi=338>
Quinn, J.C., Davis, R., 2015. "The potentials and challenges of algae based biofuels: A review of the techno-economic, life cycle, and resource assessment modeling". Bioresource Technology Vol. 184, p. 444–452
SILVA, A.G., CARTER, R., MERSS, F.L.M., CORRÊA, D.O., VARGAS, J.V.C., MARIANO, A.B., ORDONEZ, J.C., and SCHERER, M.D.,2015. "Life cycle assessment of biomass production in microalgae compact photobioreactors". GCB Bioenergy, Vol. 7, p. 184-194
Venteris, E.R., Skaggs, R.L., Wigmosta, M.S., Coleman, A.M., 2014. "A national-scale comparison of resource and nutrient demands for algae-based biofuel production by lipid extraction and hydrothermal liquefaction". Biomass and Bioenergy Vol. 64, p. 276-290

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