BIOENERGY WITH CARBON CAPTURE AND STORAGE VIA LANDFILL GAS OXY-COMBUSTION

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George Victor Brigagão
Escola Politécnica, Universidade Federal do Rio de Janeiro, CT, A, Ilha do Fundão, Rio de Janeiro, Brazil

José Luiz de Medeiros
Escola de Química, Universidade Federal do Rio de Janeiro, CT, E, Ilha do Fundão, Rio de Janeiro, Brazil

Ofélia de Queiroz Fernandes Araújo
Escola de Química, Universidade Federal do Rio de Janeiro, CT, E, Ilha do Fundão, Rio de Janeiro, Brazil

ABSTRACT: Landfill gas collection and utilization is necessary to reduce emission of greenhouse gases and promote transition into a renewable energy matrix. Power generation (landfill-gas-to-wire) is a common choice for availing this resource, as it avoids purification and transportation issues, with direct benefits of electricity supply to local community. Since urban wastes are typically rich in biomass, the generated CO_2 is partially biogenic, so a plausible implementation of carbon capture and storage would configure a way to promote carbon dioxide removal from atmosphere, from a carbon life-cycle viewpoint. In this work, economic evaluation of a zero-emission landfill-gas-to-wire process is addressed, where CO_2 capture occurs by adoption of an oxyfuel combined cycle, which performance is compared against a conventional CO_2-emitting combined cycle charged by carbon taxation. The analysis is supported by simulation in Aspen Hysys, assuming that the process has a fixed large-scale feed along 20 years of operation, as base destination for collected landfill gas. Operating conditions for different gas turbine pressure-ratios are defined for the maximization of net present value of both conventional and oxyfuel process concepts. The greatest net present value of oxyfuel and conventional processes is attained at combustion pressure of ≈20 and ≈8 bar, respectively. This indicates that compression demands and plant investment considerably lower gas turbine optimal pressure-ratio for landfill-gas processing. At best conditions, the efficiency penalty is 9.2%LHV and the proportion of CO_2 capture flow to net power export is 0.875 kg/kWh. Higher net present value of proposed zero-emission oxyfuel power generation over conventional combined cycle occurs if the CO_2 tax is above 95 USD/t.

KEYWORDS: CO_2 capture, combined cycle, oxyfuel, power generation, techno-economic analysis.

ABBREVIATIONS

ASU Air Separation Unit; BECCS Bioenergy with Carbon Capture and Sequestration; CCUS Carbon Capture, Utilization, and/or Storage; CONV Conventional; GOX Gaseous Oxygen; GT Gas-Turbine; HRSG Heat-Recovery-Steam-Generation; LGTW Landfill-Gas-To-Wire; LHV Lower Heating Value; RIOC-CC Regenerative Intercooled Oxy-Combustion Combined-Cycle; SCOC-CC Semi-Closed Oxy-Combustion Combined-Cycle; ST Steam-Turbine; TVR-2REB Top Vapor Recompression Distillation with Two Reboilers; USD US Dollar.

Nomenclature

c_p	*Specific heat capacity at constant pressure (kJ.kg^{-1}.K^{-1})*
c_v	*Specific heat capacity at constant volume (kJ.kg^{-1}.K^{-1})*
CEPCI	*Chemical engineering plant cost index (dimensionless)*
F	*Molar flow (kgmol.h^{-1})*
NPV	*Net present value (USD)*
P	*Pressure (bar)*
T	*Temperature (°C)*
W	*Mechanical power (kW)*
Y_k	*Mol-fraction of specie k (dimensionless)*
Greeks	
γ	*Gas isentropic exponent (dimensionless)*
η	*Adiabatic efficiency (%)*
Subscripts	
comb	*Combustor outlet*

1. INTRODUCTION

Major efforts in all economy sectors are necessary to reduce greenhouse gas emissions and meet the targets of the Paris Agreement. This requires large-scale employment of renewable resources and minimum fossil-based power generation, preferably associated to CO_2 capture, for a desired drastic cut on current CO_2 emissions (IPCC, 2013). To assist meeting these targets, carbon dioxide removal (CDR) from atmosphere will be important for mitigation of climate change (Fuss *et al.*, 2014). This can be done either by CO_2 biological fixation or direct air capture. The latter is significantly more expensive to invest and operate, so CDR will seriously depend on deploying bioenergy with carbon capture and storage (BECCS) (IPCC, 2014), which can offset emissions that are more expensive to mitigate (Haszeldine *et al.*, 2018). In this context, the use of biomass wastes avoids is a way to avoid social and ecological issues related to energy-oriented crops (Pour *et al.*, 2018), thus offering a sustainable alternative for fossil fuels displacement (Mukherjee *et al.*, 2020) featured by significant socio-economic benefits (Creutzig *et al.*, 2015).

1.1. LANDFILL GAS

Municipal solid waste can be viewed as a potential resource for the economy. In this regard, an ideal waste management approach would be to promote waste valorization, with only the inevitable residues being sent to landfills, or to cost-effective biochemical (e.g., anaerobic digestion, composting) or thermochemical conversion (e.g., gasification, incineration) (Garibay-Rodriguez *et al.*, 2018). The least expensive method is landfilling (Kalyani; Pandey, 2014), but the option lead to significant socio-environmental impacts – beyond the loss of valorization opportunity – if naturally-generated landfill gas is emitted to atmosphere and not recovered. In open dumps, for example, final disposal of solid waste occurs without any environmental care, thus severely impacting air, water, and soil, while bringing explosion risks (Intharathirat *et al.*, 2016) and threatening the health of local population (Kalyani; Pandey, 2014). In this case, hazardous species in landfill gas and leachate contamination could be causes of health disorder (Mataloni *et al.*, 2016). To avoid these impacts planned sanitary landfills are necessary, with suitable management of landfill gas and leachate.

Landfill gas generation is influenced by waste profile and various features of the landfill (e.g., age, size, collection system) (Aguilar-Virgen *et al.*, 2014). It normally consists in a gas comprising mostly CH_4+CO_2, which can be availed as a fuel. For example, at approximately steady conditions (after some years of operation), a typical US landfill gas has the following dry-basis composition: 50-55%vCH_4, 45-50%vCO_2, and 2-5%v other species (e.g., volatile organic compounds, N_2, H_2S, siloxanes). According to EPA (2017), this production is nearly stable for ≈20 years. Possible uses include upgrading to biomethane, heating and/or electricity generation, evaporation of leachate, and conversion to other substances (e.g., hydrogen, methanol, bio-plastic) (Chidambarampadmavathy *et al.*, 2017). The mitigation of landfill gas direct emission is of great importance for combating climate change (Broun; Sattler, 2016), as the global warming potential of 1 kg CH_4 is 28 times higher than that of 1 kg CO_2 for 100 years, and 84 times higher for 20 years (IPCC, 2014). Moreover, less greenhouse gases are emitted if landfill gas is utilized to replace fossil fuels (Broun; Sattler, 2016). Therefore, net environmental performances strongly depend on efficient collection and utilization of landfill gas (Wanichpongpan; Gheewala, 2007). The collected gas not availed for useful purpose has to be flared to ensure elimination of CH_4, volatile organic compounds, toxic and odorant components (Fei *et al.*, 2019).

Landfill gas recovery and utilization is beneficial for governments and helps improving energy efficiency and energy security, with reduced dependence on remote suppliers of natural gas and electricity (Hetland *et al.*, 2016). Power plants using landfill gas can entail significant economic growth, create jobs and revenues, increase income tax collection, and benefit the environment directly by mitigation of greenhouse gases emission and indirectly due to fossil fuels avoidance (EPA, 2016). The electricity price is not expected to increase, as the break-even value is usually not high. For example, less than 0.04 USD/kWh was required in a study based on 2005 year, without government subsidies (Jaramillo; Matthews, 2005).

Power generation from landfill gas usually adopts internal combustion engines due to small feed capacities of 50-960 standard ft^3/min (0.1-3.0 MW_e). Gas turbine (GT) is generally suitable for over 3 MW output, when supply is high and stable enough, above 1050 standard ft^3/min at ≈50%v CH_4. Lower operation and maintenance costs, compact size, greater resistance to corrosion, complete and cleaner combustion are advantages over internal combustion engines (EPA, 2011). Furthermore, steam turbine (ST) is sometimes also prescribed in large projects, offering advantages of dismissing gas compression, greater resilience to gas contaminants, and greater operational flexibility (Rajaram *et al.*, 2011).

Many works on landfill gas conversion to electricity are reported in the literature but very few focus on technical aspects of the power cycle. Purmessur and Surrop (2019) modeled gas production in a specific landfill and assessed potential for power generation, which was simply estimated using literature data on net efficiencies. Also focusing on modeling landfill gas generation and further regarding collection efficiency, Broun and Sattler (2016) compared conventional and bioreactor landfill in terms of greenhouse gas emissions and electricity potential, but similarly considered literature data for efficiency of internal combustion engines. In contrast, this work presents full techno-economic analysis of a landfill gas-driven power cycle.

1.2. BIOENERGY WITH CARBON CAPTURE AND STORAGE

Besides fossil-based carbon capture, utilization and/or storage (CCUS), geological storage of biogenic CO_2 is way to promote effective mitigation of global warming (IPCC, 2014). BECCS deployment results in negative life-cycle emission of CO_2, because biomass growth occurs with CO_2 biofixation by photosynthesis, which indirectly introduces solar energy to life-cycle production chains. Contrarily to soil carbon sequestration and afforestation, BECCS is not subjected to terrestrial carbon stocks, contributing to mitigation of global warming with permanent CO_2 sequestration (Pour *et al.*, 2018), leading to continuous carbon dioxide removal from atmosphere (Milão *et al.*, 2019). Moreover, BECCS also improves diversity and flexibility of the energy portfolio of a country (Pour *et al.*, 2018), increasing renewable share of electricity mix, and enhancing regional energy security (Hetland *et al.*, 2016). However, large-scale deployment is likely to require strong policy support, even in countries with accumulated knowledge on CCUS and bioenergy production (Pour *et al.*, 2018), wherein carbon taxation may be regarded as important instrument (Meltzer, 2014).

Widespread implementation of BECCS depends on certain technical, economic and social issues. Bioenergy also has its environmental impacts (Gibson *et al.*, 2017), especially if it depends on biomass cultivation and harvesting (Withey *et al.*, 2019). In addition, further sustainability challenges are site availability for CO_2 geological sequestration and the possibility of competition for land and resources (Fuss *et al.*, 2014), which could create a driver for deforestation and displacement of local communities, impacting biodiversity, tenure arrangements (Creutzig *et al.*, 2015), and net CO_2 balance (Johnson, 2009). In some cases, project feasibility is also challenged by biomass transportation and production costs (Brigagão *et al.*, 2019a). Nonetheless, such difficulties are alleviated if: (i) BECCS is part of a waste management system; and (ii) a CO_2 utilization pathway is adopted. The problem with the case (ii) is the large gap between potential market for CO_2 use as feedstock and scale requirements for climate stabilization (Mikulcic *et al.*, 2019). Hence, an ideal mix of CO_2 storage and utilization routes should fit the objectives of CO_2 abatement. Currently, there is no other large-scale option yet to monetize captured CO_2 (for ≈1 million t/y) other than limited and early solution of enhanced oil recovery (Bui *et al.*, 2018). Therefore, in this work, only geological storage is adopted.

1.3. OXY-COMBUSTION

Among the CO_2 capture routes for power generation, oxy-combustion is the only way for attaining zero-emission power (Foy; Yantovski, 2006). The alternative offers greater environmental performance, possibly with good profitability potential and higher overall efficiency. Combustion with nearly pure gaseous oxygen (GOX) implies in the production of flue gases constituted mainly by CO_2+H_2O, so that CO_2 is easily recovered after water condensation, being ready to be compressed for dispatch, unless finishing purification is needed depending on specificities of transport, storage and utilization (Pipitone; Bolland, 2009). The economic performance is highly dependent on air separation unit (ASU) capital investment and operating cost (Brigagão *et al.*, 2019b), where cryogenic fractionation is currently the only economical route for large-scale GOX supply to oxy-combustion (Higginbotham *et al.*, 2011). The most efficient cryogenic ASU ever developed for GOX production was presented by Brigagão *et al.* (2019b), with basis on cryogenic top vapor recompression distillation with two reboilers (TVR-2REB) to produce GOX at nearly atmospheric pressure, requiring only 139 kWh/t O_2 for 95%mol O_2. This nominal purity is conceived as a standard for oxyfuel power generation, because it avoids high power demand for Ar/O_2 fractionation, which occurs above 97%mol (Brigagão *et al.*, 2019b).

A further challenge for large-scale implementation of this capture route is the requirement of utilizing special equipment for operation in oxyfuel mode, which may be not fully developed yet, as in the case of oxy-combustion GTs (Stanger *et al.*, 2015). Nevertheless, several oxy-fired power-cycles have been proposed in the literature, among which the semi-closed oxy-combustion combined cycle (SCOC-CC), which is inspired in conventional air-blown natural gas combined cycle (Bolland; Saether, 1992). CO_2-based power-cycles sometimes comprises intercooled compression to supercritical conditions (e.g. Allam-cycle) and a bottoming steam-cycle is not always included (Stanger *et al.*, 2015). Water-injection is another design approach, where combustion temperature is abated by flue gas condensate, dismissing large gas-recycle compression in exchange to less expensive water pumping. The concept presents higher technology readiness level (Stanger *et al.*, 2015), given the report of a successful demonstration (Anderson *et al.*, 2008), but the overall efficiency is substantially lower than that of gas-recycle configurations (Chakroun; Ghoniem, 2015a). Processes combining both gas-recycle and water-injection techniques are also found in the literature (e.g. S-Graz cycle), eventually leading to greater net efficiency, at the expense of much higher design complexity (Kvamsdal *et al.*, 2007).

The GT pressure ratio is a key aspect in the design of an oxyfuel combined cycle (Dahlquist *et al.*, 2013). The optimum value highly depends on combustion temperature (T_{comb}) and steam-cycle operating conditions (Stanger *et al.*, 2015). Oxyfuel GTs have higher optimum pressure ratios than conventional air-blown GTs, if the same T_{comb} and steam-cycle conditions are considered (Mletzko; Kather, 2014). For example, in spite of usual combustion pressure of ≈20 bar in conventional machines (Dahlquist; Genrup, 2016), GTs for SCOC-CC are often conceived with 40-60 bar (Mletzko; Kather, 2014). The major reason is the lower isentropic exponent ($\gamma = c_p/c_v$) of the CO_2-rich working-fluid (Dahlquist *et al.*, 2013), which undergoes a lower temperature change on adiabatic compression and expansion (IPCC, 2005). The reduced temperature of CO_2-rich fluid adiabatic compression compared to air favors the increase of combustion pressure for higher power outputs. Nevertheless, higher combustion pressure implies in larger and more complex turbomachinery, which has to be weighed against net efficiency improvements (Dahlquist *et al.*, 2013). The behavior of the working-fluid is also influenced by greater density and lower sound speed of CO_2 in comparison with N_2-rich fluid of conventional GTs, leading to modifications in GT annular flow area (Stanger *et al.*, 2015).

Most works addressing definition of oxyfuel GT pressure-ratio only accounts the overall power efficiency, with temperature raise of gas compression being what usually limits the increase of combustion pressure (P_{comb}). However, the decision on a suitable pressure for construction of a real equipment has to account design challenges in turbomachinery and heat recovery steam generation (HRSG). In the case of SCOC-CC, the net efficiency curve plotted as a function of combustion pressure is flat around the optimum (Yang *et al.*, 2012), making the economically best condition to be slightly below the theoretical optimum for maximum efficiency (Dahlquist *et al.*, 2013). For instance, Dahlquist et al. (2013) found a theoretically optimum pressure ratio of ≈45 for the maximum net efficiency of SCOC-CC with T_{comb}≈1340°C, but indicated ≈34 as a better practical choice for equipment design. Another issue discussed in a later work (Dahlquist; Genrup, 2016) highlighted that pressure-ratios beyond 30 are common only in aero-derivative machinery – where GT compressor design seeks to favor aerodynamics and shaft-power output, at the expense of higher complexity – while industrial/heavy-duty GTs adopt a simpler design solution to minimize capital investment. In this sense, determination of the best GT pressure-ratio is addressed in this work through the perspective of economic performance, by accounting equipment sizes and their effect over the net present value (NPV), besides the fact that – on the contrary to NG-fired GTs – the fuel demands compression as it is received at atmospheric pressure, thus influencing the solution of best operating conditions.

1.4. THE PRESENT WORK

In analogy to conventional Gas-To-Wire solution applied to avail natural gas (Interlenghi *et al.*, 2019), the idea of utilizing landfill gas for power generation is hereinafter referred to as landfill-gas-to-wire (LGTW). In this sense, an oxyfuel LGTW-BECCS solution for landfill gas use to power generation is evaluated in this work through technical and economic perspectives, aiming atmospheric CO_2 removal and CH_4 emission avoidance, in a scenario of carbon taxation. Few works in the literature have presented rigorous evaluation of oxyfuel processes using CO_2-rich feed gas, and the incidence of a carbon tax charging process emissions is not usually considered in LGTW studies, despite its important role for global warming mitigation (PEREIRA et al., 2016). A relevant study was presented by Chakroun and Ghoniem (2015a), where combined cycles based on sour gas oxy-combustion were analyzed, but the work does not fully apply to LGTW context, as CO_2 and H_2S contents in feed gas substantially diverges from what would be expected in landfill gas streams (EPA, 2017; Ko *et al.*, 2015).

This work focuses on demonstrating economic performance of an oxyfuel LGTW-BECCS process, evaluated with economically optimum GT combustion pressure against a conventional air-blown combined cycle without CO_2 capture (LGTW-CONV). Besides being environmentally superior, the proposed LGTW-BECCS concept is proved as potentially more profitable than LGTW-CONV depending on CO_2 taxation charge.

2. METHODS

Assumptions adopted in this work are presented as following: Sec. 2.1 covers description of processes and simulation inputs, and Sec. 2.2 deals with equipment sizing and economic evaluation. The comparison of the concepts LGTW-BECCS – zero-emission oxyfuel combined cycle – and LGTW-CONV – CO_2-emitting air-blown combined cycle – is made after a pre-screening of process alternatives, where the economically-optimal version of each concept is explored to determine the respective base process. The comparison of the concepts does not cover feed gas upstream aspects, such as solid-waste transportation and handling, landfill operation, gas collection, and gas pre-purification, as they would perform the same regardless of the concept choice.

2.1. PROCESS SIMULATION

Figure 1 depicts a general diagram of the two concepts being compared (LGTW-CONV and LGTW-BECCS). The process alternatives were technically evaluated in Aspen HYSYS v8.8 utilizing the assumptions shown in Table 1.

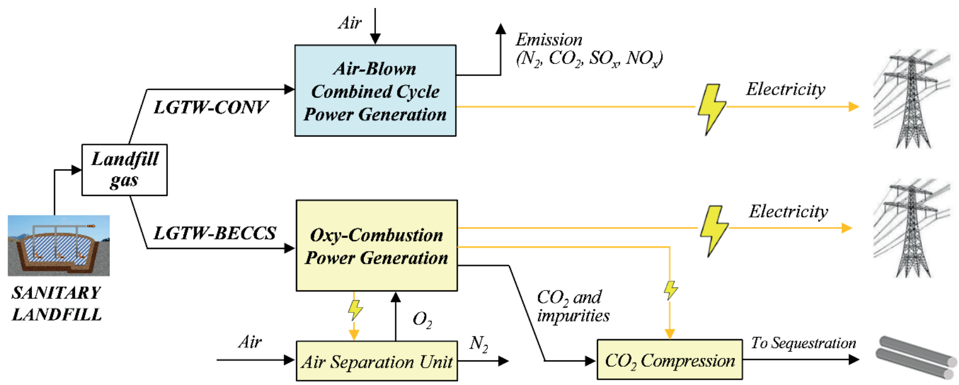

Figure 1 - Overview of considered landfill-gas-to-wire routes

All processes are combined cycles fed by ≈1.08 MMSm³/d of landfill gas. The considered composition ({P2}, Table 1) is in accordance with expected ranges reported by EPA (2017). The considered H_2S content (≈100 ppmv) was chosen with basis on Ko *et al.* (2015). Large facility for electricity generation is considered to favor combined cycle adoption and take advantage of economy of scale (Wanichpongpan; Gheewala, 2007), as feasibility of oxy-combustion requires cost-effective cryogenic ASUs. Assuming a hypothetical large landfill capable of producing more than 1.08 MMSm³/d of gas along 20 years, the fixed flow rate supplying the power plant would serve as bulk destination for the collected gas. The remaining portion is supposed to be directed to other uses (e.g. heating), which are not addressed in present analysis.

Table 1 - Assumptions of process simulation

Item	Assumption
{P1}	Thermodynamic modeling: Peng-Robinson Equation-of-State, with ASME-Table for water-steam
{P2}	Landfill gas (%mol): P=1 atm, T=40°C, F=1869 kmol/h (1.08 MMSm³/d), 46.37%CH_4, 44.51%CO_2, 1.85%N_2, 0.01%H_2S, 7.26%H_2O (water-saturated)
{P3}	GOX (%mol): P=1 atm, T=15°C, 1832 kmol/h (1.41*10^6 kg/d), 95%O_2, 2.39%Ar, 2.61%N_2
{P4}	Specific power consumption of air separation unit: 139 kWh/t O_2 (BRIGAGÃO et al., 2019b)
{P4}	Combined cycle configuration (gas turbines : steam turbines): 1:1
{P5}	Adiabatic efficiency of expanders: η=90%
{P6}	Adiabatic efficiency of axial compressors: η=85%
{P7}	Adiabatic efficiency of centrifugal compressors: η=80%
{P8}	Adiabatic efficiency of pumps: η=75%
{P9}	Gas turbine (GT) expander inlet temperature: T=1300°C
{P10}	Steam turbine (ST) inlet conditions: 560°C@70 bar (single-pressure)
{P11}	Vacuum condenser: inlet pressure 0.10 bar, ΔP=1 kPa, T^{OUTLET}=43.8°C
{P12}	Heat recovery steam generator (HRSG): $\Delta T^{APPROACH3}$ 20°C, ΔP^{GAS}=3 kPa, ΔP^{H2O}=50 kPa
{P13}	Direct contact column: theoretical-stages=3, Recycled-water 35°C, P^{TOP}=1 atm, ΔP=2 kPa
{P14}	Intercoolers: T^{GAS}=40°C, ΔP=3%$P \leq$ 50 kPa; Cooling-water: T^{SUPPLY}=30°C, T^{RETURN}=40°C
{P15}	CO_2 liquefaction: P=150 bar, T=40°C
{P16}	CO_2 exportation: P=250 bar

Landfill gas is supplied at atmospheric pressure and has to be compressed to feed the GT. A multistage intercooled compressor (maximum 150°C) is utilized for safety, as the gas may react at high temperatures (e.g., O_2 may be present in small content due to air intrusion). The hot flue gas leaving the GT is sent to HRSG, which operates with steam-cycle operated at fixed temperature and pressure conditions. Single-pressure Rankine is adopted to minimize process complexity and capital investment. Also, relatively high flue gas temperatures are known to reduce the need for multiple steam pressure levels (Dahlquist *et al.*, 2013).

2.1.1. Conventional Combined Cycle

Figure 2 depicts the process flowsheet of LGTW-CONV with values at economically optimal conditions for maximum NPV. Additional compression stages for landfill gas are included if GT P_{comb} exceeds 9 bar (not shown in Figure 2).

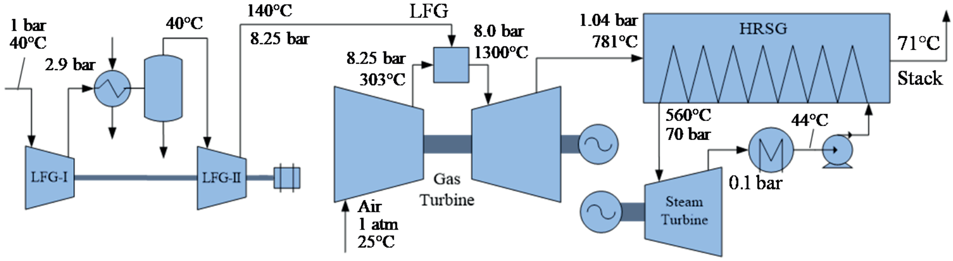

Figure 2 - LGTW-CONV base-process flowsheet

2.1.2. Oxy-Combustion Combined Cycles

Two oxyfuel configurations are compared to define the base-process of LGTW-BECCS: (a) semi-closed oxy-combustion combined cycle (SCOC-CC) (Bolland; Saether, 1992), involving adiabatic compression of gas-recycle (Figure 3); and (b) regenerative intercooled oxy-combustion combined cycle (RIOC-CC), where gas-recycle is subjected to intercooled multistage compression (Figure 4). RIOC-CC comparison with SCOC-CC aims to verify whether reduced power input to CO_2 compression improves NPV. RIOC-CC appears as modified version of the E-Matiant cycle without GT reheat (Mathieu *et al.*, 2000), into which a bottoming Rankine cycle is incorporated. Both oxyfuel processes have the following characteristics in common: (i) GOX at atmospheric pressure is supplied in stoichiometric proportion by a highly efficient standalone ASU (Brigagão *et al.* 2019b); (ii) intercooled compression (with maximum 150°C) of GOX is also considered for the best process safety and the lowest capital investment – thus contributing to process sustainability – as it avoids working with high-temperature pressurized GOX; (iii) the exhaust gas leaving HRSG is cooled by recycled condensate in a direct contact cooler (DCC) (Dahlquist *et al.*, 2013); (iv) combustion temperature abatement is promoted by recycling part of the cooled exhaust gas leaving the top of the DCC (Chakroun; Ghoniem, 2015a); (v) the unrecycled exhaust gas that leaves the DCC top (captured CO_2) is sent to compression for dispatch as a dense supercritical fluid at 250 bar.

Figure 3 presents the flowsheet of SCOC-CC, where annotations refer to economically optimal conditions for maximum NPV. The number of compression stages required for landfill gas and GOX depends on GT pressure ratio, thus entailing minor changes in the flowsheet. The recycled gas is sent to an adiabatic axial compressor installed in the front-end of the oxyfuel GT, which replaces the air compressor of a conventional GT.

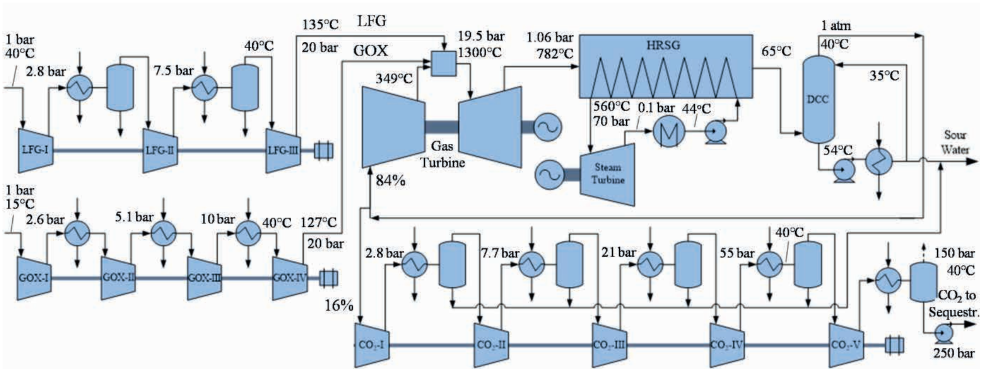

Figure 3 - Semi-closed oxy-combustion combined-cycle (SCOC-CC) at economically optimal conditions (LGTW-BECCS base-process)

Figure 4 presents RIOC-CC flowsheet with operating conditions at economically optimal values for maximum NPV. The process adopts regenerative Brayton cycle and the recycled gas is subjected to intercooled compression (as in E-Matiant cycle). Therefore, the shaft of its GT runs without driving any adiabatic axial compressor. Before entering the combustion chamber, the compressed gas recycle is heated within HRSG by GT exhausts up to a temperature 35°C below GT outlet. Even though this implies in higher recirculation flowrate, this is accomplished to ensure high-temperature injection in the combustion chamber for better overall efficiency.

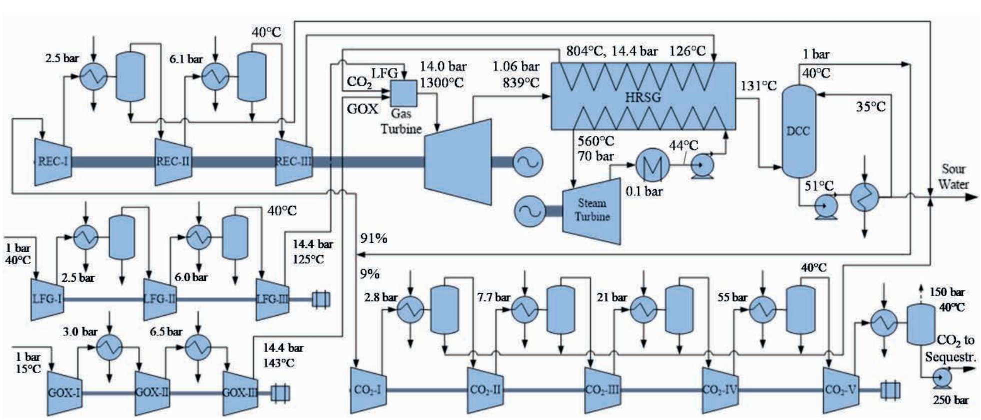

Figure 4 - Regenerative intercooled oxy-combustion combined-cycle (RIOC-CC) at economically optimal conditions

2.2. ECONOMIC EVALUATION

The economic performance of LGTW alternatives is analyzed using the assessment framework of Turton et al. (2012). Fixed capital investment estimates are updated using the chemical engineering plant cost index (CEPCI) for 2018-average. Since commercial oxyfuel GTs are not yet commercially available, the same procedure for GT capital investment estimation is adopted in LGTW-CONV and LGTW-BECCS processes, which is addressed by adding expander, compressor, and generator contributions, estimated separately via Turton et al. (2012). The equipment sizes are obtained through the methods of Campbell (1984), with basis on process simulation data.

Table 2 reveals the premises of economic analysis. Since zero-emission LGTW-BECCS can outperform CO_2-emitting LGTW-CONV in profitability potential if carbon taxation applies, the required tax level that makes the NPV of LGTW-CONV lower than that of LGTW-BECCS is estimated (for 20 years of operation). Emissions not directly related with power generation are not included in the analysis (i.e., those from other landfill gas uses, fugitive emissions, flare gas, and upstream activities).

Table 2 - Assumptions of financial analysis

Item	Assumption
{F1}	Electricity price: 108.7 USD/MWh (USA Price June/2018).
{F2}	CO_2 taxation in base-scenario: 0 USD/kg
{F3}	Utilities cost: cooling-water=0.016 USD/t
{F4}	ASU investment: extrapolated with 0.5 exponent from 141 MMUSD for GOX 52 kg/s (CLAUSEN et al)
{F5}	Fixed capital investment of equipment: extrapolated with six-tenth rule if exceeds Turton et al. ranges
{F6}	Fixed capital investment update*: *CEPCI*=603.1 (2018-average)
{F7}	Investment distribution: 20%/30%/50% (3 years of construction)
{F8}	Annual operation time: 8000 h/y
{F9}	Annual depreciation: 10% of total fixed capital investment
{F10}	Income tax rate: 34%
{F11}	Project horizon: 20 years of operation
{F12}	Annual interest rate: i=10%

*CEPCI≡Chemical engineering plant cost index

3. RESULTS AND DISCUSSION

Section 3.1 deals with definition of LGTW-CONV base process operating conditions by evaluation of P_{comb} variants ({P2}, Table 1). Similarly, Section 3.2 covers definition of LGTW-BECCS base process by techno-economic comparison of SCOC-CC and RIOC-CC variants. In Section 3.3, LGTW-CONV and LGTW-BECCS best performances are discussed, and the effect of CO_2 taxation is investigated.

3.1. LGTW-CONV VARIANTS

Five variants are evaluated, each one with its P_{comb}. Table 3 presents details on contribution of machines to net power generation, where a trade-off between ST and GT power is evinced for different GT outlet temperatures, as expected. GT pressure-ratio increase to ≈20 enhances power generation, but just a minor benefit is obtained by P_{comb} increase from 16 to 20 bar, due to power consumption to landfill gas compression. The emission factor of each variant, also presented in Table 3, ranges 711-753 g/kWh due to different net power outputs. A way to decrease the emission factor is to adopt a more efficient Rankine cycle – e.g., with reheat and multiple pressure levels – which could suit efficient operation with increased GT pressure-ratio and reduced outlet temperature, leading to higher power exportation. However, the increased complexity would also increase plant investment, possibly offsetting the advantage on NPV, so this aspect is not investigated in present work.

Table 3 - Performance of LGTW-CONV variants: power contribution of process machinery and CO_2 emission factor.

LGTW-CONV Alternative	**#1**	**#2***	**#3**	**#3**	**#4**	**Unit**
Combustion Pressure	**6.0**	**8.0**	**12.0**	**16.0**	**19.5**	**bar**
Fuel Gas Compressor	-3.35	-3.93	-4.56	-5.11	-5.49	MW
Gas Turbine	55.27	62.11	70.30	75.33	78.47	MW
Steam Turbine	48.12	45.30	-39.63	35.66	32.94	MW
Rankine-Cycle Pump	-0.38	-0.35	-0.31	-0.28	-0.26	MW
Overall Output	**99.67**	**103.13**	**105.06**	**105.59**	**105.66**	**MW**
CO_2 Emission Factor	**0.753**	**0.728**	**0.715**	**0.711**	**0.711**	**kg/kWh**

* LGTW-CONV Base-Process

While combined cycle power plants fed by natural gas usually adopts P_{comb}≈*20 bar* (Dahlquist; Genrup, 2016), a lower optimal pressure should be expected for LGTW systems given the need to compress the fuel. Table 4 confirms it in the comparison of LGTW-CONV variants regarding many techno-economic metrics, including the NPV for 20 years of operation (as a function of the various selected P_{comb}, without CO_2 tax). Figure 5 further portrays curves for net efficiency and NPV-20years, showing that despite maximum efficiency is attained in variant #5 (P_{comb}≈20 bar), the highest profitability potential is obtained in variant #2 (P_{comb}≈8 bar), indicating it as best LGTW-CONV base-process for comparison against LGTW-BECCS.

Table 4 - Summary of techno-economic sensitivity analysis for LGTW-CONV

Process alternative	P_{comb} (bar)	#Stages landfill gas	Net Power (MW)	Net Efficiency (%LHV)	*FCI*** (MMUSD)	*NPV* (MMUSD)
1	6.0	2	99.67	51.58	79.1	248.6
2*	8.0	2	103.1	53.37	84.6	254.0
3	12.0	3	105.1	54.36	91.4	252.0
4	16.0	3	105.6	54.64	96.0	248.5
5	19.5	3	105.7	54.67	99.4	244.3

* LGTW-CONV Base-Process; **FCI ≡ Fixed capital investment

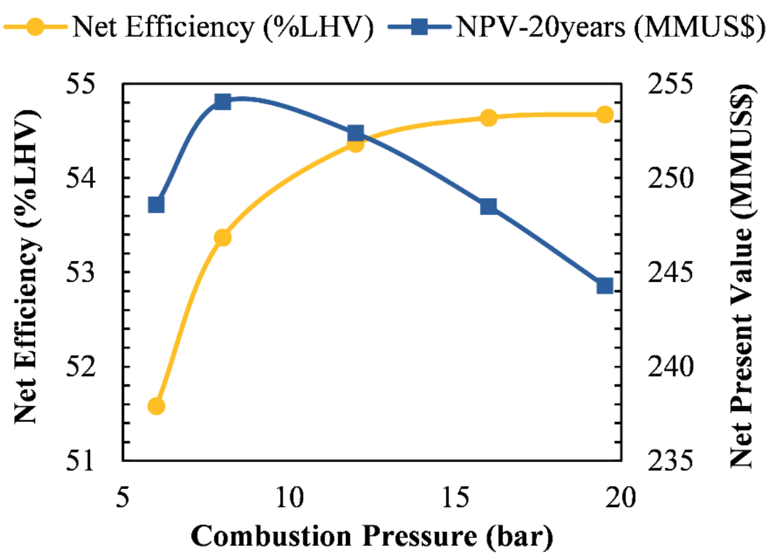

Figure 5 - Influence of GT combustion pressure on LGTW-CONV overall efficiency and NPV for 20 years of operation

3.2. LGTW-BECCS OXYFUEL VARIANTS

Ten oxyfuel variants are evaluated through energy and economic perspectives, five of which using SCOC-CC configuration for different P_{comb} (variants #1-5), while the remaining adopts RIOC-CC (variants #6-10). All LGTW-BECCS variants capture the totality of generated CO_2, presenting 74.7 t/h of CO_2 sequestration, thus leading to zero-emission power generation. Table 5 unveils the contribution of each process machine to the net power output of each variant.

Table 5 - Performance of LGTW-BECCS variants: power contribution of process machinery

LGTW-BECCS Alternative	**#1**	**#2**	**#3†**	**#4**	**#5**	**#6**	**#7**	**#8**	**#9**	**#10**	**Unit**
Combustion Pressure	**8.0**	**14.0**	**19.5**	**29.5**	**39.5**	**14.0**	**19.5**	**29.5**	**39.5**	**59.5**	**bar**
Process Configuration	**SCOC-CC**					**RIOC-CC**					
Air Separation Unit	-7.74	-7.74	-7.74	-7.74	-7.74	-7.74	-7.74	-7.74	-7.74	-7.74	MW
Oxygen Compressor	-3.84	-4.97	-5.54	-6.37	-6.97	-4.97	-5.54	-6.37	-6.97	-7.66	MW
Fuel Gas Compressor	-3.93	-4.86	-5.49	-6.12	-6.64	-4.86	-5.49	-6.11	-6.64	-7.38	MW
Gas Turbine	52.39	63.59	69.62	76.46	80.92	102.0	103.8	106.8	108.1	109.5	MW
Steam Turbine	50.59	46.51	44.28	40.81	37.89	13.43	12.16	10.56	9.41	7.86	MW
CO_2 Compressor & Pump	-9.42	-9.42	-9.42	-9.42	-9.42	-9.41	-9.41	-9.41	-9.41	-9.41	MW
Auxiliary Equipment	-0.43	-0.40	-0.38	-0.36	-0.34	-0.16	-0.15	-0.13	-0.12	-0.11	MW
Overall Output	**77.63**	**82.71**	**85.33**	**87.26**	**87.71**	**88.25**	**87.60**	**87.57**	**86.69**	**85.04**	**MW**

† LGTW-BECCS Base-Process.

The comparison of variants #3 and #7 in Table 5 shows that electricity contribution of GT for the same design P_{comb}≈20 bar is lower in SCOC-CC (69.62 MW) than in RIOC-CC (103.8 MW), mainly as a consequence of reduced recycle of exhaust gas and higher specific compression power demand, which are 306 and 264 kJ/kg recycle-gas, respectively. Differences in working-fluid circulation leads compressor demand to 35.52 and 52.32 MW, and gas-expander power to 105.14 and 156.08 MW, respectively.

In both configurations, the power output ratio of GT and ST (W_{GT}/W_{ST}) substantially diverges from that of a conventional combined-cycle. SCOC-CC working-fluid has high CO_2 content, which implies in relatively low isentropic exponent ($\gamma=c_p/c_v$), thus requiring an increase in GT pressure-ratio to ≈40 (variant#5) to obtain a typical power ratio of about 2:1 (Table 5). RIOC-CC involves much smaller ST of ≈10 times lower power output comparatively to its GT, because the available heat in hot flue gas is transferred in HRSG mostly to the recycle-gas instead of to the steam-cycle. Therefore, RIOC-CC power generation is concentrated within the regenerative Brayton cycle, which leaves small heat duty available to drive the Rankine cycle. The relatively low availability of superheated steam – and consequently low power generation capacity – allows to conceive one or two STs as compressor drivers (e.g., for compression of CO_2 and landfill gas, which in variant#6 could reduce plant investment by 4 MMUSD).

Table 5 unveils P_{comb} entailing opposite influence over the performance of SCOC-CC and RIOC-CC at considered operating ranges. RIOC-CC presented the highest overall efficiency (variant#6: 45.67%LHV), where reduced P_{comb} favored net power (88.25 MW), since it leaves more heat available to preheat recycle gas (hot flue gas leaves GT at 839°C). Further reduction on GT P_{comb} should be limited by higher losses in heat exchange and reduced power in gas expansion. In contrast, the overall efficiency of SCOC-CC is favored when P_{comb} increases up to ≈40 bar, with minor benefits seen within 30-40 bar. A higher P_{comb} is not recommended and may imply in efficiency loss, mostly because the recycle gas becomes too hot for further adiabatic compression, drastically increasing subtraction of GT shaft-power.

3.2.1. Comparative Discussion with Literature Data

Indication of simulation results similarities is worthy even when slightly different design conditions are applied (most notably the assumed T_{comb}). In this regard, similar behavior of SCOC-CC overall efficiency response to P_{comb} was evinced by Dahlquist *et al*. (2013) for T_{comb}=1340°C, which shows a curve that also flattens out at around 40 bar. Yang et al. (2012) evaluated the influence of even higher pressure-ratio levels and also found flat efficiency curves, indicating ≈60 as the theoretical-optimum for T_{comb}=1418°C. Since small benefit is evinced from pressure-ratio increase within 40-60, a more realistic design would more likely consider P_{comb}≈40 bar in view of equipment investment and other practical issues in the design of large machines. Table 5 then indicates that, from a net efficiency perspective, the suitable P_{comb} for a plausible LGTW-BECCS using SCOC-CC configuration should be within 30-40 bar. In fact, the GT pressure-ratio for SCOC-CC is typically conceived at 30-40 when T_{comb} is between 1300-1400°C, which is slightly below the condition of maximum output estimated from process simulation (Stanger *et al*., 2015). Small efficiency increase is not likely to motivate development of much larger machines of higher P_{comb}. This aspect was discussed by Dahlquist *et al*. (2013), which pointed out that designing a GT with a pressure-ratio above 40 is defying even for an air-blown machine, then becoming more challenging in case of CO_2-rich working-fluid (e.g., due to lower sound speed). Hence, P_{comb}≈32 bar was regarded as more adequate for the application with T_{comb}=1340°C, accounting for GT outlet temperature at 620°C.

3.2.2. Optimal Pressure-Ratio

Determination of the most suitable pressure-ratio is here addressed with basis on NPV criteria for 20 years of operation. Although SCOC-CC is usually conceived with P_{comb}>30 bar – due to adoption of maximum net efficiency criteria – the economic perspective of present application to LGTW-BECCS reveals that P_{comb}≈20 bar is more adequate, mainly as a consequence of high impact of capital investment on NPV. In this sense, a comparison of LGTW-BECCS variants #1-10 is shown in Table 6, which presents assumed P_{comb} and corresponding number of compression stages for GOX and landfill gas, with the respective power output, net efficiency, fixed capital investment, and NPV of the overall process.

Table 6 - Summary of techno-economic sensitivity analysis for LGTW-BECCS

Process alternative	CC. Config.	P^{Comb} (bar)	#Stages recycle	#Stages landfill gas	#Stages GOX	Net Power (MW)	Net Efficiency (%LHV)	*FCI*** (MMUSD)	*NPV* (MMUSD)
1	SCOC	8.0	1	2	3	77.63	40.18	193.1	7.81
2		14.0	1	3	3	82.71	42.81	203.6	12.39
3†		19.5	1	3	4	85.33	44.16	210.2	13.08
4		29.5	1	4	4	87.26	45.16	217.4	10.35
5		39.5	1	4	4	87.71	45.39	221.6	6.36
6	RIOC	14.0	3	3	3	88.25	45.67	237.3	-12.68
7		19.5	3	3	4	87.60	45.33	237.7	-16.24
8		29.5	4	4	4	87.57	45.31	247.1	-29.40
9		39.5	4	4	4	86.69	44.86	247.0	-32.37
10		59.5	4	4	4	85.04	44.01	248.5	-40.60

† LGTW-BECCS Base-Process; **FCI ≡ Fixed capital investment

Despite the slightly lower overall efficiency, SCOC-CC has much greater NPV than RIOC-CC. The latter is also evinced as economically unfeasible even after 20 years of operation, as a consequence of relatively high capital investment, indicating that RIOC-CC inefficiently exploits the economic potential of landfill gas-fired power generation. Therefore, only SCOC-CC is considered for application to LGTW-BECCS from this point on.

Figure 6 portrays the influence of P_{comb} over the net efficiency and NPV of SCOC-CC. The curve of net efficiency flattens out close to the maximum in a similar behavior to the results of Bolland and Saether (1992), Yang et al. (2012), and Dahlquist *et al.* (2013). Despite maximum efficiency is attained at P_{comb}≈40 bar (variant#5), the NPV curve shows that the economically-optimal condition is attained at P_{comb}≈20 bar, which defines variant#3 as LGTW-BECCS base-process for subsequent comparison with LGTW-CONV.

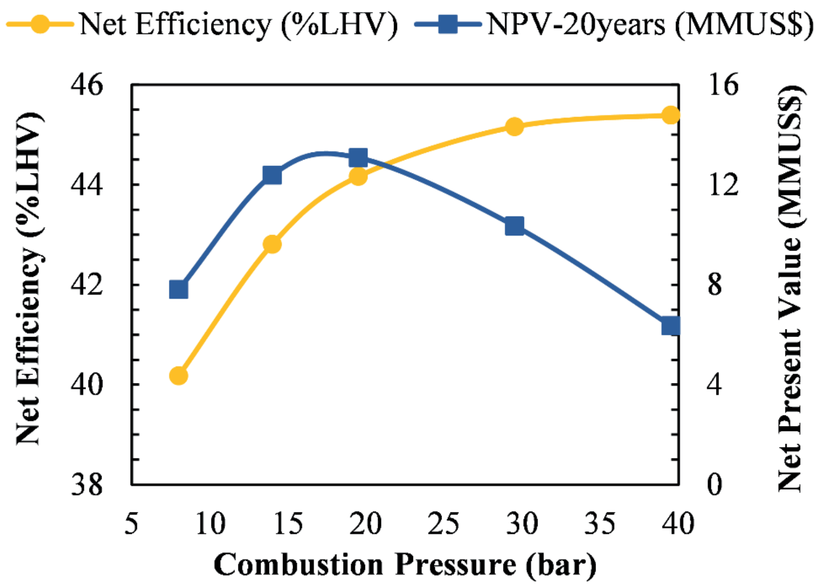

Figure 6 - Influence of GT combustion pressure on LGTW-BECCS overall efficiency and NPV for 20 years of operation

In relation to other possible oxyfuel processes, few other configurations seem suitable for LGTW-BECCS, making SCOC-CC a good choice. For example, Graz-cycles are efficient but involves complex configurations, an aspect that is likely to challenge process competitiveness. The Allam-cycle is efficient and has a simpler configuration, which reminds the E-Matiant process without a bottoming steam-cycle, but the capital investment is too high, because it is based on supercritical CO_2 cycle operated at very high pressures, with gas-expander inlet at P_{comb}≈300 bar and outlet at P≈30 bar (ALLAM et al., 2014). In contrast, water-injections processes worth investigation in a future work, as they may present a cost-effective performance due to reduced plant investment, despite of the relatively low efficiency (Chakroun; Ghoniem, 2015a), given the relatively low feed-gas capacity of typical LGTW plants.

3.3. COMPARISON OF LGTW CONCEPTS

Figures 7a-f portray sensitivity analysis profiles of NPV ÷ NPV_{max} as a function of P_{comb} – for the purpose of evaluating the influence of different parameters and confirming the obtained the optimum P_{comb} – for the concepts LGTW-CONV (Figures 7a-c) and LGTW-BECCS (Figures 7d-f). The profiles are calculated for various scenarios of annual interest rate (Figures 7a and 7d), annual operating hours (Figures 7b and 7e), and electricity price (Figures 7c and 7f). All profiles evince small influence of the selected parameters over the optimum P_{comb}. With base-processes for LGTW-CONV (variant #2) and LGTW-BECCS /

SCOC-CC (variant #3) defined accordingly to their respective P_{comb} for greatest long-term NPV, the concepts are compared in greater details in this section in technical and economic grounds.

3.3.1. Process Conditions

Table 7 presents operating conditions of main streams for LGTW-CONV and LGTW-BECCS plants, which results are complemented by process data in Figures 2 and 3, respectively. Stack emissions at LGTW-CONV reaches 75.05 t/h CO_2 with further 0.0111 t/h SO_2, while LGTW-BECCS entails no atmospheric emissions and produces 0.510 kmol/s of CO_2-rich supercritical fluid for sequestration (92.45%CO_2, 4.48%N_2, 2.38%Ar, 0.36%O_2, 0.33%H_2O, mol-basis). Significant amount of nitrogen and argon are carried to the fluid mainly due to presence of these species in GOX (95%O_2) and landfill gas ({P2}, {P3}, Table 1). A higher CO_2 content would reduce the power demand for CO_2 compression, and this can be accomplished by using GOX at a greater purity (up to 98%mol for the best overall efficiency) in exchange to slightly higher separation power in the ASU (Brigagão *et al.*, 2019b). Nevertheless, further purification unit would be necessary in case the CO_2 stream has to follow strict purity specifications.

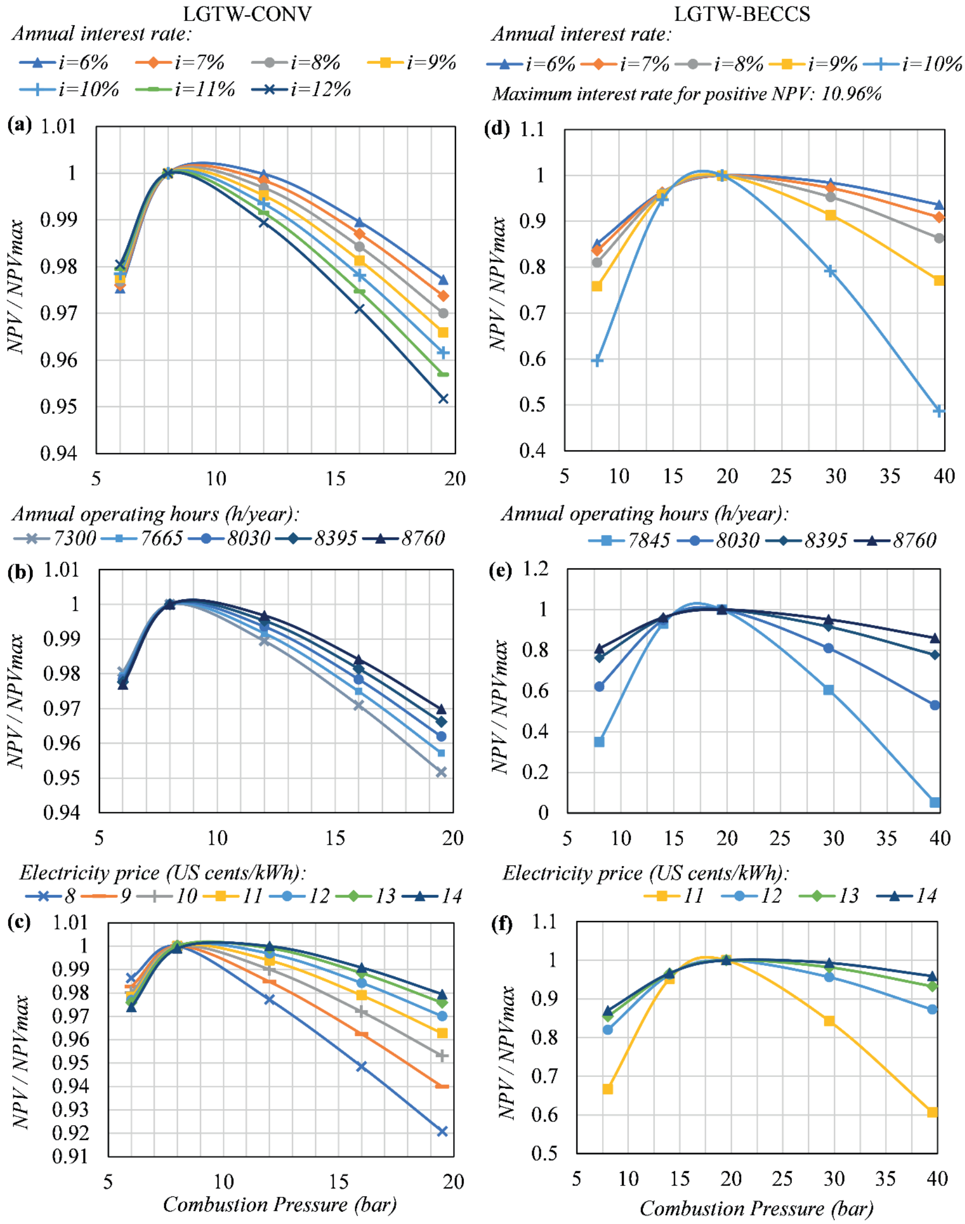

Figure 7 - Influence of Annual Interest Rate, Annual Operating Hours and Electricity Price over NPV ÷ NPV_{max} dependence upon GT combustion pressure (P_{comb}) for LGTW-CONV (a-c) and LGTW-BECCS (d-f)

Table 7 - Operating conditions and molar composition of main process streams

	LGTW-CONV				LGTW-BECCS							
Stream	Air Intake	Comb. Outlet	GT Outlet	Stack Gas	ST Inlet	GOX Feed	Comb. Outlet	GT Outlet	DCC Top	ST Inlet	Sour Water	CO_2 to Sequest.
P (bar)	1.013	8.00	1.043	1.013	70.0	1.013	19.5	1.060	1.013	70.0	1.50	250
T (°C)	25.0	1300	781	70.9	560	15.0	1300	782	40.0	560	35.4	61.2
F (kmol/h)	17254	19034	19034	19034	7482	1832	13699	13699	12089	7312	1747	1836
Y_k (molfrac)												
CO_2 :	0.0004	0.0896	0.0896	0.0896	-	-	0.7589	0.7589	0.8599	-	0.0004	0.9245
H_2O :	0.0189	0.1106	0.1106	0.1106	1.000	-	0.1817	0.1817	0.0729	1.000	0.9996	0.0033
O_2 :	0.2055	0.0953	0.0953	0.0953	-	0.9500	0.0029	0.0029	0.0033	-	0.0000	0.0036
Ar :	0.0091	0.0083	0.0083	0.0083	-	0.0239	0.0196	0.0196	0.0222	-	0.0000	0.0238
N_2 :	0.7660	0.6982	0.6982	0.6982	-	0.0261	0.0368	0.0368	0.0417	-	0.0000	0.0448

Operating conditions of LGTW-BECCS base-process (variant #3) – shown in Figure 3 – reveal an exhaust-gas recirculation ratio of 84%, which may be regarded as relatively low in relation to typical ≈90% of similar power-cycles (Stanger *et al.*, 2015). This is mainly a consequence of high CO_2 content in the fuel ({P2}, Table 1), which considerably reduces the required recycle ratio, because the temperature of landfill gas sent to GT is much lower than that of recycle gas. Even at greater P_{comb}≈40 bar (LGTW-BECCS variant #5), gas recirculation increases to only 85%, despite the higher recycle-gas temperature (442°C versus 349°C of base-process).

Regarding the flue gas temperature in oxyfuel GT outlet, other studies on SCOC-CC indicated that it is usually close to that of conventional air-blown GT at optimal pressure-ratio for combined cycle (Stanger *et al*., 2015). The results shown in Table 7 also evinces this fact, as GTs have similar outlet temperatures in LGTW-BECCS and LGTW-CONV. A relatively high temperature of ≈782°C is achieved due to adoption of low P_{comb}, which is also a consequence of assumptions on steam-cycle (Table 1), since more complex Rankine cycles usually favor reduced GT outlet temperatures as a result of more efficient heat exchange, leading to higher optimum pressure-ratio. As discussed by Dahlquist *et al*. (2013), the advantage of using multiple steam pressure levels is lowered when GT outlet temperature is increased. More available heat beyond the boiler pinch-point allows greater steam generation, and the increased water flowrate also helps recovering more heat below the pinch-point. Then, depending on the steam-cycle configuration, the exhaust gas after HRSG may vary within 65-130°C (Dahlquist *et al*., 2013). This explains relatively low temperature of this stream in both processes, as seen in Figures 2-3. The more efficient heat recovery shown in the oxyfuel process (65°C in HRSG outlet) is explained by deeper fall of flue gas specific heat capacity (c_p) along the HRSG – from 1.32 to 0.98 kJ/kgK in oxyfuel LGTW-BECCS, in contrast with 1.25-1.07 kJ/kgK shown in LGTW-CONV – which implies in less available heat to be recovered in the economizer, lowering heat transfer delta temperature in the end section of HRSG.

Tables 3 and 5 indicates ≈3.4%LHV (6.49 MW) higher gross power output of GT+ST in LGTW-BECCS, and also the consumption of 4.87%LHV in CO_2 compression and pumping, with further 4.00%LHV and 2.87%LHV for GOX production and compression, respectively. LGTW-BECCS overall efficiency is 44.16%LHV (TVR-2REB ASU demand included), thus power generation is reduced by 9.20%LHV (17.78 MW) from LGTW-CONV base-process. The efficiency penalty is consistent with the generally expected penalty of 8-11%LHV from previous works on oxyfuel GT cycles (Stanger *et al*., 2015), but this result notably assumes a highly efficient ASU demanding 139 kWh/t O_2 (Brigagão *et al*., 2019b). As conventional ASUs of double-column design typically require 200 kWh/t O_2 (Darde *et al*., 2009), if such plants were considered for LGTW-BECCS in spite of TVR-2REB, power generation would be ≈3.7 MW lower, reducing power plant net efficiency by further 1.9%LHV.

3.3.2. Environmental Aspects

LGTW-CONV offers limited potential for mitigation of greenhouse gas emissions, essentially due to conversion of CH_4, reducing from 425.90 t/h of CO_2-equivalent (100-years horizon) to 75.05 t/h of CO_2 emissions (stack). Another problem is atmospheric release of SO_2 (e.g., contributing to acid rain formation), which may be up to 30 times higher than estimated 0.0111 t/h, as H_2S content in landfill gas can be as high as 3000 ppmv depending on solid-waste profile. In contrast, oxyfuel LGTW-BECCS allows removal of up to 37.36 t/h of CO_2 from atmosphere through carbon life-cycle (i.e., CDR, negative emission), if 50% of carbon source within landfilled waste derives from biomass (POUR et al., 2018). Nevertheless, production of SO_2-containing sour water is a practical issue, related to flue gas condensate from DCC and CO_2 compression, due to high SO_2 absorption by water (e.g., solubility at 25°C/1 atm is ≈94 g/L). The condensate can be neutralized by addition of CaO/ $Ca(OH)_2$ (e.g., at DCC sump) to precipitate $CaSO_3$, which can be sent to landfill as inorganic waste or to finishing purification for sale (Chakroun; Ghoniem, 2015b).

3.3.3. Economic Analysis

Figure 8 depicts fixed capital investment comparison between LGTW-BECCS (including ASU) and LGTW-CONV with detailed contribution of process components. It evinces high investment on cryogenic ASU (1410 t/d GOX), which together with GOX compressor involves more investment than total LGTW-CONV facility. Since LGTW-BECCS also involves CO_2 compression for dispatch and requires more power to send landfill gas to GT due to increased P_{comb}, the fixed capital investment of this alternative (≈210.2 MMUSD) is unsurprisingly substantially higher, being almost 2.5 times higher than that of LGTW-CONV (≈84.6 MMUSD).

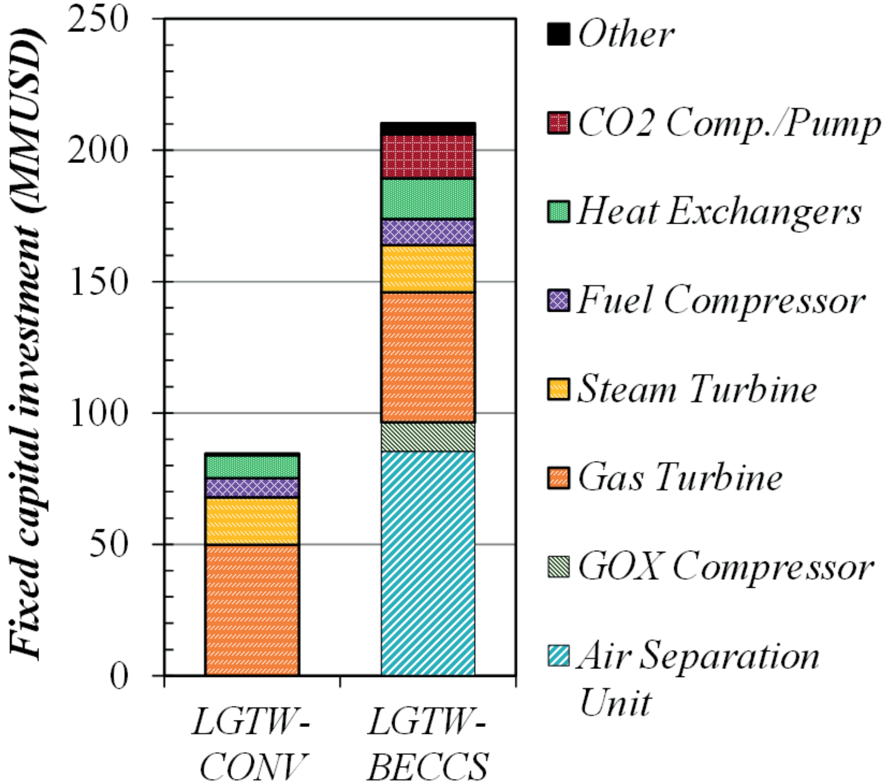

Figure 8 - Fixed capital investment of LGTW-CONV and LGTW-BECCS Base-Processes

Figure 8 further evinces both LGTW-CONV and LGTW-BECCS with similar capital investments on GT (≈50 MMUSD for ≈65 MW) and ST (≈18 MMUSD for ≈45 MW). Such results are reasonable comparatively to typical GT and ST costs collected by Jaramillo and Matthews (2005). By using CEPCI-update and log-extrapolation from their data for GT (1-40 MW) and ST (0.5-15 MW), it is possible to estimate corresponding investments to GT and ST actual capacities: ≈56 MMUSD (869 USD/kW) and ≈19 MMUSD (288 USD/kW), respectively. The small discrepancy confirms ±20% usual accuracy of Turton et al. (2012) methods and indicates suitability of utilized methods for application to main power plant equipment.

Economic performance details of selected processes LGTW-CONV and LGTW-BECCS with TVR-2REB ASU are presented in Table 8 for several carbon taxation scenarios, where positive NPVs are revealed for both concepts. LGTW-CONV has much greater NPV if no CO_2 tax is applied: 254 against 13 MMUSD, an outcome of lower capital investment and greater annual profit (51 against 30 MMUSD/y), as CO_2 capture is not involved. LGTW-BECCS produces 17% less electricity, and proportionally lower is its total revenue

(74 MMUSD/y). The manufacturing cost of LGTW-BECCS is higher mostly due to indirect contribution of greater capital investment on the plant (e.g., incurring in maintenance, insurance, fixed costs linked to plant complexity), and in a small extent due to higher cost with utilities (linked to greater use of cooling water in intercoolers).

Table 8 - Economic performance of base-processes under different CO_2 taxes

Power Plant	LGTW-CONV					LGTW-BECCS	Unit
CO_2 taxation	0	25	50	75	100	(any)	USD/t_{CO2}
Fixed capital investment	84.62	84.62	84.62	84.62	84.62	210.21	MMUSD
Total revenue	89.68	89.68	89.68	89.68	89.68	74.21	MMUSD/y
Raw material costs	0.00	0.00	0.00	0.00	0.00	0.00	MMUSD/y
Utilities costs	1.15	1.15	1.15	1.15	1.15	1.60	MMUSD/y
Manufacturing costs	17.08	32.03	46.98	61.93	76.88	40.25	MMUSD/y
Gross annual profit	72.60	57.65	42.70	27.75	12.80	33.96	MMUSD/y
Annual profit (net)	50.79	40.92	31.06	21.19	11.32	29.56	MMUSD/y
Net Present Value	254.0	190.9	127.8	64.70	1.58	13.08	MMUSD

The results shown in Table 8 are reasonable because increased operational expenses and capital investment usually follows CO_2 capture solutions, thus such economic disadvantage against CO_2-emitting conventional processes have to be compensated by CO_2 mitigation policies (e.g., carbon tax over emissions) or CO_2 monetization whenever viable (e.g., enhanced oil recovery), otherwise implementation of CO_2 capture would continue to be seen with little commercial interest. Therefore, it is possible to have an oxyfuel LGTW-BECCS outperforming the profitability of a CO_2-emitting LGTW-CONV. In this regard, comparison of NPV performances along project years under different carbon taxation scenarios (0, 25, 50, 75, or 100 USD/t) is provided in Figure 9, where several curves apply to LGTW-CONV, while LGTW-BECCS alternative is expressed as a single curve as it entails zero-emission power generation. The initial 3 years expresses the phase of plant construction with distributed capital outlay (20/30/50%), where LGTW-BECCS evinces the lowest NPV due to its higher capital investment. Table 8 presents the corresponding values of manufacturing cost, annual profit, and NPV (at 20 years of operation) for each scenario. The reduction of annual profits in LGTW-CONV caused by payment of CO_2 taxes allows the zero-emission solution LGTW-BECCS to progressively surpass its economic performance throughout the years of analysis. By the 17th year from start-up, the proposed oxyfuel LGTW-BECCS starts to outperform LGTW-CONV if carbon taxes are above 95.45 USD/t CO_2.

Figure 9 shows that 3 years of operation are enough to occur the discounted payback of LGTW-CONV without CO_2 taxation charge. Since the adoption of a combined cycle allows the production of more power than a Rankine cycle alone based on steam turbines, it is reasonable to find a faster payback than that of the Puente Hills project, where a large-scale project based on steam turbines had payback within only 5 years of operation (Rajaram *et al.*, 2011). Under CO_2 taxation, LGTW-CONV project payback is delayed, especially if CO_2 taxes are above 75 USD/t (Figure 9), where reduced annual profits (Table 8) would require a medium-term (5-10 years) or long-term (>10 years) horizon of operation for a positive NPV. At 75 USD/t, LGTW-BECCS already outperforms LGTW-CONV in terms of annual profit, but the much higher capital investment (Figure 7) hinders the attainment of a greater NPV.

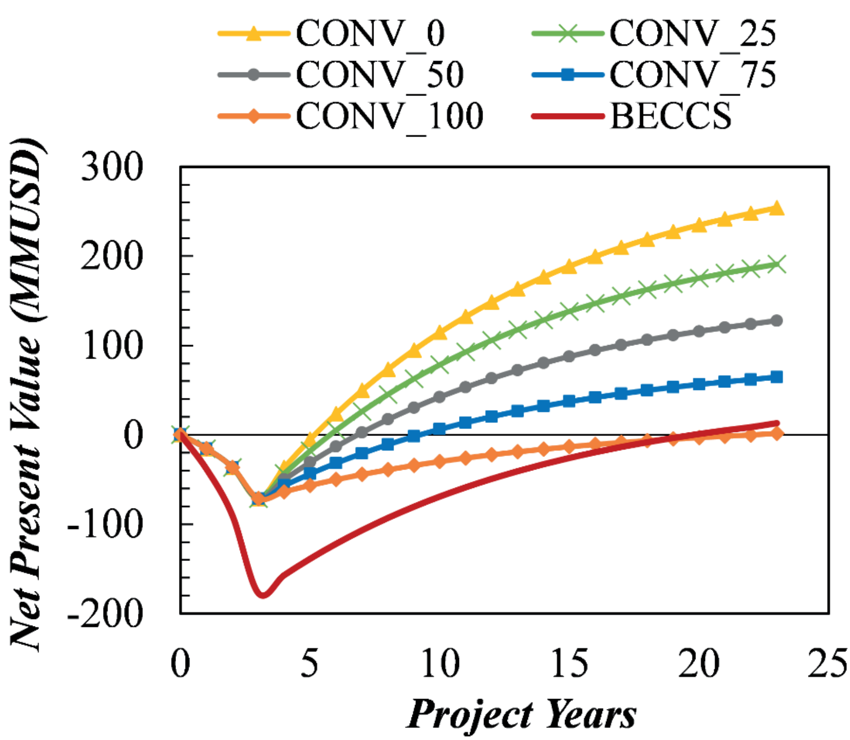

Figure 9 - Net present value profile of LGTW-BECCS coupled to TVR-2REB ASU and LGTW-CONV under different CO_2 taxation scenarios (USD/t)

By last, Figure 10 portrays sensitivity analysis of delta NPV between LGTW-BECCS and LGTW-CONV, as a function of CO_2 tax and electricity price, with indication of the most profitable LGTW concept for each region of the graph, defined by zero contour line. Figure 10 reveals break-even CO_2 tax within ≈85-102 USD/t for greater NPV of zero-emission LGTW-BECCS, if it is subjected to electricity price variations of ≈25% around base-price (0.1087 USD/kWh). Although such taxation level is relatively high for current practice, it is already seen in some European countries and is plausible to be widely employed in the future, due to intensification of climate change mitigation policies.

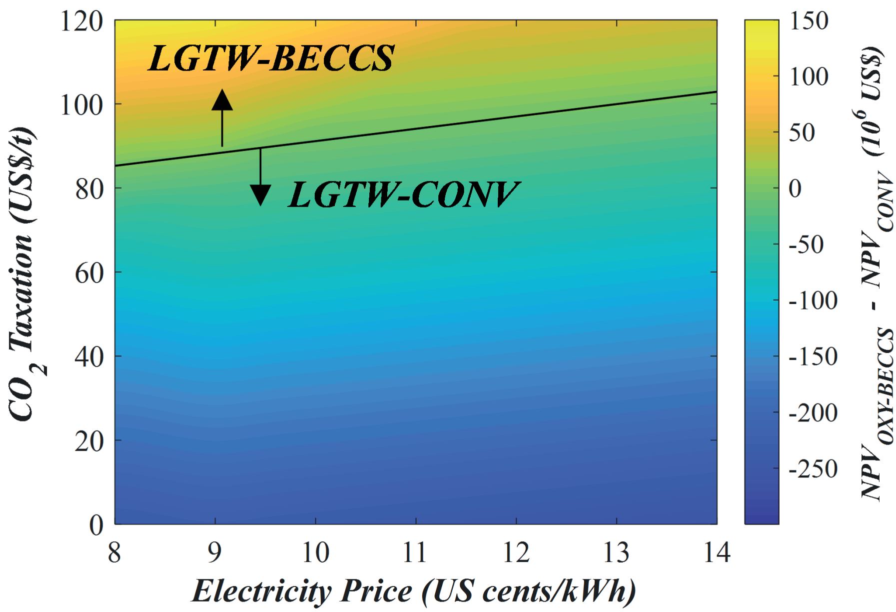

Figure 10 - Delta NPV (*$NPV_{OXY-BECCS}$–NPV_{CONV}*) as a function of electricity price (¢/kWh) and CO_2 tax level (USD/t). *NPV_{CONV}≡NPV of LGTW-CONV base process. $NPV_{OXY-BECCS}$≡NPV of LGTW-BECCS base process*

CONCLUSIONS

Assuming fixed large-scale fuel supply as base destination for collected landfill gas, economic viability and competitiveness of LGTW-BECCS based on oxy-combustion combined cycle for zero-emission power generation is presented against CO_2-emitting LGTW-CONV process charged by carbon taxes. Two different oxy-combustion configurations based on CO_2 recirculation to GT are evaluated by process simulation and compared by economic perspective: SCOC-CC (where gas recycle compression is adiabatic) and RIOC-CC (where multistage intercooled compression of gas recycle is adopted). RIOC-CC has greater net efficiency but is economically inferior to SCOC-CC. Therefore, SCOC-CC is selected for LGTW-BECCS application.

Sensitivity analysis on GT combustion pressure evinced highest NPV at ≈20 and ≈8.0 bar in LGTW-BECCS and LGTW-CONV, respectively. Major influence of total capital investment and compression requirements for landfill gas feed to GT are main causes for relatively low GT pressure-ratios. At best operating conditions, 9.2%LHV of efficiency penalty is attained, resulting in ratio of CO_2 capture flow by net power produced of 0.875 kg/

kWh. The comparison of NPV of LGTW-BECCS against LGTW-CONV charged by carbon taxation showed higher profitability of proposed zero-emission alternative when CO_2 tax is above 95 USD/t.

By accounting the life-cycle of the captured CO_2, the proposed solution offers as a sustainable mean of power generation with CDR – since urban solid-wastes typically present substantial content of organic matter from biomass – which makes this concept an effective instrument for climate change mitigation. The solution is profitable and economically feasible in the long-term without need for electricity overpricing and/or government subsidies, with the break-even price for positive NPV being 0.104 USD/kWh. From a stable feed of 1.08 MMSm³/d landfill gas, LGTW-BECCS is capable of producing 85.33 MW, which is enough power to supply ≈70,000 US average homes (EPA, 2019), which consumption is more than 3 times world average. Besides the advantage of promoting CDR, LGTW-BECCS presents low environmental impacts and is thus demonstrated as a sustainable solution for waste monetization, also capable of promoting health-social benefits and local economic growth.

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