A Zero-Emission Sustainable Landfill-Gas-To-Wire Oxyfuel Process: Bioenergy with Carbon Capture and Sequestration

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Abstract

Landfill-gas basically consists of methane and carbon dioxide and its reclamation is mandatory for better waste utilization and low greenhouse-gas emissions to transition towards renewable-energy matrices. Power generation or landfill-gas-to-wire is a solution for landfill-gas utilization with electricity-supply benefits skipping complex purification/transportation steps. As municipal solid-waste is rich in biomass, landfill-gas-fired power generation, with carbon capture and sequestration, leads to negative emissions and, consequently, climate-change mitigation. This work investigates the feasibility of zero-emission landfill-gas-to-wire concepts with oxyfuel carbon sequestration against conventional landfill-gas-fired plant facing carbon charges. Economic analysis is supported by Aspen-HYSYS simulation assuming large-scale landfill-gas supply. Different gas-turbine pressure-ratios are economically sought for both conventional and oxyfuel power plants to establish most profitable configurations. The greatest net values of conventional and oxyfuel plants are respectively attained for combustion pressures around 8 and 20 bar. This indicates investment and compression costs pulling down gas-turbine pressure-ratio in the landfill-gas combined-cycle plant. At such conditions, carbon dioxide is captured at 0.875 kg/kWh entailing oxyfuel efficiency penalty of 9.2% based on landfill-gas lower heating value, and increasing the long-term break-even electricity price from US$36/MWh to US$104/MWh. Economic superiority of zero-emission oxyfuel-combined-cycle over conventional plant occurs for carbon taxes above US$95/t.

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Keywords: Landfill-Gas; Power Generation; Oxy-Combustion; CO_2; Bioenergy; CCS.

Highlights

- Oxyfuel landfill-gas-to-wire is evinced as a viable and sustainable solution.
- Two different oxyfuel landfill-gas-to-wire are evaluated and economically compared.
- Optimization of gas-turbine combustor pressure executed from economic perspective.
- Proposed oxyfuel landfill-gas-to-wire has break-even power price of US$0.104/kWh.
- Oxyfuel landfill-gas-to-wire overcomes ordinary landfill-gas-to-wire at US$95/t$CO_2$.

Abbreviations

ASU Air Separation Unit; BECCS Bioenergy with Carbon Capture and Sequestration; CCS Carbon Capture and Sequestration; CCU Carbon Capture and Utilization; CW Cooling-Water; DCC Direct-Contact-Column; EOR Enhanced Oil Recovery; GT Gas-Turbine; HRSG Heat-Recovery Steam-Generator; LCOE Levelized Cost of Electricity; LGTW Landfill-Gas-to-Wire; LHV Lower Heating Value; PCC-MEA Aqueous-Monoethanolamine Post-Combustion CO_2 Capture; RIOC-CC Regenerative Intercooled Oxy-Combustion Combined-Cycle; SCOC-CC Semi-Closed Oxy-Combustion Combined-Cycle; ST Steam-Turbine; TVR-2REB Top-Vapor Recompression Two-Reboiler Distillation; USD US-Dollar.

Nomenclature

AP, CEPCI : *Annual profit (USD/y), chemical engineering plant cost index*
c_p, c_v : *Specific heat capacities at constant pressure and constant volume (kJ/kgK)*
COM, CUT : *Costs of manufacturing, cost of utilities (USD/y)*
E_{sep} : *ASU specific power consumption (kWh/tO_2)*
F : *Molar flow rate (kmol/h)*
FCI, GAP : *Fixed capital investment (USD), Gross annual profit (USD/y)*
GWP_n : *Global warming potential for n years (kgCO_2eq/kg)*
i, ITR : *Annual interest rate, income tax rate (%)*
NPV, P, REV : *Net present value (USD), pressure (bar), revenues (USD/y)*
T, W : *Temperature (°C), mechanical power (kW)*
Y_k : *Molar fraction of component k*

Greek Symbols
γ : *Isentropic exponent of gas expansion/compression*
η : *Adiabatic efficiency of gas expansion/compression (%)*

Subscripts
Comb, CONV : *Combustor outlet, Conventional combined-cycle*
OXY-BECCS : *Oxyfuel-BECCS*

1. Introduction

The Paris Agreement targets require strong mitigation efforts to all sectors, demanding widespread adoption of renewable resources whenever possible and phasing out unmitigated fossil-based power generation, in order to cut CO_2 emissions by ≈50% [1]. Consequently, negative-emission initiatives play important role in climate-change stabilization [2] and depend on widespread deployment of bioenergy with carbon capture and sequestration (BECCS) enterprises [3], allowing to offset impacts from sectors where mitigation is more expensive [4]. In this context, waste utilization avoids ecological and social issues associated to biomass production for energy purposes [5]. In other words, waste-to-power BECCS initiatives lead to socio-economic-environmental benefits [6] and provide fossil-fuel displacement alternatives [7].

1.1. Landfill-Gas

Efficient municipal solid-waste management must explore waste valorization opportunities and should promote circular economy principles, sending excess to landfills, and applying thermochemical or biochemical conversion in a cost-effective sustainable manner [8]. Landfilling is the cheapest solid-waste management option [9], but without the recovery of landfill-gas, considerable environmental/social impacts follow, besides loss of valorization opportunities. Open dumps are the extreme example, being characterized by solid-waste deposition on sites without due environmental care, severely polluting air, soil, and water, besides offering explosion risks [10] and imposing threats to population health [9]. Both leachate contamination and toxic compounds in landfill-gas are identified as health disorder causes [11]. Thus, planned construction of sanitary landfills is conceived for mitigation of such impacts and appropriate management of leachate and landfill-gas.

Landfill-gas production varies accordingly to landfill characteristics (e.g., size, age, collection system) and solid-waste profile [12]. In volume dry-basis, a typical US landfill-gas generated at steady conditions (i.e., after some operation years) has 50-55%CH_4, 45-50%CO_2 and 2-5% of other gases – e.g, N_2, H_2S, volatile organic compounds and siloxanes. At such conditions, landfill-gas production is approximately stable for about 20 years [13]. Some possible landfill-gas uses comprise electricity generation, biomethane commercialization, heating, steam generation, leachate evaporation, and production of chemical/biochemical derivatives [14]. The reduction of landfill emissions greatly results in climate-change mitigation [15], as CH_4 has 28 times more global warming potential than CO_2 on weight basis for 100 years (GWP_{100}), and 84 times for 20 years (GWP_{20}) [3]. In addition, further greenhouse-gas emissions are abated if landfill-gas displaces fossil-fuel uses [15]. Thus, good overall environmental performances depend on efficient landfill-gas collection systems [16]. If landfill-gas is not sent to useful purposes, it must be flared to eliminate CH_4, volatile organics, and toxic/odorant compounds [17].

Landfill-gas utilization entails governance benefits due to improved urban energy security and less dependence on distant electricity or natural gas suppliers [18]. Thus landfill-gas power plants provide economic growth, creating revenues and jobs, while benefitting the environment by reducing greenhouse-gas emissions and fossil-fuel utilization [19]. Electricity tariffs are not supposed to increase, as the 2005 break-even price was showed to be lower than 0.04 USD/kWh without government subsidies [20].

Landfill-gas power generation usually resorts to internal combustion engines of 0.1–3.0 MW for small landfill-gas capacities of 50-960 scfm. Gas-turbines (GT) over 3 MW of power are suitable when landfill-gas supply is sufficiently high and stable over 1050 scfm at ≈50%v/v CH_4 [21]. Steam-turbines (ST) are also valid in large projects, with advantages of greater flexibility and resiliency to landfill-gas contaminants, dismissing compression [22]. Some GT advantages over internal combustion engines comprise greater corrosion resistance, compact size, complete and cleaner combustion, and lower operation/maintenance costs [21].

1.2. Bioenergy with Carbon Capture and Sequestration

Beyond fossil-carbon capture and sequestration (CCS) and fossil-carbon capture and utilization (CCU), geological sequestration of biogenic CO_2 has been suggested for effective global warming mitigation [3]. BECCS allows negative life-cycle emissions due to CO_2 biofixation by photosynthesis and differently from afforestation and soil carbon sequestration – without disturbances over terrestrial carbon stocks – BECCS contributes to the climate with permanent CO_2 storage [5], promoting continuous drainage of atmospheric CO_2 [23]. BECCS electricity generation also enhances flexibility and diversity of the energy portfolio [5], besides improving regional energy independence [18]. Some countries, like US and Australia, have been considered ready for BECCS deployment, considering their CCS and bioenergy experiences. However, effective implementation will demand policy guidance [5], wherein carbon taxation is a conceivable instrument [24].

On the other hand, widespread deployment of BECCS has techno-economic and social challenges to overcome. Bioenergy often generates environmental impacts [25] related to biomass cultivation and harvesting [26]. Other sustainability issues are storage availability and possible competition for land and resources [2], potentially creating drivers for deforestation, community displacements and biodiversity threats [6]. In some cases, positive net CO_2 balance [27] and project feasibility are threatened by biomass production and transportation costs and associated emissions [28]. However, these difficulties are attenuated if BECCS is embedded in waste management and CCU is employed. A problem with the latter is a lack of scale compatibility between CCU market and climate stabilization requirements [29], so that a mix of CCS and many CCU routes should match the purpose of CO_2 abatement. In this regard, the limited solution of enhanced oil recovery (EOR) is currently the only way to add value to CO_2 at large-scales (≈10^6 t/y) [30]. Due to this handicap, CO_2 geological sequestration is considered in this work.

1.3. Oxy-Combustion Carbon Capture

Among the power production routes with carbon capture, oxy-combustion allows better environmental performance with profitability potential and greater net efficiencies, being the only option capable of zero-emission power generation [31]. Oxy-combustion economic competitiveness is heavily dependent on cost-effective air fractionation [32]. Currently, cryogenic air separation is the most practical route for oxygen supply to large-scale oxy-combustion systems [33]. The most efficient cryogenic air separation unit (ASU) for 95%mol atmospheric gas oxygen production [32] is based on top-vapor recompression two-reboiler cryogenic distillation (TVR-2REB) which requires 139 kWh/tO_2.

Another challenge for large-scale oxy-combustion implementation is the need of special equipment operating in oxy-firing mode; i.e., oxyfuel GTs [34]. Nevertheless, oxyfuel power-cycles have been proposed requiring reduced degree of modification in GT machinery. The most intuitive is the so-called semi-closed oxy-combustion combined-cycle (SCOC-CC) [35]. Other CO_2-based cycles were developed without a bottoming steam-cycle, frequently comprising intercooled compression to supercritical conditions (e.g., Allam-cycle) [34]. Another approach is water-based cycle, where condensate abates the combustion temperature dismissing a gas-recycle; i.e., large CO_2-recycle compressors are substituted by water pumps. Water-based cycles currently present the highest technology readiness level [34] accounting for a successful demonstration project [36], but significantly lower efficiencies, comparatively to gas-recycle configurations, have been reported [37]. Combining CO_2-

recycle and water-recycle is also possible (e.g., S-Graz cycle) and was reported to yield the best results, though at the expenses of high complexity [38].

For a given combustor temperature (T_{Comb}) and steam-cycle conditions, there is an optimum operational GT pressure-ratio [34]. According to Dahlquist et al. [39], this design parameter is the linchpin of oxyfuel combined-cycles. For same T_{Comb} and exhaust temperature, oxyfuel GTs uses higher pressure-ratios compared to conventional air-blown GTs [40], which typically run at ≈20 bar combustion pressure (P_{Comb}) [41], while SCOC-CC GTs often run with P_{Comb} ranges of 40-60 bar [40]. The underlying reason is the relatively low isentropic exponent ($\gamma=c_p/c_v$) of CO_2-rich fluid in SCOC-CC [39], entailing lower temperature changes through adiabatic compression/expansion [42]. The milder final temperatures (comparatively to air) of CO_2-rich recycle adiabatic compression, favors P_{Comb} increases for higher power outputs. However, high pressure-ratios increase turbo-machinery size and complexity, which must be pondered over net efficiency gains [39]. The fluid behavior is also affected by the higher density/compressibility and lower sound speed of CO_2-rich fluids comparatively to N_2-rich fluids of usual GTs, changing GT annulus flow section [34]. The majority of works addressing pressure-ratio of oxyfuel GTs only consider net power output perspective, so the compression temperature raise is what generally limits P_{Comb} increase. The selection of the most suitable pressure-ratio for equipment construction is then usually left to a subjective decision accounting for turbo-machinery and heat-recovery steam-generator (HRSG) design concerns. In SCOC-CC, the net efficiency curve is typically flat at optimum net efficiency [43], so that the realistic best condition is slightly below the theoretical maximum [39]. In this regard, Dahlquist et al. [39] obtained an optimum pressure-ratio of 45 for T_{Comb}≈1340°C, but considered that ≈34 should be the most advantageous solution. A further issue [41] is that pressure-ratios above 30 are only common in aero-derivative GTs – where compressor design favors aerodynamics and power efficiency – while industrial GTs adopt simpler designs towards minimal fixed capital investment (*FCI*). In this work the optimal GT pressure-ratio determination follows an economic formulation, taking into account equipment sizes and their influence on profitability. Additionally, there is the fact that landfill-gas – contrarily to natural gas – needs compression from atmospheric pressure, which also affects optimal operating conditions.

1.4. The Present Work

An oxyfuel BECCS landfill-gas utilization is analyzed for zero-emission power generation, entailing net removal of atmospheric CO_2 and avoidance of CH_4 emissions. The concept is hereinafter named as landfill-gas-to-wire, analogously to natural gas gas-to-wire [44].

Currently, there are few literature works dealing with rigorous simulation of oxyfuel power generation burning CO_2-rich fuel-gas. In addition, CO_2 emission taxation has not been considered in landfill-gas-to-wire studies, though its recognized role for climate-change mitigation [45]. In Chakroun and Ghoniem [37], the analyzed processes were not compared to conventional natural gas combined-cycle and their fuel-gas composition differs from landfill-gas CO_2 and H_2S ranges [46], significantly impacting power-cycle performance.

The present work demonstrates economic feasibility of oxyfuel BECCS-landfill-gas-to-wire without overpriced electricity. Moreover, economically optimal oxyfuel GT P_{Comb} for a low-pressure CO_2-rich fuel-gas is first-time used. These aspects are literature gaps that the present work intends to fill. The proposed oxyfuel BECCS-landfill-gas-to-wire (LGTW-BECCS) is proved not only environmentally superior, but also more profitable than landfill-gas air-fired combined-cycle (LGTW-CONV) under CO_2 taxation. To the authors knowledge, energy and economic assessments of oxyfuel landfill-gas combined-cycle LGTW-BECCS against conventional air-blown LGTW-CONV never appeared before in the literature.

2. Methods

Assumptions for simulation, design and economic analysis of landfill-gas power plants are presented. Pre-screening of alternatives determines the base-case process of each concept: the oxyfuel LGTW-BECCS and its CO_2-emitting conventional counterpart LGTW-CONV.

2.1. Simulation of Landfill-Gas-To-Wire Alternatives

Fig. 1 depicts a diagram of LGTW-CONV and LGTW-BECCS wherein operating conditions are investigated. All LGTW solutions were simulated in Aspen-HYSYS v8.8 according to assumptions in Table 1 and have several aspects in common: (i) as landfill-gas may inflame at high temperatures due to O_2 intrusion from air, it is compressed through multistage intercooled compressor train ($T^{Max}=150°C$) to feed the GT; (ii) all LGTW's are combined-cycles with HRSG fed with GT exhausts generating the same superheated steam ($T=560°C$, $P=70bar$) to the Rankine-Cycle; (iii) single-pressure Rankine-Cycle to reduce investment and because high exhaust temperatures weakens the need for multiple steam pressure levels [39]; (iv) ST discharges at 0.10 bar allowing ordinary cooling-water (CW) in the condenser.

Moreover, all LGTW's consume ≈1.08MMSm^3/d of landfill-gas at atmospheric pressure with ≈50%mol CH_4 in dry-basis. Landfill-gas composition (Table 1, {A2}) is in agreement with the EPA ranges [13]. H_2S content of ≈100 ppm-mol is chosen accordingly to data available elsewhere [46]. Large-scale electricity generation is assumed for cost-effectiveness [16], since large-scales favor high investments like combined-cycles and cryogenic oxygen production. Through 20 years of a large-scale hypothetical landfill, the bulk of the collected landfill-gas is assumed supplied at constant flow rate to the LGTW. The scope for the comparison of different LGTW solutions does not comprehend: (i) the upstream chain aspects (costs and CO_2 emissions included) of landfill-gas supply; (ii) possibilities regarding minor parallel landfill-gas utilizations (e.g., heating); and (iii) possibly unnecessary landfill-gas pre-purification steps (e.g., siloxanes removal).

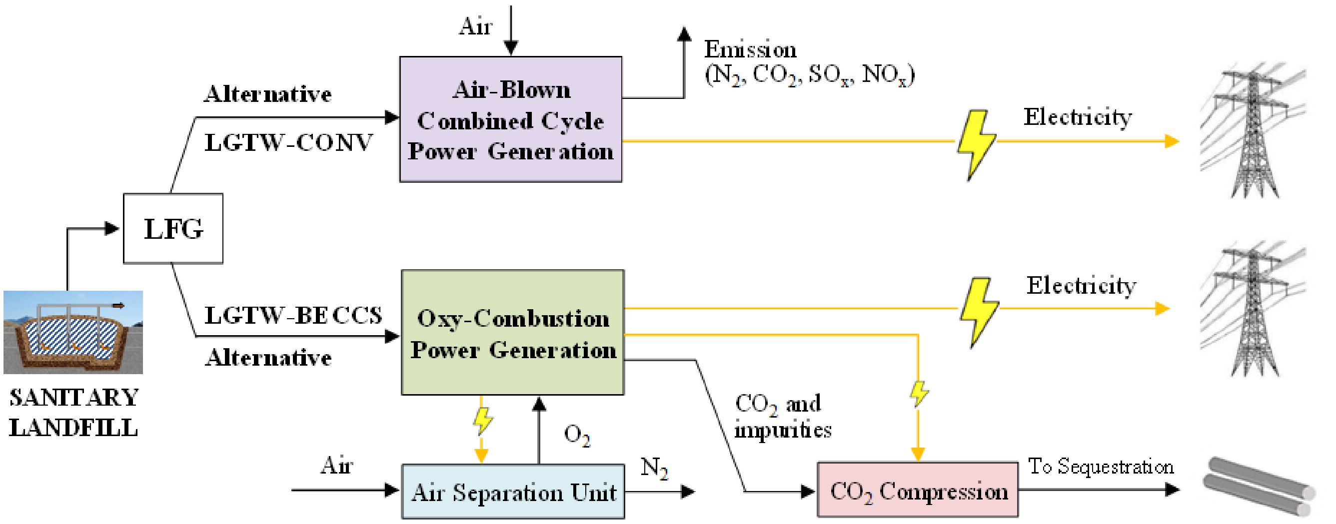

Figure 1. Landfill-Gas-To-Wire routes (LFG=landfill-gas).

Table 1. Simulation assumptions for LGTW alternatives.

Item	*Assumption*
{A1}	*Thermodynamic Modeling: Peng-Robinson Equation-of-State, ASME-Table for Steam-Cycle*
{A2}	*Landfill-Gas (%mol): F=1869 kmol/h (1.08MMSm³/d), T=40°C, P=1 atm, 46.37%CH_4, 44.51%CO_2, 1.85%N_2, 0.01%H_2S, 7.26%H_2O (water-saturated)*
{A3}	*Oxygen (%mol): 1832 kmol/h (1.41*10^6 kg/d), T=15°C, P=1 atm, 95%O_2, 2.39%Ar, 2.61%N_2*
{A4}	*ASU Specific Power Consumption: E_{sep}=139kWh/tO_2 [32]*
{A5}	*Combined-Cycle: 1:1 (Gas-Turbine:Steam-Turbine)*
{A6}	*Adiabatic Efficiencies: $\eta^{Expander}=90\%$; $\eta^{Axial\text{-}Compressor}=85\%$; $\eta^{Centrifugal\text{-}Compressor}=80\%$; $\eta^{Pump}=75\%$.*
{A7}	*Gas-Turbine (GT) Expander: $T^{Inlet}=1300°C$.*
{A8}	*Single-Pressure Steam-Turbine (ST): $T^{Inlet}=560°C$; $P^{Inlet}=70bar$.*
{A9}	*Vacuum-Condenser: $P^{Inlet}=0.10$ bar, $\Delta P^{Head\text{-}Loss}=1$ kPa, $T^{Outlet}=43.8°C$.*
{A10}	*HRSG: $\Delta T^{Approach}\geq 20°C$, $\Delta P^{GAS}=3$ kPa, $\Delta P^{H2O}=50$ kPa.*
{A11}	*Flue-Gas Direct-Contact Column: Structured-Packing, Theoretical-Stages=3; Recycled-Water: 35°C, $P^{TOP}=1atm$, $\Delta P=2kPa$*
{A12}	*Cooling-Water (CW): $T^{CW\text{-}INLET}=30°C$, $T^{CW\text{-}OUTLET}=40°C$.*
{A12}	*Intercoolers: $T^{GAS}=40°C$, $\Delta P=3\%P^{Inlet}\leq 50kPa$.*
{A13}	*CO_2: $T^{Liquefaction}=40°C$; $P^{Liquefaction}=150bar$; $P^{Exportation}=250bar$.*
{A14}	*Landfill-Gas Upstream/Parallel Processes: Not Evaluated*

2.1.1. Landfill-Gas-To-Wire Conventional Process

Fig. 2 presents LGTW-CONV flowsheet with economically optimal values. Compressed landfill-gas feeds a conventional air-blown GT whose exhausts feed the HRSG.

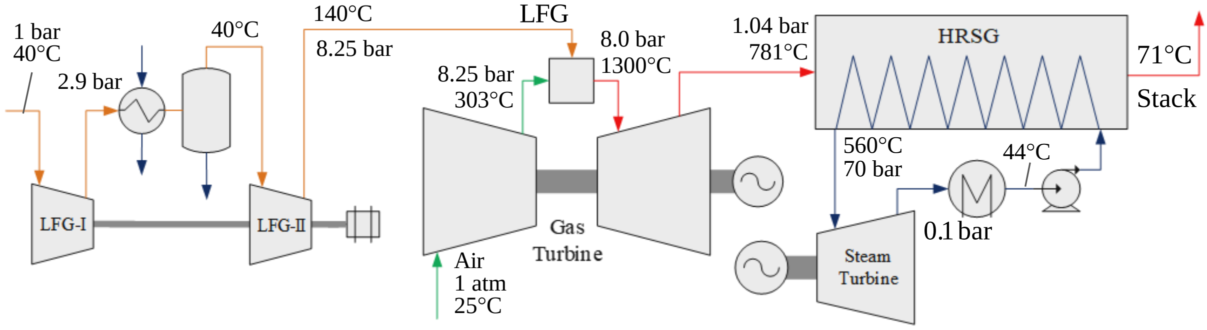

Figure 2. LGTW-CONV Base-Case.

2.1.2. Landfill-Gas-To-Wire Oxyfuel Process

Two configurations are considered for oxyfuel LGTW-BECCS: (i) semi-closed oxy-combustion combined-cycle (SCOC-CC) [35], with single-stage adiabatic CO_2-recycle compression (Fig. 3); and (ii) regenerative intercooled oxy-combustion combined-cycle (RIOC-CC), with multistage intercooled CO_2-recycle compression (Fig. 4). RIOC-CC resembles the E-Matiant cycle without GT reheat [47], incorporating a bottoming Rankine-Cycle. SCOC-CC and RIOC-CC share several aspects in common: (i) a standalone TVR-2REB ASU [32] supplies atmospheric oxygen at stoichiometric proportion; (ii) oxygen and landfill-gas have multistage intercooled compressor trains ($T^{Max}=150°C$) to feed the GT, wherein, multistage intercooled oxygen compression guarantees safety, minimal investment and better process sustainability by avoiding high-pressure hot O_2; (iii) after the HRSG, flue-gas is cooled in a direct-contact column (DCC) with recirculated condensate at the top [39]; (iv) part of the DCC top (CO_2-rich) gas is the CO_2 product sent to a multistage intercooled compressor train to be dispatched as 250 bar dense fluid for CCS, the rest recycles to the GT. Fig. 3 presents the SCOC-CC version of LGTW-BECCS with economically optimal values.

Part of the DCC CO_2-rich gas recycles to GT combustion chamber to abate combustion temperature [37] through the single-stage adiabatic axial compressor driven by GT shaft.

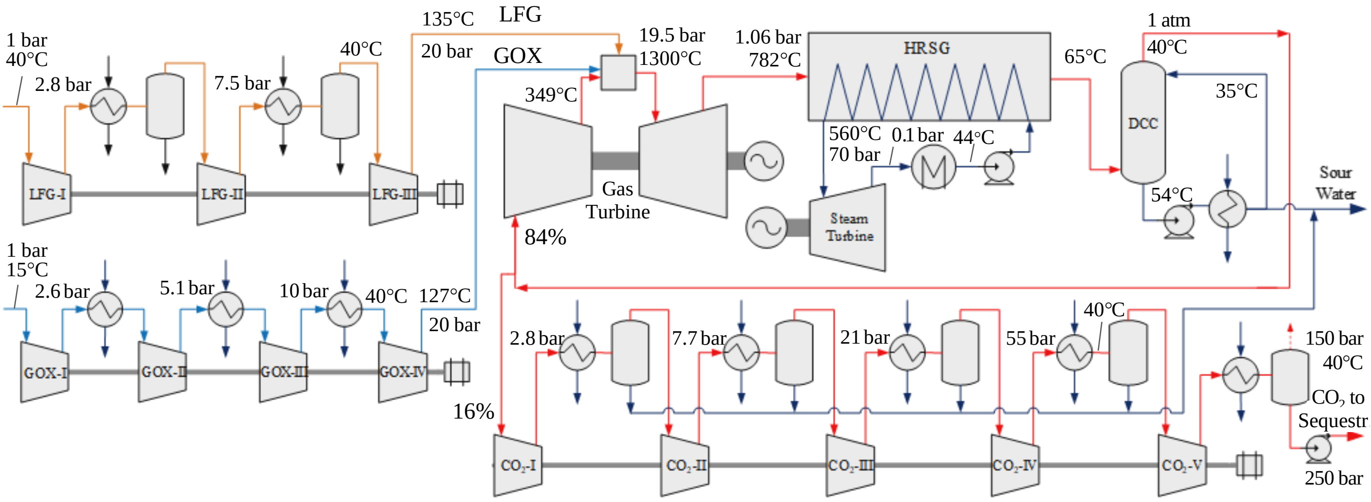

Figure 3. SCOC-CC LGTW-BECCS Base-Case (LFG=landfill-gas, GOX=gas-O₂).

Fig. 4 depicts RIOC-CC at economically optimal conditions. Regenerative Brayton-Cycle and intercooled recycle compression are considered (similarly to E-Matiant cycle) to investigate whether lower power demand and reduced size of CO_2-recycle compressors improves profitability. The main differences to SCOC-CC comprehend a larger CO_2-recycle stream passing through the intercooled centrifugal-compressor train and subsequently through the HRSG to be heated to ≈804°C for injection in the GT chamber.

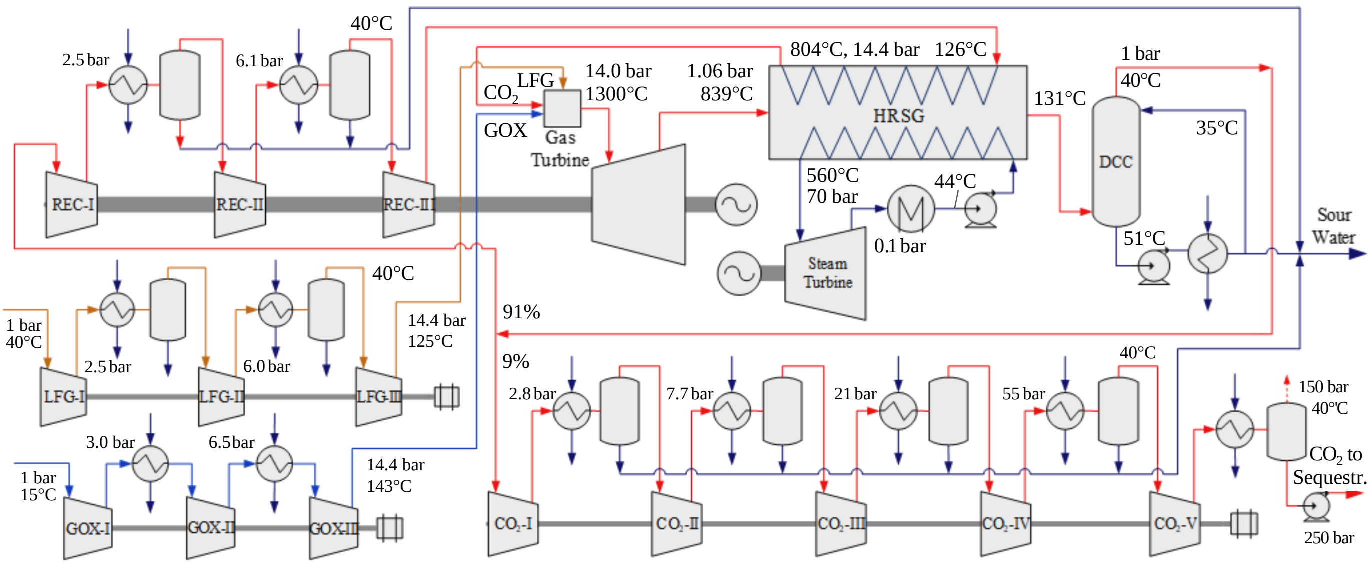

Figure 4. RIOC-CC LGTW-BECCS Base-Case (LFG=landfill-gas, GOX=gas-O₂).

2.2. Economic Analysis of Landfill-Gas-To-Wire Processes

The economic assessment of LGTWs is performed via Turton et al. [48]. *FCI* is calculated with equipment sizes via Campbell [49]. GT *FCI* (FCI_{GT}) is estimated adding compressor, expander and generator *FCI* contributions. As commercial GTs for CO_2-rich fluids are still inexistent, the same GT *FCI* correlations are used in LGTW-CONV and LGTW-BECCS. Economic equations are in Supplement S1, Supplementary Materials. Table 2 presents economic assumptions. Considering that a zero-emission oxyfuel LGTW-BECCS can be more profitable than LGTW-CONV under CO_2 taxation, it is desired to find the required tax level to make the net present value (*NPV*) of LGTW-BECCS greater than that of LGTW-CONV after 20 operation years. Thus, economic performances are evaluated under several taxation scenarios. Landfill operation related emissions – e.g., fugitive emissions, flare gas, other landfill-gas uses – were not accounted. Similarly, the analysis does not cover solid-waste handling, collection, transportation, and processing steps.

Table 2. Economic assumptions.

Item	Assumption
{E1}	Electricity=0.1087 USD/kWh (USA-Price June/2017).
{E2}	Base-Scenario CO_2 Taxation: 0 USD/kg
{E3}	Cost of Utilities (*CUT*): *CW*=0.016 USD/t
{E4}	Equipment *FCI*: extrapolated with 0.6 exponent if out of correlation ranges [48]
{E5}	ASU *FCI*: extrapolated with 0.5 exponent from *FCI*=141 MMUSD for 52 kg/s Oxygen [50]
{E6}	*FCI* Inflation Factor: *CEPCI*=603.1 (2018-average)
{E7}	Construction: three years (20%/30%/50% investment allocations)
{E8}	Operation: 8000 h/y
{E9}	Annual Depreciation: 10%*FCI*
{E10}	Income Tax Rate: *ITR*=34%
{E11}	Project Horizon: 20 operation years
{E12}	Annual Interest Rate: *i*=10%
{E13}	Landfill-Gas Price: zero

3. Results and Discussion

Sec. 3.1 addresses techno-economic evaluation of LGTW-CONV variants to seek most profitable operating conditions for the landfill-gas (Table 1, {A2}). Sec. 3.2 compares the performance of the two LGTW-BECCS configurations and similarly evaluates their variants for the best configuration and operating conditions. Sec. 3.3 consolidates the comparison of energy/economic performances of base-cases LGTW-CONV and LGTW-BECCS considering CO_2 taxation.

3.1. Conventional Landfill-Gas-To-Wire Variants

Five LGTW-CONV variants are evaluated; each one featuring a different P_{Comb}. Detailed conditions of LGTW-CONV variants #1 to #5 are found in Supplement S2, Supplementary Materials. Breakdown of machinery contributions to overall power output is presented in Table 3, clearly revealing the expected trade-off between GT and ST powers from different GT outlet temperatures. Raising GT pressure-ratio up to ≈20 improves power generation, with smaller gains being attained from 16 to 20 bar due to negative contribution of landfill-gas compressors (Table 3). The corresponding CO_2 emission-factors (Table 3) range from 0.711 to 0.753 kg/kWh from different power capacities. Changing Rankine-Cycle conditions to more complex schemes – with multiple pressure levels and reheat – can improve Rankine-Cycle efficiency for reduced GT outlet temperatures (i.e., at higher pressure-ratios), allowing slightly greater net power outputs, which are offset by the respective greater investments from a *NPV* perspective. Therefore, this aspect is ignored for searching the best possible *NPV*.

Although conventional natural gas combined-cycles generally operate with P_{Comb}≈20 bar [39], a GT with reduced pressure-ratio is found to be more suitable for this application, which is unveiled via a long-term *NPV* viewpoint. In this sense, techno-economic comparison of

LGTW-CONV variants #1 to #5 is consolidated in Table 4 and Fig. 5. Table 4 presents power output, revenues (*REV*), manufacturing cost (*COM*), *FCI*, and 20 years *NPV* (without CO_2 tax) as functions of P_{Comb}, with the corresponding numbers of landfill-gas compression stages. *REV* expresses gains with power output (Table 2, {E1}), while *COM* combines utilities and labor costs in addition to *FCI* derived costs (maintenance, insurance, taxes, overhead and administration). *FCI* and *COM* increase considerably at greater P_{Comb}, while *REV* improvement becomes gradually smaller. Fig. 5 illustrates net efficiency and *NPV-20years*, showing that despite maximum efficiency occurs at P_{Comb}≈20 bar (variant #5) the highest *NPV-20years* is nearby P_{Comb}≈8 bar, thus indicating variant #2 as LGTW-CONV Base-Case for further comparisons with LGTW-BECCS. Appendix A (Figs. A.1a to A.1c) presents $NPV \div NPV_{max}$ dependence upon P_{Comb} for LGTW-CONV in scenarios of interest rate, operating hours and electricity price, all showing small influence over optimal P_{Comb}.

Table 3. Power contributions and CO_2 emission-factor of LGTW-CONV variants.

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

* LGTW-CONV Base-Case

Table 4. LGTW-CONV techno-economic sensitivity analysis.

LGTW-CONV Variant	**P_{Comb} (bar)**	**#Stages landfill-gas**	**Net Power (MW)**	***REV* (MMUSD/y)**	***COM* (MMUSD/y)**	***FCI* (MMUSD)**	***NPV-20y (MMUSD)***
1	6.0	2	99.67	86.67	16.17	79.1	248.6
2*	8.0	2	103.1	89.68	17.08	84.6	254.0
3	12.0	3	105.1	91.35	18.14	91.4	252.0
4	16.0	3	105.6	91.81	18.86	96.0	248.5
5	19.5	3	105.7	91.87	19.40	99.4	244.3

* LGTW-CONV Base-Case

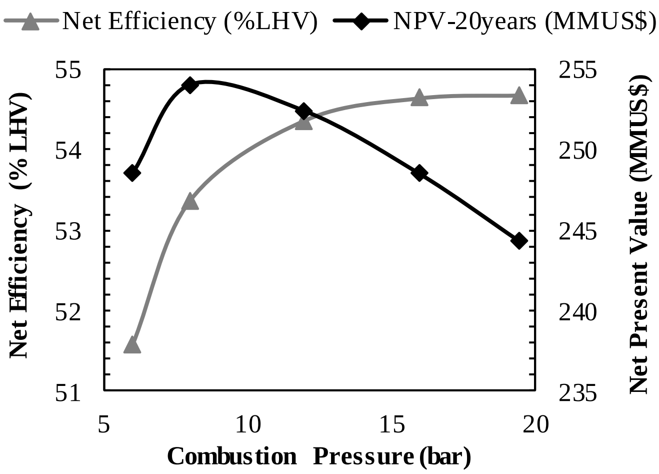

Figure 5. Influence of P_{Comb} on LGTW-CONV net efficiency and *NPV-20years*.

3.2. Oxy-Combustion Variants

Ten oxyfuel LGTW-BECCS variants are compared on energy/economic grounds, either adopting SCOC-CC (variants #1 to #5) or RIOC-CC (variants #6 to #10) configuration at different P_{Comb}. Detailed conditions of LGTW-BECCS variants #1 to #10 are in Supplement S3, Supplementary Materials. LGTW-BECCS variants generate power without CO_2 emissions and sequestrating 74.7 tCO_2/h. Table 5 presents machinery contributions to overall power output of variants.

SCOC-CC has lower GT power than RIOC-CC – 69.62 against 103.8 MW – mainly accounting for reduced CO_2-recycle flow rate and higher specific CO_2-recycle compression power. In variants #3 and #7 (P_{Comb}≈20 bar), the specific CO_2-recycle power demands are 306 and 264 kJ/kg respectively, but flow rate differences entail total demands of 35.52 and 52.32 MW, with respective expander powers of 105.14 and 156.08 MW.

Table 5. Power contribution of process machinery: LGTW-BECCS variants.

LGTW-BECCS Variant	**#1**	**#2**	**#3†**	**#4**	**#5**	**#6**	**#7**	**#8**	**#9**	**#10**
Combustion Pressure (bar)	**8.0**	**14.0**	**19.5**	**29.5**	**39.5**	**14.0**	**19.5**	**29.5**	**39.5**	**59.5**
Configuration	**SCOC-CC**					**RIOC-CC**				
Air Separation Unit **(MW)**	-7.74	-7.74	-7.74	-7.74	-7.74	-7.74	-7.74	-7.74	-7.74	-7.74
Oxygen Compressor **(MW)**	-3.84	-4.97	-5.54	-6.37	-6.97	-4.97	-5.54	-6.37	-6.97	-7.66
Fuel-Gas Compressor **(MW)**	-3.93	-4.86	-5.49	-6.12	-6.64	-4.86	-5.49	-6.11	-6.64	-7.38
Gas-Turbine **(MW)**	52.39	63.59	69.62	76.46	80.92	102.0	103.8	106.8	108.1	109.5
Steam-turbine **(MW)**	50.59	46.51	44.28	40.81	37.89	13.43	12.16	10.56	9.41	7.86
CO_2 Compressor/Pump**(MW)**	-9.42	-9.42	-9.42	-9.42	-9.42	-9.41	-9.41	-9.41	-9.41	-9.41
Auxiliary Equipment **(MW)**	-0.43	-0.40	-0.38	-0.36	-0.34	-0.16	-0.15	-0.13	-0.12	-0.11
Overall Output (MW)	**77.63**	**82.71**	**85.33**	**87.26**	**87.71**	**88.25**	**87.60**	**87.57**	**86.69**	**85.04**
CO_2 Ratio (kg/kWh)	**0.962**	**0.903**	**0.875**	**0.856**	**0.852**	**0.846**	**0.853**	**0.853**	**0.862**	**0.878**

† LGTW-BECCS Base-Case.

The proportion between GT and ST outputs differs considerably from LGTW-CONV in both LGTW-BECCS configurations (notably RIOC-CC). In SCOC-CC, due to low isentropic exponent ($\gamma=c_p/c_v$) of CO_2-rich fluid, the GT pressure-ratio needs to be shifted to ≈40 to attain usual ST power proportion of 1/3 of total power (Table 5). In RIOC-CC, ST has a minor role – ≈1/10 of GT power – since the exhaust gas mostly heats CO_2-recycle instead of condensate. This concentrates power generation within the regenerative Brayton-Cycle, leaving a small duty to Rankine-Cycle; i.e., superheated steam can optionally be used in one or two ST drivers due to low capacity (e.g., driving landfill-gas and CO_2 compressors, saving $4*10^6$ USD of *FCI* in variant #6).

Table 5 shows that P_{Comb} has opposite effects over SCOC-CC and RIOC-CC performances within the evaluated ranges. The highest net efficiency was evinced in RIOC-CC (45.67% LHV), whose output is favored by reduced P_{Comb} of 14 bar (88.25 MW), because more heat is available to increase CO_2-recycle temperature (GT exhaust at T≈839°C). Further pressure reduction in RIOC-CC is limited by reduced GT power and increased losses in heat exchange. SCOC-CC, on the other hand, produces more power with P_{Comb} increase up to ≈40 bar (87.71 MW), exhibiting minor gains from 30 to 40 bar. Further P_{Comb} increase in SCOC-

CC is limited by increased power consumption of CO_2-recycle adiabatic compression, as CO_2 becomes too hot for compression.

3.2.1. Comparison with Literature

It is worthwhile to indicate similarities of SCOC-CC simulation results with literature works, even if slightly different design conditions apply (notably T_{Comb}). Dahlquist et al. [39] results showed similar SCOC-CC net efficiency dependence with GT pressure-ratio and presented a curve that coincidently flattens out at P_{Comb}≈40 bar for T_{Comb}=1340°C. Assuming higher T_{Comb}, Yang et al. [43] investigated the effect of higher pressure-ratios beyond the point of efficiency reduction, finding the maximum output in the middle of flat efficiency curves at ≈60 for T_{Comb}=1418°C, and at ≈90 for T_{Comb}=1600°C. As small power gains occurred for P_{Comb} from 40 to 60 bar at T_{Comb}=1418°C, operation with P_{Comb}≈40 bar should be more suitable in view of other *FCI* aspects. Table 5 indicates that, from power generation perspective, the appropriate P_{Comb} for application in SCOC-CC LGTW-BECCS should be between 30-40 bar. Indeed, for T_{Comb} within 1300-1400°C, the SCOC-CC GT pressure-ratio ranges typically from 30 to 40; slightly below the maximum output condition via simulation [34]. The development of high pressure-ratio machines would hardly be motivated by small efficiency gains, as discussed by Dahlquist et al. [39] regarding defying GT designs for pressure-ratios above 40 even for conventional GTs, and becoming even more challenging for CO_2-rich fluid (e.g., low sound speed). Thus, for applications with T_{Comb}=1340°C and GT outlet temperature of 620°C, P_{Comb}≈32 bar was selected in [39].

3.2.2. Oxyfuel Optimal Combustion Pressure

Contrasting with abovementioned references, determination of the best P_{Comb} is here approached for maximal *NPV*. Although high GT pressure-ratios are generally conceived for SCOC-CC aiming at efficiency optimization, the viewpoint of long-term *NPV* reveals that usual P_{Comb}≈20 bar is suitable for LGTW-BECCS application, mainly due to a major role of *FCI* in *NPV* analysis. Table 6 consolidates techno-economic comparison of LGTW-BECCS variants #1 to #10 and presents power output, *REV*, *COM*, *FCI*, *NPV-20years* and numbers of compressor stages (for CO_2-recycle, oxygen and landfill-gas) as functions of P_{Comb}. As in LGTW-CONV variants, depending on whether SCOC-CC or RIOC-CC is adopted, greater P_{Comb} entails considerable increase of *FCI* and *COM*, while *REV* behaves proportionally to power output.

Table 6. LGTW-BECCS techno-economic sensitivity analysis.

Process Variant	CC	P^{Comb} (bar)	#Stages Recycle	#Stages landfill-gas	#Stages O_2	Net Power (MW)	*REV* (MMUSD/y)	*COM* (MMUSD/y)	*FCI* (MMUSD)	*NPV-20y* (MMUSD)
1	SCOC	8.0	1	2	3	77.63	67.52	37.31	193.1	7.81
2		14.0	1	3	3	82.71	71.94	39.11	203.6	12.39
3†		19.5	1	3	4	85.33	74.21	40.25	210.2	13.08
4		29.5	1	4	4	87.26	75.88	41.50	217.4	10.35
5		39.5	1	4	4	87.71	76.27	42.22	221.6	6.36
6	RIOC	14.0	3	3	3	88.25	76.75	44.90	237.3	-12.68
7		19.5	3	3	4	87.60	76.17	45.12	237.7	-16.24
8		29.5	4	4	4	87.57	76.15	46.81	247.1	-29.40
9		39.5	4	4	4	86.69	75.38	46.79	247.0	-32.37
10		59.5	4	4	4	85.04	73.95	47.08	248.5	-40.60

† LGTW-BECCS Base-Case.

Albeit presenting slightly lower net efficiency, SCOC-CC is much more profitable than RIOC-CC, which, in turn, was proved economically unfeasible at the end of the horizon due to significantly higher *FCI*. Therefore, as RIOC-CC performs economically worse, inefficiently exploiting landfill-gas potential, from this point on only SCOC-CC is considered for LGTW-BECCS.

Fig. 6 depicts sensitivity analysis for SCOC-CC net efficiency and *NPV*-20years dependence upon P_{Comb}. The net efficiency curve flattens out around the maximum as similarly showed elsewhere [39]. Despite the maximum efficiency at P_{Comb}≈40 bar (variant #5), *NPV* shows that the highest profitability is nearby P_{Comb}≈20 bar, thus indicating variant #3 as LGTW-

BECCS Base-Case for comparison with LGTW-CONV Base-Case. Appendix A (Figs. A.1d to A.1f) presents *NPV÷NPV*$_{max}$ dependence upon P_{Comb} for SCOC-CC LGTW-BECCS in scenarios of interest rate, operating hours and electricity price, all showing small influence over optimal P_{Comb}, and confirming P_{Comb}≈20 bar for best long-term profitability.

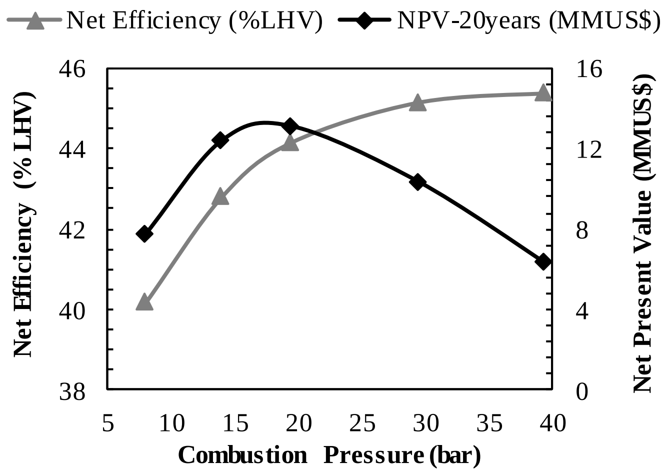

Figure 6. Influence of P_{Comb} on LGTW-BECCS net efficiency and *NPV-20years*.

Considering other oxyfuel LGTW-BECCS candidates, few other cycles appear to be suitable, making SCOC-CC a competitive LGTW-BECCS configuration. Water-injection oxyfuel processes worth investigation in future work because, despite of their lower efficiency [37], expensive CO_2-recycles are dismissed entailing lower *FCI* and cost-effectiveness. In contrast, competitiveness of efficient Graz-cycles is hampered due to process complexity. The Allam-cycle has efficiency and a simpler configuration – resembling E-Matiant flowsheet without bottoming-cycle – but is based on high-pressure supercritical CO_2 cycle (P_{Comb}=300 bar) operating at high-pressure GT discharge (≈30 bar, 775°C) negatively impacting *FCI* [51].

3.3. Performance Comparison of Landfill-Gas-To-Wire Concepts

Performances of LGTW-CONV using conventional combined-cycle (variant #2) and LGTW-BECCS using SCOC-CC configuration (variant #3) are technically/economically compared at their respective optimal P_{Comb} for maximum *NPV-20years*. Considering a conceivable

BECCS version of LGTW-CONV coupled to post-combustion capture by aqueous-monoethanolamine absorption (PCC-MEA), it is techno-economically demonstrated in Appendix B the conditional superiority of oxyfuel LGTW-BECCS over LGTW-CONV+PCC-MEA.

3.3.1. Performances of Processes

Table 7 presents main streams of LGTW-CONV and LGTW-BECCS regarding Figs. 2 and 3. LGTW-CONV emissions reach 75.05 tCO_2/h accompanied by 0.0111 tSO_2/h, while zero-emission LGTW-BECCS produces 1837 kmol/h of high-pressure CO_2-rich dense fluid (92.45%molCO_2, 4.48%molN_2, 2.38%molAr, 0.36%molO_2, 0.33%molH_2O). Some N_2 and Ar are carried to the CO_2 fluid thanks to their presence in landfill-gas and in the (95%mol) O_2 stream (Table 1, {A2,A3}). Higher %CO_2, reducing CO_2-rich fluid compression costs, can be attained via higher purity O_2 supply – up to 98%mol for reasonable overall efficiency – at the expense of slightly higher E_{sep} [32]. Nevertheless, for strict CO_2 purity, further purification of CO_2-rich fluid is necessary.

Fig. 3 reveals lower CO_2-recycle to GT of 84% vis-à-vis typical ≈90% [34]. This has to do with the high %CO_2 of landfill-gas (Table 1, {A2}), as the landfill-gas CO_2 enters the combustor at much lower temperature than CO_2-recycle lowering the required CO_2-recycle flow rate. LGTW-BECCS with P_{Comb}≈40 bar, the optimal power output case (variant#5, Table 6), has slightly higher CO_2-recycle (≈85%) due to its higher CO_2-recycle temperature (442°C) comparatively to 349°C in LGTW-BECCS Base-Case (variant#3, Table 6).

Regarding GT exhaust temperature, some studies indicate that it is close to the exhaust temperature of air-blown combined-cycle at optimal pressure-ratio [34]. This is confirmed in Table 7, which presents similar GT outlet temperature for LGTW-CONV and LGTW-BECCS. The achieved high exhaust temperature (≈782°C), caused by low P_{Comb}, is also an outcome of steam-cycle assumptions (Table 1), as advanced Rankine-Cycles favor lower GT temperatures due to more efficient heat exchange, entailing higher optimum P_{Comb}. As discussed in [39], the higher the GT outlet temperature, the lower the need for multiple pressure levels in Rankine-Cycle. More heat above the boiler pinch-point produces more steam; and, as a result of increased water flows, more heat is extracted below the pinch-point. Thus, depending on steam-cycle configuration, the HRSG flue-gas temperature typically varies from 65°C to 130°C [39]. This explains the low temperature of HRSG flue-gas in LGTW-CONV and LGTW-BECCS (Figs. 2 and 3). Lower flue-gas temperature is attained in LGTW-BECCS (65°C), indicating better heat recovery. This is caused by higher fall of fluid specific heat capacity (c_p) through HRSG – 1.32→0.98 kJ/kg.K in LGTW-BECCS against 1.25→1.07 kJ/kg.K in LGTW-CONV – implying lower heat recovery in the economizer, thus lower detachment of temperature profiles along HRSG end section.

Table 7. Conditions and molar composition of main streams.

	LGTW-CONV					**LGTW-BECCS**						
Stream	*Air Inlet*	*Comb. Outlet*	*GT Outlet*	*Stack Gas*	*ST Inlet*	*O_2 Feed*	*Comb. Outlet*	*GT Outlet*	*DCC Top*	*ST Inlet*	*Sour Water*	*CO_2*
T (°C)	25.0	1300	781	70.9	560	15.0	1300	782	40.0	560	35.4	61.2
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
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

From power results in Tables 4 and 6, the gross combined-cycle power output is ≈3.4%LHV (6.49 MW) higher in LGTW-BECCS, but oxygen production and compression consume 4.00%LHV and 2.87%LHV, respectively; while CO_2 compression demand further 4.87%LHV (Tables 5 and 7). LGTW-BECCS net efficiency (including ASU consumption) is

44.16%LHV, hence electricity generation is 9.20%LHV (17.78 MW) lower than LGTW-CONV Base-Case counterpart. This efficiency penalty assumes an efficient TVR-2REB ASU consuming E_{sep}=139 kWh/tO_2 [32] and is consistent with the expected penalty of 8-11%LHV from oxyfuel GT works [34]. Since conventional double-column ASUs typically require E_{sep}=200kWh/tO_2 [52], if such ASUs replace TVR-2REB in LGTW-BECCS, ≈3.7 MW less power would be produced, further reducing overall efficiency by 1.9%LHV.

3.3.2. Environmental Performances

Assuming that biomass is the carbon source of 50% of landfill-gas CO_2 [5], LGTW-BECCS drains up to 37.36 tCO_2/h from atmosphere through the carbon cycle. In contrast, LGTW-CONV has limited mitigation potential, besides emitting SO_2, as greenhouse-gas emissions are reduced from 425.90 t/h of CO_2-equivalent in collected landfill-gas (GWP_{100} basis) to 75.05 tCO_2/h (stack). Since H_2S contents as high as 3000 ppm-mol can be found in landfill-gas, SO_2 generation may be 30 times higher, intensifying environmental impacts of LGTW-CONV (e.g., acid rain). On the other hand, sour-water production is an issue of LGTW-BECCS, as SO_2 is almost totally dissolved in water effluents from DCC and CO_2 compressors knockout-vessels (≈94 g/L solubility at 25°C, 1 atm). Such sour-waters can be treated by adding $Ca(OH)_2$ suspensions [53] precipitating insoluble $CaSO_3$ for landfilling or for sale.

3.3.3. Economic Performances

Fig. 7 presents *FCI* comparison of LGTW-CONV and Oxyfuel LGTW-BECCS including TVR-2REB ASU. Fig. 7 clearly shows that a major shortcoming of LGTW-BECCS is the high *FCI* of cryogenic ASU – $1.41*10^3$ tO_2/d capacity – together with the O_2 compressor train counterpart. LGTW-BECCS also involves landfill-gas compression to the oxyfuel GT at high pressure-ratio, besides CO_2–rich fluid compression to dispatch and a greater number of intercooler heat exchangers. Hence, not surprisingly, the *FCI* of LGTW-BECCS (≈210.2 MMUSD) is ≈150% higher than LGTW-CONV *FCI* (≈84.6 MMUSD).

Fig. 7 also unveils similar ≈65 MW GT *FCI* (≈50 MMUSD) and ≈45 MW ST *FCI* (≈18 MMUSD). These are reasonable GT/ST values according to Jaramillo and Matthews [20] data for 1-40 MW GT and 0.5-15 MW ST. Using log-extrapolation and *CEPCI* correction, *FCI* for 65 MW GT and 45 MW ST become 869 USD/kW (≈56 MMUSD) and 288 USD/kW (≈19 MMUSD), respectively. This confirms adequacy and ±20% accuracy of Turton et al. [48] methods used here.

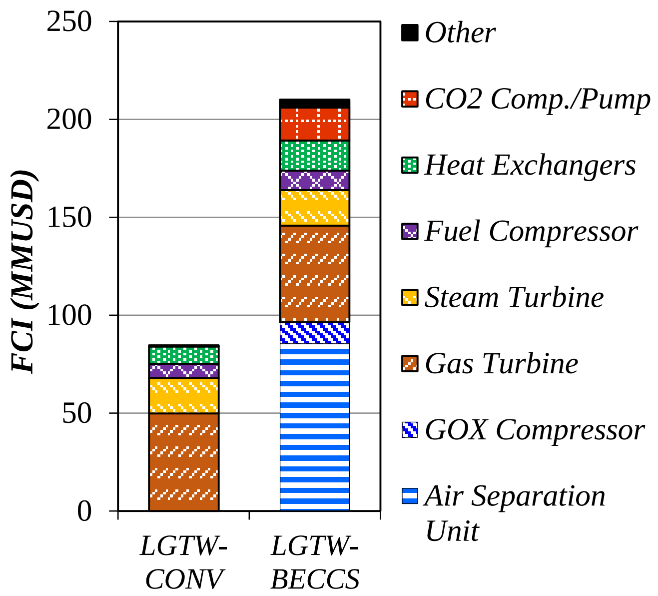

Figure 7. *FCI* of LGTW-CONV and LGTW-BECCS Base-Cases.

Table 8 shows economic indicators – gross annual profit (*GAP*), annual profit (*AP*), *COM* and *NPV-20years* – of LGTW-CONV and LGTW-BECCS with TVR-2REB ASU for several carbon taxations, indicating that both concepts have positive *NPV-20years*. Without CO_2 tax, LGTW-CONV has evidently greater *NPV-20years* (254 vs 13 MMUSD) due to lower *FCI* and greater *AP* (51 vs 30 MMUSD/y) which results from higher *REV* and lower *COM*. The *REV* of LGTW-BECCS (74 MMUSD/y) is lower in the same proportion of power output (-

17%) and its *COM* is higher due to its 150% higher *FCI*. LGTW-BECCS also has higher cost of utilities (*CUT*) from higher CW utilization, though with small influence over *COM*.

Table 8. Economic performance: LGTW alternatives under CO_2 taxes.

Power Plant	**LGTW-CONV**					**LGTW-BECCS**
CO_2 Tax (USD/t)	**0**	**25**	**50**	**75**	**100**	**(any)**
FCI (MMUSD)	84.62	84.62	84.62	84.62	84.62	210.21
REV (MMUSD/y)	89.68	89.68	89.68	89.68	89.68	74.21
CRM (MMUSD/y)	0.00	0.00	0.00	0.00	0.00	0.00
CUT (MMUSD/y)	1.15	1.15	1.15	1.15	1.15	1.60
COM (MMUSD/y)	17.08	32.03	46.98	61.93	76.88	40.25
GAP (MMUSD/y)	72.60	57.65	42.70	27.75	12.80	33.96
AP (MMUSD/y)	50.79	40.92	31.06	21.19	11.32	29.56
NPV-20years (MMUSD)	254.0	190.9	127.8	64.70	1.58	13.08

These results are reasonable since higher costs and investments are inherent to CCS solutions. Such economic LGTW-BECCS disadvantage against conventional CO_2-emitting LGTW-CONV should be offset by carbon reduction policies (e.g., emission taxation) or CO_2 monetization whenever possible (e.g., EOR). Therefore, despite of CCS costs, LGTW-BECCS can overcome the CO_2-emitting LGTW-CONV in terms of profitability as shown in Fig. 8, which compares *NPV* versus years under five CO_2 taxation scenarios – 0, 25, 50, 75, 100 USD/t – where the first three years account for plant construction with 20/30/50% capital outlay. In Fig. 8 five curves belong to LGTW-CONV and a sole curve corresponds to LGTW-BECCS as it performs zero-emission power generation. Bending of LGTW-CONV *NPV* profiles, caused by increasing CO_2 taxes, allows the zero-emission LGTW-BECCS to progressively approximate the LGTW-CONV economic performance through the years. By the 20th year from construction, LGTW-BECCS overcomes LGTW-CONV for taxes above 95.45 USD/t CO_2.

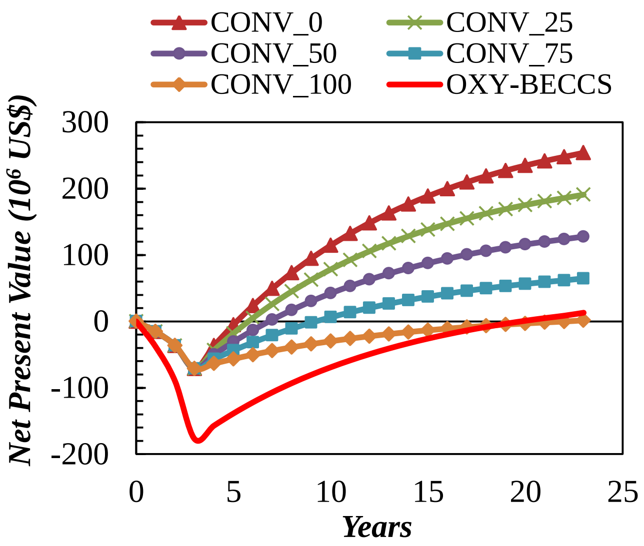

Figure 8. ***NPV*** **profiles of LGTW-BECCS with TVR-2REB ASU and LGTW-CONV under carbon taxation scenarios (USD/tCO_2).**

Without CO_2 taxes, Fig. 8 shows that 3 years of operation would be sufficient for the payback of LGTW-CONV. As gas-fired combined-cycles entails higher power outputs than simple gas-fired Rankine-Cycles with steam-turbines, one can find a faster payback than the 5 years of Puente Hills project [22]. However, incidence of CO_2 taxation naturally delays LGTW-CONV payback, with medium-term (5-10 years) to long-term (10+ years) campaigns being required above 75 USD/tCO_2 (Fig. 8) due to reduced *AP* (Table 8). At 75 USD/tCO_2 LGTW-BECCS outperforms LGTW-CONV in terms of *AP*, but its huge *FCI* (Fig. 7) hampers a superior *NPV*.

Fig. 9 depicts the sensitivity analysis of LGTW-BECCS *NPV* excess to LGTW-CONV as a function of electricity price and CO_2 tax. Fig. 9 indicates the most profitable solution for each region, unveiling superior performance of LGTW-BECCS within ≈85-102 USD/tCO_2 tax range for variations of ≈25% around the assumed base-price (0.1087 USD/kWh). Albeit high for current standards, similar taxations are already seen in European countries, and it is plausible that such taxation levels become extensively employed in incoming decades.

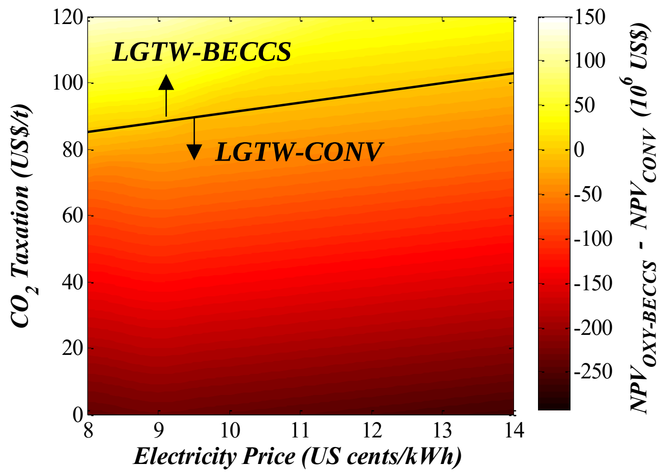

Figure 9. Difference $NPV_{OXY\text{-}BECCS}$ - NPV_{CONV} versus CO_2 tax and electricity price.

4. Conclusions

Competitiveness of zero-emission LGTW-BECCS concept based on oxyfuel landfill-gas-fired combined-cycle is demonstrated against CO_2-emitting LGTW-CONV charged by CO_2 taxation. A scenario of large-scale landfill-gas stable supply is considered. Two different LGTW-BECCS oxyfuel configurations using CO_2-recycle are evaluated and economically compared: SCOC-CC and RIOC-CC, the former with single-stage adiabatic compression of CO_2-recycle, and the latter with intercooled compression and preheating of CO_2-recycle. RIOC-CC allows slightly greater net efficiency comparatively to SCOC-CC but at the expenses of inferior *NPV*, so SCOC-CC configuration is indicated to LGTW-BECCS.

Sensitivity analysis on P_{Comb} showed that the highest *NPV* in LGTW-CONV and LGTW-BECCS via SCOC-CC is attained at ≈8.0 bar and ≈20 bar, respectively. These relatively low GT pressure-ratios derive from investment and compression requirements for landfill-gas processing. At such conditions, the oxyfuel efficiency penalty is 9.2%LHV with CO_2 capture ratio of 0.875 kg/kWh (Table 5). Comparison of *NPV* performances along project years under different CO_2 taxation scenarios is provided. Superior profitability of proposed zero-emission LGTW-BECCS over LGTW-CONV exists for ≈95 USD/t CO_2 tax.

This work contributes to the literature at evaluating the zero-emission LGTW-BECCS concept as sustainable power generation allowing net removal of CO_2 from atmosphere – as urban wastes have reasonable biomass content – making LGTW-BECCS an reliable tool for climate-change mitigation. The proposed concept is demonstrated to be economically feasible without government subsidies and electricity overpricing, attaining break-even price of 0.104 USD/kWh. LGTW-BECCS fed by 1.08 MMSm³/d landfill-gas, generates 85.33 MW, the equivalent demand of ≈70,000 US average homes. Therefore, besides presenting remarkable environment performance – particularly against greenhouse-gas emissions – LGTW-BECCS is evinced as a viable and sustainable waste monetization solution that entails economic growth and health-social benefits.

Supplementary Materials

Supplements S1, S2, S3 and S4 are found in the Supplementary Materials available online.

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Appendix A: Effect of Economic Parameters on Optimal Combustion Pressure

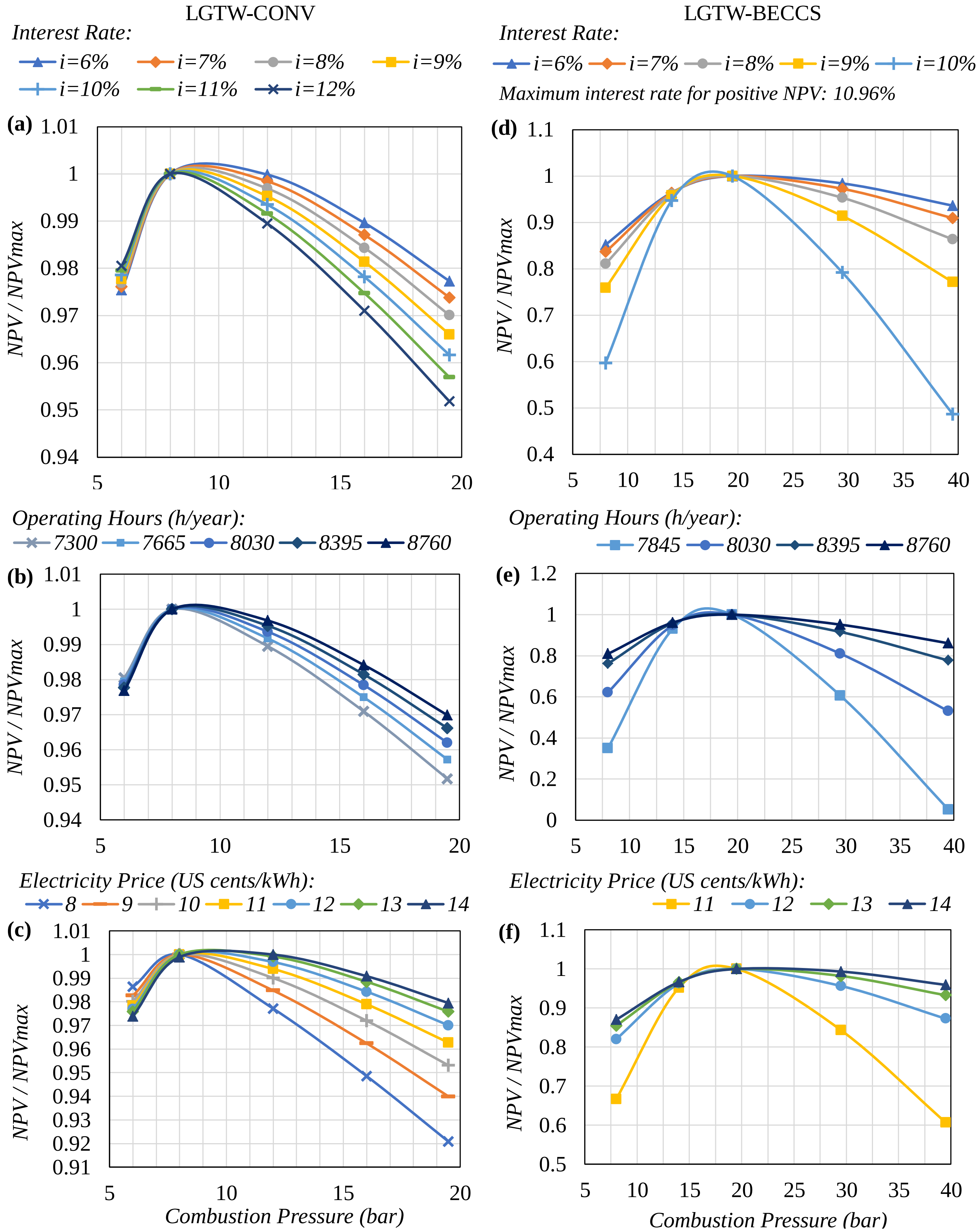

Figure A.1. Influence of Interest Rate, Operating Hours and Electricity Price over the *NPV÷NPV$_{max}$* dependence upon *P$_{Comb}$* for LGTW-CONV (a-c) and LGTW-BECCS (d-f).

Appendix B: Conventional Landfill-Gas-to-Wire with Post-Combustion CO_2 Capture

Techno-economic evaluation of a BECCS version of LGTW-CONV coupled to post-combustion CO_2 capture via aqueous-monoethanolamine absorption (PCC-MEA) is performed aiming to unveil oxyfuel LGTW-BECCS superiority over LGTW-CONV+PCC-MEA as BECCS solutions. Table B.1 lists LGTW-CONV+PCC-MEA technical assumptions. Fig. B.1 presents LGTW-CONV+PCC-MEA with operating conditions. Detailed conditions of LGTW-CONV+PCC-MEA are found in Supplement S4, Supplementary Materials. Extraction of low-pressure steam from HRSG for PCC-MEA solvent regeneration is the only change required in the LGTW-CONV.

Table B.1. Technical assumptions: LGTW-CONV+PCC-MEA.

Item	***Assumption***
{B1}	*PCC-MEA Thermodynamic Modeling: Aspen-HYSYS Acid-Gas Package*
{B2}	*Solvent: Aqueous-Monoethanolamine 30%w/w*
{B3}	*Capture-efficiency=90%*
{B4}	*Absorber: Capture-Ratio=20.1* $kg^{Solvent}/kg^{CO2inlet}$*, Structured-Packing (Mellapak-250X), Theoretical-Stages=30, Gas-Feed-Stages={15, 23, 30}, D=8m;* P^{TOP}*=1atm,* ΔP*=6kPa*
{B5}	*Regenerator: Heat-Ratio=4.03* $MJ/kg^{CO2captured}$*, Structured-Packing (Mellapak-250X), Theoretical-Stages=15, Feed-Stage=7, D=4.5m;* P^{TOP}*=1atm,* ΔP*=3kPa*
{B6}	*Reboiler Utility: Low-Pressure Saturated-Steam from HRSG, T=134°C*

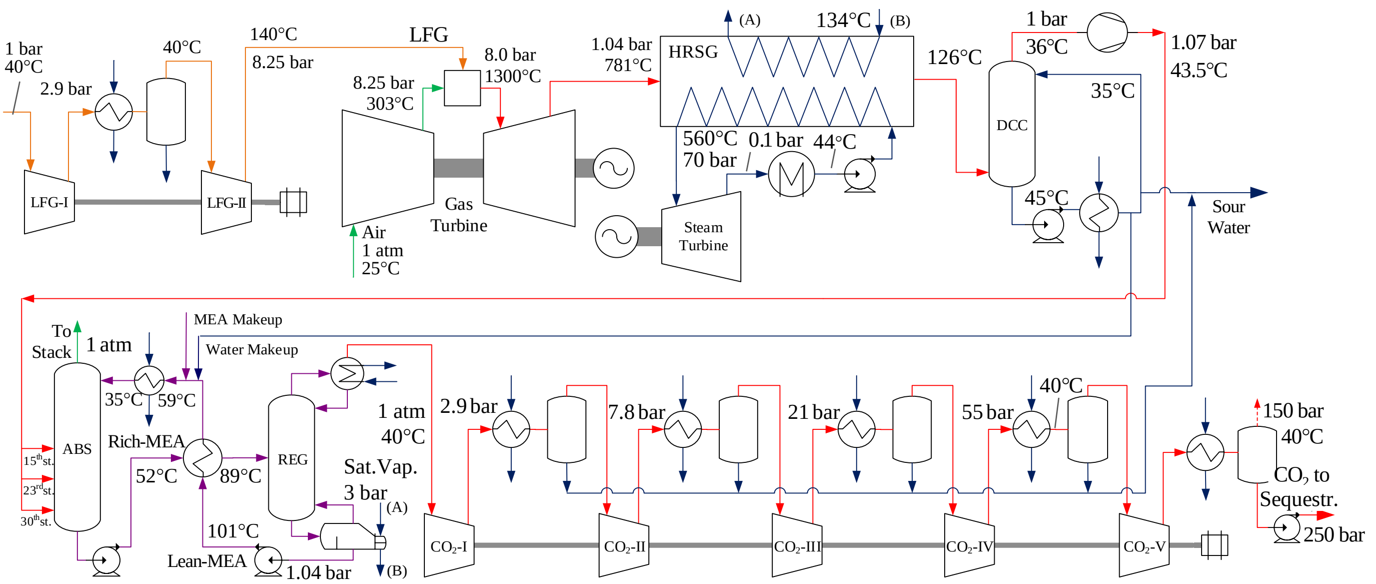

Figure B.1. LGTW-CONV+PCC-MEA (ABS=Absorber, REG=Regenerator).

Flue-gas from HRSG is cooled down to 36°C in DCC and blown from 1.00 to 1.07 bar to feed PCC-MEA at three different inlets to improve capture [44]. The CO_2-rich solvent is pre-heated before feeding the regeneration column. Hot lean solvent leaves the regenerator as bottoms and water-saturated CO_2 (1 atm, 40°C) is the top-condenser gas product. The CO_2 loadings of Lean-MEA and Rich-MEA are 0.300 and 0.504 mol^{CO2}/mol^{MEA}, respectively. Captured CO_2 is compressed to 250 bar for dense fluid dispatch as in the oxyfuel LGTW-BECCS. The CO_2 flow rate is 67.61 t/h (99.5%molCO_2). Table B.2 presents machinery contributions to overall power output and CO_2 emission-factor of LGTW-CONV+PCC-MEA. Results are compared to LGTW-CONV and LGTW-BECCS Base-Cases (Tables 3 and 5). The available heat to Rankine-Cycle is reduced thanks to HRSG supply of low-pressure steam for PCC-MEA solvent regeneration (4.03 $MJ/kg^{CO2captured}$), entailing a drastic fall in ST output from 45.30 to 14.91 MW. Such high CCS penalty is an outcome of high CO_2 content in the landfill-gas. Compression of CO_2 further rises the CCS penalty (7.74 MW), though less impacting than oxyfuel LGTW-BECCS (9.42 MW, Table 5) due to higher CO_2 purity and inferior capture-efficiency. Hence, LGTW-CONV+PCC-MEA loses power output from 103.13 to 63.93 MW (Tables 3 and B.2), and is outperformed by oxyfuel LGTW-BECCS output (85.33 MW, Table 5). PCC-MEA reduces the CO_2 emission-factor of LGTW-CONV from 0.728 to 0.120 kg/kWh (Tables 3 and B.2), being still susceptible to carbon charges.

Table B.2. Power contributions and emission-factor: LGTW-CONV+PCC-MEA.

Item	LGTW + PCC-MEA
Landfill-Gas Compressor (MW)	-3.93
Gas-Turbine (MW)	62.11
Steam-Turbine (MW)	14.91
Rankine-Cycle Pump (MW)	-0.12
Flue-Gas Blower (MW)	-1.14
CO_2 Compressor/Pump(MW)	-7.74
Auxiliary Equipment (MW)	-0.17
Overall Output (MW)	**63.93**
CO_2 Emission-Factor (kg/kWh)	**0.120**

Table B.3 presents economic performance of LGTW-CONV+PCC-MEA for several carbon taxes, attaining positive *NPV-20years* for taxes below 100 USD/tCO_2. In terms of *FCI*, the low-emission LGTW-CONV+PCC-MEA overcomes oxyfuel LGTW-BECCS (141.87 vs 210.21 MMUSD). Consequently, without CO_2 tax, LGTW-CONV+PCC-MEA has also greater *NPV-20years* (26 vs 13 MMUSD) despite of its lower *AP* (22.6 vs 29.6 MMUSD/y). The corresponding break-even electricity price for positive *NPV-20years* is 0.097 USD/kWh. Lower *REV* results, following inferior power output (-25%).The *COM* is lower as a result of inferior *FCI*, despite of monoethanolamine raw materials cost for makeup (0.59 MMUSD/y).

Table B.3. Economic performance under CO_2 taxes: LGTW-CONV+PCC-MEA .

	LGTW-CONV+PCC-MEA				
CO_2 Tax (USD/tCO_2)	**0**	**25**	**50**	**75**	**100**
FCI (MMUSD)	141.87	141.87	141.87	141.87	141.87
REV (MMUSD/y)	55.60	55.60	55.60	55.60	55.60
CRM (MMUSD/y)	0.00	0.00	0.00	0.00	0.00
CUT (MMUSD/y)	2.17	2.17	2.17	2.17	2.17
COM (MMUSD/y)	28.64	30.17	31.70	33.23	34.76
GAP (MMUSD/y)	26.96	25.43	23.90	22.37	20.84
AP (MMUSD/y)	22.62	21.61	20.60	19.59	18.58
NPV-20years (MMUSD)	25.85	19.40	12.94	6.48	0.02

Tables B.3 and 8 demonstrate that the proposed zero-emission LGTW-BECCS (*NPV-20years* of 13.08 MMUSD) overcomes LGTW-CONV+PCC-MEA in terms of profitability for CO_2 taxes above ≈50 USD/tCO_2. This is also evinced in Fig. B.2 which depicts *NPV* profiles under CO_2 taxation scenarios. Reduced annual profit (*AP*) of LGTW-CONV+PCC-MEA caused by CO_2 taxes allows the zero-emission LGTW-BECCS to progressively surpass its *NPV* through the years. Similarly to LGTW-BECCS, LGTW-CONV+PCC-MEA is also superior to emitting LGTW-CONV (Fig. 8) in long-term *NPV* for taxes above 100.7 USD/tCO_2, though with slightly negative *NPV-20years*.

Adoption of PCC-MEA implies some sustainability concerns absent in oxyfuel LGTW-BECCS, such as, some generation of solvent-wastes, occupational issues regarding solvent proximity, and monoethanolamine steady supply for solvent makeup entailing costs/storage/logistic issues. Therefore, viewed as two BECCS solutions, oxyfuel LGTW-BECCS is slight inferior to post-combustion LGTW-CONV+PCC-MEA in terms of *NPV-20years*, but can outperform LGTW-CONV+PCC-MEA economically for taxes above 50 USD/tCO_2 with superior sustainability.

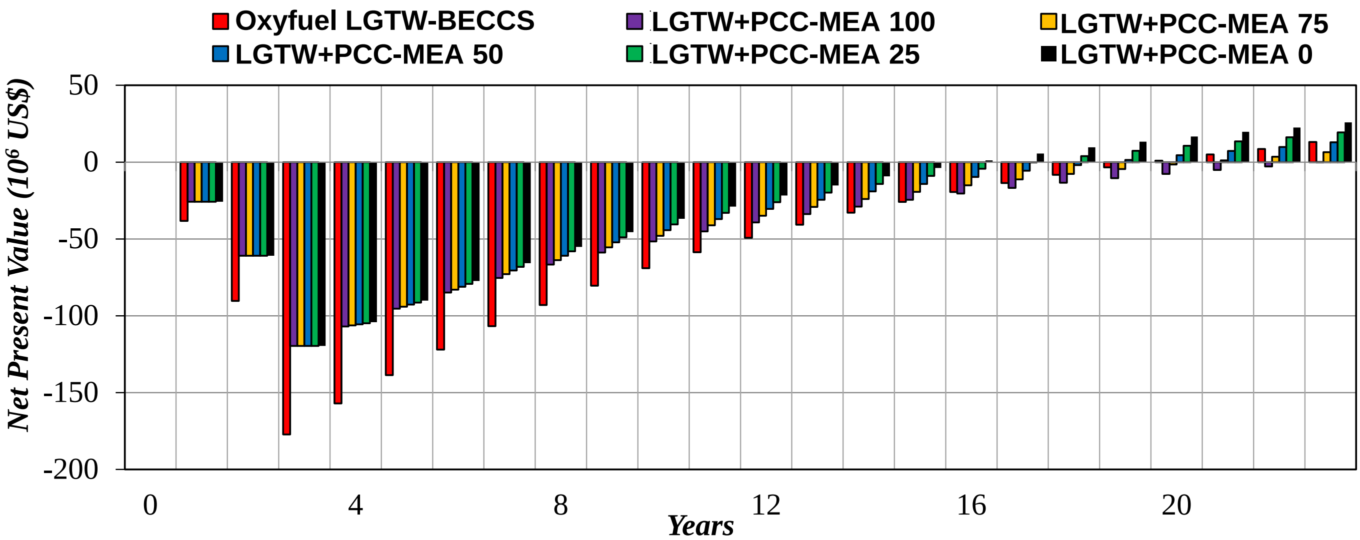

Figure B.2. ***NPV*** **profiles under carbon taxation (values in USD/tCO_2): zero-emission LGTW-BECCS with TVR-2REB ASU versus low-emission LGTW-CONV+PCC-MEA.**