Integration of Tropical Renewable Energies

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Abstract: Main sources of renewable energy in the tropics are solar thermal and biomass. High-performance concrete (HPC) allows prefabrication of stakes, planks, boards, U-, L-, and I-profiles, prestressed thick-wall cylinders, and arc sectors. They are used to construct fences, level curves, buildings, contention walls, water and anaerobic tanks, and silos. Biomass production is increased by retention of rain water in the soil by level curves, in riparian tanks, and with fertigation. HPC anaerobic digesters produce biogas, biochar, and liquid fertilizer. Biogas is partially washed in medium-pressure vessel to obtain vehicular methane gas, which is partially burned in engine generator sets, whose combustion gases are fed into a boiler of a thermoelectric unit. The cycle is thermal solar regenerative Rankine cycle with heat recovery. Boiler receives hot water from thermal solar parabolic collectors, burns residual biomass and biochar generating steam for a turbogenerator set and combustion gas for condenser dryer silo, whose exhaustion heat goes to anaerobic digesters.

Key words: High-performance concrete profiles, thermal solar-biomass energy generation, biomass, anaerobic digester, biogas.

1. Introduction

A significant portion of the rural areas between Capricorn and Cancer tropics is characterized by the presence of the sun, rain, biomass, medium and large declivities (> 15%), and degraded soil. We are developing an integrated tropical renewable energy (ITRE) technology based on high-performance concrete (HPC) structural profiles for erosion control, rain water retention, thermal solar collection, biomass production, biogas from anaerobic digestion (AD) of biomass inoculated with cattle deject, electric energy generation, and transference of urban industries to rural areas (TUIRA). Digestible biomass for AD process is three-cut per year elephant grass and source separate organic (SSO) from municipal solid waste (MSW). Non-digestible biomass is burned in a thermoelectric unit (TEU) to complement the thermal solar energy collection thus eliminating its intermittence.

2. Objectives

The main objective of this work is to present the integration of renewable energies sources in tropical countries to generate electric, thermal, and vehicular energy.

The sustainability of the three forms of energy generation is achieved by developing devices made of HPC structural profiles replacing major part of steel in TEU equipments. The proposal is based on a regenerative Rankine cycle without steam extraction but collecting thermal solar energy by parabolic troughs generating saturated water and steam, which are fed into a firetube boiler that burns supplementary biomass to superheat the steam.

Heat is recovered from combustion gases of an engine generator set (EGS) burning biogas (ca. 500 °C), drying process of biomass (160 °C), and anaerobic digesters temperature control (50 °C). Heat losses are mainly through insulation.

3. Description of ITRE Technology

3.1 HPC Role in the ITRE Technology

HPC mixture proportions are given elsewhere [1, 2]. The sources of active silica added to the mixture are silica fumes or rice rusk silica or and calcined quartzite clay (CQC). HPC compression resistance is
90 MPa. Water to cementitious materials ratio—\( w/(cement + \text{active silica}) \) —is 0.327. The main limitation is the small resistance of the reinforcing steel (521.7 MPa); for some applications we use 1,600 MPa allowable tensile strength heated treated 6,150 SAE grade steel. Production of HPC profiles is depicted in the block diagram of Fig. 1. Blocks 1 to 7 indicate the profiles prefabricated at the HPC mini-factory. Profiles of blocks 2 to 4 are used to construct the products of blocks 10 to 13, which allow a high rate of biomass production (block 23) due to retention of rainwater, erosion contention, and fertigation that will recover degraded bare hills for grass production. Profiles of blocks 5 and 6 are used to construct the products of blocks 13 to 17. Profiles of block 7 construct pressure vessels (block 18). Profiles of block 8 are used in bridges (block 9). Blocks 19 to 22 are under development. Blocks 24 to 30 represent the proposed cycle with three thermal energy supplies: exhaustion of EGS, residual biomass (RB), and thermal solar parabolic collector (TSPC), with three heat recoveries: in the condenser dryer silo (CDS), in the anaerobic digesters, and air sucked from turbogenerator (TG) by forced draft fan. Block 31 refers to medium pressure vessels to wash part of the biogas to generate vehicular methane gas (VMG).

### 3.2 Combination of Renewable Energy Resources

Technology of steam generation is presently based on fossil fuels with adaptation for biomass firing; more than half of fuel energy is lost in the cooling tower, chimney, and thermal insulation. Solar and biomass renewable energies need to be reengineered to energy recovery, regeneration, and respective control. Economical, energetic, and environmental reasons claim to begin the reengineering by using existent equipments. Some configuration suggestions for small power TEU are (Fig. 2): (a) horizontal thermal insulated firetube boiler to generate saturated steam with mobile grating burning RB (wood chip, grass, biochar—BC). Boiler receives at the top saturated steam from TSPCs and hot water at the bottom of the drum; (b) superheater with air preheater (AP) separated from the boiler to facilitate controlling...
of low heating value (LHV) of dry biomass (4,400 kcal/kg), solar heat, and combustion gas from EGS, with air control in the air preheater; (c) to accommodate all controls a twin furnace arrangement is recommended [3]. Harvesting of sun energy from TSPC coverage of rural and industrial installations is more efficient than biomass energy harvesting.

Energy balance is reached by adjusting RB plus BC burning in both gratings of twin boiler. Integration and recovery of renewable sources are accomplished by a firetube boiler receiving preheated water from the TSPCs, exhaustion gas from the EGS, and burning RB and BC; superheated steam is expanded into a TG set; steam is condensed in a condenser dryer silo (CDS) that dries RB and BC and also receives heat from the combustion gas from the boiler and delivers warming gas to the anaerobic digestion process.

Three capacities are used as reference for electric energy systems: maximum of 1 MWₑ (2 MPa, 330 °C, η = 15.3%) to be dispatched to 13.8 kV distribution network; 10 MWₑ (6.7 MPa, 500 °C, η = 32%) as an economic capacity for a conventional biomass fueled TEU; 30 MWₑ (6.7 MPa, 500 °C, η = 38%) as legal maximum capacity for distributed generation commercialized in the free market. Considering biomass LHV of 18.4 MJ/kg, 80% of 8,760 hours per year, and production of 40 tons of dry biomass per hectare per year the above capacities would demand reference areas of 224, 1,071, and 2,706 hectares, respectively. ITRE has TSPC as the major source of thermal energy; biomass accounts for steam evaporation and superheating or only for superheating if there is enough area covered with TSPCs. Fig. 3, described in details in Ref. [4], shows the contribution of thermal solar and biomass sources to water preheat and to evaporate and superheat the steam in a Rankine cycle as a function of pressure. Thermal efficiency of TEU without the contribution of AP and reheating for two-stage turbine expansion is also presented. Thermal efficiency does not depend on the type of energy source (thermal solar and biomass) [4].

Those results show that for 2 MPa and 6.7 MPa TEU biomass contributes, respectively, with 8.0% and 18.5% of the thermal energy (curve 4); the remaining comes from TSPC (curve 3) decreasing the biomass areas to 18, 198, and 500 hectares for 1, 10 and 30 MWₑ, respectively, that are 12.4 times for 2 MPa and 5.4 times for 6.7 MPa, smaller than the required for TEU burning only biomass. For power capacities less than 5 MWₑ the combination of biodigester-EGS is more economical than conventional biomass TEU. Capital cost for power capacities of 10 MWₑ for combination of solar thermal collection and biomass is of the order of USD 1,500.00/kW. Table 1 shows TSPC area calculation for 7-h daylight period.

Thermal energy supplied by TSPC plus other sources is the electric power divided by the practical thermoelectric efficiency 15.3, 32, and 38%, respectively, for 1, 10, and 30 MWₑ, multiplied by the TSPC contribution to generate saturated steam (92,
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Fig. 3  Rankine cycle efficiency and thermal sources contribution as a function of TEU pressure. Adapted from Ref. [4], with permission.

Table 1  TSPC area calculation for 7-h daylight period.

<table>
<thead>
<tr>
<th>TEU electric power</th>
<th>Thermal power supplied to TEU by TSPC</th>
<th>TSPC area for 7-h operation</th>
<th>TSPC/biomass ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 MW&lt;sub&gt;e&lt;/sub&gt;, P&lt;sub&gt;0&lt;/sub&gt; = 2 MPa, T = 330 °C</td>
<td>[1 MW&lt;sub&gt;e&lt;/sub&gt; x 92%](\eta = 15.3% = 6.01) MW&lt;sub&gt;t&lt;/sub&gt;</td>
<td>20,868 m&lt;sup&gt;2&lt;/sup&gt; – 2.09 ha (a)</td>
<td>9.33 (b)</td>
</tr>
<tr>
<td>10 MW&lt;sub&gt;e&lt;/sub&gt;, P&lt;sub&gt;0&lt;/sub&gt; = 6.7 MPa, T = 500 °C</td>
<td>[10 MW&lt;sub&gt;e&lt;/sub&gt; x 81.55%](\eta = 32% = 25.48) MW&lt;sub&gt;t&lt;/sub&gt;</td>
<td>88,472 m&lt;sup&gt;2&lt;/sup&gt; – 8.85 ha (c)</td>
<td>3.57 (d)</td>
</tr>
<tr>
<td>30 MW&lt;sub&gt;e&lt;/sub&gt;, P&lt;sub&gt;0&lt;/sub&gt; = 6.7 MPa, T = 500 °C</td>
<td>[30 MW&lt;sub&gt;e&lt;/sub&gt; x 81.55%](\eta = 38% = 64.38) MW&lt;sub&gt;t&lt;/sub&gt;</td>
<td>223,547 m&lt;sup&gt;2&lt;/sup&gt; – 22.35 ha (e)</td>
<td>3.58 (f)</td>
</tr>
</tbody>
</table>

81.6, and 81.6%, respectively, for 2, 6.7, and 6.7 MPa—Fig. 3). TSPC area is calculated dividing the thermal power by the average solar incidence of 4.8 kW<sub>ht</sub> per square meter per day, TSPC efficiency of 70% [5], and annual percentage of clear sky of 60%. TSPC to biomass area ratio is 9.3, 3.6, and 3.6%, respectively for 1, 10, and 30 MW<sub>e</sub>. Using BC, combustion gas from the EGS, and RB to fuel the boiler and SSO to feed the AD, the biomass area decreases, whose quantification will be pragmatically done. Biomass supply is not a limitation for electrical energy generation in tropical countries. Extrapolation of curve 4 for zero biomass consumption TSPC contribution goes to 100% similar to photovoltaic replaced by thermal solar collection.

The structure of TSPC is assembled with pillar, trusses and structural cable spaced by 2.6 m. Steel trapezoidal tile supporting a reflective thin stainless steel sheet is installed at the top of parabolic HPC profiles supported by trusses. Focal tube is composed by water/steam pipe inside a borosilicate glass tube for heat insulation by stagnated air. Trusses are oriented as close as possible to the east-west direction and at their top the steam collector pipe with drains to the hot water pipe is installed.

Anaerobic digesters fed with digestible grass and SSO generate biogas, biochar, and liquid fertilizer. Biogas can fuel an EGS or be pressure washed to obtain VMG. Anaerobic digester walls are constructed with HPC boards whose dimensions are L × W × H = 6 m × 1.25 m × 0.04 m and with U-profile dimensions of basis = 0.35 m, rim = 0.13 m, and thickness = 0.04 m in a zig-zag arrangement to increase the moment of inertia of the wall. Zig-zag wall resembles a triangular undulation of 0.6 m high (Fig. 4). Details of AD construction are underway.
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In addition to the AD reactor the biodigestion process has the following facilities: biomass pre-processing, slurry pump and tank, heat exchanger, buffer tank to receive digestate and biogas, EGS, and pumping for fertigation [6]; slurry has a maximum of 15% of solids to make it pumpable. Hydraulic retention time (60 days) and biogas production (160 normal cubic meters per ton of dry biomass) are conservative values. Table 2 presents the biogas production of a pair of ADs and its thermal power taking into account the biomass quantities for the three TEU reference sizes. BC production (50% of the biomass input) will be 860 t/yr, 3,960 t/yr, and 10,000 t/yr; correspondent thermal powers are 0.74 MW\(_t\), 3.4 MW\(_t\), and 8.6 MW\(_t\). Pre-processing, pumps, dewatering facilities are conventional equipments [6]. Electric energy generated by biogas from the three AD sizes (40% efficiency of the EGS) is, respectively, 80.2 kW\(_e\), 369.6 kW\(_e\), and 933.2 kW\(_e\). Heat from combustion gas is recovered in the TEU that also burns BC and RB.

4. Transference of Urban Industry to Rural Area (TUIRA)

ITRE technology opens the opportunity to install energy generation next to the source sites (sun, biomass and wind) and transfer urban industries to rural areas, decreasing the cost of transmission and distribution. At TUIRA site many facilities are available like electrical and thermal energy supply, space, water supply, effluent treatment, and housing, which can be covered by TSPC that uses an average area of 5% leaving the remaining to be occupied by biomass growing. Energy cost for TUIRA will have only the generation cost (46%); infrastructure and cattle confinement offer large areas for TSPC coverage allowing installation of hydrothermal energy storage (HTES) [7] for hot water supply for additional 5 hours for peak demand (from 4 to 9 PM).

5. Technical Economic Overview

From material’s point of view HPC 90 MPa with addition of CQC has the same cost as conventional concrete but the amount of HPC profiles has an optimized material distribution similar to steel profiles. Automatic prefabrication decreases labor cost, construction time, and residues generation. From energy generation viewpoint high efficiency is usually achieved at high vapor pressure and temperature demanding expensive materials and equipments. TEU implemented with ITRE technologies achieves same efficiency at medium pressure and temperature by recovering heat from processes that increases biomass LHV and using low cost materials (mainly HPC and carbon steel). TSPC for solar energy harvesting is paid by ground occupation below the coverage. Serial production cost of firetube boiler and separated small superheater is lower than watertube boilers for small

Table 2  Sequence of calculation of AD volumes, biogas production and correspondent thermal energy generation.

<table>
<thead>
<tr>
<th>Biomass area for a pair of AD (ha)</th>
<th>Biomass production (TDB/yr)</th>
<th>Biomass per 60-day cycle (TDB)</th>
<th>Volume of AD (TDB/60-days  15%)</th>
<th>AD base with 6 m height (m x m)</th>
<th>Base dimension adjustment((%)</th>
<th>Final volume per AD (m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.0</td>
<td>720</td>
<td>120</td>
<td>800</td>
<td>2 x (8.2 x 8.2)</td>
<td>3 x 2.6 m</td>
<td>365</td>
</tr>
<tr>
<td>198.0</td>
<td>7,920</td>
<td>1,320</td>
<td>8,800</td>
<td>2 x (27.0 x 27.0)</td>
<td>11 x 2.6 m</td>
<td>4,928</td>
</tr>
<tr>
<td>500.0</td>
<td>20,000</td>
<td>3,333</td>
<td>22,220</td>
<td>2 x (43.0 x 43.0)</td>
<td>17 x 2.6 m</td>
<td>11,722</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Biogas production (Nm(^3)/yr)(^{b)}\</th>
<th>Thermal energy generation (kW)(^{c)}\</th>
</tr>
</thead>
<tbody>
<tr>
<td>115,200</td>
<td>84</td>
</tr>
<tr>
<td>1,267,200</td>
<td>924</td>
</tr>
<tr>
<td>3,200,000</td>
<td>2,333</td>
</tr>
</tbody>
</table>

(a) Adjustment of base dimensions to match HPC profiles; (b) Biomass production (column 2) x 160 Nm\(^3\)/TDB; (c) = [(b) x 5,500kcal/Nm\(^3\) x 1.187/cal] / 365 days x 86,400 s/day
size TEU. According to the demand ITRE installations are prepared to receive sequential implementations. Final focus is to achieve self-sufficiency in energy (electrical, thermal, air conditioning and vehicular). Detailed technical economic analysis will be published in future paper for each specific technology and application.

6. Conclusions

The optimized use of HPC and its prefabricated profiles allow ample heat recovery based on the Rankine cycle. Lost energy in the cooling tower and chimney is recovered in the CDS as higher LHV biomass and biochar and as higher rate of biogas production in the AD. Energy from EGS exhaustion gas is also recovered in the boiler. However the big gain is the collecting capacity of the sun energy by the TSPC coverage of industrial and rural installations attracted to the ITRE site. Simultaneously with energy integration other goals are achieved: recovery of degraded bare hills, retention of rainwater, reduction of erosion, recycling of fertilizers, and effluent treatment. Cost reduction is also due to simultaneous generation and consumption.

Above optimizations are adequate for tropical zones and inappropriate for temperate and cold zones of the globe due to freezing and low-rate biomass growth.

References


