Energy Analysis and Environmental Impacts of Hybrid Giant Napier (Pennisetum Hydridum) Direct-fired Power Generation in South China

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Abstract. To meet with the demand of energy conservation and emission reduction policies, the method of life cycle assessment (LCA) was used to assess the feasibility of Hybrid Giant Napier (HGN) direct-fired power generation in this study. The entire life cycle is consisted of five stages (cultivation and harvesting, transportation, drying and comminuting, direct-fired power generation, constructing and decommissioning of biomass power plant). Analytical results revealed that to generate 10000kWh electricity, 10.925 t of customized HGN fuel (moisture content: 30 wt\%) and 6659.430 MJ of energy were required. The total environmental impact potential was 0.927 PET2010 (person equivalents, targeted, in 2010) and the global warming (GW), acidification (AC), and nutrient (NE) emissions were 339.235 kg CO$_2$-eq, 22.033 kg SO$_2$-eq, and 25.486 kg NOx-eq respectively. The effect of AC was the most serious among all calculated category impacts. The energy requirements and environmental impacts were found to be sensitive to single yield, average transport distance, cutting frequency, and moisture content. The results indicated that HGN direct-fired power generation accorded well with Chinese energy planning; in addition, HGN proved to be a promising contribution to reducing non-renewable energy consumption and had encouraging prospects as a renewable energy plant.

1. Introduction

With concerns over energy crises and high emissions of gaseous pollutants, attention is increasingly being paid to use of biomass energy throughout the world. As a renewable, multifunctional, and fast-growing energy plant throughout southern China, HGN has played an important role in bio-energy. Recently, many efforts have been devoted to research on using HGN. It has been proved that HGN is a high-quality grass and rich nutritious substance; hence, HGN is appropriate as fodder for raising livestock \cite{1-3}. It has also been used to make a specially flavored health beverage. HGN has also been used for papermaking because of its good fiber characteristics and has promising prospects in the papermaking industry compared with other grasses \cite{4-6}. One researcher used HGN to manufacture cellulose membranes and achieved good result \cite{7}. Certainly, as a kind of biomass fuel \cite{8, 9}, it could be used to manufacture methane \cite{9} and ethanol \cite{10}. Finally, because HGN is a fast-growing energy plant, HGN direct-fired power generation has also been shown to be a promising and commercially viable potential use and would perform better in the energy-saving field \cite{8, 9} than other plant fuels.
However, few references have discussed energy analysis and environmental impacts in a given process chain using HGN. In this study, work was done to identify and quantify the energy requirements and environmental impacts in each stage of HGN direct-fired power generation. The LCA method was used to analyze the energy requirements and total gas emissions of the entire production process from cultivation to disposal of residual waste; in addition, sensitivity analysis was performed to determine the most significant impacts. In consequence, some suggestions were presented to improve commercial HGN production for direct-fired power generation.

2. Methodology

Until now, there has been no systematic commercial production chain for HGN direct-fired power generation in China; hence, the entire life cycle was described and illustrated in Figure 1. Reasonable assumptions and simplified formulations in each stage were introduced as described below.

- Cultivation and harvesting (stage 1): this stage included seeding, transplanting, weeding, irrigation, pest control, fertilization, and harvesting; the cultivation technology was adapted from Chinese farming methods [11, 12]. To acquire available data, the energy requirements and gas emissions in the manufacturing and use of farm machinery were ignored. Certainly, plant growth needs to absorb mineral elements, water, and CO$_2$, but CO$_2$ was the only substance that entailed environmental impacts.

- Transportation (stage 2): first, fresh HGN was sent to a beverage factory to make a beverage. In the beverage factory, a juice extractor removed most of the HGN juice, and the remaining HGN fiber and residues were transported to the biomass power plant. Because the beverage factory did not belong to this product chain, only transportation was considered here.

- Drying and comminution (stage 3): flue gas from the rear smoke channel of the biomass power plant was used to dry HGN fuel. After the drying process, the customized HGN fuel was comminuted to some extent to make it easier to burn it quickly and completely in the biomass power plant’s fluidized-bed boiler. The energy for drying and comminution in this stage came from flue gas and an auxiliary power supply respectively.

- Direct-fired power generation (stage 4): first, the heat energy that was obtained in the fluidized-bed boiler was used to heat steam-drum water. Second, high-temperature, high-pressure steam drove a steam turbine to generate electricity. Meanwhile, the fluidized-bed boiler exhausted huge amounts of flue gas. Certainly, this flue gas contained excess SO$_x$, NO$_x$, and fly ash; this emission load was controlled to a certain extent through desulfurization, denitrification, and dust-control technologies. The fly ash that was recovered in the dust-control process was used for other applications.

- Biomass power-plant construction and decommissioning (stage 5): constructing a biomass power plant requires a series of materials, including steel, cement, and certain corrosion-resistant materials. To simplify the calculations, only steel and cement were taken into consideration at this stage. Because no biomass power plant has been taken out of commission to date in south China, the energy requirements and materials used in decommissioning were ignored.
Figure 1. Life cycle boundaries and system flowchart of direct combustion power of HGN.

Because the emissions were diverse and complex, assumptions were made that waste liquid and solids produced in each stage were emitted to the environment without any additional disposal measures, and that gas emissions were disposed of and reduced to meet the requirements of the Comprehensive Emission Standard for Air Pollutants (GB16297-1996) and the Emission Standard of Air Pollutants for Thermal Power Plants 2014.

The HGN fuel investigated in this study came from Zhuhai, Guangdong Province. According to Chinese measurement standards (GB/T 28731-2012 and SN/T 3005-2011), industrial and elemental analyses of HGN fuel were obtained. The results are shown in Table 1. In this paper, the chosen functional unit was 10000 kWh, which meant that this study calculated the energy requirements and gas emissions in each stage for the purpose of generating 10000 kWh of electricity.

Table 1. Industrial analysis and elemental analysis of air-dried basis and as received basis.

| Sign   | Unit | Stem | Leaf | Stem: Leaf = 3: 5 | Sign | Data   |
|--------|------|------|------|-------------------|------|--------|
| M_ad   | %    | 9.24 | 7.57 | 8.20              | M_ar | 30     |
| A_ad   | %    | 4.75 | 10.8 | 8.53              | A_ar | 6.51   |
| V_ad   | %    | 74.52| 70.21| 71.83             | V_ar | 54.77  |
| FC_ad  | %    | 11.49| 11.42| 11.45             | FC_ar| 8.73   |
| C_ad   | %    | 41.89| 39.54| 40.42             | C_ar | 30.82  |
| H_ad   | %    | 5.96 | 6.1  | 6.05              | H_ar | 4.61   |
| O_ad   | %    | 37.05| 33.93| 35.10             | O_ar | 26.76  |
| N_ad   | %    | 0.48 | 1.69 | 1.24              | N_ar | 26.76  |
| S_ad   | %    | 0.63 | 0.37 | 0.47              | S_ar | 0.94   |
| Q_ad,net | kJ/kg | 16144.69 | 15845.87 | 15957.93 | Q_ar,net | 11574.097 |

3. Results

3.1. Life cycle inventory
By combining the stages, total inventories of energy consumption and gas emissions were obtained. Total energy consumption was 6659.430 MJ, of which the energy consumption in each stage was 4017.193 MJ, 1263.817 MJ, 0 MJ, 878.959 MJ, and 499.461 MJ, respectively, accounting for 60.32%, 18.98%, 0.00%, 13.20%, and 7.50% of total energy consumption. From these figures, the cultivation and harvesting stage consumed the most energy; by contrast, the drying and comminution stage needed no energy from external sources.
The direct combustion and electricity generation stage emitted the most gaseous pollutants. Emissions of SO\(_2\), NO\(_x\), and CO\(_2\) were 7.805 kg, 17.268 kg, and 12200.184 kg respectively. Because CO\(_2\) net absorption from the atmosphere was 120001.786 kg in the cultivation and harvesting stage, total CO\(_2\) emissions for the entire process decreased to 328.226 kg. SO\(_2\) and NO\(_x\) emissions were respectively 7.805 kg and 17.268 kg, accounting for 88.51% of SO\(_2\) emissions and 91.47% of NO\(_x\) emissions.

Because SO\(_2\), NO\(_x\), and dust are inevitably produced by combustion, denitration, desulfurization, and dust-removal technologies with higher removal efficiency should be used to achieve better gas-emissions reduction. In addition, the fact that the greatest energy consumption occurred in the cultivation and harvesting stage suggested that reducing fertilizer application and using farmyard manure as an alternative would be a more appropriate way to reduce energy consumption.

3.2. Impact assessment
To identify significant environmental impacts and clarify the extent of resource consumption, the detailed data about energy consumption and gas emissions for each stage were transferred to environmental impact assessments. According to the International Organization for Standardization (ISO) 14040 framework, environmental impact assessments consisted of three steps: characterization, normalization, and weighting.

3.2.1. Characterization. In accordance with the method of the Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences [13], gas emissions in this research were grouped into five impact categories: global warming (GW), acidification (AC), nutrient enrichment (NE), photochemical ozone formation (PO), and soot and ashes (SA). Through calculation, the results for GW, AC, NE, PO, and SA for the entire life cycle were obtained and are shown in Table 2.

![Table 2. The values of different environmental impact categories.](image)
3.2.2. Normalization and weighting. Evaluation of the weighted environment potential for each effect was calculated based on the following formula:

\[
\text{Weighted environment potential} = \frac{\text{equivalent mass}}{\text{normalization reference} \times \text{weighting reference}}
\]

Politically determined environmental targets were selected for weighting by the EDIP method, and 2010 was chosen as a common target year. The weighting was used to produce a weighted environmental impact potential, with units of targeted person equivalents, or PET2010.

Environmental impacts were aligned in the following rank order: acidification (0.447 PET2010) > nutrient enrichment (0.305 PET2010) > photochemical ozone formation (0.108 PET2010) > soot and ashes (0.035 PET2010) > global warming (0.032 PET2010). The environmental impact loads of acidification and nutrient enrichment were 48.19% and 32.90%, respectively; hence, acidification and nutrient enrichment played primary roles in environmental impacts. This result indicated that regional impact was the most serious problem, meaning that remote regions (far away from residential districts) would be appropriate places for constructing chemical fertilizer and biomass power plants.

![Figure 2. Sensitivity analysis of four factors.](image)

3.3. Sensitivity analysis (Figure 2).

In the entire life cycle, the most important factors on energy consumption and gas emissions were found to be single yield (SY), average transport distance (ATD), cutting frequency (CF), and moisture content of customized HGN fuel (MC). Therefore, sensitivity analysis was an essential step in determining the most significant impact factor to give appropriate suggestions for commercial production.

When the single yield increased by 20%, the change rate of energy consumption, GWP, AC, NE, PO, and SA was -9.30%, -9.14%, -0.31%, 0.15%, -10.28% and -4.93%, while a decrease of 20% resulted in change rates of 13.95%, 13.71%, 0.47%, 0.22%, 15.41% and 7.4%, respectively. The amount of energy consumption, GWP and PO changed obviously because the cultivation area extended in the case of constant fertilizing amount per mu. Certainly, south China has abundant rainfall and sunlight; hence, cultivation places without floods or debris flows would be an excellent choice to ensure steady high yields of HGN.

When the cutting frequency changed into 60 days/time, the change rate of energy consumption, GWP, AC, NE, PO, and SA was 13.00%, 6.74%, 0.30%, 0.29%, 14.35% and 0.60%, while a decrease of 50% resulted in change rates of -8.78%, -7.24%, -0.30%, -0.29%, -14.35% and -0.6%, respectively. Obviously, the longer the average transport distance, the more diesels would be consumed; hence, cultivation places should not be far away from biomass power plant for saving vehicle fuel.

When the cutting frequency changed into 60 days/time, the change rate of energy consumption, GWP, AC, NE, PO, and SA was 13.00%, 6.74%, -9.96%, -12.15%, 13.68% and 6.75%. When the cutting frequency changed into 120 days/time, the change rates were -9.30%, -9.14%, -0.31%, -0.15%, -10.28% and -4.93%, respectively. Actually, cutting frequency had indirectly influence on environmental impacts because it affected single yield, stem-leaf ratio and moisture content of fresh Hybrid Giant Napier. From this perspective, 120 days/time was appropriate choice for reducing energy consumption and gas emissions.
When the moisture content of designed Hybrid Giant Napier fuel increased 5% (namely 35%), the change rate of energy consumption, GWP, AC, NE, PO, and SA was 2.77%, 2.80%, 2.97%, 2.97%, 2.44%, -2.44%, -2.42% and -0.84%, respectively. The effect of moisture content was relatively weak.

When the four factors were changed simultaneously, the maximum percentage changes in energy consumption, GW, AC, NE, PO, and SA were respectively 42.39%, 66.67%, 2.91%, 4.52%, 51.45% and 16.36%; conversely, the minimum percentage changes in energy consumption, GW, AC, NE, PO, and SA were -31.85%, -50.71%, -5.85%, -39.13%, and -11.56%. Therefore, if the four factors were reasonably optimized, energy consumption and gas emissions would be greatly reduced.

4. Conclusions
Through detailed analysis of Hybrid Giant Napier direct-fired power generation by the method of LCA, following conclusions were obtained:

- Because of growth and fuel characteristic of Hybrid Giant Napier, it was a potential and wonderful energy crop with upcoming large scale utilization in south China;
- In the process of Hybrid Giant Napier direct-fired power generation, stage of cultivation and harvesting accounted for more than half energy consumption (4017.193 MJ/104 kWh, 55.80%) which made the most significant contribution to the entire process. From the point of view of energy consumption, improvement of cultivating technology was the most important way to reduce energy consumption;
- The total environmental impact potential was 0.927 PET2010, with the depth of environmental impact: nutrient enrichment > acidification > photochemical ozone formation > global warming > soot and ashes. Therefore, the nutrient enrichment was the primarily environmental problem which meant regional impact was the most serious. From this analysis, the direct combustion of biomass power plants should be constructed in remote place for the sake of people’s living environment.

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