DESIGN OF A SMALL-SCALE RENEWABLE FUEL-BURNING POWER PLANT

EMS604U: Fuels and Sustainability

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Power Generation Technology

The design of a power plant for a remote island that disconnected to any national grid, is discussed in this report. The employment of combined cycles in the island of Dominica to achieve a power output of 60MW for small-scale power plant that burns renewable fuels as the working fluid.

In a combined cycle, energy generation is optimized by integrating two thermodynamic cycles: the Brayton cycle (gas turbine cycle) and the Rankine cycle (steam cycle). In the first stage, air is compressed and mixed with fuel, then ignited in a combustion chamber, producing hot gases that expand through a gas turbine, generating electricity [1]. The high-temperature exhaust gases from the gas turbine are then used to produce steam in a heat recovery steam generator (HRSG). The steam drives a steam turbine connected to a generator, producing additional electricity in the second cycle [2]. This combined system significantly improves overall efficiency compared to traditional single-cycle plants by harnessing waste heat for additional energy production.

A combined cycle power plant would be a perfect fit for Dominica because of its wealth of renewable resources, dedication to the environment, and remote island location. With its vast agricultural and forestry resources, Dominica offers an extensive range of options for obtaining biomass and biofuels. the combined cycle plant can be powered by these resources, increasing the project's viability and sustainability [3]. With a focus on the development of renewable energy, Dominica wants to become the first country in the world to be climate resilient [4]. Support for renewable energy initiatives in Dominica has come from the government and international organizations, which may make it easier to get funding, knowledge, and infrastructure development.

By encouraging the production of biofuel, supply chain management, and facility maintenance, investing in a combined cycle power plant can boost the local economy and provide jobs. The project might promote community involvement in biomass resource management and sustainability. switching from expensive imported fuels to locally accessible, renewable resources, the facility might reduce electricity costs. Dominica being a isolated island with expensive shipping and imports, the combined cycle technology can lessen dependency on foreign fuels, particularly when combined with renewable biofuels. Biomass-derived fuels such as biogas or biodiesel are suitable options.

Biogas can be produced locally from organic materials such as agricultural residues, animal manure, and food waste, which are abundant on Dominica. A Biogas programmed was stared in February of 1986 where initially 15 biogas units were built and were tested with different organic materials [5]. Furthermore, biogas production reduces methane emissions from waste decomposition, contributing to the island's climate resilience goals.

Dominica's agricultural sector produces crops like coconut and palm, which can serve as feedstocks for biodiesel production and biodiesel is made through a process called transesterification [6]. Although there is no current biodiesel production in Dominica, an introduction of this technology would benefit the countries carbon neutral goal. When produced sustainably, biodiesel can offer a nearly carbon-neutral solution since the carbon emitted during combustion is offset by the CO_2 absorbed during plant growth.

Both can be produced at different scales, depending on local demand and supply capabilities. As well as utilizing locally sourced biomass or feedstock for biogas or biodiesel production creates jobs and promotes energy independence.

Thermodynamic Design of the Plant

To design the combined cycle, several assumptions should be made. Air was assumed to act as an ideal gas for the gas cycle, with a specific heat ratio (k) of 1.4 and a specific heat capacity (C_p) of 1.005 kJ/kgK. A pressure ratio of 18 was chosen for the compressor, and the pre-compression ambient temperature was at 300 K. T_1 was considered to be 300K and T_3 was considered to be 2300K. All equations used were gathered from Thermodynamics : an Engineering Approach [18], Gas Turbine Engineering Handbook Second Edition[1] and Fundamentals of Engineering Thermodynamics[2]. Initially, the Gas Turbine calculations, using the Brayton cycle, were done. The compressor exit temperature was calculated using equation below. T_2 is the ideal temperature however, $T_{2'}$ is the actual compressor exit temperature.

$$T_2 = T_1 \times r_p^{\frac{\gamma-1}{\gamma}} = 300 \times 18^{0.286} = 685.69\,K$$

$$T_{2'} = T_1 + \frac{T_2 - T_1}{0.8} = 300 + \frac{385.69}{0.8} = 782.11\,K$$

Then the compressor work, $W_{compressor}$, can be solved below which will be later on used to work out the net work output for the gas turbine.

$$W_{compressor} = C_p \times (T_{2'} - T_1) = 1.005 \times 482.11 = 484.53\,kJ/kg$$

Following that, the ideal and actual turbine exit temperature, T_4 and $T_{4'}$ respectively, were solved to find the turbine work. Subsequently it was used to work out net work output of the gas turbine.

$$T_4 = T_3 \times (\frac{1}{r_p})^{\frac{k-1}{k}} = 2300 \times (\frac{1}{18})^{0.286} = 1006.282\,K$$

$$T_{4'} = T_3 - 0.8(2300 - T_3(\frac{1}{r_p})^{\frac{k-1}{k}}) = 2300 - 0.8\left(2300 \times \left(\frac{1}{18}\right)^{0.286}\right) = 1494.974\,K$$

$$W_{turbine} = C_p \times (T_3 - T_{4'}) = 1.005 \times 805.026 = 809.051\,kJ/kg$$

To calculate the thermal efficiency of gas turbine, the heat input to the gas turbine, Q_{in} was also needed.

$$Q_{in\,turbine} = C_p \times (T_3 - T_{2'}) = 1.005 \times 1517.89 = 1525.479\,kJ/kg$$

Given a mass flow rate of 250 kg/s, the total power output from the gas turbine could be solved below.

$$W_{gas\,turbine} = \dot{m}_{air} \times (W_{turbine} - W_{Compressor}) = 150 \times 324.521 = 48678.15\,kW = 48.68\,MW$$

Following the gas turbine calculations, we move on to the steam calculations. To complete the steam calculations we need to figure out the heat to the HRSG Q_{Exaust}.

$$Q_{Exaust} = \dot{m}_{air} \times C_p(T_{4'} - T_1) = 150 \times 1.005 \times 1194.974 = 180142.3305\,kJ/kg$$

In figure 1, we can see the thermodynamic cycle diagram (T-s diagram) for the gas turbine where it shows the temperature vs entropy and the process of the thermodynamic cycle. Between stage 1 and 2, we can see isentropic compression, where air is compressed. In an ideal situation, the entropy should remain the same, however in a non-ideal situation it increases. During stage 2 and 3, the fuel is combusted in the combustion chamber, heating the air, increasing the temperature to the maximum point. Then The high pressure and temperature gas spins the turbine. The from stage 4 to 1, waste heat is removed from the system, where it goes towards the steam cycle.

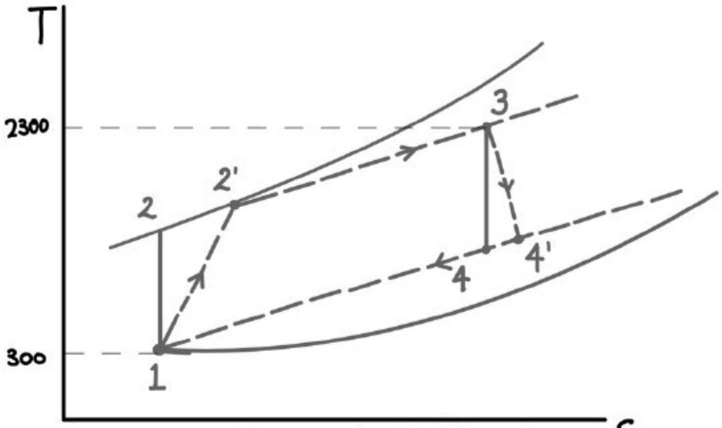

Figure 1. T-s Diagram for Gas turbine (self drawn)

To continue with the calculations, a few more assumptions would have to be made. Firstly, the boiler pressure and condenser pressure is set as 120 bar at 550∘C and 0.08 bar respectively. The enthalpy at the turbine inlet was found at 3500 kJ/kg and the enthalpy at the turbine outlet is 200 kJ/kg using the steam tables(14) and a specific volume of 0.001 m^3/kg . Given this, the work of the steam turbine could be solved as shown below.

$$W_{turbine} = h_6 - h_7 = 3500 - 200 = 3300\ kJ/kg$$

$$ideal\ W_{pump} = v \times (P_B - P_C) = 0.001 \times 119{,}992 = 11.992\ kJ/kg$$

$$W_{pump} = \frac{ideal\ W_{pump}}{0.8} = \frac{11.992}{0.8} = 14.99\ kJ/kg$$

Then the ideal pump work was solved and subsequently the actual work. Following the net work was solved.

$$W_{net\ steam} = h_6 - h_7 - W_{pump} = 3500 - 200 - 14.99 = 3285.01\ kJ/kg$$

Assuming there is a steam mass flow rate of 3.5 kg/s, we can work out the heat input needed for the boiler and also solve for the power output of the steam cycle.

$$Q_{in\ boiler} = \dot{m}_{steam} \times (h_6 - h_5) = 3.5 \times (3500 - 1491) = 7031.5\ kJ/kg$$

$$P_{steam} = \dot{m}_{steam} \times W_{net\ steam} = 3.5 \times 3285.535 = 11497.535\ kW = 11.498\ MW$$

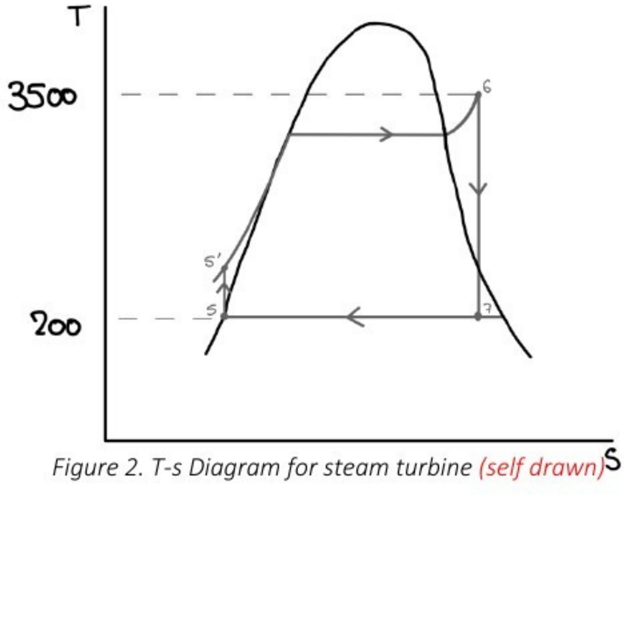

*Figure 2. T-s Diagram for steam turbine (self drawn)*S

Figure 2 is a T-S diagram representing the Rankine cycle, showing four key processes. Isentropic compression is in stage 5 in the pump, where liquid water is pressurized with a slight temperature rise. The second stage involves in the boiler, where water is heated and converted into superheated steam. Isentropic expansion occurs between stage 6 and 7 in the turbine, where steam expands to produce work, causing a significant drop in temperature and then, steam is condensed into liquid in the next stage.

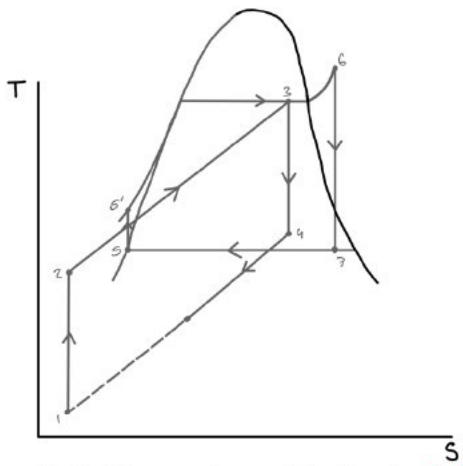

Figure 3. T-s Diagram for combined system(self drawn)

Figure 3 shows the thermodynamic cycle diagram for the whole system and shows the different temperatures and enthalpy at each stage.

Solving both the power generation for the Rankine cycle and Brayton cycle, we can then solve for the total power output of the plant.

$$P_{Total} = P_{gas} + P_{steam} = 48.68 + 11.498 = 60.178\ MW$$

The total power output was solved to be 60.178 MW surpassing the asked of us.

Cycle Efficiency Calculation

To solve efficiency, multiple equations were used. It was determined that the net work done by the component divided by the heat input. Initially, the efficiency for the gas cycle and steam cycle were solved separately and it was discovered that the gas cycle has approximately a efficiency of 23% and the steam cycle has approximately a efficiency of 47%. A reason why the steam cycle might have a higher efficancy might be due to the fact that it has a way smaller output of electricity of approximately 11 MW compared to almost 49 MW.

$$gas\ cycle\ \eta_{thermal} = \frac{W_{turbine} - W_{compressor}}{Q_{in\ turbine}} = \frac{809.051 - 484.530}{1525.479} = 0.227 \approx 23\%$$

$$steam\ cycle\ \eta_{thermal} = \frac{W_{net\ steam}}{Q_{in\ boiler}} = \frac{3285.535}{7031.5} = 0.467 \approx 47\%$$

$$combined\ \eta_{thermal} = \frac{(W_{turbine} - W_{compressor}) + W_{net\ steam}}{Q_{in\ turbine} + Q_{in\ boiler}} = \frac{809.051 - 484.530 + 3285.535}{1525.479 + 7031.5}$$
$$= 0.4218 \approx 42\%$$

Even a good efficiency of 42% was achieved, previous studies done by others have achieved efficiency close to 63%(15). This means that through a practical, cost-conscious way, we can improve the efficiency of the combined cycle. We can split it up to increasing the different cycles efficiencies resulting in the increase of the overall efficiencies. Firstly, the Brayton cycle can be optimized, through gradually increasing the compressor pressure ratio, ensuring that turbine inlet materials can withstand higher temperatures and pressures. Following this, the Rankine cycle could be enhanced. Increasing the boiler pressure to achieve higher steam quality would allow this in addition to using advanced heat exchangers to maximize heat recovery. The high-pressure boilers and advanced turbine materials are more expensive to buy making it not worth the pay off short term however in the long term it would.

Renewable Fuel Specification

A renewable fuel that will be used is Land fill gas (LFG). It is a methane-rich biogas produced from anaerobic digestion of organic materials. The majority of LFG is made up of methane, account for just over 50% with the other parts being almost 50% carbon dioxide and small amounts of non-methane organic compounds(9). Although the island's waste management practices suggest potential for LFG generation, implementing LFG recovery systems can convert waste into a valuable energy resource.(9) Furthermore, LFG is continuously produced, making it a sustainable energy source, as long as the organic waste decomposes. Using LFG reduces methane emissions, a potent greenhouse gas, helping to combat climate change and further help them to become the first country in the world to be climate resilient. (10)

A problem facing LFG is that is often contains small amounts hydrogen sulfide and siloxanes, which can corrode equipment, shortening its lifespan. These impurities must be removed through scrubbing and filtering before use using a a biogas treatment system to clean the gas before combustion(11). In addition, the amount of organic material found in landfills has a direct impact on the creation of LFG. Gas generation will decrease as landfills get older or waste management practices change. this also means there is a finite amount of LFG available unless organic waste keeps getting added to landfills.

LFG require some equipment to be extracted as well. These include gas extraction wells, condensate management system, gas processing and treatment units. To extract LFG from within the landfill, gas extraction wells are needed.(16) A condensate management system allows the moisture to be removed from the LFG and this is due to stop corrosion and blockages(17). Following this other impurities must be removed through a gas processing and treatment unit.(17)

To work out the fuel cost per annum, we need to see how much fuel will be required. As the power output is 60 MW, we can multiply that hours a day and days in the year (taking into consideration a leap year as this is long term project) to find the annual electrical energy output which divided by the plant total efficiency would give the Fuel Energy Input. this is shown in the calculations below.

$$\text{Fuel needed} = \frac{P_{Total} \times 24 \times 365.25}{combined\ \eta_{thermal}} = 1256000.829\ \text{MWh/year}$$

Knowing that LFG has a heating value of about 500 British thermal units (Btu) per standard cubic foot (18), this converts to 18.63 MJ per cubic meter which is 0.005166 MWh/m^3. This allows us to find the amount of the LFG per year required.

$$\text{LFG volume} = \frac{Fuel\ needed}{0.005166} = 243128306\ m^3/year = 665649.0241\ m^3/day$$

This means that approximately 16 wells will be needed costing $30,000 US each(17). This would bring the total cost of the wells to $480,000 US. A condensate management system for a plant this size would cost $100,000 US and a gas processing and treatment unit like the NiTech Nitrogen Rejection Unit would cost

$2,000,000 US. This would bring the CAPEX to $2,580,000 US with another $300,000 US for infrastructure of the fuel bringing the total for $665649.0241\ m^3/day$ of LFG volume to $2,880,000 US. (17) in addition to this the OPEX would include the electricity cost of this process. During the initial run of the plant, the power would need to be outsourced, however later on can source the electricity from the plant itself lowering the cost.

Key Component Suppliers

The success of a 60 MW combined cycle power plant depends heavily on the selection of reliable and efficient components. Some of the components required include a gas turbine, steam turbine, heat recovery steam generator (HRSG).

The General Electric LM6000-PF+, known for its efficiency, flexibility, and reliability in power generation applications, is an advanced gas turbine. Capable of making 53.8 MW of power in simple-cycle operation, it is a suitable choice for my application. Having over 40 million operating hours and more than 1,200 units shipped, the LM6000-PF+ is a very reliable option costing $15 million USD. (12) A steam turbine was also needed, choosing the Siemens SST-300 being able to produce 15MW. As it allows configurations with upward, downward, or axial exhaust orientations, it allows diverse plant layouts making it more suitable for our application(12). Costing just over $5 million dollar making it a suitable option to us.(13) Another piece of equipment required is the HRSG. Although most of the times HSRG are developed to the plant it self, however looking at similar projects we can see the most useful is the Nooter/Eriksen Standard HRSG which costs $5 million dollars(13). Other costs involved are the engineering, design, construction and installation of the power plant we can estimate the cost. The engineering and design of the plant will approximately e 10-15% of the total project cost and construction and installation expenses typically represent 20-25% of the total project cost(13). Annual maintenance. And upkeeping would cost around 5% of the total cost of equipment per year. (13) Table 1 shows all the equipment and all the prices required.

Table 1. Cost of equipment used

Equipment	Model	Cost (US$)
Gas turbine	GE LM6000-PF+,	15,000,000
Steam turbine	Siemens SST-300	5,000,000
HRSG	Nooter/Eriksen Standard HRSG	5,000,000
Gas processing/treatment unit	NiTech Nitrogen Rejection Unit	2,000,000
Infrastructure		2,800,000
Total		29,800,000

Cost Estimation of Generated Electricity

The cost estimation is based costs divided by the energy output of the system. The cost is split up into CAPEX and OPEX where it is the capital expenditures and the operating expenditures. It was assumed that a life span of 20 years was assumed for the plant. The calculation below shows this.

$$\text{Annual CAPEX} = \frac{Total\ cost}{\text{Life span}} = \frac{2980000}{20} = \$1{,}490{,}000$$

$$\text{Annual OPEX} = \frac{Total\ cost\ \times 0.05}{\text{Life span}} = \frac{1490000}{20} = \$74{,}500$$

$$annual\ energy\ output = P_{Total} \times (365 \times 24) \times combined\ \eta_{thermal} = 60.178 \times 8760 \times 0.42 = 221406.8976\ MWh/year$$

$$\text{Cost per kWh} = \frac{\text{Annual CAPEX} + \text{Annual OPEX}}{annual\ energy\ output} = \frac{1490000 + 74500}{221406897.6} = 0.007066\ \$/kWh$$

Cost Minimization Justification

Firstly, we can see the combined cycle, through combining the Brayton and Rankine cycles, boosts the energy produced. This is due to the fact that the waste heat from the gas turbine is used in the boilers to make steam. This makes us not waste additional resources as no extra few costs are needed. The overall efficiency can be improved through either increase the pressure ratio or could decrease the mass flow rate. The increase in the ratio however could be disastrous unless the equipment can materials can withstand higher pressures and temperatures. To also maximise energy, the boiler and steam quality can be upgraded. Although upgrading might cost more up front, they save money over time by lowering emissions and operating fuel use.

The capital and operational costs requires a balanced strategy to allow cost effectiveness. The addition of the optional equipment like the LFG wells, condensate management systems, HSRG and gas processing units might increase the CAPEX of the project. However, the addition of this equipment extends the longevity of power plant. One of the ways this is done is through the gas processing units where impurities are removed helping prevent oxidation or contamination. This could prevent maintience or replacement costs further down. Reliance on external power sources is also lower by using electricity for the different systems created by the plant.

The selection of renewable fuel was a difficult choice to make due to many factors. Although LFG is the best option for Dominica due to its size and waste, other options can be introduced aswell. A example of this is biogas, produced from agricultural residues or food waste. It also is readily available, also reducing. The need for imported fuels. Although the initial costs for producing Biogas is higher, compared to LFG, where it creates local jobs, promotes energy independence, and reduces long-term energy costs. Another option would be Biodiesel. This is due to the excess crops like coconut or palm. Another benefit is that the by product of biodiesel production, glycerin, could be sold bringing down the overall cost per KWh.

In conclusion, a balance between cost-effectiveness, sustainability, and efficiency in the design of a small-scale renewable fuel-burning power plant for Dominica was evaluated. A. power output of 60.178 MW was made with a efficiency of 42%. The fuel selected was LFG which is the perfect fit for Dominica. It is solved that $1256000.829\ \text{MWh/year}$ of fuel was needed to run the powerplant The equipment required was identified and the capital expenditures was identified aswell. Then operating expenditures was identified and was ale to figure out the price per KWh of generated electricity to be $0.007066\ \$/kWh.$

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