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Carbon and Economic Analysis on Cogeneration Natural Gas Boiler and Solar Photovoltaic in Pulp and Paper Industry

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The increasing demand for world paper consumption stimulates the growth of paper and pulp industries and lead to high carbon emission. Electricity and thermal energy are critically demanded by the paper and pulp industries. The premises utilizing grid electricity are carbon intensive as the grid energy mainly generates electricity from burning coal. Alternative energy resources that are less carbon-intensive such as natural gas and solar energy, can be used to generate electricity to fulfil the energy demand of the pulp and paper industry and mitigate carbon emissions. This study implemented cogeneration natural gas boilers and solar energy to substitute the dependency on grid electricity from Tenaga National Berhad as they are less carbon intensive than coal fuel. Carbon and economic analysis were conducted on the case studies that replaced grid electricity supply from TNB by implementing cogeneration natural gas boilers and solar energy. The results show that the total savings/kWh of energy produced from cogeneration natural gas boiler range from 0.155 MYR/kWh to 0.164 MYR/kWh. The total savings per kWh of energy produced from solar energy is higher, which was 0.207 MYR/kWh of solar energy produced. Solar has better operation cost savings per unit of electricity generated, but a limited installation area restricts the implementation. In the future, the increasing efficiency of solar technology will make the option viable while achieving more cost savings and carbon emission reduction.

1. Introduction

The world paper consumption will exceed 409 Mt in 2021, and the estimated consumption is expected to exceed 466 Mt in 2030 (Suzano, 2022). The pulp and paper industry is recognized as one of the energy-intensive sectors accounting 4 % of the global energy usage. Electrical energy mainly being used for mechanical pulping and refining, thermal energy mainly involved in the process of chemical pulping, bleaching and drying (Pathak and Sharma, 2021). The increasing demand for paper directly leads to higher electricity and thermal energy consumption in the pulp and paper industry. In the case of electricity, most industry uses electricity from the grid. The grid electricity from the centralized power plant mainly consumes natural gas and coal. The increasing demand for paper consumption contributes to more CO_2 emissions. However, as the paper industry consumes both electricity and steam (Pandey and Prakash, 2018), it is advantageous to invest in a cogeneration plant that produces both electricity and steam. Combined heat and power system is recommended to be installed so that the fuel utilization can be maximized. The simultaneous production of electrical and thermal energies is known as cogeneration or combined heat and power (CHP) energy systems (Tay et al., 2021). Zailan et al. (2021) implemented biomass cogeneration facilities to reduce fuel and electricity costs. More than 80 % of Malaysia's energy mix is from coal and natural gas (Energy Commission, 2020). Coal has a carbon emission factor of 92 kg CO_2-eq/MMBTU of coal (Hong and Slatick, 1994). Natural gas is still considered a non-renewable source and contributes to carbon emissions. However, compared to electricity from the grid, it has lower carbon emissions per kWh of electricity consumed. Another viable option now for industries to consider is using solar PV system to generate electricity, as Malaysia is a tropical country and one issue is that solar PV cannot

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effectively reduce the monthly peak load, as any day in a month that is raining will result in the original energy consumption trend. Gambini et al. (2019) use the GateCycle software to study the energy, environmental, and economic performance parameters when implementing the CHP system in the pulp and paper industry. The study only includes the CHP unit but not renewable energy. This study intends to determine the cost savings and carbon emission reduction can be achieved by switching the grid electricity supply from TNB to electricity generated by cogeneration natural gas (NG) boiler and solar PV system. Sensitivity analysis was done by altering the electricity supply from different sources such as the grid, cogeneration NG boiler, and solar PV systems.

2. Methodology and case study

2.1 Carbon emission reduction by implementing cogeneration natural gas boiler to replace grid electricity supply from TNB

An energy audit was done on a paper mill plant with daily production of 800 t in Malaysia, the electricity and heat energy are the dominant types of energy required to operate the processes. The total monthly electricity consumed by the paper mill plant was 1.09×10^7 kWh/mth, with the support of a conventional NG steam boiler with an efficiency of 85 % that consumes 9.61×10^4 MMBTU/mth of natural gas to produce steam every month. To study the relationship between carbon emission reduction and the type of energy sources, an initiative to install cogeneration natural gas boiler with efficiencies of 30 % and 55 % for electricity and thermal generation was done, with the assumption that the transition of energy supply method does not interrupt with the operations of paper mill plant. After the implementation of the cogeneration NG boiler, the dependency on electrical supply from TNB was decreased to 1.3×10^6 kWh/mth, but the demand for NG was increased to 1.49×10^5 MMBTU/mth to satisfy the electricity demand of the paper mill plant. The stepwise calculation to measure the carbon emission reduction before and after the implementation of cogeneration NG boiler was as follows and listed in Table 1. First, the carbon emission for consuming grid electricity, CE_{TNB} (t CO_2-eq/mth), is calculated via Eq(1), based on the amount of monthly electricity consumed, MEC_{TNB} (kWh/mth) by a paper mill plant multiplied by the Peninsular Malaysia grid carbon emission factor, CEF_{TNB}, that is 0.6 kg CO_2-eq/kWh (Maryam *et al.*, 2017). The carbon emission for natural gas consumption, CE_{NG} (t CO_2-eq /mth), is calculated via Eq(2), based on the quantity of natural gas monthly consumption, MEC_{NG} (MMBTU/mth), by the cogeneration NG boiler in the paper mill plant multiplied with the carbon emission factor for natural gas, CEF_{NG}, that is 53 kg CO_2-eq/MMBTU NG (U.S. EPA, 2008). The total carbon emission, TCE (t CO_2-eq/mth), is calculated by adding the CE_{TNB} and CE_{NG} as shown in Eq(3). The TCE before implementation of cogeneration natural gas boiler is 11,595.85 t CO_2-eq/mth, while the TCE after the installation of cogeneration natural gas boiler is 8,647.10 t CO_2-eq/mth. The total carbon emission reduction, $TCER$ (%), is calculated via Eq(4), where the subscript "b" and "a" represent the TCE before and after the installation of cogeneration NG boiler.

$$CE_{TNB} = MEC_{TNB} \times CEF_{TNB} \tag{1}$$

$$CE_{NG} = MEC_{NG} \times CEF_{NG} \tag{2}$$

$$TCE = CE_{TNB} + CE_{NG} \tag{3}$$

$$TCER = \frac{TCE_b - TCE_a}{TCE_b} \times 100\ \% \tag{4}$$

2.2 Total monthly saving per unit of electricity generated from cogeneration NG boiler and solar PV

Two case studies were created to implement cogeneration NG boiler and solar PV system. Each case study has 6 scenarios, generating 0 %, 20 %, 40 %, 60 %, 80 %, and 100 % electricity to substitute the TNB electricity consumption of the paper mill plant. The stepwise method to calculate the monthly grid electricity TNB cost, monthly cost for electricity generation from cogeneration NG boiler and solar PV, and the total monthly savings per kWh of electricity produced from cogeneration NG boiler and solar PV are shown in Section 2.2.1 and 2.2.2.

2.2.1 Implementation of cogeneration NG to replace electricity supply from TNB

The first case study is the implementation of cogeneration NG boiler to generate electricity. There are six scenarios created to substitute the monthly electricity supply from TNB, ES_{TNB} (kWh/mth) with electricity supply generated from cogeneration NG boiler, ES_{NG} (kWh/mth). The total monthly saving per unit of electricity generated from natural gas, $TMSpNG$ (MYR/kWh) was calculated via a series of calculations, as shown in Table 2. The monthly electricity cost from TNB, C_{TNB} (MYR/mth) of the paper mill plant was calculated via Eq(5) by referring to the Tariff E3 set by TNB (Tenaga, 2014) that entitled to high voltage peak and off-peak industrial. The C_{max} (MYR/mth) is the extra cost that accounted for only one of the hourly electricity demand (kW/mth) with the greatest value during peak hours (from 8 am to 10 pm) within a month, C_{peak} (MYR/mth) is the cost for all the electricity consumed during the peak period, and $C_{offpeak}$ (MYR/mth) is the cost for all the electricity used during the off-peak period (from 10 pm to 8 am). This study assumed that the paper mill plant operates for 30 d/mth and 24 h/d throughout the year with steady electricity consumption. The C_{max} was calculated via Eq(6) by multiplying the greatest hourly energy consumption during the peak hours within a month, $EC_{maxpeak}$ (kW/mth), with the tariff of C_{max}, T_{max} (35.5 MYR/kW). The C_{peak} was calculated via Eq(7) by multiplying all the electricity consumption during peak hours, EC_{peak} (kWh/mth) for a month, with the tariff during peak hour, T_{peak} (0.337 MYR /kWh). The $C_{offpeak}$ was calculated via Eq(8) by multiplying all the electricity consumption during off-peak hour, $EC_{offpeak}$ (kWh/mth) for a month, with the tariff during off-peak hour, $T_{offpeak}$ (0.202 MYR /kWh).

$$C_{TNB} = C_{max} + C_{peak} + C_{offpeak} \tag{5}$$

$$C_{max} = EC_{maxpeak} \times T_{max} \tag{6}$$

$$C_{peak} = EC_{peak} \times T_{peak} \tag{7}$$

$$C_{offpeak} = EC_{offpeak} \times T_{offpeak} \tag{8}$$

The monthly cost of natural gas used to generate electricity, C_{NG} (MYR/mth) was calculated via Eq(9) by multiplying the electricity supply from natural gas, ES_{NG} (kWh/mth) with the corresponding tariff pricing for natural gas, T_{NG} (MYR/MMBTU) announced by Suruhanjaya Tenaga (2021) based on the quantity of consumption. The heat rate for cogeneration boiler, HR_{boiler} (MMBTU/kWh) will be calculated via Eq(10) for the unit conversion of ES_{NG} from kWh/mth to MMBTU/mth. The $EC_{NG(after)}$, $EC_{NG(before)}$, $EC_{TNB(after)}$ and $EC_{TNB(before)}$ represents the energy consumption for NG and TNB, after and before the implementation of cogeneration NG boiler as shown in Table 1. The HR_{boiler} calculated via Eq(10) was 5.477×10^{-3} MMBTU/kWh. Since only 30 % of the total energy consumed by the cogeneration NG boiler is for electricity generation, 55 % of the total energy was used for heating purposes and the rest are energy losses during the conversion of fuel to energy process. A fractionization factor, F_e for electricity generated from cogeneration NG boiler that includes the losses percentage was calculated via Eq(11), where P_e (%) and P_t (%) indicated the percentage of electricity and thermal energy generated from cogeneration NG boiler. In this case study, the F_e value for the cogeneration NG boiler was calculated, 0.353.

$$C_{NG} = ES_{NG} \times HR_{boiler} \times T_{NG} \tag{9}$$

$$HR_{boiler} = \frac{F_e \times \left| EC_{NG(after)} - EC_{NG(before)} \right|}{\left| EC_{TNB(after)} - EC_{TNB(before)} \right|} \tag{10}$$

$$F_e = \frac{P_e}{P_e + P_t} \tag{11}$$

The total monthly saving per kWh of electricity produced from NG, $TMSpNG$ (MYR/kWh NG) was calculated via Eq(12), where the total monthly saving for natural gas, TMS_{NG} (MYR/mth) was divided by the ES_{NG}. The TMS_{NG} (n % NG) was calculated via Eq(13), by deducting the C_{NG} (n% NG) from total monthly cost, TMC (100 % TNB). The TMC (100 % TNB) indicates only TNB is supplying electricity to support the paper mill plant, and the n % NG represents the percentage of NG that was implemented to replace the TNB electricity supply. The TMC was calculated via Eq(14) by totaling up the C_{TNB} and C_{NG} within the same scenario.

$$TMSpNG\ (n\ \%\ NG) = \frac{TMS_{NG}\ (n\ \%\ NG)}{ES_{NG}\ (n\ \%\ NG)} \tag{12}$$

$$TMS_{NG}\ (n\ \%\ NG) = TMC\ (100\ \%\ TNB) - TMC\ (n\ \%\ NG) \tag{13}$$

$$TMC\ (n\ \%\ NG) = C_{TNB}\ (100 - n\ \%) + C_{NG}\ (n\ \%\ NG) \tag{14}$$

2.2.2 Installation of solar PV system to replace the electricity supply from TNB

Another case study is a paper mill plant with an estimated rooftop area of 24,000 m^2 available for solar PV installation. Six scenarios were created to substitute the ES_{TNB} with electricity supply generated from solar PV,

ES_{SPV} (kWh/mth). The total monthly saving per kWh of electricity produced from solar PV, *TMSpSPV* (MYR/kWh) was calculated via Eq(15) and listed in Table 3, where the total monthly saving for solar, TMS_{SPV} (MYR/mth) divided by the ES_{SPV}. The TMS_{SPV} was calculated via Eq(16), by deducting monthly solar operating cost, C_{SPV} (MYR/mth) from total monthly cost, *TMC*. The *TMC* (0 % SPV) indicates that the paper mill plant is fully electrified from TNB, and the n % SPV represents the percentage of solar energy implemented to replace the TNB electricity supply. The *TMC* was calculated via Eq(17) by totaling up the C_{TNB} and C_{SPV} within the same scenario. The C_{SPV} was calculated via Eq(18) by using the capital cost of solar PV, C_{capSPV} (MYR) and considering the amortization factors, where the interest rate, i is 7 %, duration of payment, n is 20 y. The C_{capSPV} was calculated via Eq(19), by multiplying the solar PV sizing, $Size_{SPV}$ (kWp), with the specification of the solar PV, $Spec_{SPV}$ (8 m^2/kWp), and multiplying with the price of solar PV per kWp, P_{SPV} (3800 MYR/kWp) (Ilham et al., 2022). To determine the $Size_{SPV}$ via Eq(20), the ES_{SPV} (kWh/mth) was divided by 30 to convert into a daily basis, then divided by the total solar irradiation, *TSI* for a day, that is 6.725 kW/m^2 and divided by efficiency of the solar PV module, Eff_{SPV}, that is 15 % (Ho et al., 2014).

$$TMSpSPV\ (n\ \%\ SPV) = \frac{TMS_{SPV}\ (n\ \%\ SPV)}{ES_{SPV}\ (n\ \%\ SPV)} \tag{15}$$

$$TMS_{SPV}\ (n\ \%\ SPV) = TMC\ (0\ \%\ SPV) - C_{SPV}\ (n\ \%\ SPV) \tag{16}$$

$$TMC\ (n\ \%\ SPV) = C_{TNB}\ (100 - n\ \%) + C_{SPV}\ (n\ \%\ SPV) \tag{17}$$

$$C_{SPV} = \frac{C_{capSPV} \times i\,(1+i)^n}{12 \times ((1+i)^n - 1)} \tag{18}$$

$$C_{capSPV} = Size_{SPV} \times Spec_{SPV} \times P_{SPV} \tag{19}$$

$$Size_{SPV} = \frac{ES_{SPV}}{30 \times Eff_{SPV} \times TSI} \tag{20}$$

3. Results and discussion

Table 1 summarised the monthly energy consumption, carbon emission and total carbon emission reduction for a paper mill plant before and after the implementation of cogeneration NG boiler to substitute part of the electricity supply from the grid. A 25.43 % carbon emission reduction was achieved after implementing the cogeneration NG boiler. This is mainly due to almost 90 % of the electricity supply coming from cogeneration NG boiler that is fully powered by NG, 10 % of the TNB electricity supply originated from electricity generation mix of fuels mainly dominated by coal and NG. The more the energy fuel with a lower carbon emission factor in generating electricity, the more carbon emission reduction can be achieved. The grid electricity supply from TNB is produced from the generation mix mainly from the combustion of coal and NG. The cogeneration NG boiler in this study is fully operated on NG to generate electricity and thermal energy for the operation of paper mill plant. The carbon emission factor of coal is 92 kg CO_2-eq/MMBTU, roughly 42 % more than that of NG, which has a carbon emission factor of 53 kg CO_2-eq/MMBTU. The implementation of cogeneration NG boiler that monthly consumes 1.49×10^5 MMBTU of NG to substitute 9.6×10^6 kWh of the grid electricity supply from TNB able to reduce 25.43 % of carbon emission. For the case study implementing NG boiler to replace electricity supply from TNB, the carbon emission reduction achievable ranged from 10.32 to 51.61 %. As the solar PV do not emit CO_2 during electricity generation, the total carbon reduction is directly proportional to the percentage of solar PV in substituting the electricity supply from TNB.

Table 1: Carbon reduction from using cogeneration NG boiler to produce electricity

		Monthly energy consumption, *MEC*	Carbon emission, *CE* (t CO_2-eq/mth)	Total carbon emission, *TCE* (t CO_2-eq/mth)	Total carbon emission reduction, *TCER* (%)
Before	TNB electricity (kWh/mth)	1.09×10^7	6,503.19	11,595.85	25.43
	Natural Gas[1] (MMBTU/mth)	9.61×10^4	5,092.66		
After	TNB electricity (kWh/mth)	1.3×10^6	776.60	8,647.10	
	Natural Gas (MMBTU/mth)	1.49×10^5	7,870.50		

For economic analysis, the monthly cost for electricity supply via TNB, solar PV and NG are shown in Table 2 and Table 3, then tabulated in Figure 1 and Figure 2. Before implementing cogeneration NG boiler and solar PV to substitute part of the grid electricity supply from TNB, the monthly cost of electricity is MYR 3.60 million. However, the monthly electricity cost can be reduced to MYR 2.13 and MYR 1.35 million after the implementation of cogeneration NG boiler and solar PV to fully supply the electricity for the operation of the paper mill plant. The total monthly saving per kWh of electricity produced from solar PV is 0.207 MYR/kWh, that is more than 50 % higher than that of NG, which ranges from 0.125-0.135 MYR/kWh. The *TMSpNG* for all the scenarios implementing NG for electricity generation are the same, except for scenario fully use NG to generate electricity. This is because the NG cost depends on the NG selling price tariff set by Suruhanjaya Tenaga, based on the amount of NG used. The *TMSpSPV* for all the scenarios are the same as the cost of the solar PV was calculated based on the capacity required. Assuming the rooftop area available of the paper mill is 24×10^3 m^2 and receives daily solar irradiance of 6.725 kWh/m^2, the solar PV with an efficiency of 15 % is only able to produce 726,300 kWh of electricity, which only accounted for 6.66 % of the total electricity demand required by the paper mill. In reality, solar PV is still an unfeasible solution. Still, in the future, it will become a feasible and sustainable option when the efficiency and technology of solar PV increase with the advancement of materials breakthroughs.

Table 2: Scenarios of implementing cogeneration NG boiler to substitute the grid electricity supply from TNB

Scenario	Electricity supply from TNB, ES_{TNB} (kWh/mth)	Electricity supply from natural gas, ES_{NG} (kWh/mth)	TNB monthly cost, C_{TNB} (MYR/mth)	Natural gas monthly cost, C_{NG} (MYR/mth)	Total monthly saving/kWh energy produced from natural gas, *TMSpNG* (MYR/kWh)
100 % TNB	1.09×10^7	0	3.60×10^6	0	-
80 % TNB + 20 % NG	8.72×10^6	2.18×10^6	2.88×10^6	4.48×10^5	1.25×10^{-1}
60 % TNB + 40 % NG	6.54×10^6	4.36×10^6	2.16×10^6	8.96×10^5	1.25×10^{-1}
40 % TNB + 60 % NG	4.36×10^6	6.54×10^6	1.44×10^6	1.34×10^6	1.25×10^{-1}
20 % TNB + 80 % NG	2.18×10^6	8.72×10^6	7.2×10^5	1.79×10^6	1.25×10^{-1}
100 % NG	0	1.09×10^7	0	2.13×10^6	1.35×10^{-1}

Table 3: Scenarios of installing solar PV to substitute the electricity consumption of the paper mill

Scenario	Electricity supply from TNB, ES_{TNB} (kWh/mth)	Electricity supply from solar, ES_{SPV} (kWh/mth)	Solar monthly cost, C_{SPV} (MYR/mth)	Total monthly saving/kWh energy produced from Solar, *TMSpSPV* (MYR/kWh)
100 % TNB	1.09×10^7	0	0	-
80 % TNB + 20 % Solar	8.72×10^6	2.18×10^6	2.69×10^5	2.07×10^{-1}
60 % TNB + 40 % Solar	6.54×10^6	4.36×10^6	5.38×10^5	2.07×10^{-1}
40 % TNB + 60 % Solar	4.36×10^6	6.54×10^6	8.07×10^5	2.07×10^{-1}
20 % TNB + 80 % Solar	2.18×10^6	8.72×10^6	1.08×10^6	2.07×10^{-1}
100 % Solar	0	1.09×10^7	1.35×10^6	2.07×10^{-1}

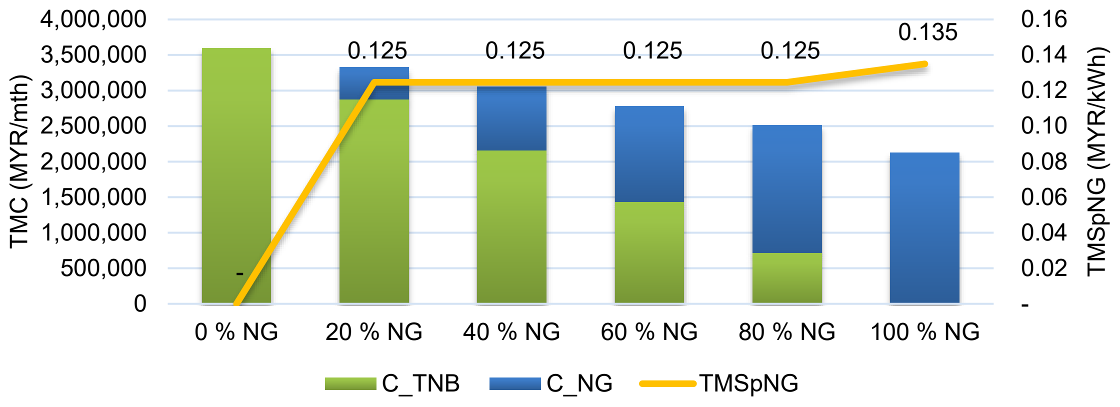

Figure 1 The monthly cost and total monthly saving per kWh of electricity produced from NG boiler

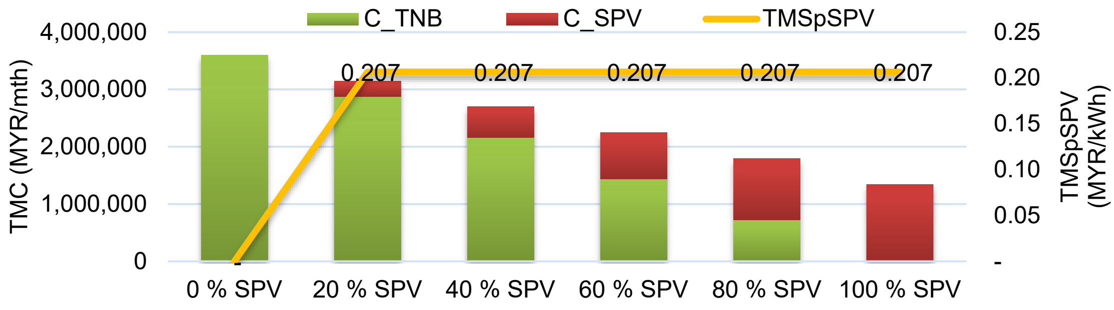

Figure 2 The monthly cost and total monthly saving per kWh of electricity produced from solar PV

4. Conclusion

In terms of CO_2 emission reduction, the implementation of cogeneration NG boiler to generate electricity is better than getting supply from the grid, as it able to reduce 10.32 to 51.61 %. Still, the best option is solar PV which emits zero carbon during electricity generation. The monthly cost of generating the same electricity via cogeneration NG boiler is 36.71 – 39.9 % more expensive than solar PV. The installation of solar PV in generating electricity is generally saving 34.66 – 39.67 % of the monthly costs than NG in generating the same amount of electricity. The results clearly show that solar PV is a better option than NG in replacing the electricity supply from TNB. Although solar PV has better results in terms of cost saving and CO_2 emission, the area available for installation is the most significant restriction for solar PV to be implemented. With an estimated area of 24,000 m^2 available for solar PV installation, only 726,300 kWh/month of electricity can be produced from solar PV, that accounted for 6.66 % of the total electricity demand in the paper mill plant. In the future, the efficiency of solar PV is expected to increase and make the implementation of solar PV viable.

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