Techno-Economic Analysis of Natural Gas-Based Polygeneration System of Electricity, Cooling, and Heating

Widodo Wahyu Purwanto, Kriska Setyawati

Abstract: ***Some remote and rurar areas in Indonesia have low electrification levels and this poses a undermines their economic development potential. In response to the aforementioned challenges, it is necessary to develop an integrated energy system that produces multi-utilities (polygeneration) in producing energy to meet local needs. The aim of this work is to investigate the technical and economic analysis on a polygeneration system of a gas-fired power plant to produce electricity and heating, and to be integrated with an LNG regasification system for the utilization of cold energy as well. This polygeneration system is located in Manokwari District, West Papua. The polygeneration system was simulated using Unisim Design R390.1 to evaluate the technical performances and its economic analysis was done by using cash flow method with several business schemes, financial and fiscal incentives. The results showed that technically the polygeneration system is able to increase the efficiency of power generation system of a stand-alone power plant, from 32.9% to 59.7%. Economically, the polygeneration system can reduce the electricity tariff of a stand-alone power system from 19.32 US cents/kWh to 12.31 USD cents /kWh.***

Index Terms: ***LNG; polygeneration; electricity; heating; cooling; remote.***

I. INTRODUCTION

Electricity is a vital utility to support productivity of society and economic development. Therefore, the government of Indonesia continues to promote an increase in the electrification ratio, one of which is through the 35,000 MW Electricity Development Program. It is expected that an increased electricity infrastructure capacity, in turn increase the electrification ratio then improve community activities, which eventually can contribute to sustainable economic growth. The Indonesia Terang (Bright Indonesia) Program, especially in eastern Indonesia, constitute one of the measures to enhance the electrification ratio (1). In Manokwari, a gas-fired power plant with a capacity of 2 × 20 MW will be built to support Towards Bright Papua program. Moreover, it is also expected to improve the local economy, especially in agriculture sector.

A polygeneration system includes three principles of sustainable energy, which are optimal use of resources, reduced green house gas emissions, and economic feasibility (2). The polygeneration is complex system (3) and it requires higher investment, however this technology provides many benefits with multi-utility output, high energy efficiency, and reduced GHG emissions. The researchers (4), (5), and (3) conducted researches on techno-economic design optimization of polygeneration system to meet energy demand in remote areas i.e. electricity, cooling, heating, ethanol, hydrogen and drinking water, simultaneously by using multi energy sources i.e. solar thermal and natural gas (4), solar photovoltaic and biomass (5), and solar photovoltaic and wind (3). Whereas the researcher (6) and (7) conducted studies on techno-economic analysis of polygeneration system biogas-based (6) and biomass-based (7) to produce utilities in the forms of electricity, drinking water, biogas for cooking, ethanol, and cooling. Moreover, natural gas-based polygeneration system were conducted by (8) and (9), hybrid with solar thermal, biomass (8), and municipal solid waste (9).

In this research, the polygeneration is based on an integrated small scale liquefied natural gas (LNG) with cold energy utilization of regasification for cooling and combined heating power (CHP) with waste heat produced from gas tubine is used for drying of agricultural products.

The aim of this study is to simulate the technical performances of a natural gas-fired polygeneration system to produce electricity, cooling, and heating, simultaneously, and to find an economically viable business scheme for the development of polygeneration system in Manokwari District, West Papua.

II. METHODOLOGY

The design of the polygeneration system is illustrated in Figure 1. Electricity was produced by a gas turbine power plant powered by natural gas from the small scale LNG regasification unit. Waste heat of the gas turbine is flowed simultaneously through a heat exchanger to produce hot air for cocoa drying. While the cooling system is obtained from the cold energy utilization of LNG regasification process with CO_2 as the working fluid to produce cold air.

Revised Manuscript Received on 14 September, 2019.

Widodo Wahyu Purwanto, Chemical Engineering Department, Faculty of Engineering, Universitas Indonesia, Depok, 16424, Indonesia, widodo@che.ui.ac.id

Kriska Setyawati, Chemical Engineering Department, Faculty of Engineering, Universitas Indonesia, Depok, 16424, Indonesia**,** Maluku and Papua Regional Development Division, PT PLN (Persero), Jakarta, 12160, Indonesia

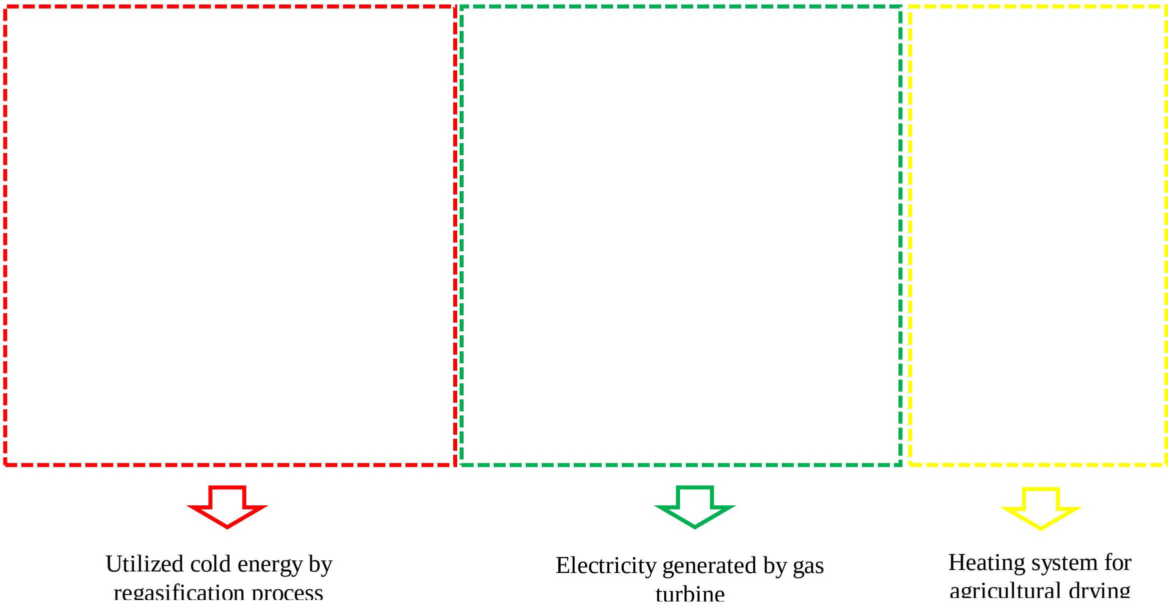

Fig 1 Schematic diagram of polygeneration system

Analysis method of the polygeneration system is illustrated in Figure 2.. The energy demands for electricity, cooling, and heating were calculated using an engineering model based on historical data and energy intensity, then capacity of polygeneration is determined. Futhermore, the process simulation of polygeneration is carried out by Unisim Design R390 to analyze the improvement of efficiency compare to the stand alone power generation. The economic evaluation is undertaken using cash flow analysis with some the business and incentives schemes to achieve a target tariff as willingness to pay of users.

Fig 2 Research flowchart

A. Technical analysis

The energy demand data of electricity, cooling and heating energy consumption in Manokwari District are summarized in Table 1.

Table 1 Energy demand data in Manokwari District

Sector / Amount	Power (kW)
Electricity	
Household : 1342 consumers	1235.9
Industry : 10 consumers	1867.5
Business : 735 consumers	2680
Social : 163 consumers	511
Office Building : 101 consumers	821.6
Cooling	
Governor's office : 1 unit	782.3
Residential : 250 units	746
Heating	
Drying for agriculture product (Cacao) : 638 tons	1475.4

The process flow diagram of polygeneration system is illustrated in Figure 3, where the composition of LNG to be regasified from Tangguh LNG plant are methane 96.73%, ethane 2.43%, propane 0.48%, i-butane 0.09%, n-butane 0.11%, i-pentane 0.01% and nitrogen 0.15%.

Some data and operating conditions that must be considered for the simulation were summarized in Table 2, 3 and 4.

Table 2 Input data of electricity system

Parameters	Value
Air to fuel ratio	20:1
Compression ratio	1:6
Inlet air temperature (°C)	35
Inlet air pressure (kPa)	101.3
Inlet air flow (m^3/h)	190.4
Inlet gas temperature (°C)	20
Inlet gas pressure (kPa)	971.8
Exhaust gas temperature (°C)	964.7
Exhaust gas pressure (kPa)	303.4

Table 3 Input data of cooling system

Parameters	Value
Inlet CO_2 gas temperature (°C)	-24.7
Inlet CO_2 gas pressure (kPa)	800
Inlet CO_2 gas flow (m^3/h)	8.082
Inlet CO_2 liquid temperature (°C)	-81.97
Inlet CO_2 liquid pressure (kPa)	2450
Inlet CO_2 liquid flow (m^3/h)	6670
Cool air temperature	15.0

Table 4 Input data of drying system

Parameters	Value
Inlet gas temperature (°C)	631
Inlet gas pressure (kPa)	19.31
Inlet gas flow (m^3/h)	197.8
Inlet air temperature (°C)	30
Inlet air pressure (kPa)	101.3
Outlet gas temperature (°C)	65
Outlet gas pressure (kPa)	100

To achieve the expected efficiency, the variables changed were the compression ratio and the air-fuel ratios, by maintaining other condition parameters based on equipment specifications.

The gas-fired stand-alone power plant efficiency can be calculated by the power output of the net generator compared to the energy from natural gas entering the plant. Furthermore, the efficiency of polygeneration system can be calculated by multiplying the efficiency of electricity and heating segment (dryer) and the efficiency of regasification and cooling segment (Figure 3) as stated in the following equation.

$$\eta_p = \eta_{EH} \times \eta_{RC} \quad (1)$$

η_P is efficiency of polygeneration, η_{EH} is efficiency of electricity and heating segment, and η_{RC} is efficiency of regasification and cooling segment. Where the efficiency of electricity and heating system segment calculated by the heat flow generated by the heat exchanger of drying system plus the power generated by the generator compared to the energy from natural gas entering the plant. The efficiency of the regasification and cooling system was obtained from the vaporizer duty which was calculated by the heat flow rate produced by the LNG vaporizer compared to the heat flow rate of LNG heat exchanger plus the heat flow rate of CO_2 heat exchanger.

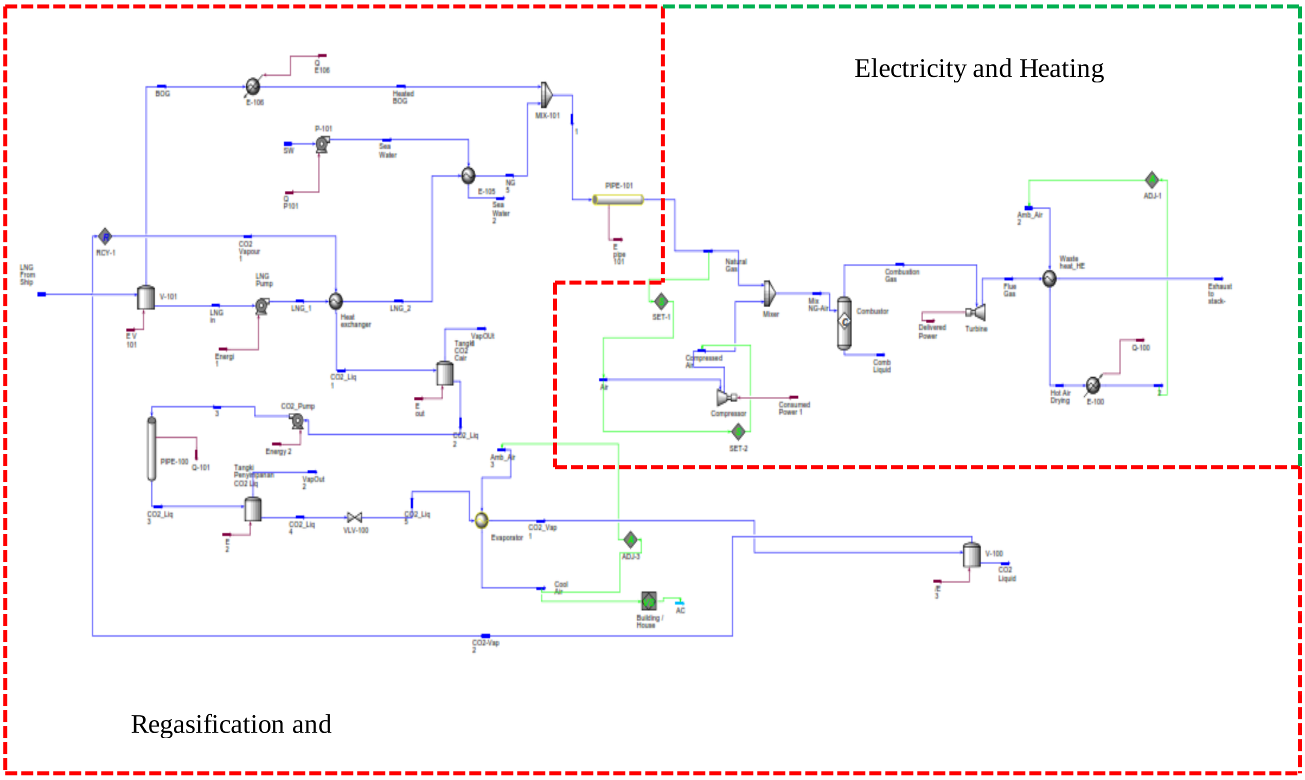

Fig 3 Process flow diagram of polygeneration system

A. Economic analysis

The equity to loan ratio that was used in this study was 30:70. The project life time was set to be 25 years while the loan payment period was set to be 10 years. The interest of debt was 6%. The Internal Rate of Return (IRR) was set to be 12%.

Technical specifications of equipment obtained from process flow diagram were then matched with equipment data availability in the market. The estimated costs required for polygeneration system consisted of Fixed Capital Expenditure (CAPEX) and Operational Expenditure (OPEX). After determining CAPEX and OPEX, financial feasibility of such construction was calculated using the cashflow method and then Net Present Value (NPV) and the payback period could be calculated. While Total CAPEX of the polygeneration system is USD 25,084,925 with the detail value is stated in Table 5.

Table 5 Cost breakdown of CAPEX

Component	thousands USD
Gas turbine power plant	19,980
Regasification system	2,666.7
Shell and tube heat exchanger (sea water)	124.4
Shell and tube heat exchanger (CO_2)	138.8
CO_2 Storage Tank (2 units)	524.4
Shell and tube heat exchanger (drying)	60.9
Dryer	450.9
Ducting (cooling system)	712.9
Natural gas pipeline	426
Total Investment Cost	**25,085**

The business scheme and incentives scenarios developed for the analysis are presented in Table 6.

Table 6 Scenarios of the polygeneration system business scheme

Scenario	Description
EPC	• EPC business scheme • The production of electricity, cooling, and drying are managed in a single management
SPC	• BOT business scheme • The production of electricity, cooling, and drying are managed separately by each public utility
SPC IFN	• SPC scheme supported by Viability Gap Fund (VGF) from the government of a maximum of 49% of the construction costs
SPC IFC	• SPC scheme with 100% tax reduction for 5 years with an investment ranging from Rp500 billion to Rp1 trillion, and 50% for 2 years thereafter.
SPC IFN IFC	Combination of SPC IFN and IFC

Note:

1. EPC is Engineering Procurement and Construction.
2. SPC is Specific Purpose Company which is similar to Build Operate and Transfer (BOT) scheme.
3. SPC IFN is SPC scheme with Financial Incentive from government.
4. SPC IFC is SPC scheme with Fiscal Incentive from government.
5. SPC IFN IFC is SPC scheme with Financial and Fiscal Incentive from government.

III. RESULTS AND DISCUSSION

Results of technical and economic analysis of polygeneration are discussed in this section.

A. Energy demand and polygeneration capacity

Referring to the calculation based on historical data, the energy demands reveals that electricity required reach 7,116 kW, cold energy needed by the West Papua Governor's office building is 782.3 kW, cold energy required by residential areas amount to 746 kW, and heat energy needed for cocoa drying amount to 1,475.4 kW. Therefore, the total capacity of the polygeneration system to be designed is 9,376.2 kW. The amount of potential energies generated by polygeneration system were nett electricity of 16,092 kW, cooling duty of 782.3 kW, and heating of 10,600 kW.

B. Technical performances

Based on process simulation, the efficiency of a stand-alone gas turbine power plant and that of a polygeneration system is illustrated in Sankey diagram as shown in Figure 5, i.e. 32.9 % for a stand-alone gas turbine power plant, 83.2 % for the electricity and heating system segment, 71.8% for the regasification and cooling system segment, and 59.79% for the total efficiency of the polygeneration system.

It is interesting to note that a polygeneration system can increase system efficiency by 26.89%, i.e. from 32.9% for a stand-alone power generation to 59.79% for polygeneration system, due to utilization of waste heat from LNG regasification unit and gas turbine.

Figure 4 shows the profile of cooling load of Governor's office building and the residentials. The cold energy was allocated at 7:00 a.m. to 4:00 p.m. for Governor's office building during work hour. The rest of time, the cold energy was delivered to the residential when the people stay at home for take a rest. The cooling energy can supply energy to the West Papua Governor's office building and residential areas during the day, the customers may use a heat exchanger (evaporator) separately, i.e. two-stage air cooling using liquid CO_2. Thus, two heat exchanger systems are required and its affects the CAPEX.

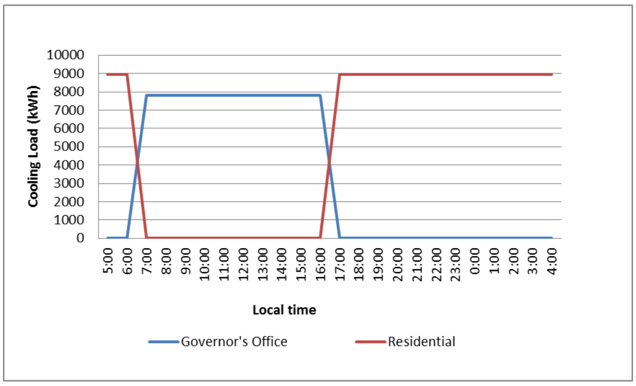

Fig 4 Cooling load profile

For heating, the temperature of the exhaust gas with a capacity of 1,475 kW, was still deemed high, which was at 570 °C, thereby it can be optimized to produce larger dryer heat energy, by up to 10,600 kW. Thus, the final temperature of the exhaust gas was 165.2 °C. This can be done as there is a chance to carry out more drying for other agricultural products such as cloves, coffee, and nutmeg to improve their economic values.

The condition will be different if a high exhaust gas temperature is used for other purposes, where waste heat was used to operate absorption chillers used to provide supplies to cooling systems for office buildings and hospitals.

The cold energy utilized by the small scale LNG regasification unit can also be used for fisheries cold storage in the West Papua area, but due to the long distance between the regasification unit and Manokwari District fishery center, then it is used for air conditioning. If in the upcoming year, in the Manokwari District will be developed a fishery center, it can also be used for cold storage. Compared to cold energy utilization, the LNG regasification process to produce cold energy for cold storage, as stated in the research conducted by (10), can also supply cooling loads and substitute for conventional cooling systems requiring 4400 MWh of electricity per year. Cold storage systems (10) are used for storage of agro-food ingredients (wheat, potatoes, carrots, and so on) in Sicily, Italy.

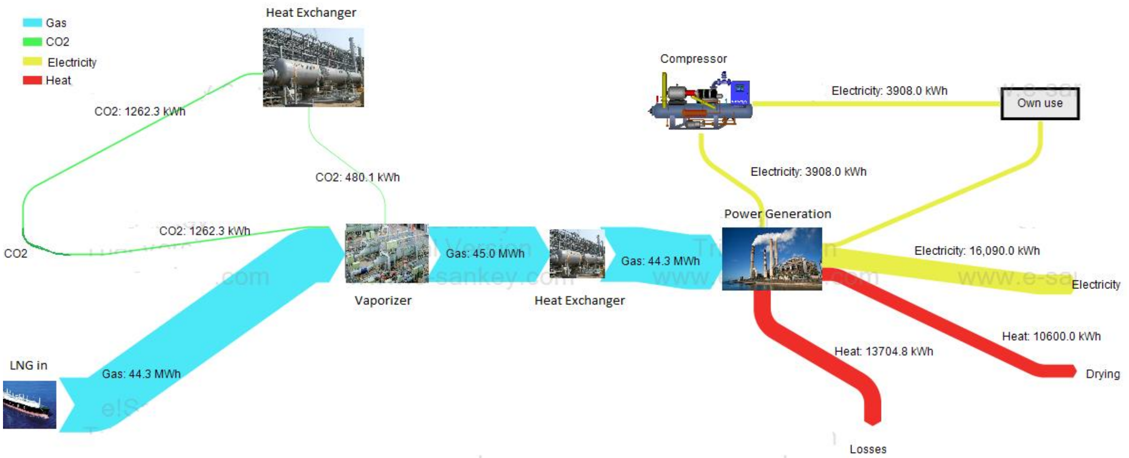

Fig 5 Sankey Diagram

In addition, as a way to minimize losses during polygeneration system implementation, potential heat energy to be disposed of can also be reused at a high temperature range of 570 °C using absorption chiller or absorption heat pump technology depend on the condition of Manokwari District itself in the future. This way may provide added value both technically and economically.

A. Economic viability

Figure 6 shows electricity tariff comparison between a stand-alone power plant and a polygeneration system with different business schemes. It can be seen that the polygeneration system can reduce the electricity tariff, due to increased system efficiency.

Figure 7 shows that for EPC and SPC business scheme scenarios, the electricity tariffs, are 15.23 USD cents/kWh and 15.39 USD cents/kWh, respectively, are higher than the base tariff of the regional electricity cost of production of Manokwari amounting to 14.78 USD cents/kWh. This is because the construction of a polygeneration system in remote areas requires additional costs for the gas component, i.e. shipping and LNG regasification costs, making the electricity tariffs is higher. However, compared to the current conditions in Papua and West Papua where electricity is supplied with diesel power plants with electricity tariff is much higher, i.e. 20.93 USD cents/kWh. It means that the electricity tariff of a polygeneration system, either EPC- and SPC-based, remains lower and has a more competitive compared to the current tariff of electricity generated using diesel-fired power plant. Besides, using financial and fiscal incentive, its give significantly affect to the electricity tariff of polygeneration system, became more competitive.

Figure 8 presents cooling tariffs, where all scenarios offer a lower tariff than the base tariff of 8.70 USD cents/ton h. The cooling base tariff used as a reference here is the tariff for cooling by air conditioning using electricity. The SPC IFC IFN scenario gives the lowest tariff of 5.47 USD cents/ton h.

Figure 9 shows that drying tariff is cheaper than the steam drying tariff of all drying tariffs generated by several scenarios, the lowest one amounts to 2.5 USD cents/kg, which is generated using the SPC IFN IFC scenario.

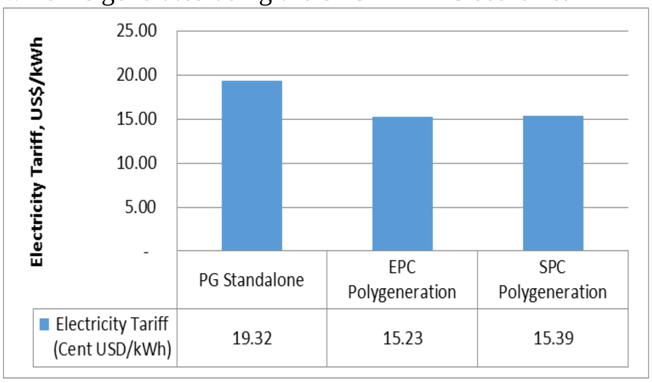

Fig 6 Electricity tariff comparison before and after polygeneration

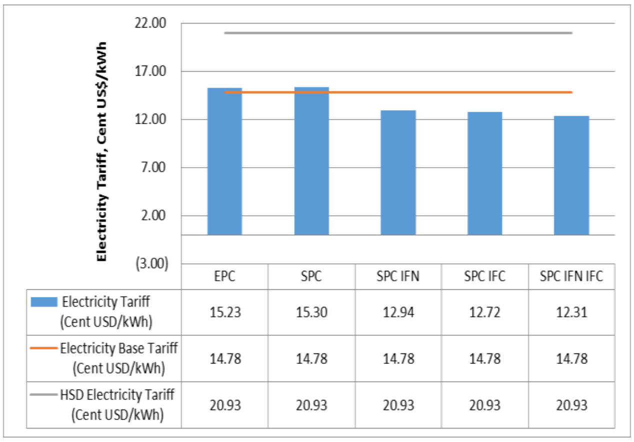

Fig 7 Electricity tariffs by various scenarios

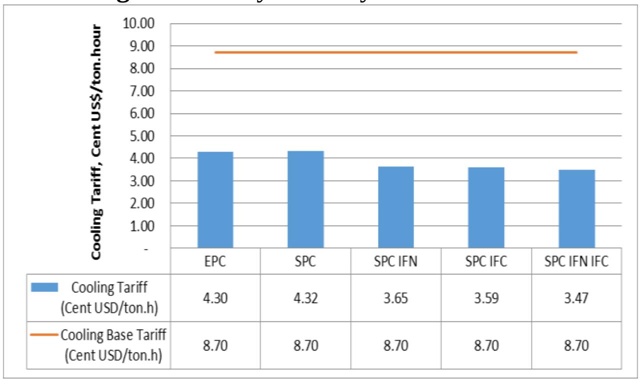

Fig 8 Cooling tariffs by various scenarios

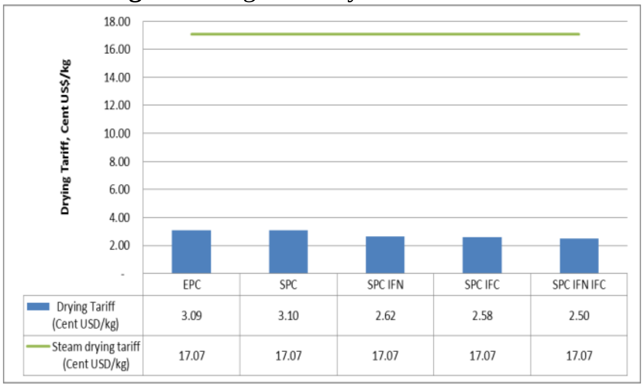

Fig 9 Drying tariffs by various scenarios

Table 7 presents an economic calculation result of polygeneration system by business scenarios. From the economic perspective, all scenarios are feasible because they have a positive NPV and offer a competitive energy tariffs.

Table 7 Resultsof Economic Calculation for Polygeneration by Scenarios

Scenario	NPV (million USD)	Payback Period (in year)	Electricity Tariff (Cent USD/kWh)	Cooling Tariff (Cent USD/ton.h)	Drying Tariff (Cent USD/kg)
EPC	44.55	9	15.23	3.65	2.63
SPC	25.07	7	15.39	3.76	2.70
SPC IFN	24.31	7	12.94	3.65	2.62

SPC IFC	21.71	7	12.72	3.59	2.58
SPC IFN IFC	20.90	7	12.31	3.47	2.50

Compared to electricity-based cooling, polygeneration system-based cooling has advantages, i.e. in the event of blackout in Manokwari, it will not affect the supply of cold energy to customers because it is generated using a regasification system. Thus, the polygeneration-based cooling tariff is very achievable compared to the electricity-based cooling tariff.

As for the advantage of the polygeneration-based drying system is that customers can use heat energy for drying throughout the year without any effect due to changes in the weather or season during the operation of the power plant.

IV. CONCLUSIONS

From the results and discussion section, it can be concluded that:

1. This polygeneration system is able to meet electricity, cooling, and heating needs of Manokwari District with supply capacities: net electricity of 16,092 kW, cooling of 782.3 kW, and heating for drying of 10,600 kW.
2. Polygeneration can improve a system's energy efficiency by 26.89%, i.e. from 32.9% (stand-alone gas turbine power plant) to 59.7%.
3. The SPC IFN IFC business scheme offers the minimum tariffs with electricity tariff of 12.31 USD cents/kWh, cooling tariff of 3.47 USD cents/ton.h, and drying tariff of 2.50 USD cents/kg.

ACKNOWLEDGEMENTS

The authors are grateful to the DRPM UI for financial support under the Hibah Penugasan Publikasi Internasional Terindeks 9 (PIT 9) Universitas Indonesia, Contract Number: NKB-0081/UN2.R3.1/HKP.05.00/2019. Kriska Setyawati gratefully acknowledges the Master Program Scholarship awarded by PT Perusahaan Listrik Negara (Persero).

REFERENCES

[1] PLN. Laporan Tahunan 2016 : Listrik Untuk Membangun & Mensejahterakan Jakarta: PT Perusahaan Listrik Negara (Persero), 2016.
[2] Kuntal Jana AR, Mohammad Mansouri Majoumerd, Mohsen Assadi, Sudipta De. Polygeneration as a future sustainable energy solution - A comprehensive review. Applied Energy. 2017;202(25 May 2017):88-111.
[3] George Kyriakarakos AID, Stelios Rozakis, Konstantinos G. Arvanitis, George Papadakis. Polygeneration microgrids: A viable solution in remote areas for supplying power, potable water and hydrogen as transportation fuel. Applied Energy. 2011;88(15 June 2011):4517-26.
[4] Lukas Aichmayer JSaBL. Small Scale Hybrid Solar Power Plants for Polygeneration in Rural Areas. Energy Procedia : 2013 ISES Solar World Congress. 2014;57(2014):1536-45.
[5] Avishek Ray KJ, Sudipta De. Polygeneration for an off-grid Indian Village: Optimization by economic and reliability analysis. Applied Thermal Engineering. 2017;116(25 January 2017):182-96.
[6] Ershad BM, Andrew Martin, Semida Silveira. Techno-economic Analysis of Small Scale Biogas Based Polygeneration systems : Bangladesh case study. Sustainable Energy Technologiest and Assessments. 2014;7(16 March 2014):68-78.
[7] Kuntal Jana SD. Techno-economic evaluation of a polygeneration using agricultural residue - A case study for an Indian district. Bioresource Technology. 2015;181(22 January 2015):163-73.
[8] Carlos Rubio-Maya JU-M, Amaya Matinez-Gracia, Angel A. Bayod-Rajula. Design optimization of a polygeneration plant fuelled by natural gas and renewable energy sources. Applied Energy. 2010;88(3 August 2010):449-57.
[9] Matthew Kieffer TB, Robert C. Brown. Flex Fuel Polygeneration : Integrating renewable natural gas into Fischer-Tropsch synthesis. Applied Energy. 2016;170(26 March 2016):208-18.
[10] Antonio Messineo GP. LNG Cold Energy Use in Agro-Food : A Case Study in Sicily. Journal of Natural Gas Science and Engineering. 2011;3(1 April 2011):356-63.

AUTHOR'S PROFILE

Widodo Wahyu Purwanto, Chemical Engineering Department, Faculty of Engineering, Universitas Indonesia, Areas of expertise include; Energy, Energy Engineering, Energy Management and Carbon Nanotubes.

Kriska Setyawati, Chemical Engineering Department, Faculty of Engineering, Universitas Indonesia, Area of expertise is Process Engineering.