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Scientific paper
ISSN 0351-9465, E-ISSN 2466-2585
https://doi.org/10.5937/zasmat2201089O

Zastita Materijala 63 (1)
89 - 100 (2022)

Modeling of GTL-Power Coproduction as a means of optimisation of GTL plants

ABSTRACT

Gas-to-Liquids (GTL) technologies have the potential to convert associated flare gases into premium transport liquids, creating a market for the otherwise stranded resource. However, the capital cost of GTL plants has over the years hampered the choice of the project. The drive for GTL is improved by optimization of the plant such that its efficiency and profitability is increased. One such notable improvement in GTL plant configuration is the integration of power production unit in the GTL process plant such that GTL liquids production and electricity production can occur concurrently in the same plant. This method generally called GTL-power co-production will increase the overall efficiency and profitability of existing GTL plant process and present ways to economically optimize the heat loss through the by-product streams (steam and flue gas streams). The utilization of the by-product streams will account for reductions in thermal inefficiencies within the GTL plant process. In this work, additional unit is added to the 863.3 m^3/d GTL product plant configuration to utilize the by-product steam stream for electricity generation. This additional electricity unit generated 10 MW of electricity increasing the net present value (NPV) of the plant by 4.72% while the net cash recovery (NCR) increased by 3.87%. Furthermore the pay-out time reduced by 2%. The GTL-Electricity co-production has proven to be a means of optimizing GTL plant, having capability to yield more profits due to reduced capital and operational expenses than if the plants were operated separately.

Keywords: *Gas-to-liquids, electricity, Co-production, Fischer-Tropsch, Waste heat*

1. INTRODUCTION

Through gas-to-liquids technology, small and/or medium sized gas reserves that were uneconomical or difficult to bring to the market because of their remoteness could be facilitated and several sulphur free premium products are produced for local and international markets. GTL technology has good potentials to turn associated natural gas into marketable fuels and chemicals which meet environmental regulations of many nations and performs comparatively better than same fuels derived from crude oil distillation [1].

The GTL technology process mainly is with the intention of producing transport fuels. This method makes it possible to utilize and monetise gases which were otherwise flared. Aside the production of clean transport fuels, GTL plant processes offers opportunity to generate electricity from the by-product steam and/off-gases. It has been stated that electricity can also be produced from GTL waste waters.

Thermal inefficiencies and high cost of GTL processes have discouraged investors from participating in stranded gas monetisation via GTL technologies [2]. GTL have been regarded as capital intensive venture whose profitability requires adequate plant scheduling and optimisation techniques aimed at integrating processes and units to enhance profitability through high performance and technically improved operations [2]. Thermal losses in steam stream and tail gas stream have resulted to high energy requirement for GTL operations which makes the overall plant capital intensive. The combined production of electricity with GTL liquids concurrently in a GTL-power plant ensures a means of improving the thermal efficiency of the GTL plant while providing

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Paper received: 20. 09. 2021.
Paper corrected: 12. 11. 2021.
Paper accepted: 23. 11. 2021.
Paper is available on the website: www.idk.org.rs/journal

additional economic returns for the operators and/or investors.

In production of electricity from GTL processes, steam generated from the GTL plant is used in steam turbines [3]. Conventionally, electricity generated from GTL plant has been used for powering site equipment and for site utility. This was made possible by utilising some of the steam produced in the various processes. The steam used for electricity production from GTL plant comes from two main sources: steam of high pressures from the synthesis gas production and steam of medium pressure from the Fischer-Trospch reaction. The use of these steam systems depends on the target goal of the GTL operators, the demand and overall economics of the processes involved [4,5].

GTL-Power plant is a hybrid GTL process that involves the production of GTL liquids (which of course involves self-sufficient electricity production solely for onsite plant and crew requirement) and the production of commercial electricity from the heat content of steam and in some cases flue gases [6]. This method generally called GTL-Power coproduction will increase the overall efficiency and profitability of existing GTL plant processes and present ways to economically optimize the heat loss through the by-product streams (steam and flue gas streams). The utilization of the by-product streams will account for reductions in thermal inefficiencies within the GTL plant process. About 17% and 23% thermal inefficiency is associated with GTL steam stream and tail gas stream respectively making it a total of 40% thermal inefficiency from the combined by-product streams [7].

GTL-Power co-production is a solution to the Nigeria electricity problem by making electrical power available for the host communities where GTL plant are situated and sale of excess via the national grid system. In this work, existing GTL facility upgrade is simulated with inclusion of power plant for the conversion of the medium pressure steam generated in the Fischer Tropsch reactor for electricity conversion. Steam requirement generally depends on the capacity of the steam turbine output power requirement and additional steam may be provided by use of boilers to heat up water which will compensate steam from GTL processes.

2. THEORETICAL CONCEPTS

GTL plant and GTL-power co-production is discussed in this section

2.1. The GTL Process

This GTL plant comprises the processes involved in the collection of the gas from the operators to the conversion of the gas to useable transport fuels. The various intermediate processes are listed below: i)The gas collection, pretreatment and processing stage, ii) The synthesis gas production stage, iii) The syncrude production stage (Fischer Tropsch reaction stage), iv).The final products work-up stage

The gas coming from the flare line needs to be treated to remove entrained impurities like acid gases, sulphur compounds, nitrogen etc. In most cases, depending on the mole composition, higher molecular weight hydrocarbons are separated prior to the entrance into the GTL plant. However, unlike LNG plants, GTL plants may accommodate some degree of natural gas liquids in the natural gas stream. The downstream pre-reformer has the capacity to convert further the higher molecular weight hydrocarbons into methane or synthesis gas [8,9]. The synthesis gas unit ensures that the resulting treated natural gas is converted to synthesis gas. Synthesis gas is a mixture of hydrogen and carbon monoxide. It is mainly the intermediate product in most petrochemical plant operations for the production of varieties of chemical products like methanol, ammonia, fuels etc. Most of the capital cost of the GTL plant comes from the synthesis gas unit. As such, the synthesis gas unit is usually the target for most optimisation works in GTL plants. The synthesis gas method to adopt depends on the desire output product, and economics. For GTL plant, the best H_2/CO ratio for synthesis gas is 2.0 [10]. This is optimal as required by the downstream Fischer-Tropsch reactor which favours the production hydrocarbons that could be further processed into clean transport fuels. Other processes like hydrogen production may require higher H_2/CO ratios.

Autothermal reforming method has mostly been used commercially in the production of synthesis gas, because of its higher efficiency and less emission characteristics [2].

The equation of reaction for autothermal reforming is given as

$$CH_4 + 1.5O_2 \rightarrow CO + 2H_2O \qquad (1)$$

The methane combustion in equation 1 is followed by steam methane reaction and water gas shift reaction given in equation 2 and equation 3 respectively

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \qquad (2)$$

$$CO + 3H_2O \leftrightarrow 3H_2 + CO_2 \qquad (3)$$

The autothermal reformer requires three feedstocks which are natural gas, steam and oxygen. The oxygen is produced in the air separation unit which may be part of the autothermal reformer system or externally sourced.

The watergas shift (WGS) reaction is used to adjust and control the H_2/CO ratio. Typically, WGS reaction ensures that some of the carbon monoxide is converted to carbon dioxide and more hydrogen gas is produced. In F-T GTL process, WGS reaction is one of the most important reactions used to balance the H_2/CO ratio [11]. WGS reaction being considered as a moderately exothermic reversible reaction depends highly on the reaction temperature. Meanwhile, despite the fact that the reaction proceeds more at high temperatures, high temperatures inhibits the production of carbon dioxide, while low temperature favours the production of carbon monoxide. To optimize the process both thermodynamically and kinetically, industrial WGS reaction application are conducted in multiple adiabatic stages consisting of a high temperature shift (HTS) followed by a low temperature shift (LTS) with intersystem cooling. Thus two equilibrium reactors may be desired; the first being HTS to ensure the complete conversion of carbon monoxide and about 3% carbon monoxide exit composition and a later LTS equilibrium reactor is needed to produce carbon monoxide exit composition of less than 1% thus increasing hydrogen production [12].

The hydrocarbons obtained from the F-T unit consist of hydrocarbons mix which includes gaseous light, liquid, and waxy, long chain paraffinic hydrocarbons, and olefins. These products typically need to be further processed to be useful as desired GTL products. The product upgrading involves the processing of GTL liquids produced from the F-T reactor into final salable liquid products. The upgrading unit involves operations such as cracking, isomerisation, distillation etc. the product upgrading process is similar to the processes involved in conventional oil refinery [12].

The most important catalysts used in GTL processes are iron and cobalt and nickel catalysts. However cobalt catalysts are more preferred in the production of paraffinic products. Catalysts deactivation is a very critical problem in GTL process. Being that catalysts of precious metals are very expensive, regeneration of catalysts is usually very desirable to reduce the operational cost of GTL processes [13]. The main causes of catalyst deactivation are sintering, re-oxidation, formation of stable compounds between catalysts and the support, surface reconstruction, formation of carbon species on the cobalt surface, carbiding and poisoning. Catalyst regenerations are ways to reverse the deactivation process of carbon deposition, metal oxidation and sintering by combustion, reduction and re-dispersion, respectively. Regeneration of catalyst can occur in-situ (inside the F-T reactor) or ex-situ (outside the F-T reactor) [13].

Large volumes of waste water are generated from GTL processes especially from the F-T reaction. This produced water is typically more than 25% by weight of the hydrocarbons produced [14]. This wastewater needs to be adequately treated before reuse or disposal to comply for the standards and regulations of the host country. Treatment for GTL process wastewater could be primary, secondary or tertiary treatments. Primary treatment eliminates or reduces unwanted wastewater characteristics that will be deterrent to downstream treatment processes. It helps to condition the wastewater for further treatments. Example of primary treatment of GTL wastewater includes: oil-water separation, hot-effluents cooling, neutralization etc. primary treatment makes it easier to conduct secondary or biological treatment on the GTL process wastewater.

Secondary GTL process wastewater treatment utilizes biological treatment processes in the removal of organic contaminants. Example of biological treatment is activated sludge. In this method, organisms like bacteria are allowed to degrade the waste water following successive steps. Oftentimes, tertiary treatment following secondary treatment of GTL wastewater could be achieved. Tertiary treatment is advanced treatment processes that produce high quality water. This may include direct air floatation (DAF) with integral sand filters to achieve the removal of sand, oil and biochemical oxygen demand (BOD) and chemical oxygen demand (COD) contained in the wastewater [15].

2.2. GTL plants

There are currently five operational large-scale GTL plants in the world. Large scale GTL plants are those that produce more than 1,589.87m^3 of GTL products per day. Table 1 below gives a summary of commercial-scale GTL plants in the world highlighting the ones operational and those still under construction.

The high capital cost of large-scale GTL plants have led to the abandonment of commercial-scale GTL plants such as the Shell Louisiana GTL project cancelled in late 2013 which would have been the first large-scaled GTL plant in the US, and the 15,263 m^3/d Sasol Lake Charles also in Louisiana was abandoned because the declining oil price made the project not to be economical. Most commercial-scale GTL plants are designed during periods of high oil prices. Declining oil prices caused commercial-scale GTL plants not to be viable [16].

Table 1. Summary of some current large-scale GTL plants in the world [17]

Tabela 1. Rezime nekih trenutnih velikih GTL postrojenja u svetu [17]

Project Name	**Company**	**Location**	**Size, m^3/d**	**Status**
Bintulu GTL	Shell BP	Malaysia	2337	Operational
Escravos GTL	Chevron and Sasoil, NNPC	Nigeria	5247	Operational
MosselBay GTL	Sasoil	South Africa	5724	Operational
Oryx GTL	Shell BP	Qatar	5406	Operational
Pearl GTL	Shell BP	Qatar	22,258	Operational
Ovadan-Depe GTL	Turkmengaz	Turkmenistan	2703	Under Construction
Ovadan-Depe GTL	Turkmengaz	Turkmenistan	3657	Under Construction
OltinYo'l GTL	Sasol, Petronas, and Uzbekneftegaz	Uzbekistan	6042	Under Construction
Sweetwater	Syntroleum	Australia	1828	Under Construction

Consequently, operators in gas-to-liquids seek ways by resorting to smaller economies of scale and modular units. Modular units allows for monetisation of stranded gases that otherwise would have been flared due to volume constraints, pressure or proximity to market that makes these gases stranded. Many smaller scale GTL plants have been developed either as pilot or demonstration plants especially in the US [16]. Some companies that played visible parts in the advancement of smaller scaled GTL technologies are: G2X, CompactGTL, Siluria, Primus Green Energy, INFRA Technology, Juniper GTL, Velocys and ENVIA Energy.Some small scale and modular plants operational around the world are given in the table 2 below.

Table 2: Some smaller-scale GTL plants [16]

Tabela 2. Neka GTL postrojenja manjih razmera [16]

Plant Name	**Location**	**Owner**	**Capacity m^3/d**
Offshore GTL	Brazil	Petrobas	318
Lake Charles GTL	Louisian, USA	Juniper GTL	16
Ashtabula	Ohio USA	Pinto Energy	445
Pilot plant	Alaska, USA	BP PLC	48

Smaller scale GTL plants are emerging and provide means to monetise stranded gases for the future. Research has been ongoing in ways to optimize modular GTL technologies so as to reduce cost and increase product yields. GTL-power co-production is one of the ways to increase the economic returns from modular GTL plants through the sale of the electricity generated to nearby communities or to the grid line. Until now, power has been produced alongside GTL processes, but this electricity has been limited to onsite usages without channels provided to generate additional revenue to the company through the sale of the power generated.

2.3. GTL Plant Waste Heat Utilization

Integrated GTL Power-Generation process is a GTL process configuration that combines power generation alongside production of GTL fuels, on the same existing GTL technology. The power generation is achieved using the thermal energy (heat content) of the steam stream and/or the tail-gas stream [6]. The electricity is utilized onsite as utility for the powering of onsite plants and equipment and excess is either sold and revenue recovered or sent to host communities as part of host community development initiatives.

Steam turbines utilize the steam produced in GTL plants to produce electricity. The steam is produced basically in two places; the synthesis gas unit and the Fischer-Tropsch unit. Medium pressure and/or high pressure steam are used to drive turbines to produce electricity [18]. Steam turbines operate on the Rankine cycle. In this thermodynamic cycle, water is pumped to high pressure and then heated to generate high pressure steam [19].There is expansion of the high pressure steam using a steam turbine and subsequent conversion of the thermal energy in the steam to mechanical energy that is then used to drive the electrical generator.

Since the steam which is already superheated comes from the GTL plants as by-product, the boiler section in the steam power plant is obviated. By this design, there is huge reduction in the capital and operating expenditure in the plant due to the removal of boiler unit of the steam turbine plant.

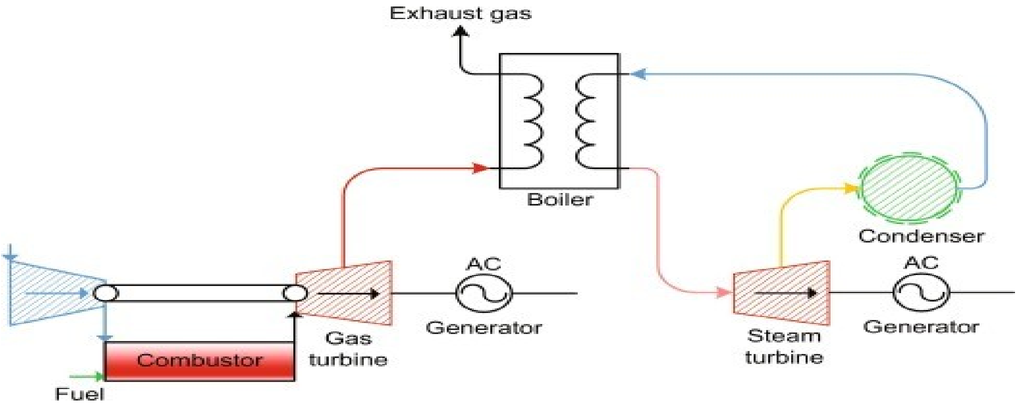

Figure 1. Illustration of steam power plants [6]

Slika 1. Ilustracija parnih elektrana [6]

3. METHODS

The methods for the GTL-Coproduction of electricity shall take the following procedures: i) Flare gas capture from flare stack, ii) Flare gas treatment/processing, iii) Conversion of treated recovered gas to premium liquids via GTL process, iv) Conversion of resulting Heat from GTL-steam to electricity via steam turbines.

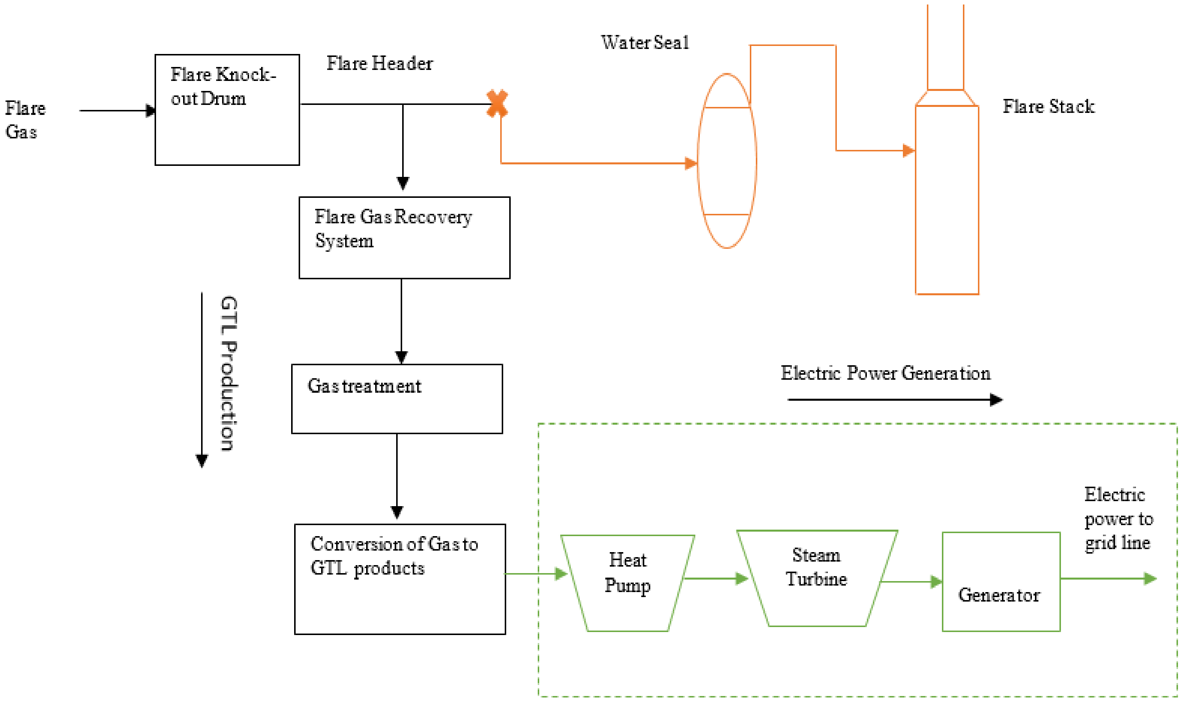

Figure 2. Block Diagram of the whole process

Slika 2. Blok dijagram celog procesa

In figure 2, the knock-out drum removes the free liquids which are mainly condensates and free water. If the gas was to be flared, the gas from the flare knock-out drum goes to the flare header and to the water seal, the water seal removes some of the water and the gas is flare at the flare stack. Using the flare gas recovery technology enables the otherwise flared gas to be captured and redirected for processing and utilization. The flare header is between the flare knock-out drum and the water seal. The captured flare gas is stored in a storage vessel awaiting treatment and processing.

3.1. Gas Treatment and Processing

The recovered flare gas from the flare stack contains impurities that are harmful to the GTL plant. These impurities can result in corrosion of the metal components of the plant; reduce the efficiency of the catalytic units and generally impacts on the performance of the overall GTL plant. The impurities in the gas stream include acid gases, water vapour, sulphur components, nitrogen, and higher molecular mass hydrocarbons. Acid gases must be removed because it corrodes the metal components. In GTL plants, CO_2 of 0.1-0.5% mole composition can be tolerated but the sulphur level in the gas stream must be less than 0.1 ppm weight [10]. GTL plants can allow some percentage of the heavier hydrocarbon components as these components will be later broken down into methane components in the pre-reformer before the actual synthesis of the gas in the reformer unit

3.2. GTL conversion and Electricity Production

The GTL conversion was modeled in Honeywell Unisim R380. Peng-Robinson fluid property package was used in the model setup. All the C_4^+ components were added as n-type hydrocarbons and $C_{21\rightarrow\infty}$ was modeled as C_{30} due to similarities in their properties. Two reactors were used for the synthesis gas unit. Autothermal reforming synthesis gas method was used with natural gas, oxygen and steam as the feed gas. Both the pre-reformer and the reformer were modeled as conversion type reactors.

In modeling the Fischer-Trospch reactor (FTR), a plug flow reactor (PFR) was chosen because it represented the flow pattern closely resembling a multi-tubular fixed bed (MTFB) reactor typical for FTR. A reactor starting volume of 1000 m^3 was chosen for the simulation. The simulation design process diagram for the reformer section and the FTR unit are given in figure 3 and 4 respectively.

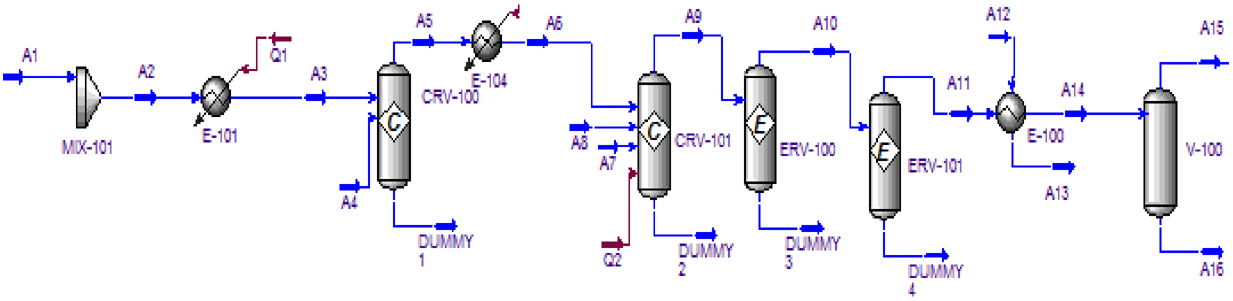

Figure 3. Production of synthesis gas in the reformer unit

Slika 3. Proizvodnja sintetskog gasa u reformer jedinici

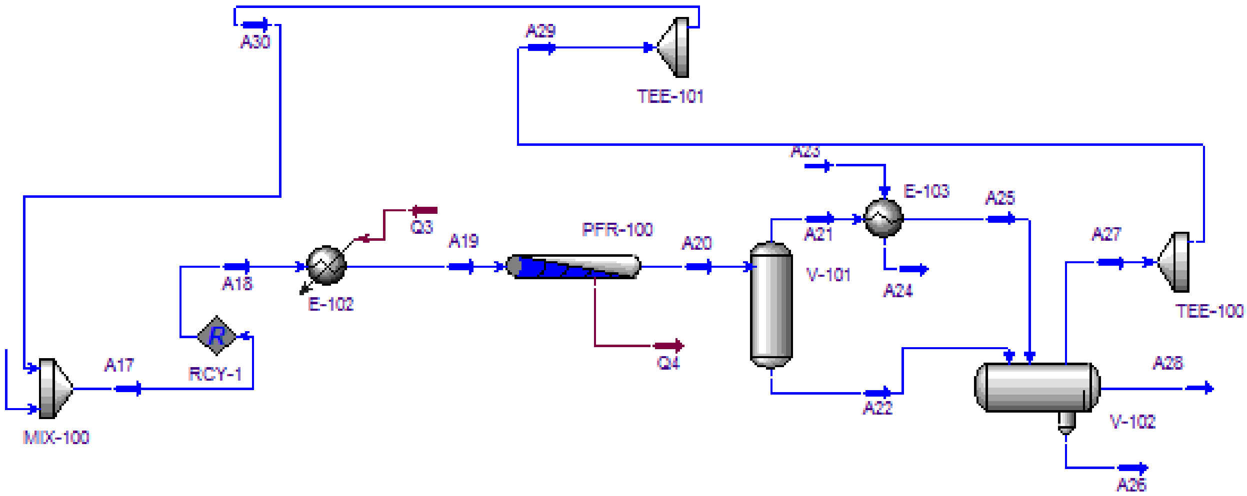

Figure 4: Conversion of the synthesis gas to syncrude in the FTR

Slika 4. Konverzija gasa za sintezu u sinkrut u FTR

The abbreviations in figure 3 is given in table 3.

Table 3. Process flow -Abbreviation meaning for reformer unit

Tabela 3. Procesni tok - Značenje skraćenice za reformatorsku jedinicu

Stream	**Description**
A1	Natural gas
A2	Mixed natural gas
E-101	Heater
Q1	Heat in
A3	Heated natural gas (pre-reformer inlet)
A4	Steam
A5	Pre-reformed gas
A6	Reformer inlet gas
CRV-100	Conversion reactor (Pre-reformer)
E-104	Heater
A7	Steam
A8	O_2
Q2	Heat
CRV-101	Conversion reactor (Reformer)
ERV-100	Equilibrium reactor (Water gas shift reactor)
ERV-101	Equilibrium reactor (Water gas shift reactor)
A9	Reformer outlet gas
A10	First water gas shift gas (WGS gas)
A11	Second WGS gas
E-100	Heat Exchanger
A12	Cold water
A13	Saturated steam
A14	Cooled synthesis gas
V-100	Two-stage separator
A15	Separator gas
A16	Separator liquid

Three reformers are used to model the reformer section aside the pre-reformer. The pre-reformed treated gas enters the conversion type reformer where a conversion reaction take place on the natural gas stream and then the resulting stream are passed on to two equilibrium reformers. The two equilibrium reactors modeled the water gas shit reaction that helped to adjust the H_2/CO ratio to the desired level. The water gas shift reactor typically converts (shifts) a portion of the CO in the synthesis gas to CO_2 by reacting with steam thereby yielding more H_2 and hence increasing the H_2/CO ratio. After the reformer, a heat exchanger placed ahead of the reformer brought down the temperature of the resulting syngas stream to about 310.93K so that the steam generated in the reforming process can be condensed to water and separated. A two-way separator is used to separate the synthesis gas from the cooled water. When the water is separated out, the synthesis gas (hydrogen and carbon monoxide) are passed to the next stage which is the Fisher-Tropsch reaction unit where the synthesis gas are converted to synthesis crude through a catalytic reaction process.

The abbreviations in figure 4 is explained in table 4.

Table 4. Process flow -Abbreviation meaning for FTR unit

Tabela 4. Procesni tok -Značenje skraćenice za FTR jedinicu

Stream	Description
MIX-100	Mixer
A17	Recycle gas inlet
RCY-1	Recycler
A18	Recycle gas outlet
E-102	Heater
Q3	Heat in
A19	PFR inlet (FT outlet)
PFR-100	Plug flow reactor (Fischer-Tropsch reactor)
Q4	Heat out
V-101	Two-way separator
A20	PFR outlet
A21	Separated FT gas
E-103	Heat exchanger
A22	Separated FT liquid
A23	Cold water
A24	MPP saturated steam
A25	Cold FT gas
V-102	Three-way separator
A26	Separated FT heavy liquid
A27	Flue gas
A28	Separated FT light liquid
A29	Mixed flue gas
TEE-100	Mixer
TEE-101	Mixer
A30	Recycled flue gas

The FTR catalytically converted the synthesis gas into synthesis crude using Cobalt catalyst. The reaction proceeds exothermically and heat was produced in the process. A three-way separator was chosen for separator to enable separation of the water that came from the steam. The required product was then sent to the upgrading unit.

Table 5. Inlet conditions of feed streams

Tabela 5. Ulazni uslovi napojnih tokova

Input	Temperature (K)	Pressure (MPa)	Molar Flow (mol/s)
Natural Gas	311.15	3.11	691.67
Steam	524.82	4.17	2500
Oxygen	473.15	3.11	694.4

The inlet conditions of the steam turbine for the production of electricity from the GTL plant waste heat is given in table 5.

Table 6. Turbine conditions for the electricity production

Tabela 6. Turbinski uslovi za proizvodnju električne energije

Turbine Parameters	Values
Mass flowrate of steam kg/s	77
Turbine Inlet Pressure (MPa)	3
T1 (K)	325
T2 (K)	508
Ws (Net-J/kg)	815961
Q (Heater-J/kg)	3049386
Thermal efficiency, %	30

Table 6 gives the turbine conditions for electricity generation using steam from GTL process. The mass flowrate of steam going to the turbine plant is 77.22 kg/s at a pressure of 3.09 MPa.

3.3. Economic Analyses

In the economic analyses the following economic indicators shall be determined for the GTL plant and for the GTL and electricity co-production: Net present value (NPV), Net cash recovery (NCR), pay-out-time (POT), internal rate of return (IRR), profit per dollar invested (P/$). Parameters that will be used for the economic evaluation of the project are given below.

i. Natural gas flowrate of 1,415,842.3 m^3/d and a GTL product yield of 863.3 m^3/d
ii. Capital cost is US$347.6 million (excluding Air separation unit (ASU)) and Turbine capital cost of US$10 million. This amounts to a unit capital cost of US$402641/ m^3
iii. Natural gas cost is US$8.83/$Mm^3$
iv. GTL plant OPEX is 5% of CAPEX (this excludes the cost of natural gas and cost of O_2 or CO_2)
v. Steam turbine OPEX of US$0.02/kWh
vi. Electricity sale price of US$0.086/kWh
vii. Discount rate of 10%
viii. 25 years plant operational period
ix. Plant operational days per year is 350 days
x. Product prices of refined GTL products produced are $629/$m^3$ for diesel and kerosene and $566/$m^3$ for gasoline
xi. Income tax of 35% base case
xii. 100% owners' equity

4. RESULTS AND DISCUSSION

The result from the simulations are presented below.

4.1. GTL Process Yield

The result for the yield of the GTL plant yield and the electricity produced is given in table 7.

Table 7. Yields from GTL plant and steam turbine

Tabela 7. Prinosi iz GTL postrojenja i parne turbine

Product	Plant	Value
Gasoline	GTL	480.94 m^3/d
Kerosene	GTL	219.40 m^3/d
Diesel	GTL	162.96 m^3/d
Electricity	Steam Turbine	10 MW

From table 7, a total of 863.3 m^3/d of GTL liquids are produced from the GTL plant while 10 MW of electricity is produced from the steam turbine using the by-product steam stream from the GTL plant process.

The result from economic investigation of the GTL plant and the Combined GTL-power co-production is given in the table 8.

Table 8. Economic analyses results

Tabela 8. Rezultati ekonomske analize

Parameter	GTL	Electricity	GTL-Power co-production	Absolute difference (%) between GTL-Power coproduction and GTL
NPV, MMUS$*	299.25	23.98	313.96	14.71 (4.72%)
NCR, MMUS$	71.26	3.7	73.99	2.76 (3.87%)
POT, years	4.9	2.7	4.8	0.1 (2%)
IRR, %	20.3	37.4	20.5	0.2 (1%)
P/$	4.13	8.36	4.17	0.04 (1%)

*@ 10% discount rate

The economic indicators in table 8 show that there is a 4.72% increase in NPV as a result of co-production of electricity from that realized in GTL plant alone. Also, the POT reduced from 4.9 years in GTL to 4.8 years for the co-production making a percentage decrease in POT of 2%. The IRR increased from 20.3% in GTL plant to 20.5% for co-production, an increase of 1%. The NCR increased from US$ 71.26 million to US$ 73.99 million, an increase of US$2.76 million or 3.87% increase. The P/$ increased from 4.13 to 4.17 representing a percentage increase of 1%.

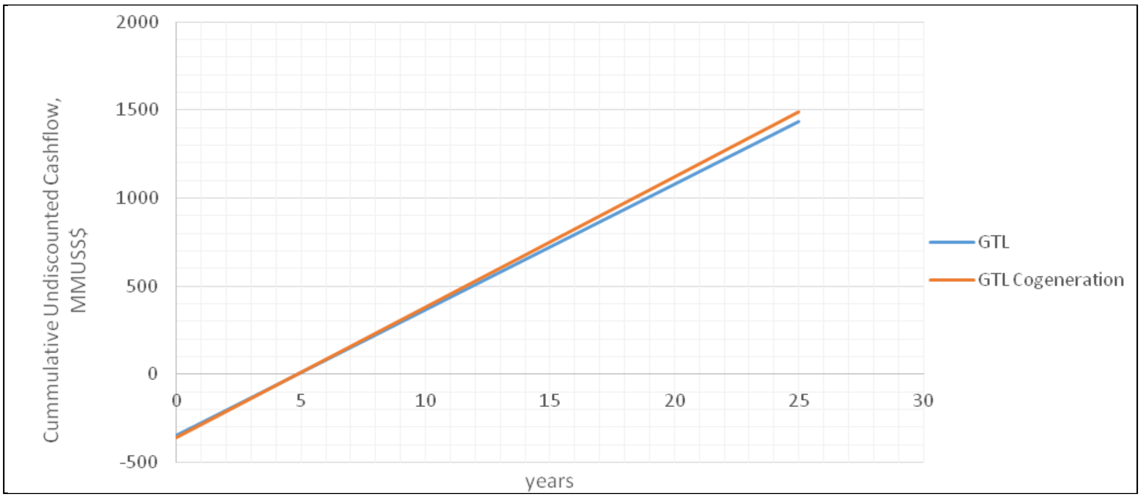

Figure 5. Plot of pay-out time for GTL and GTL-power co-production processes

Slika 5. Prikaz vremena isplate za GTL i GTL-power koprodukcijske procese

The addition of commercial electricity production technology to the GTL plant reduces the time to realize the investment cost as shown in figure 5. Concurrent production of GTL and electricity provides additional revenue for the operator which increases the overall profitability of the GTL process.

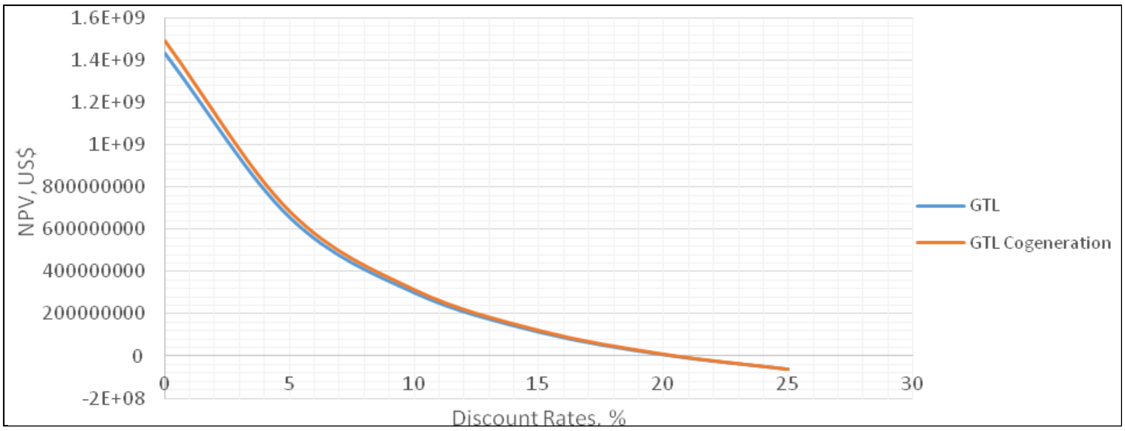

Figure 6. NPV vs discount rate plot for the GTL and GTL-power co-production.

Slika 6. Grafikon NPV naspram diskontne stope za koprodukciju GTL i GTL-power

The IRR is the point where the curve touches the x-axis (i.e. the discount rate axes). The internal rate of return increased due to production f electricity alongside GTL products as can be observed from figure 6. The blue line represents the GTL plant alone while the red line represents the GTL-power co-production which includes the production of GTL products with electricity from the by-product steam stream using steam turbine.

The profitability indices for GTL-power is higher than the standalone GTL operation showing that the GTL-power production is more profitable than the GTL standalone in all the economic indicators considered.

4.2. Comparison of results

Results from the simulation in this study are compared with the results obtained by Adegoke et al [6]. Adegoke et al considered GTL-power coproduction for very large GTL plants of capacity of 15,899 m^3 of GTL fuels produced utilizing 158,987,303 m^3 of natural gas. They studied the electricity production from the waste steam of GTL plant using steam turbines for 95% and 90% steam stream. The NPV of the result from this sudy and Adegoke et al were both calculated using discount rate of 10%. Adegoke et al. used an electricity tariff of 10 cents per kWh while an electricity tariff of 8.6 cents per kWh was used in this study. Table 9 compares the result from Adegoke et al [6] using 95% steam stream and the results from this study.

Table 9. Comparison of results from study with results on similar study conducted by Adegoke et al [6]

Tabela 9. Poređenje rezultata studije sa rezultatima slične studije koju su sproveli Adegoke et al [6]

Parameter	**Study**	**Adegoke et al**	**Study**	**Adegoke et al**	**Study**	**Adegoke et al**
	GTL		**GTL-Power**		**Absolute difference (%) between GTL-Power and GTL**	
NPV, MMUS$**	299.25	8,910	313.96	9250	14.71 (4.72%)	0.35 (4%)
POT, years	4.9	0.5	4.8	0.5	0.1 (2%)	0 (0%)
IRR, %	20.3	43.25	20.5	43.99	0.2 (1%)	0.74 (1.7%)
Profitability index	1.86	4.18	1.88	4.21	0.02 (1.08%)	0.3 (0.72%)
Capital cost, MMUS$	347.6	2800	357.6	2880	10 (2.88%)	80 (2.86%)
Unit Capital cost US$/m^3	402,641	176,111.7	-	-	-	-

*@ 10% discount rate

From table 9, it can be observed that for GTL standalone plant, the economic performance of the large GTL plant considered by Adegoke et al [6] is far more profitable than the modular GTL plant considered in this study. This is evident in the POT, IRR and profitability index. The IRR, POT and profitability index for the 15,899 m^3 capacity GTL plant considered by Adegoke et al are 43.25%, 0.5 year and 4.18 respectively. The IRR POT and profitability index for the 863.3 m^3/d capacity GTL plant considered in this study are 20.3%, 4.9 years and 1.86 respectively. It is very evident that larger plants have more economic attractiveness than smaller plants. However the drive for small-scale modular plants hinges on the capital cost for startups. Most investors shy away from the rather high total capital costs associated with large/commercial plants. Secondly, the reason for increased consideration in small-scale or modular plants is that most fields cannot yield enough gas resource needed by the large plants. Nonetheless, even though larger plants have higher total capital costs (for instance, US$2.8 billion for 15,899 m^3 from the study conducted by Adegoke et al.), the unit capital cost (which is the capital cost per m^3 of GTL product produced) is smaller and this is the principal reason for the better economic indices for standalone GTL projects as is evident in table 9. For instance, the unit capital cost for small-sale modular plant (used in this study) is US$402,641/ m^3 while that of the large-scale GTL plant (used by Adegoke et al) is US$176,111.7/m^3. Thus there is a 128% increase in unit capital cost due to scale down of the capacity of GTL plant from 15,899 m^3 to 863.3 m^3/d.

Considering the results for GTL-power coproduction for this study and that of Adegoke et al, the situation rather changed. There is higher difference in the absolute percentage difference between GTL-power and GTL results realized from this study (for small-scale plant) than that realized from Adegoke et al (large-scale plant). This is owing to the enhanced optimization process in the research conducted in this study which higher percentage differences.

4.2. Discussion

The conversion of 1,415,842.3 m^3/d of natural gas F-T GTL plant produced 863.3 m^3/d of premium GTL fuels comprising 480.94 m^3/d of gasoline, 219.4 m^3/d of kerosene and 162.96 m^3/d of diesel. From rule of thumb, 283.17 m^3 of natural gas yields 0.159 m^3 of liquid GTL product per day [4, 10]. The GTL plant in this study produced higher than the baseline with an of 8.6% increase in GTL product (i.e. 863.3 m^3/d instead of 794.94 m^3/d as suggested by rule-of-thumb). The NPV of the GTL products is US$299.25 million, while the NCR is US$71.26 million. The pay-out-time, IRR and Profit-per-investment ratio are 4.9 years, 20.3% and 4.13 respectively

Additionally, the electricity generation unit produced an NPV and an NCR of US$23.98 million and US$3.7 million respectively. The pay-out-time, IRR and Profit-per-investment ratio of the electricity generation unit are 2.7 years, 37.4% and 8.36 respectively. Thus, generally, the GTL-coproduction process yielded an NPV and NCR of US$313.96 million, an NCR of US$73.99 million, a POT of 4.8 years, an IRR of 20.5% and a profit-per-dollar invested (P/$) ratio of 4.17. Thus it is seen that the inclusion of electricity production unit alongside the GTL plant increased the NPV by US$14.71 million, an increase of 4.72%.The NCR increased by US$2.76 million, an increase of 3.87%. Furthermore the POT reduced by 0.1 year (reduction of 2%) while the IRR increased by 1%. The P/$ increased by 0.04 which represents an increase of 1%.

Figure 5 and 6 show the POT and IRR plots for GTL and GTL-coproduction systems. It can be seen that the GTL-coproduction system appears more favourable than the GTL system alone. This additional profit realized from GTL-coproduction system can help offset the high capital investment associated with GTL ventures and increase investment interest on the side of investors.

These relatively small improvements translate to huge economic returns for the operator. Because only small capacity (modular) GTL plant was considered in this study, the difference between GTL-Power and GTL standalone projects did not differ much. However for large-commercial plants, there is greater tendency for wider difference between the economic returns from the GTL-power and GTL standalone projects because of the production of more volumes of GTL products and steam from the GTL plant.

Adegoke et al [6] did similar study using waste steam from GTL plant, but their study considered large plant of 15,899 m^3 of GTL fuels produced utilizing 158,987,303 m^3 of natural gas. They utilized a capital cost of US$176211.5/$m^3$ of GTL products. Although the entire capital cost of this large plant is US$2.8 billion, the unit capital cost per barrel is far lower than that used in our study which amounts to US$402,641/ m^3 of GTL products. Thus, the large plant reduced the capital cost per unit of GTL product by 56%. This large reduction in unit capital cost affects the profitability and economics of the GTL capital cost both in standalone and in combination with electricity generating unit.

5. CONCLUSION

The following conclusions are drawn from this study

1. Much facility integration, enhanced configuration and technology upgrade are needed to improve the profitability of GTL ventures and reduce initial startup capital
2. Modular plants require lower total capital costs than large-scale GTL plants, but the unit capital costs for small-scale (modular) plants are higher than the large-scale plants and this affects the total profitability index of standalone GTL projects.
3. GTL-power co-production provides an integrated approach to produce marketable transport liquids and electrical power for commercial purposes with the intention of maximizing the potentials in GTL operations.
4. GTL-power co-production increased the NPV of the GTL process by 4.72% while the annual cashflow increased by 3.87%
5. Large-scale GTL plants have higher economic potentials for standalone GTL projects than small-scale plants but small-scale plants ensures that small volumes of natural gas scattered in remote locations find a market.
6. Small-scale modular plants have greater potential investment opportunities than large-scale plants because of higher risks occasioned by higher total capital costs, product price instability etc.
7. The small-scale plant profitability is enhanced by retrofitting through addition of power generating units
8. The integrated GTL and power production offers a cost effective means of associated gas monetisation with quicker pay-out and higher internal rates of return than standalone GTL processes.
9. GTL technologies offers means to monetise vast stranded associated gases that have often been flared

Abbreviations

ASU: Air Separation Unit
BOD: biochemical oxygen demand
CAPEX: Capital Expenses
COD: Chemical Oxygen demand
DOE: Department of Energy
FTR: Fischer-Tropsch Reactor
GTL: Gas-to-Liquids
IRR: Internal Rate of Return
LNG: Liquefied Natural Gas
Mm^3: Thousand cubic meter
MMUS$: Million US dollars
Mpa: Mega Pascals
MTFB: Multi-tubular Fixed Bed Reactor
NCR: Net Cash Recovery
NPV: Net Present Value
OPEX: Operating Expenses
P/$: Profit-per-dollar invested
PFR: Plug Flow Reactor

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IZVOD

MODELIRANJE GTL-KOPRODUKCIJE ENERGIJE KAO SREDSTVO ZA OPTIMIZACIJU GTL POSTROJENJA

Tehnologije Gas-to- Liquids (GTL) imaju potencijal da pretvore povezane gasove iz baklje u premium transportne tečnosti, stvarajući tržište za inače nasukan resurs. Međutim, kapitalni troškovi GTL postrojenja su tokom godina ometali izbor projekta. Pogon za GTL je poboljšan optimizacijom postrojenja tako da se poveća njegova efikasnost i profitabilnost. Jedno takvo značajno poboljšanje u konfiguraciji GTL postrojenja je integracija jedinice za proizvodnju energije u GTL procesno postrojenje tako da se proizvodnja GTL tečnosti i proizvodnja električne energije mogu odvijati istovremeno u istom postrojenju. Ovaj metod koji se generalno naziva GTL-energetska koprodukcija će povećati ukupnu efikasnost i profitabilnost postojećeg procesa GTL postrojenja i predstaviti načine za ekonomičnu optimizaciju gubitka toplote kroz tokove nusproizvoda (tokove pare i dimnih gasova). Korišćenje tokova nusproizvoda će uzeti u obzir smanjenje termičke neefikasnosti u procesu GTL postrojenja. U ovom radu, dodatna jedinica je dodata konfiguraciji proizvodnog postrojenja od 863,3 m^3/d GTL kako bi se tok pare nusproizvoda koristio za proizvodnju električne energije. Ova dodatna jedinica električne energije proizvela je 10 MW električne energije povećavajući neto sadašnju vrijednost (NPV) postrojenja za 4,72%, dok je neto gotovinski povrat (NCR) povećan za 3,87%. Pored toga, vreme isplate je smanjeno za 2%. Koprodukcija GTL-Electriciti se pokazala kao sredstvo za optimizaciju GTL postrojenja, imajući sposobnost da donese više profita zbog smanjenih kapitalnih i operativnih troškova nego kada bi postrojenja radila odvojeno.

Ključne reči: *gas-tečnost, električna energija, koproizvodnja, Fišer-Tropš, otpadna toplota*

Naučni rad
Rad primljen: 20. 09. 2021.
Rad korigovan: 12. 11. 2021.
Rad prihvaćen: 23. 11. 2021.
Rad je dostupan na sajtu: www.idk.org.rs/casopis
