



Assessment of Feasible and Effective Technologies for the Chemical Utilization of Domestic Coal for Value-Added Production in Vietnam

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Abstract. Vietnam is a country rich in coal resources. Currently, coal is mainly combusted for energy production. However, there is increasing interest to generate additional value from domestic coal via chemical utilization as feedstock for production of chemicals and/or transportation fuels.

This article evaluated the chemical utilization of Vietnam's coal via gasification for the production of syngas, and the subsequent synthesis of syngas via Fischer Tropsch (FT) technology for the production of FT diesel. A technology overview of coal gasification technologies provided insights into different types of gasification processes as well as a comparative evaluation of their advantages and disadvantages. Similarly, a review of FT technologies enabled a comparative technology overview of commercial FT reactors and associated processes, their advantages and disadvantages.

Using a case study approach, the suitability of identified commercial gasification and FT technologies are evaluated based on their applicability for the conversion of high ash-containing Vietnamese anthracite with high melting temperature to produce FT-diesel. Evaluation results indicated that the Fixed Bed Dry Ash (FBDA) gasification technology in combination with the medium-temperature Fischer Tropsch (MTFT) synthesis would be the most advantageous technologies for the production of FT-diesel from Vietnamese anthracite. The importance of considering the gas loop and product recovery is also highlighted.

Keywords: Vietnamese anthracite · Chemical utilization · Gasification · Fischer tropsch synthesis · Technology assessment

1 Introduction

Vietnam is a coal-rich country with 3,704 million tons (MMst) of proven coal reserves [1]. Although domestic coal is utilized mainly for energy production today, there is growing interest to generate additional value from domestic coal resources. This is observable from projects which have been implemented for alternative coal applications such as coal gasification. Via gasification, coal resources can be converted into a chemical feedstock for production of chemicals and transportation fuels rather than using it for energy production via combustion. Not only could it support value-added production from domestic coal resources, the alternative utilization of coal as a chemical feedstock via gasification – rather than as an energy feedstock via combustion – could also contribute to lowering Vietnam's carbon footprint by reducing CO₂ emissions associated with coal combustion. Moreover, it could also contribute to reducing the country's dependence on imported materials for the chemical and transport sectors [2–4].

Predominantly, coal gasification projects in Vietnam utilized underground coal gasification (UCG) processes. With UCG, the actual gasification process occurs underground. Subsequently, synthesis gas (i.e. syngas) produced via gasification reactions are collected for further processing and utilization. For instance, underground coal gasification (UCG) and underground coal bio-gasification (UCBG) technologies are proposed for test implementation in the coal area Red River Basin at Thai Binh and Hung Yen [5]. Another project using Russian UCG technology is also recommended to Vietnam's Dong Duong Corporation [6].

Following gasification, the syngas generated can be used for the production of diverse products. Via Fischer Tropsch (FT) synthesis – a Coal-to-Liquid (CtL) process – syngas from coal gasification can be subsequently synthesized to produce liquid products such as FT-diesel [7]. This would provide an alternative coal-based fuel to conventional diesel for Vietnam's transportation sector. Note that FT synthesis is an indirect coal liquefaction technology. Besides FT synthesis, other CtL technologies include coal pyrolysis technology and direct coal liquefaction technology [8]. These however are beyond the scope of this article.

Currently, while CtL technologies are being investigated on a laboratory-scale in the country, no CtL projects have been implemented so far in Vietnam. Application of CtL technologies such as the combination of coal gasification with FT synthesis for the production of FT-fuels has considerable relevance for Vietnam. Not only could it contribute to increasing the domestic coal value-chain and generate new employment opportunities within the country, in providing a domestic alternative to conventional fuels, it could also decrease Vietnam's dependence on fuel imports.

In view of its strategic significance for Vietnam, this article assessed CtL technologies for the production of FT-diesel. Specifically, the investigation focused on gasification and FT technologies. The article has three main objectives namely (1) technology overview and assessment of gasification technologies, (2) technology overview and assessment of FT technologies, and (3) case analysis of suitability of diverse gasification and FT technologies for FT-diesel production from domestic coal in Vietnam. The article is structured as follows: First, a technology overview and assessment of gasification and FT technologies/processes is provided. Subsequently, the technologies/processes are evaluated according to their suitability for FT-diesel production from domestic coal in

Vietnam. A case study based on high ash-containing anthracite with high ash melting temperature formed the basis for the technology evaluation. The article then concluded with a summary of insights gained from the technology evaluation for the development of Coal-to-FT-diesel as alternative to conventional imported diesel in Vietnam.

2 Technology Overview

Gasification and FT-synthesis technologies represent two key technological components in the Coal-to-FT diesel process chain (see Fig. 1). A technology overview of these two technological components is provided in this section.

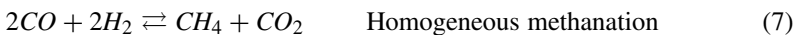
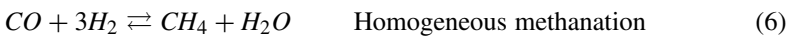
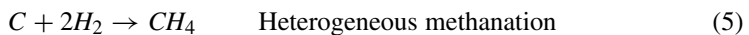
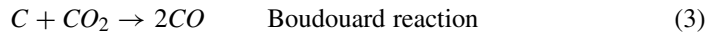
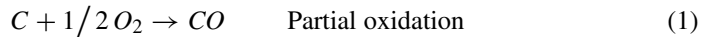


Fig. 1. Simplified Coal-to-FT diesel process chain

2.1 Gasification Technologies

Gasification as a Thermochemical Conversion Process. Gasification is the thermochemical conversion of a fuel (gasification feedstock) with a reactant (gasification agent) to a combustible gas (syngas). The primarily desired components of the produced gas are hydrogen and carbon monoxide. Other products include carbon dioxide, methane and higher hydrocarbons. There are different potential feedstock materials and target products (see Fig. 2).

The main occurring reactions during gasification are:



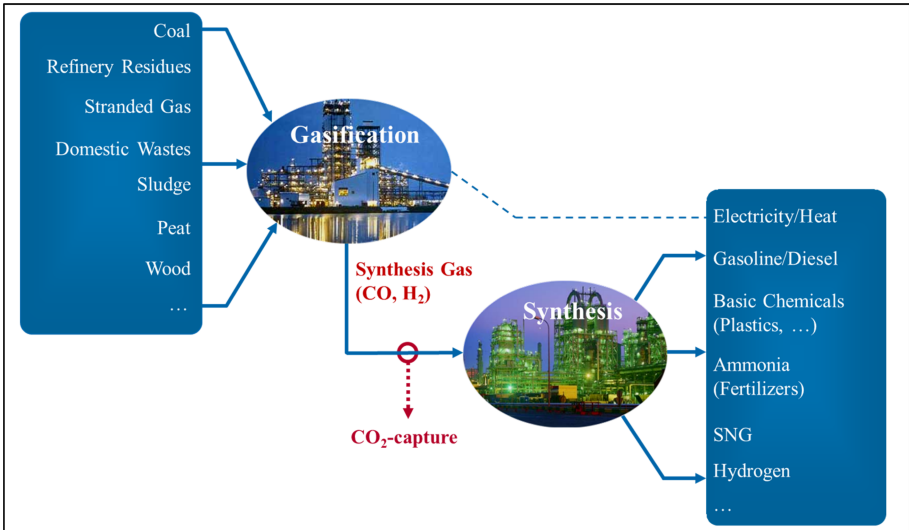


Fig. 2. Potential feedstock materials and target products of gasification processes

For autothermal gasification, required reaction heat for the endothermic gasification reactions is provided by oxygen supply and subsequent partial oxidation. In allothermal gasification operations, the necessary heat (energy) is supplied from outside sources such as hot flue gas or electrical energy. The principles of allothermal and autothermal gasification are illustrated in Fig. 3.

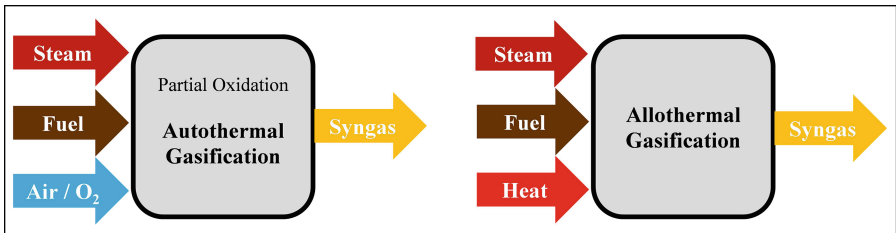


Fig. 3. Autothermal vs. allothermal gasification

The gasification process takes place at temperatures in the range of 800 °C to 1800 °C. The exact temperature depends on the characteristics of the feedstock, in particular the softening and melting temperatures of the ash, and the gasification technology.

There are considerable advantages for gasification under pressure, including savings in compression energy for the generated syngas and reduction of equipment size for the gasification and downstream gas treatment plant [9–13]. Consequently, practically all modern processes are operated at pressures of 10 bar to 100 bar.

Classification of Gasification Processes According to Bed Type. In practical realization of gasification processes, a broad range of reactor types and gasification systems have been developed and applied commercially. For most purposes, these reactor types can be classified by the type of contact between fuel and gasification agent into three categories namely moving-bed (also called fixed-bed), fluidized-bed and entrained-flow gasifiers (see Fig. 4) [9–13].

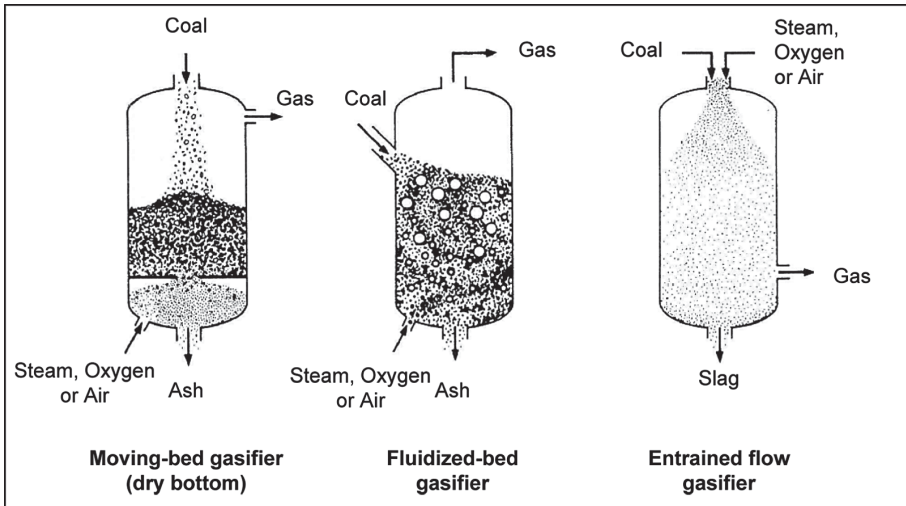


Fig. 4. Main gasification categories [14]

Moving-bed gasifiers (or fixed-bed gasifiers) are characterized by a bed in which the coal moves slowly downwards under gravity. The gasification agents such as oxygen and steam are introduced at the bottom of the reactor – either via a rotating grate for the non-slugging version of the gasifier (Fixed Bed Dry Ash (FBDA) gasifier) or via tuyère nozzles above the slag bath (British Gas/Lurgi (BGL) gasifier). In such a counter-current arrangement, the hot synthesis gas (syngas) from the gasification zone is used to preheat and pyrolyze the downward flowing coal. Therefore, the oxygen consumption is very low. Note that the presence of pyrolysis products in the product synthesis gas requires extensive tar separation steps. Furthermore, the syngas also contains significant amounts of methane. Even though high temperatures are achieved in the heart of the bed – as in the case of the BGL-Gasifier – the outlet temperature of the synthesis gas is comparably low (about 400 to 800 °C). Moving-bed processes operate on lump coal. Advantages of this feedstock preparation method include low cost preparation compared to fluidized-bed and entrained-flow gasifiers and the ability to use waste material as a co-feedstock. A disadvantage of moving-bed gasifiers is that an excessive amount of fines, particularly if the coal has strong caking properties, could block the passage of the up-flowing syngas.

Commercial technologies (Licensors):

- Non-slugging FBDA gasification technology (SEDIN Engineering/China in Asia; Air Liquide Engineering & Construction (formerly Lurgi/Germany) in Europe), see Fig. 5a.
- Slugging BGL gasification technology (ZEMAG/China in Asia; Envirotherm/Germany in Europe), see Fig. 5b.

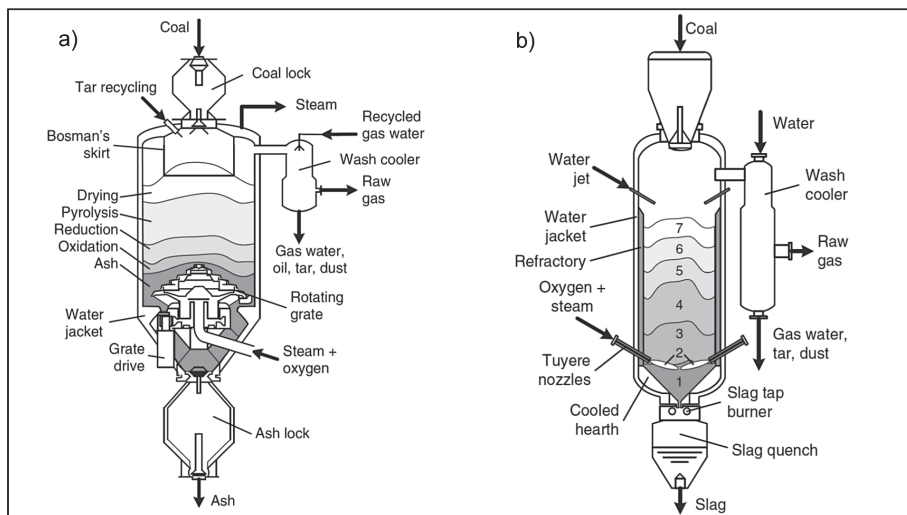


Fig. 5. Moving-bed gasifiers: a) Non-slugging version according to the FBDA technology, b) Slugging version according to the BGL technology [10]

Fluidized-bed gasifiers convert crushed feedstock which is fluidized with a gas flow of gasification agents. It offers a good mixing between feedstock and oxidant, which promotes both heat and mass transfer. However, the good mixing of the bed simultaneously leads to the main disadvantage of the technology. The fresh feedstock and the converted material (mainly ash) cannot be extracted separately. Therefore, there will always be residual carbon in the discharged ash which limits the carbon conversion of fluidized-bed processes and requires further ash treatment. The operation of fluidized-bed gasifiers is generally restricted to temperatures below the softening point of the ash, since ash slugging will disturb the fluidization of the bed. Sizing of the particles in the feedstock is critical; material that is too coarse will settle down to the ash discharge and material that is too fine will tend to become entrained with the syngas at the top of the reactor. Such coal fines are usually partially captured in a cyclone or hot gas filter and returned to the bed. Furthermore, the operation window of the process that is defined by the introduced gas flow of gasification agents is narrow and needs to be carefully predicted in advance. The lower operation temperature of fluid-bed processes (800–1100 °C) means that they are more suited for gasifying reactive feedstocks such as low-rank coals and biomass and for feedstock with a high ash content. Due to the challenges in process handling and

the ash treatment, the worldwide employment of this technology in an industrial context remains limited. Examples of fluidized-bed technologies are presented in Fig. 6.

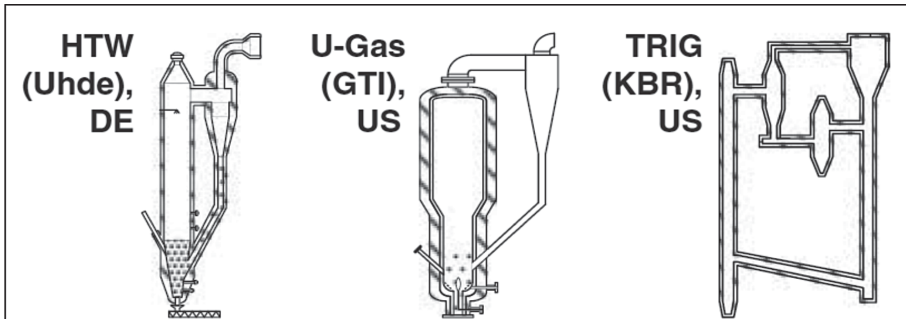


Fig. 6. Fluidized-bed gasifiers (examples) [10]

Commercial technologies (Licensors):

- Agglomerating Fluidized Bed (AFB) gasification technology (Institute of Coal Chemistry, Chinese Academy of Sciences/China).
- High-Temperature Winkler Technology (HTW) gasification technology (ThyssenKrupp Uhde/Germany).
- Utility-Gas (U-Gas) gasification technology (Chicago Gas Technology Institute (GTI)/USA).
- Transport-integrated gasifier (TRIG) (Kellogg Brown & Root (KBR)/USA).

Entrained-flow gasifiers operate with pulverized or liquid (slurry) feedstock in co-current flow. The residence time in the gasifier is short (a few seconds). The feed is grounded to a size of 500 μm or less to promote mass transfer and facilitate transport in a dense flow feeding. Feedstock preparation is essential and also more expensive for this type of gasifier. Given the short residence time, high temperatures are required to ensure a good carbon conversion. Hence, all entrained-flow gasifiers operate in the slagging range (above 1200 $^{\circ}\text{C}$). The high-temperature operation creates a high oxygen demand for this type of process. Entrained-flow gasifiers do not have any specific technical limitations on the type of coal used. However, coals with a high ash melting temperature or high ash content (>30%) will drive the oxygen consumption to levels where alternative processes may be economic advantageous. The generated gas is free of hydrocarbons, has a low amount of methane and needs less efforts for gas cleaning. Examples of entrained-flow technologies are presented in Fig. 7.

Commercial technologies (Licensors):

- Opposed multiple burner (OMB) gasification technology (Institute of Clean Coal Technology at the East China University of Science and Technology (ECUST)/China).
- Hangtian Lu (HT-L) gasification technology (China Aerospace Science and Technology Corporation (CASC)/China).

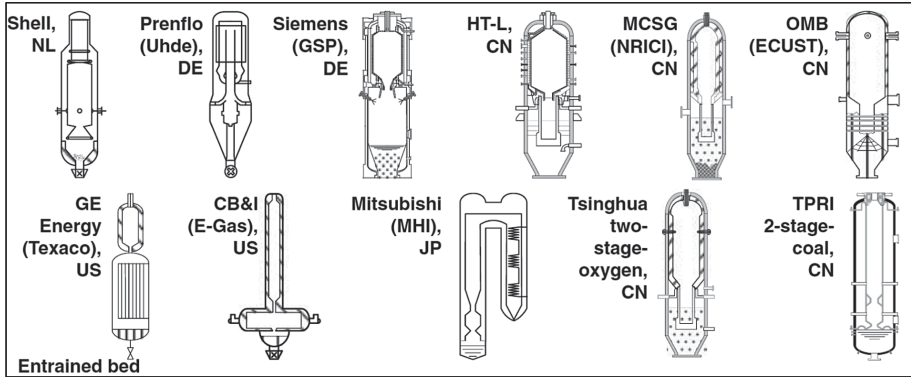


Fig. 7. Entrained-flow gasifiers (examples) [10]

- Thermal Power Research Institute (TPRI) gasification technology (Thermal Power Research Institute (TPRI)/China).
- Multicomponent slurry gasification (MCSG) technology (Chinese Northwest Research Institute of Chemical Industry/China).
- Tsinghua two-stage oxygen gasification technology (Beijing Tsinghua University/China).
- Pressurized entrained-flow (Prenflo) gasification technology (Shell and Uhde/Germany).
- Siemens fuel gasification technology (Siemens Fuel Gasification Technology Freiberg/Germany – no longer traded).
- General Electric (GE) Energy gasification technology (General Electric, formerly Texaco/USA).
- E-Gas gasification technology (Lummus Technology/USA).
- Mitsubishi Heavy Industries gasification technology (Mitsubishi Heavy Industries/Japan).
- Pratt & Whitney Rocketdyne (PWR) gasification technology (Aerojet Rocketdyne/USA).
- Choren Clean Coal gasification (CCG) technology (Choren/Germany).

The main properties of the three gasifier categories are summarized in Table 1. Where special characteristics can be classified into very advantageous (++), advantageous (+) or less advantageous (–), the corresponding table cells are marked. However, in many cases this assessment cannot be generalized.

For moving-bed (fixed-bed) gasifiers, the non-slugging (FBDA) and slugging (BGL) version of the gasifier should be considered individually. For fluidized-bed and entrained-flow gasifiers, the reactor types and process principles can significantly differ depending on individual solutions of different technology providers. Therefore, it is important to note that process selection is always a complex process taking coal properties, boundary conditions and desired product specifications into account.

Table 1. Comparison of different gasification processes (++: very advantageous, +: advantageous or -: less advantageous)

Bed type	Moving-bed (fixed-bed)		Fluidized-bed		Entrained-flow	
Fuel: Particle size	Coarse-grained to lumpy 6 to 60 mm	++	Small-grained 0.5 to 10 mm	+	Pulverized / slurry Up to 0.5 mm	-
& Preparation	None		Crushing		Grinding	
Oxygen consumption	Low/moderate	++	Medium	+	High	-
Steam consumption	High/moderate	-	Low	+	Very low or slurry	++
Ash melting (slagging)	No (FBDA) / Yes (BGL)		No	+	Yes	-
Residence time	15 - 30 minutes	-	5 - 50 seconds	+	2 - 10 seconds	++
Carbon conversion	High Up to 99%	++	Medium 95 to 96%	-	High Up to 99%	++
Raw gas temperature	350 – 800 °C	++	800 – 1000 °C	+	1300 – 1500 °C	-
Synthesis gas ingredients	High in hydrocarbons (tar, PAH's); secondary cracking necessary	-	Low in hydrocarbons; secondary treatment necessary	+	Free from hydrocarbons	++
Typical components CO/H ₂ /CO ₂ /CH ₄	20 / 38 / 28 / 12		38 / 32 / 25 / 5		60 / 35 / 5 / < 0.1	
Typical ash	Fine-grained to glassy		Fine-grained	-	Granulated slag	++
Single unit capacity	Up to 400 MW	+	Up to 500 MW	+	Up to 1000 MW	++
Main challenges	Clogging of bed / fine particles		Particle agglomeration; erosion; limited operation window		Coal preparation; temperature control, oxygen demand	
Process examples	FBDA, BGL		AFB, HTW, U-Gas, TRIG		OMB, HT-L, TPRI, MCSG, Tsinghua, Prenflo, Siemens, GE, E-Gas	

2.2 Fischer Tropsch (FT) Technologies

FT Synthesis for Liquid Production. FT synthesis is a catalytic process based on the conversion of synthesis gas for the production of liquid hydrocarbons from coal, natural gas and other carbonaceous feedstock such as waste, biomass and CO₂. FT products are characterized by a very broad product spectrum containing up to 50 carbon atoms. While main products are generally transportation fuels (see Fig. 8), in some cases waxes and olefins for the cosmetic and chemical industry are desirable products as well.

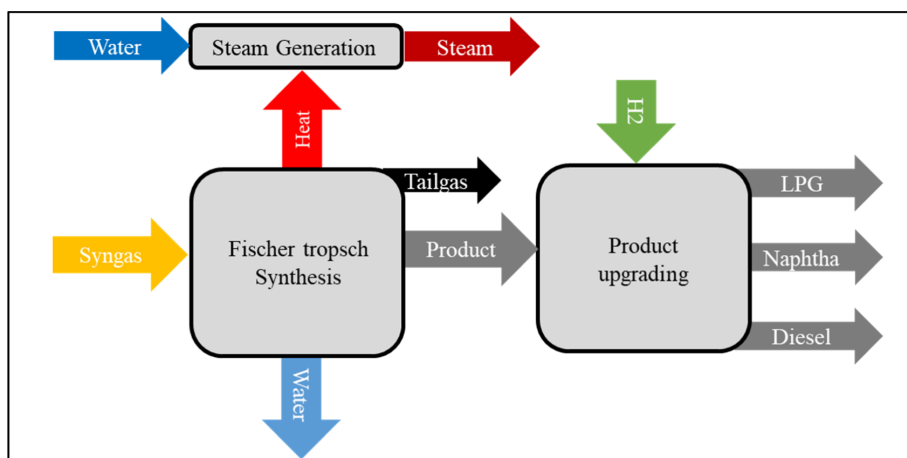
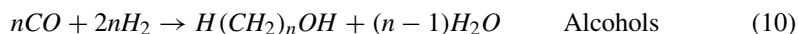
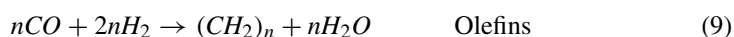
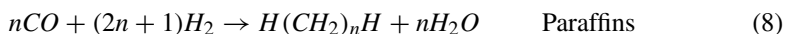


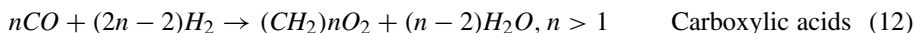
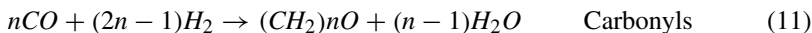
Fig. 8. Inputs and outputs of FT synthesis including product processing

In chemical terms, this synthesis involves the polymerization of carbon monoxide in combination with hydrogenation. These reactions take place in a three-phase system: gas (carbon monoxide, hydrogen, steam and light hydrocarbons), liquid (hydrocarbons and waxes) and solid (catalyst). The most abundant class of produced compounds via FT synthesis are paraffins and olefins, whose proportion in the product spectrum depends directly on the applied catalyst, process conditions and reactor technology.

Three different industrial applications have been developed over the years, namely high-temperature Fischer Tropsch synthesis (HTFT), low-temperature Fischer Tropsch synthesis (LTFT) and the latest medium-temperature Fischer Tropsch (MTFT) synthesis. In recent years, LTFT processes are predominantly used to obtain products with higher molar mass. These technologies are suitable for the production of diesel and waxes [13]. This trend towards LTFT synthesis and especially cobalt-based synthesis can be seen in the latest publications and studies on the techno-economic evaluation of process chains in which FT processes are involved [15–22]. MTFT synthesis produces a similar spectrum of products as LTFT. This synthesis is available for a production of fuels as main product. HTFT synthesis is a process variant mainly used for the production of chemicals (olefins) and gasoline. A co-production of long chains fuels together with chemicals and gasoline through HTFT synthesis is only possible with a suitable short olefin Oligomerization Unit.

The following chemical reactions represents the main reactions during FT synthesis, which occur mainly in all industrial applications. The FT reactions are exothermic, producing an average heat of reaction of 10 MJ per kg of hydrocarbon product produced [23].





All these reactions can be catalysed by a variety of active metals capable of catalyzing them. These include among others, Fe, Co, Ni, Ru and Rh. Of these, only cobalt and iron have exhibited good results in industrial applications [24]. The FT-catalyst not only contains one active metal, it also includes several promoters and can be combined with a carrier [23]. The development of promoters and supports in catalysis plays an essential role in the intensification of the FT process and its transition from laboratory scale to commercial plant.

Technical aspects such as catalysis, catalyst lifetime, FT crude chemistry, heat integration and process conditions, are of key importance when selecting an appropriate FT technology. The selection of a specific FT technology for an industrial/commercial application has a ripple effect on many of the design decisions [25]. Hence, this assessment focused on the applied metal catalyst, the composition of the FT crude, the quality of the FT crude, the quality of steam produced and the operating conditions of the process.

Classification of FT-Reactors & Associated FT-Processes. In current commercial applications, four main multiphase reactors can be identified for FT synthesis (See Fig. 9). On the one hand, there are stirred flow reactors such as the Slurry Bubble Reactor Column (SBRC) and Fluidized Beds (CFB and FFB). On the other hand, there are plugged flow reactors such as the Multi Tubular Fixed Bed reactor (MTR) and Microchannel Reactor (MCR). FT reactors are typically catalyzed at 190–360 °C and 15–50 bar [26]. Subsequently, the different FT reactors and associated FT processes are briefly discussed and their respective commercial licensors specified.

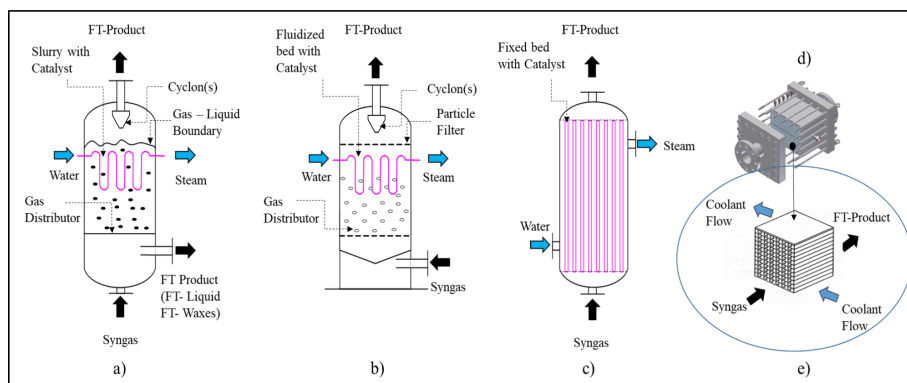


Fig. 9. Slurry Bubble Column (a); Fluidized bed (b); Multi-tubular Fixed bed (c); Two bpd Microchannel plant (d) & Microreactor scheme (e). (a): taken and adapted from [26, 27]; (b) and (c): taken and adapted from [27]; (d): taken from [28] and (e): taken and adapted from [29].

Slurry Bubble Reactor Column (SBRC): Slurry reactors are three-phase systems, including solids (catalyst), liquid and gas fractions. The reactor consists of a vertical vessel with a gas distributor for the synthesis gas, a stack of heat exchanger tubes inside for steam generation and a cyclone on top of the vessel. The cyclone is necessary for the separation of the catalyst powder, which is carried in the gas stream. These technologies are developed to overcome the difficulties associated with multi-tubular reactors [30]. Catalyst wear (catalyst deactivation) as well as separation of the catalyst from the liquid and wax are the main challenges for these technologies. This is because for expensive catalysis such as cobalt in LTFT synthesis, wear is a significant negative aspect. Comparing prices of FT catalysts [31], iron catalyst are a thousand times cheaper than cobalt catalyst.

Commercial technologies (Licensors):

- Slurry Bed Process/Slurry Bed Reactor (SBP/SBR): Slurry technology for the Fe and Co-LTFT synthesis (SASOL/South Africa).
- High temperature Fischer Tropsch process (HTSFTP): Slurry technology for the Fe-MTFT synthesis (Synfuels/China).

Fluidized Bed Reactor (CFB and FFB): Fluidized Bed reactors are used for two-phase systems, where gas reacts on a solid catalyst surface. Normally, fluidized beds need a fluidization gas but in the case of FT synthesis this is not necessary because synthesis gas serves as medium for the fluidization [31]. This type of reactor is mainly used for the iron-based HTFT technology. Originally, the technology is based on a recirculation system (circulating fluidized bed CFB), which is further developed over the last years to a fixed fluidized reactor (FFB). The fixed fluidized bed has a simpler design than CFB and includes a gas distributor and a number of heat exchangers and cyclones for the separation of catalysts particles. The design of FFB is similar to the Slurry Bubble Reactor and is developed for the improvement of issues present in the Multi Tubular Fixed Bed Reactor. However fluidized beds present problems such as agglomeration and the formation of blockages that compromise the scale-up on this application [30].

Commercial technologies (Licensors):

- Synthol: CFB technology for the Fe-HTFT synthesis (SASOL/South Africa).
- Sasol advance Synthol (SAS): FFB technology for the Fe-HTFT synthesis (SASOL/South Africa).

Multi-tubular Fixed Bed Reactor (MTR): This multiphase application is available for reactions in the gaseous, solid and liquid phases and is originally developed in Germany for Fe-LTFT synthesis [32]. The reactor contains a defined number of catalyst packed tubes with heat removal through steam generation on the shell side of the reactor. MTR is most robust of all commercial reactors and is the technology with the longest and most proven history of stable and reliable FT operation [23]. Operational problems include a relatively high pressure drop, low heat removal, low catalyst utilization, heat and material transport limitations (filling the pores of the catalyst with wax) and need for periodic replacement of the catalyst [30].

Commercial technologies (Licensors):

- ARGE Reactor: MTR Technology for the Fe-LTFT synthesis (Lurgi/Germany and SASOL/South Africa).
- Shell Middle Distillate Synthesis (SMDS): MTR technology for the Co-LTFT synthesis (SHELL/Netherlands).

Microchannel Reactor (MCR): Chemical reactor units based on microchannel technology are characterized by parallel sets of microchannels in a range of less than millimeters (<1 mm) [33]. The application of this technology in FT synthesis offers different advantages such as, intrinsic catalyst kinetic phenomena, good temperature control (quasi-isothermal operation), catalyst activity, good mass and heat transport conditions and high volumetric productivity [28]. The main challenges of this type of reactor are the difficulty of changing the catalyst [30] and the higher methane selectivity characteristic of cobalt-based FT synthesis [25].

Commercial technologies (Licensors):

- Micro reactor technology for the Co-LTFT (Velocys/USA)
- Micro structured reactors for the Co-LTFT (Ineratec/Germany)

Comparing the capacity of the different projects, the one project involving a Microreactor technology represents a very small production compared with the actual standards of FT crude production. The highest production of FT crude achieved using the Microreactor represents approximately 60% of the capacity of the ARGE multi tubular fixed bed reactor implemented at SASOL 1 in the 1950s.

The main properties of FT processes and associated FT reactors are summarized in Table 2. Specific characteristics are classified into very advantageous (++), advantageous (+) or less advantageous (-).

Table 2. Comparison of FT-Synthesis in different processes (++: very advantageous, +: advantageous or -: less advantageous)

Item	Fe-LTFT [8]		Co-LTFT [8]		Fe-HTFT [8]		Fe-MTFT [34]	
Temperature (°C)	200-270		170-230		320-360		260-290	
Operation pressure (MPa)	2.0-2.5		2.0-2.5		2.0-2.5		1.5-4.0	
Reaction phase	Gas+liquid +solid		Gas+liquid +solid		Gas		Gas+liquid +solid	
Reactor Types	MTR SBRC		MTR SBRC MCR		CFB FFB		SBRC	
Liquid fraction in FT crude	High	++	High	++	Low	-	High	++
CO ₂ Co-Production	Yes	-	No	++	Yes	-	Yes	-
Methane Production	Medium	-	Medium	-	High	-	Low	++
Olefin Production	Medium	+	Low	-	High	+	High	+
Pressure of Steam (MPa)	Medium	+	Medium	+	High	++	High	++
Temperature of Steam (°C)	180-230	+	180-230	+	320-360	++	270-320	++
Catalysts life time (approximate)	6 months	-	4-6 years	++	6 months	-	6 months	-
Process examples	Sasol 1 (SASOL)		Mossgas (SASOL), SMDS (Shell) and micro reactors (Velocys)		Sasol 2 and Sasol 3 (SASOL and Petro S.A.)		HTFTSP (Synfuels China)	

Along with the classification of the reactors and their respective processes, it is important to consider how the catalysts can be changed during the FT process. Generally, stirred reactors (SBRC, CFB and FFB) change their catalyst online (in operation). On the other hand, in plugged flow reactors such as MTR and MCR, a repositioning off-line of the catalyst is necessary.

3 Technology Evaluation for the Production of FT-Diesel from Anthracite in Vietnam

Globally, the search for suitable technological solutions for value-added production from high ash-containing coal is ongoing. High ash-containing coal, in particular those with high ash melting point as identified in Vietnamese anthracite, are especially challenging for most gasification technologies. Hence, to evaluate the suitability of different gasification and FT synthesis technologies for the chemical utilization of Vietnam's coal, we utilized a case analysis approach and focused our evaluation on identifying suitable technologies for the chemical utilization of high ash-containing anthracite with high ash melting temperature for the production of FT-diesel.

3.1 Evaluation of the Suitability of Gasification Technologies

Generally, compared to other carbon resources, anthracite has a low hydrogen to carbon atomic ratio and a low oxygen to carbon atomic ratio. Figure 10 illustrates the H/C-atomic ratio and O/C-atomic ratio of anthracite in comparison to hard coal, lignite, peat, biomass and refinery residues in the van Krevelen diagram.

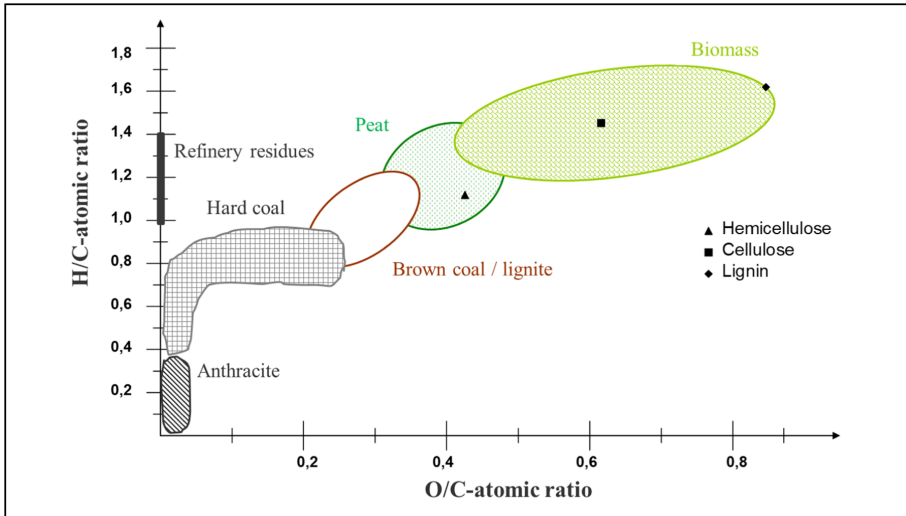


Fig. 10. Anthracite in the van Krevelen diagram (modified from [35])

High ash-containing Vietnamese anthracite will reduce the heating value to a moderate level and significantly influences the selection of suitable gasification processes. In combination with high ash fusion temperatures (AFT) i.e. high ash melting points, slagging gasification processes are unsuitable. Gasifying at temperatures this high would increase the oxygen consumption of the gasification process and with it the operation costs, whereby the overall process efficiency would be reduced. An addition of flux to the coal feedstock in order to lower the ash melting point is also not economic with such a high ash content. For these reasons, entrained-flow gasification and moving-bed gasification using British Gas/Lurgi (BGL) gasifiers are also not suitable for the conversion of Vietnam's high-ash anthracite into syngas.

Looking at fluidized-bed gasification, there are several critical process characteristics to consider. As indicated in Table 1, the moderate temperatures will lower the reaction rate and lead to less cracking of higher hydrocarbons (tars), which then contaminate the raw gas. Furthermore, fluidized bed gasification has a limited carbon conversion of about 95%, whereby an ash with residual carbon leaves the reactor. The unexploited carbon in the ash reduces the overall efficiency of the process and makes ash disposal difficult and expensive. Usually the ash cannot be landfilled without further treatment due to its high leachability and the environmental issues involved in this. Therefore, it must be further treated via post-combustion to remove the carbon. For those disadvantages

mentioned, the worldwide industrial application of fluidized bed gasification is limited. Hence, fluidized bed gasification is also evaluated as not being suitable for the conversion of Vietnam’s anthracite to syngas.

The analysis of coal characteristics leads us to the conclusion that a non-slugging moving-bed (fixed-bed) gasification process according to the FBDA technology is most suitable for the conversion of high ash-containing Vietnamese anthracite with high ash melting temperature to syngas designated for FT diesel production. This process is able to cope with the high ash content in combination with the high ash fusion temperatures. The limited effort for coal preparation, low oxygen consumption due to the internal heat exchange between coal and evolving syngas and a high carbon conversion rate is beneficial for the overall process efficiency and for the economics. Due to the high ash fusion temperature of Vietnamese anthracite, the reaction temperature can be comparably high, which reduces the steam consumption that usually acts as cooling medium. The amount of waste water is comparably low. Furthermore, produced tar/oil fractions are suitable and even beneficial for integration into FT product upgrading. The decisive criteria for gasification process evaluation is summarized in Table 3.

Table 3. Overview about decisive criteria of gasification process selection for the conversion of high ash-containing Vietnamese anthracite to syngas

Bed Type	Criteria	
Moving-bed (non-slugging)	<ul style="list-style-type: none"> • Proven and robust technology for high-ash coals • High carbon conversion • Low-moderate oxygen consumption • Low steam consumption • Tar/oil fractions in syngas can be beneficial for FT product upgrading 	++
Moving-bed (slugging)	<ul style="list-style-type: none"> • High oxygen demand due to high ash content and high ash fusion temperature • High costs • Low overall efficiency 	-
Fluidized-bed	<ul style="list-style-type: none"> • Low carbon conversion • High ash treatment effort due to residual carbon in the ash • Limited industrial application worldwide 	-
Entrained-flow	<ul style="list-style-type: none"> • High oxygen demand due to high ash content and high ash fusion temperature • High costs • Low overall efficiency 	-

After gasification, the produced syngas requires subsequent state-of-the art gas treatment steps such as the removal of higher hydrocarbons (tars/oils) from the raw gas by means of a wash cooler, the configuration of a desired H₂/CO ratio by means of a raw gas conversion step and the removal of CO₂ and sulfur compounds by means of a Rectisol wash. Following that, the purified syngas is ready for conversion to FT-diesel via the FT synthesis.

3.2 Evaluation of the Suitability of FT Technologies

A summary of the comparative analysis of the advantages and disadvantages of different FT processes is presented in Table 2. From the information in Table 2, it is observable that the use of a specific catalyst defines the productivity of the main products (liquid fraction of the FT crude) and that of the co-products water and carbon dioxide in the tail gas. Note that carbon dioxide will be produced in all iron-catalyzed FT syntheses, a disadvantage compared to cobalt-based FT synthesis as an additional unit will be needed for the separation of carbon dioxide from the tail gas (read more about carbon dioxide and the gas loop in the following Chapter).

With respect to the amount of liquids produced, the only technology at a disadvantage is Fe-HTFT as it produces mainly short-chain hydrocarbons (more than 90% of the crude oil is short-chain). In contrast, cobalt is a catalyst with a much longer life than iron catalysts.

In evaluating the suitability of different FT processes, the chemistry of the crude must also be considered. One way to characterize it is the amount of olefin produced. Olefins are valuable products for the chemical industry and their co-production (e.g. of lubricants) is an advantage over other processes where only fuels are produced (see more in Sect. 3.3). Iron catalysts generally produces more olefins than cobalt.

In energy terms, the production of steam and methane are aspects to be considered. The integration of heat or power generation in a FT plant with high quality steam (high temperature and high pressure) determines the usefulness of the energy co-produced during synthesis (steam contains approximately 15 to 20% of the energy present in syngas [25]). Methane, in principle, is a valuable co-product and can be sold as synthetic natural gas (SNG) or recycled to the FT synthesis (gas loop). The problem is that methane for recycling or separation requires the implementation of more units. For this reason, low concentration of methane in gas loop is considered advantageous in our evaluation.

The analysis summarized in Table 2 show that the MTFT exhibits more favorable process conditions than other FT technologies. Our evaluation indicated that Fe-MTFT would be the most advantageous of the considered FT technologies for fuel production from coal. Not only does Fe-MTFT generate high productivity of the main products (liquid fraction of the FT crude), it has low production of methane, produces olefins as valuable co-products in addition to producing high quality steam suitable for plant integration.

Note that for a complete analysis and selection of the most suitable FT technology, aspects relating to gas loop and product recovery will also need to be considered. This is briefly summarized in the following section.

3.3 Perspective: Gas Loop and Product Recovery

The recycling (recovery) of unreacted carbon monoxide and unreacted hydrogen as well the possible reforming of the co-produced methane is known in the field of process engineering as gas loop. In this case it is dependent on the choice of FT technology. In [27], de Klerk showed a general diagram for the gas loop and product recovery which served as the basis for our evaluation (see Fig. 11). It provides an overview of the

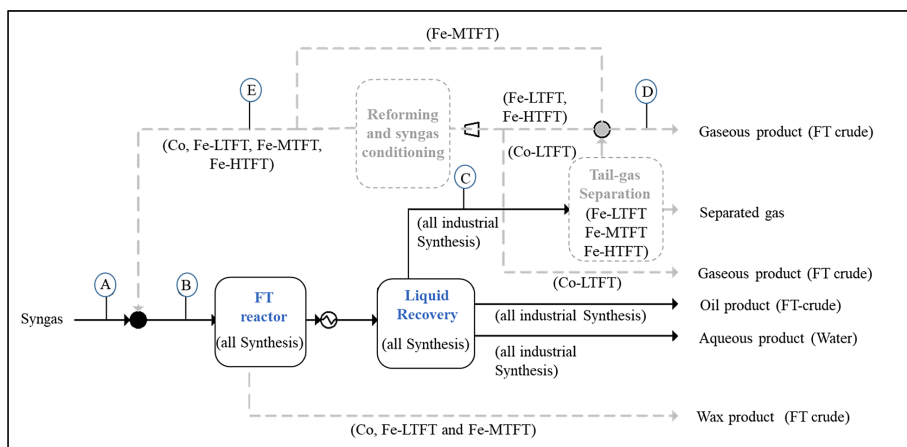


Fig. 11. Steps and units for the recovery of product, gas-loop and balance points of FT process. A: Point for the feed into the FT-System; B: Point after the mixing of the feed with the gas loop; C: Point for measurement before gas treatment (if necessary); D: Treated gas as FT tail gas as part of FT-Syncrude and E: Stream for gas loop. (Adapted from [27])

necessary processes required for FT technology in the case of treatment and integration of the respective gas loop.

The primary liquid recovery from FT synthesis is a phase separation (normally in two stages) which is present in all FT processes. However, it possesses different characteristics depending on the selected FT process. The main difference is that a larger gaseous phase is obtained from the higher yield of gaseous components of the HTFT. In comparison, LTFT and MTFT produce more liquid hydrocarbons and waxes. Note that the separation of olefins from the FT liquid is unusual in a diesel production context. Normally the olefin content in the liquid phase will be saturated with a hydrotreater. The separation of linear olefins from the FT liquid, as a detergent precursor for example, is a possibility for diversification of FT products in the chemical industry.

After the recovery of liquids and waxes and water separation, the light hydrocarbons (C_1-C_4) together with the unreacted synthesis gas are treated and separated. The process route for gas separation depends strongly on synthesis gas sources as well on the selected FT process.

For the treatment of the tail gas of all FT processes where an iron catalyst (i.e. Fe-MTFT, Fe-LTFT and Fe-HTFT) is used, it is necessary to implement a unit for the separation of the co-produced carbon dioxide. This is also known as the Benfield process. After the separation of carbon dioxide, the subsequent gas loop application for iron-based FT processes is variable. Since the selectivity for methane and the production of shorts olefins is the highest for the Fe-HTFT, a cryogenic separation of the short olefins and an additional Autothermal Reformer (ATR) is necessary to reintegrate methane to achieve high liquid product yields. The Fe-LTFT contains a similar gas loop as the Fe-HTFT, with the difference that a cryogenic separation is not necessary as Fe-LTFT does not produce as much short olefins as Fe-HTFT. In the case of Fe-MTFT, the gas loop only requires the Benfield process. If the synthesis gas used contains a high concentration of

methane, there is the possibility of reforming with an ATR (see Fig. 11) or the possibility to sell as synthetic natural gas SNG.

With respect to the Co-LTFT process, a determination of the use of the methane in the gas loop is necessary. The preferable utilization of the methane depends on the project framework and source of the synthesis gas. If Co-LTFT synthesis is applied in a gas-to-liquid (GtL) context, this synthesis will operate with an ATR or reformer unit. This process has a superior methane concentration in the gas loop than the Fe-MTFT.

4 Summary

Vietnam is a country rich in coal resources. Currently, coal is mainly combusted for energy production. However, there is increasing interest to generate additional value from domestic coal via chemical utilization as feedstock for production of chemicals and/or transportation fuels. Not only could the use of coal as a chemical feedstock – rather than an energy feedstock – contribute to lowering Vietnam's carbon footprint, it could also contribute to reducing the country's dependence on imported materials for the chemical and transportation sectors, in addition to generating new employment opportunities in the domestic coal value chain.

This article evaluated the chemical utilization of Vietnam's coal via gasification for the production of syngas, and the subsequent synthesis of syngas via Fischer Tropsch (FT) technology for the production of FT diesel. A technology overview of coal gasification technologies provided insights into different types of gasification processes as well as a comparative evaluation of their advantages and disadvantages. Similarly, a review of FT technologies enabled a comparative overview of commercial FT reactors and associated processes, their advantages and disadvantages as well as typical FT crude compositions. Using a case study approach, the suitability of identified commercial gasification and FT technologies are evaluated based on their applicability for the conversion of high ash-containing Vietnamese anthracite with high melting temperature to produce FT-diesel. Evaluation results indicated that the Fixed Bed Dry Ash (FBDA) gasification technology in combination with the medium-temperature Fischer Tropsch (MTFT) synthesis would be the most advantageous technologies for the production of FT-diesel from Vietnamese anthracite. The importance of considering the gas loop and product recovery is also highlighted.

The current investigation provided decision-makers in Vietnam with first insights into the suitability of gasification and FT technologies – as key technological components of the coal-to-liquid process chain – for the chemical utilization of Vietnamese anthracite for the production of FT diesel. To support strategic decision-making process regarding developing Vietnam's coal resources in this direction, additional technical evaluation of entire process chains as well as economic evaluation of investment and operating costs (i.e. CAPEX and OPEX) for producing FT diesel from Vietnamese anthracite will be required.

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