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Upgraded Methodology for Process Intensification in Natural Gas Dehydration

Rozšířená metodika pro intenzifikaci procesu vysoušení zemního plynu

SHORT VERSION OF DOCTORAL THESIS
TEZE DIZERTAČNÍ PRÁCE

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ABSTRACT

Natural gas dehydration (NGD) is essential in the processing of the associated and non-associated natural gas (NG). Its role is crucial in avoiding the hydraulic slugs, hydrate formation prevention, electrochemical corrosion control, beneficial production, and quality requirement fulfillment.

From the perspectives of capital and operational expenses (CAPEX and OPEX), energy consumption, pollution, and greenhouse gas emissions (GHG), the natural gas dehydration (NGD) has all the drivers that support approaching it via the modern process engineering concepts, such as process intensification (PI). The global requests to consider the health and environmental aspects of any development apply further pressure toward this implementation.

The literature review reveals a concern with the PI equipment, more than the PI methods and the concepts of the process itself. Furthermore, there is a limited utilization of the computer-aided simulation to serve the PI research.

This thesis presents an **upgraded methodology for PI in the NGD**. The developed method is a **systematic simulation-based one** that integrates the rated energy consumption (REC) with the dry gas water content specification. The presented method focuses on the mutual relation between the REC as a key driver and evaluation tool of the PI, and the water content specification which is the key input for NGD design. The REC is formulated of two components, process or equipment energy consumption, and enthalpy loss by venting.

A combination of two methods is used to formulate the upgraded methodology,

- a systematic method that recognizes unit intensification and extended process intensification.
- a concise framework for PI implementation in the O&G proposed originally by the author.

The established simulation-based method used a powerful process simulator to simulate an absorption-based dehydration unit as a case study for an existing gas plant. The studied dehydration unit uses triethylene glycol (TEG) as a solvent.

A sensitivity analysis of the unit independent variables' impacts on the PI approach is done. The method defines three scenarios to effectively intensify the process in the core unit (TEG), (1) the TEG circulation, (2) stripping gas flow rate, and (3) regeneration reboiler temperature. The defined scenarios can reduce the REC by 11%-18%, BTEX emissions up to 69%, $CO_{2\text{-(process)}}$ up to 37%, and TEG loss reduction of about 35%, without compromising the product specification. Due to no CAPEX impacts, these scenarios are valid for both, future design, and current TEG units in operation.

Furthermore, the proposed systematic method was also implemented for the upstream and downstream adjacent units. The output indicated the potential PI in terms of REC that could be achieved over the entire process. Moreover, the same method can be used for approaching the PI in any other process by incorporating the specific independent variables of the studied process.

ABSTRAKT

Vysoušení zemního plynu, anglicky *natural gas dehydration*, je zásadní součástí procesu zpracování vytěženého zemního plynu. Klíčová úloha vysoušení spočívá především v podpoře množství a kvality produktu, ale také v prevenci tvorby hydrátů, koroze či nežádoucí vodní kontaminace při transportu plynu.

Tento petrochemický proces má všechny předpoklady pro aplikaci tzv. *intenzifikace procesů* (PI), moderního přístupu z oblasti procesního inženýrství. Jeho intenzifikace je žádoucí z pohledu investičních a provozních nákladů (CAPEX and OPEX), spotřeby energie i produkce nežádoucích emisí. Současné globální požadavky v oblasti ochrany životního prostředí i ochrany zdraví osob umocňují význam těchto snah. V odborné literatuře v posledních letech významně roste zájem o intenzifikovaná zařízení (*PI equipment*), méně však už o rozvoj metod intenzifikace procesů a jejich aplikaci na komplexnější procesy. Překvapivě málo se také při výzkumu PI využívá počítačové podpory ve formě simulace procesů.

Předložená práce představuje **novou systematickou metodu pro intenzifikaci procesu vysoušení zemního plynu** založenou na počítačové simulaci, která využívá dva hodnotící parametry: jmenovitou spotřebu energie (Rated energy consumption, REC) a předepsaný obsah vody v produkovaném zemním plynu. Spotřeba energie je tvořena přímou spotřebou samotného procesu a entalpickými ztrátami přes hranici procesu. Snižování jmenovité spotřeby energie je klíčovou motivací intenzifikace a současně prostředkem k jejímu hodnocení. Předepsaný obsah vody je klíčovým projekčním a provozním parametrem procesu. Navržená metoda vychází z interakce těchto dvou parametrů.

Práce staví na zodpovědném rozlišování mezi intenzifikací konkrétní procesní jednotky a intenzifikací komplexnějšího procesu, který zahrnuje více dílčích jednotek. Využívá přitom efektivní rámec pro implementaci PI v petrochemickém průmyslu, který byl definován autorem práce.

Navržená metoda byla aplikována na existující průmyslový provoz zpracovávající vytěžený zemní plyn. Pro analýzu nejčastěji využívané technologie sušení, tzv. triethylenglykolové absorpce (TEG), byl použit výkonný software pro simulaci procesů. Byla provedena citlivostní analýza jmenovité spotřeby energie (Rated energy consumption, REC) této jednotky na změnu tří vybraných proměnných – průtoku triethylenglykolu, teploty v koloně a průtoku stripovacího plynu. Ukázalo se, že tyto proměnné mají obrovský potenciál pro intenzifikaci TEG jednotky. Jejich cílenou změnou je možné snížit jmenovitou spotřebu energie o 11 až 18 %, BTEX emise až o 69 %, emise CO_2 až o 37 % a ztráty triethylenglykolu až o 35%, přičemž není negativně ovlivněna předepsaná kvalita produktu. Metoda předpokládá postupné provozní zásahy do procesu a nevyužívá technologických změn. Navržené úpravy jsou proto velmi dobře využitelné při optimalizaci provozu stávajících jednotek glykolové absorpce i návrhu nových.

Navržená systematická metoda byla použita i na další jednotky, které předchází a navazují na glykolovou absorpci. Výsledky potvrzují výše uvedený přínos a významný potenciál PI při snižování spotřeby energie, kterého může být dosaženo v rámci celého procesu vysoušení zemního plynu.

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Chapter 1 Research objective and methodology

Oil and gas (O&G) continue to be the **dominant shareholder** of energy sources and raw materials for many applications, especially with the **steady increase** in the consumption of O&G to overcome the increase in demand. There is a need for powerful methodologies for process intensification (PI), which support achieving sustainable development of this sector in an efficient, profitable, and environmentally friendly manner.

The comprehensive literature review reveals

- a concern with the PI equipment, more than the PI methods and the concepts of the process itself, and
- limited utilization of the computer-aided simulation to serve the PI research.

This work aims to fill the gap and develop a clear systematic simulated-based method for process intensification in O&G that meets

- the PI drivers and process specifications, and
- easy and efficient utilization, that serves the **future design**, as well as the **current facilities** in operation.

To achieve the desired target, this work combines

- a method that recognizes unit intensification and extended process intensification, and
- a concise framework for PI implementation in the O&G proposed originally by the author. The used framework adopted the rated energy consumption (REC) as a key driver and evaluation tool of the intensified solution.

An overview of the objectives of the dissertation and applied methods is presented in Table 1.

Table 1 Overview of objectives and methods of implementation

Chapter	Partial target	Applied methodology
3	Investigating the current status of the process intensification in the petrochemical industries	• Establish a basic knowledge and understanding of fundamental concepts, which secure proper analyzes of the studied topic • Analysis of the statistics data about PI implementation and PI drivers in the petrochemical industries
4	Problem definition and goal setting	• Literature review of PI in the O&G • State of the art of PI in natural gas dehydration • Identifying research gaps • Goals setting • Solution approach
5	Theoretical base about natural gas dehydration	• Introduction to the natural gas processing and dehydration role • Definition of the fundamental concepts of dehydration and product specification • Review of the dehydration methods
6	Process intensification method	• Solution approach • Used tools (powerful process simulator)
7	Current state modeling	• Case study definition via the provided documentation and operator's available data • Establishing the simulation model of the facility using • Extract the current state results for benchmarking
7	Intensified solution modeling	• Simulation of the intensified solutions at the level of the unit, and the entire process • Extracting the results and graphical representation
7 & 8	Results analysis and evaluation	• Comparison between the intensified solution and the current state • Benefits evaluation • Conclusions

Chapter 2 Introduction

Natural gas dehydration (NGD) is essential in avoiding hydraulic problems such as slugs, hydrate formation prevention, electrochemical corrosion control, storage, transportation, and fulfillment of product specifications. Its role is integrated with the upstream phase separation process, and crucial for the performance of the downstream processes such as natural gas liquids (NGL_s) recovery. When the phase separation isolates the water in the liquid phase of the stream, the water vapor flows with the gas phase, and dehydration is the process responsible to catch this water. This guarantees a dew point less than the minimum operating temperature in the downstream units, especially those which work at a very low operating temperature [1]. The NG processing basic sequence is shown in Figure 1.

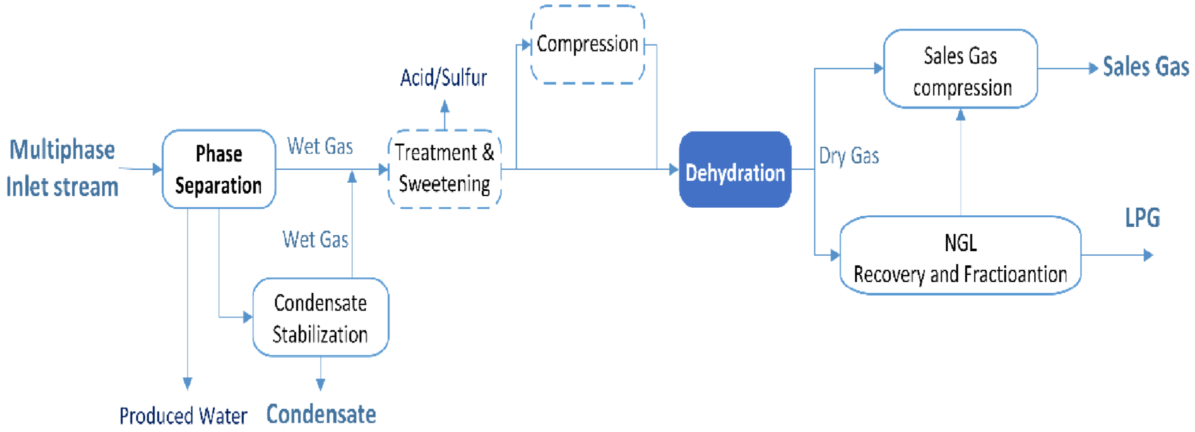


Figure 1 Basic sequence of natural gas processing

Due to its high capital and operational costs, energy consumption, greenhouse gas emissions, and some hazardous pollutants, the NGD is one of the most preferred processes for modern process engineering concepts such as **process intensification** (PI). The PI represents a promising solution that could serve the NG industry, especially since the PI drivers exist throughout the supply chain, from production wellheads to end consumers. This is valid for both types of NG processing facilities, the associated NG units, and the non-associated NG treatment and processing plants. The high capital and operational expenses (CAPEX and OPEX) of the NG industry are not limited to the processing facilities, as it is in the oil refining. The pipeline, transportation, and storage facilities are all of very high CAPEX and OPEX in comparison to the oil refining production and non-process facilities.

All these reasons motivated the companies to invest in the PI of the NG facilities, in addition, there were some new technologies which are developed particularly for the previously abandoned gas fields. The PI provided promising solutions for investing even in those areas with low economic paybacks.

The NGL fractionation and NGD are classified as potential candidates for any PI approach that could be applied in the NG industry. The PI in the fractionation units was studied widely in the oil refining and the results could be generalized to the NG processing units. On the other hand, further efforts have to be done concerning the PI in the NGD due to its crucial role in this industry. The development of an effective methodology for PI implementation in the NGD requires a clear understanding of the fundamentals of both PI and NG processing.

Chapter 3 Process intensification and its drivers in the O&G

Achieving development in the traditional industries becomes an insisting need due to economic and technical reasons. The global requests to consider the energy, health, and environmental aspects of any development apply more pressure to manage this development sustainably. Oil and Gas (O&G) is one of the most preferred sectors to be considered for such sustainable development, as it has all drivers to be developed via the modern process engineering concepts, such as process optimization, process integration, and process intensification (PI), which can significantly lead this development.

3.1 Process intensification fundamental concepts

The first definition of PI was presented in the works of Ramshaw and Cross in the 1980s [2], and expanded by Stankiewicz and Mouljin [3] to be "*Any chemical engineering development that leads to a substantially smaller, cleaner, and more energy-efficient technology*." Reay and Baldea [4] added safety as an additional driver for consideration in the PI.

Van Gereven and Stankiewicz [5] proposed four **fundamental principles**,

- Principle 1: Maximize the effectiveness of intra- and intermolecular events
- Principle 2: Give each molecule the same processing experience
- Principle 3: Optimize the driving forces at every scale and maximize the specific surface area to which these forces apply
- Principle 4: Maximize the synergistic effects

The **domains** of PI were also defined. Spatial (structure), thermodynamic (energy), functional (synergy), and temporal (time) [6]. The Ideal PI requires realizing the four fundamental principles in one or more of the realization domains.

The realization **tools** are classified into [3] [7]

- intensified equipment, such as novel apparatuses and devices, which represent the hardware structures of PI, and
- intensified technologies which represent the software part of it. Such techniques include incorporating chemical reactions into unit operations, combining two or more different processes, and using various types of energy.

In addition to the realization tools, there was a need to present the PI as a systematic method rather than a toolbox with specific equipment or technologies. Process systems engineering (PSE) for modeling and powerful systematic methods are used for the identification and synthesis of the PI processes [8], [9]. Ponce-Ortega [10] approached the PI by recognizing unit intensification and plant intensification.

Synthesis of intensified processes is classified into [11]

- knowledge or experienced-based methods (heuristic), where the PI design presented by Siirola according to task identification and integration [12],

- optimization-based methods, where a generated superstructure is translated into a problem with an objective function, and operational constraints. The flowsheet structure and operating conditions would give then an improved design, as per the works of Grossmann, I.E. et al [13], and
- hybrid methods which combine the previous two methods to reduce the computational complexity of the studied design [14].

Based on the presented background a **hierarchy of the PI** could be structured as per Figure 2.

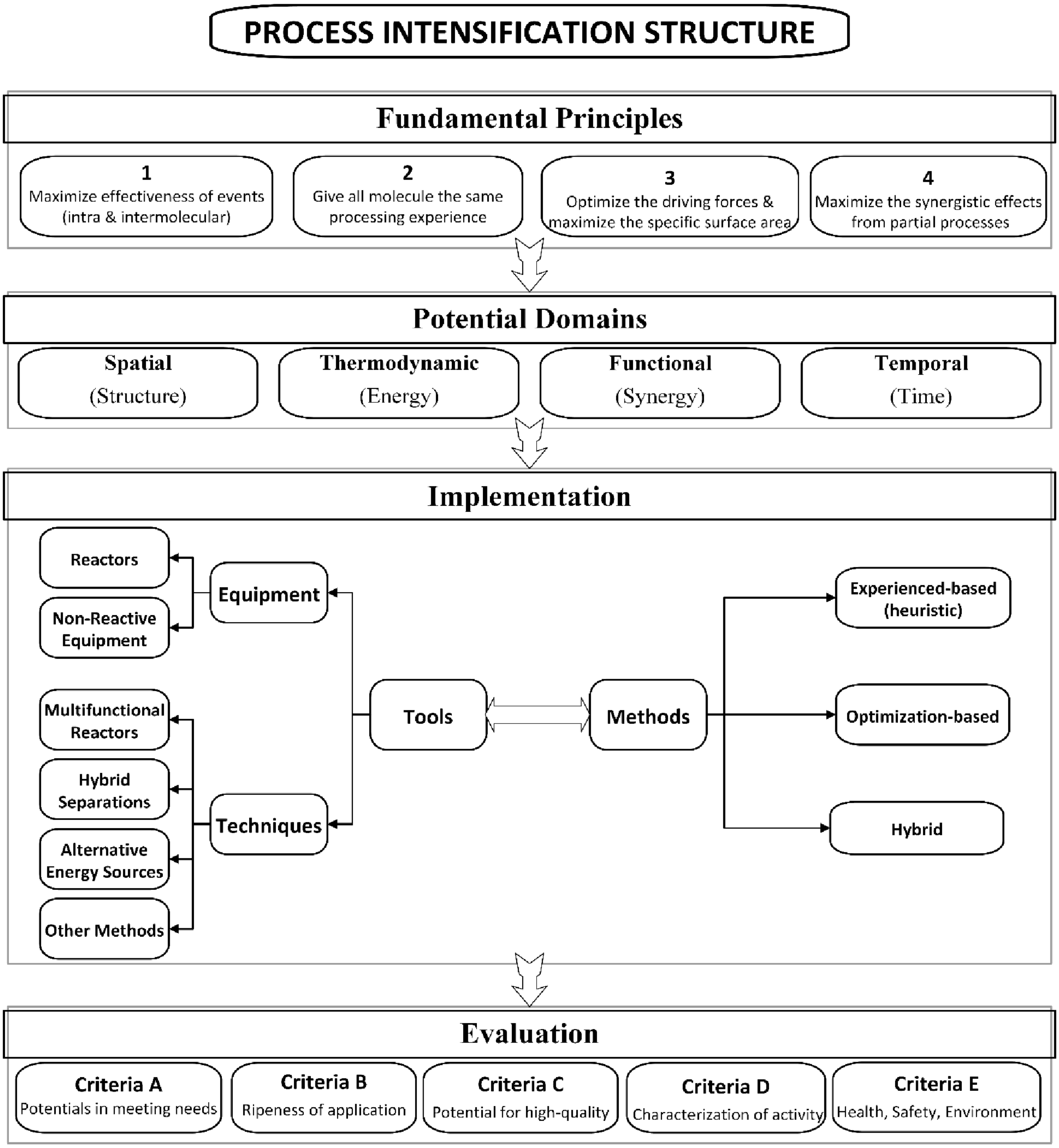


Figure 2 Process Intensification Structure (Extended concept from Van Gerven and Stankiewicz [9], Stankiewicz [6], European PI roadmap [36])

3.2 PI implementation drivers in the O&G

The PI definition by Stankiewicz [3] provides the best entrance to clarify the implementation drivers of PI technologies in the petrochemical industries: **energy consumption, GHG, and cost**.

A) Energy Consumption

The industrial sector shares 32 % of total global energy consumption [15] and holds the position of the dominant energy consumer with estimations of steady growth. This is accompanied by an increase in the consumption of the O&G due to the increasing demand for energy generally, and in the industrial sector particularly. The projections indicate an increase in energy use of about 50 % for the next three decades. The consumption of O&G would increase consequentially. Oil would share more than 20 % of this increase, while it would be more than 40 % for natural gas [15]. On the other hand, the sector of O&G and petrochemical industries is the major consumer among all industries (30 % of industrial sector energy consumption, about 10 % of the global energy demand) [7]. Energy is needed all over the supply chain Figure 3.

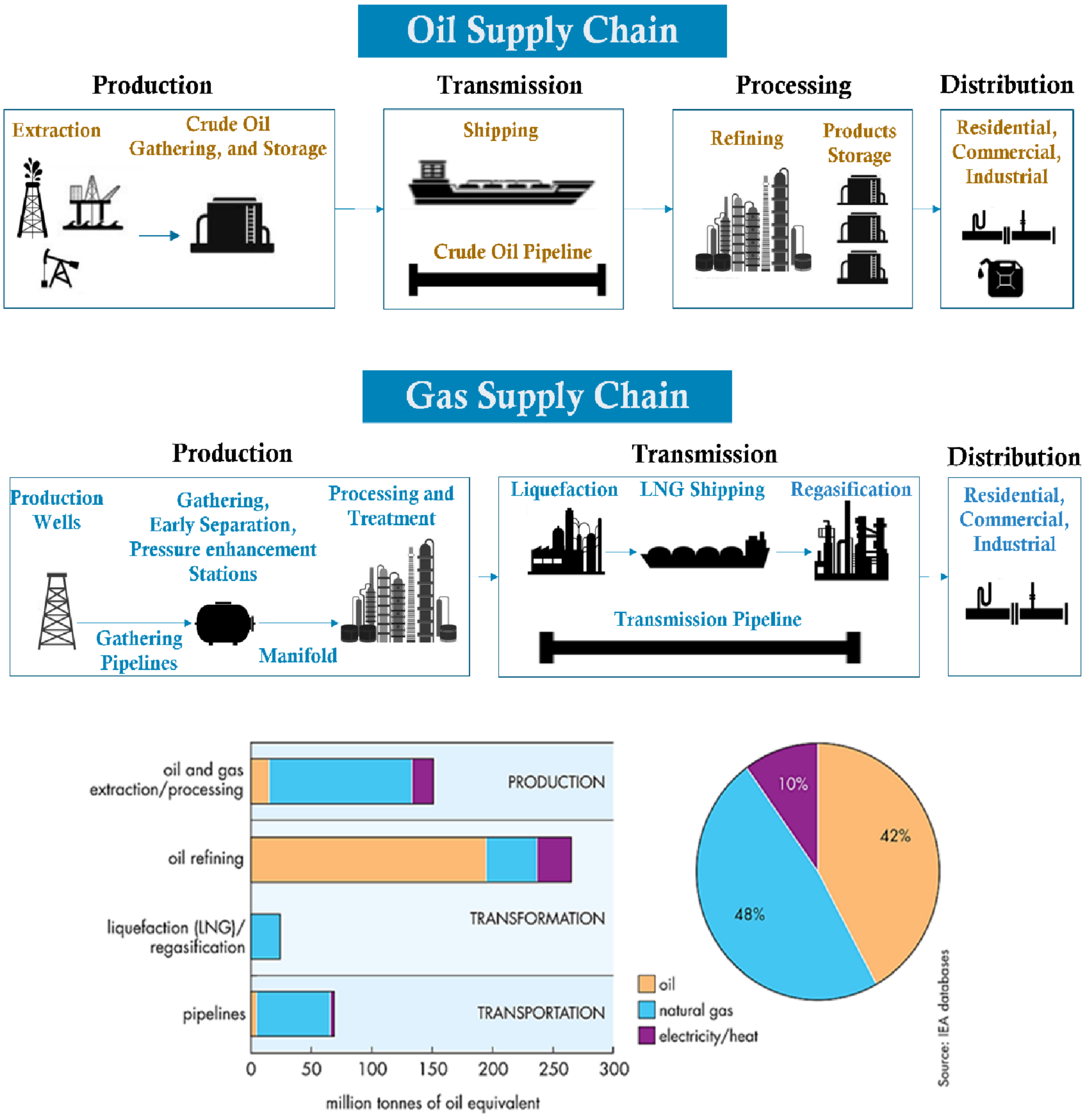


Figure 3 World energy consumption along the O&G supply chain (Data source: IEA [16])

B) **Pollution and greenhouse gas emissions** (**GHG**)

Chemical and petrochemical industries are the main producers of GHG emissions with a share of 7 % of the global CO_2 total emissions [7]. In addition to the GHG, the range of pollutants produced by the O&G includes several other pollutants that cause immediate and long-impacts on health, environment, and safety, such as CO, CH_4, SO_x, NO_x, NH_3, Pb, Hg, acids, sulfides, and solid wastes [17]. Accordingly, the safety driver of the PI becomes essential.

C) **Capital cost**

To achieve cost savings, it was used to apply the two-thirds power rule to estimate the capital cost changes at various production scales [3]. Later on, the capital cost statistics provided more realistic data. Anyway, increasing the facility size is limited by technological restrictions, production, operational costs, and stability of the market [18] [7]. Nowadays, small equipment that fulfills the operational restrictions, and achieves the minimum operational costs are a need, especially for offshore and abandoned field applications.

3.3 Rated energy consumption as a key driver of PI implementation

The enhancement of the PI implementation in the O&G requires a well-defined technical framework and procedures, which consider the measurability and feedback evaluation characteristics. This was presented by the author in "*Process intensification in the oil and gas industry: A technological framework*" [19]. The author suggested the rated energy consumption (REC) as a key driver of the PI implementation. The specific energy consumption (SEC) represents the amount of energy that is needed for the unit of the product, and it is proportional to the emissions and OPEX. The CAPEX is related to the size of the equipment or facility, and together with the OPEX, has a mutual proportional relation with the processing capacity (PRC) (production per time interval). Merging the PRC with the SEC will result in the rated energy (REC) Figure 4, as per:

$$(REC) = (SEC) \times (PRC)$$

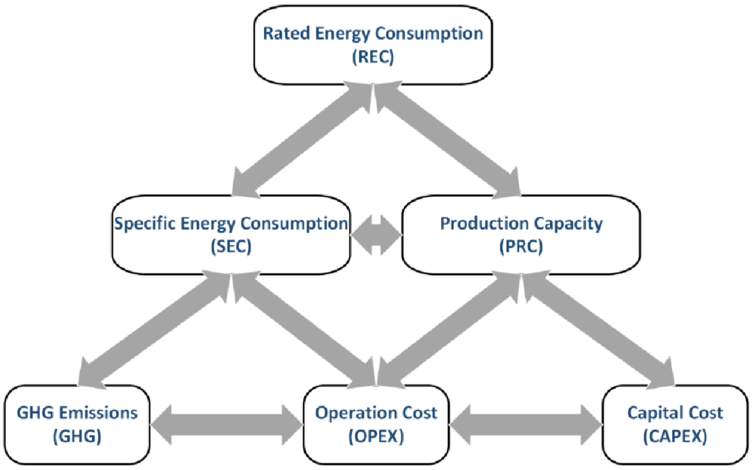


Figure 4 PI drivers' participatory relations [19]

The REC was firstly investigated in other work by Miklas and the author [20]. Within the scope of this work, the rated energy consumption is further investigated as a key driver for PI implementation.

Chapter 4 Literature review and state-of-the-art of PI in O&G and gas processing

A literature review about the PI implementation in the O&G reveals that

- higher research interest in PI in the O&G field since 2008, and the publications about natural gas represent 63% of the publications about PI in the O&G. O&G publications hold only 30 % of the total number of PI publications in the chemical and energy sectors.
- It can be noticed that the most implemented technologies in petroleum refining are reactive distillation (RD), dividing wall column (DWC), and reverse flow reactor (RFR) [21]. Pressure swing adsorption (PSA) is the most hit topic for PI in Natural gas processing [22] [23].

The state of the art was studied based on the literature review of PI in the O&G, and specifically of NGD. It was realized that the implementation of PI equipment is more used than the PI systemized methods. Process Systems Engineering (PSE) is used for the modeling and simulation, and less frequently, systematic methods for the identification and synthesis of the PI processes.

Extending the above-presented review, and limiting the searching (on Scopus) to specific wording that gathers “natural gas” and “process intensification” reveals a limited number of articles. The majority of them were published after 2014. Reviewing the relevant papers highlights that

- most publications about the PI implementation in the NG are more concerned with the technology, **rather than the NG process itself**,
- the sweetening, NGL fractionation, and recovery process were investigated **more frequently than dehydration**, although of its high importance in terms of PI drivers,
- **very limited utilization of computer-aided tools** like CFD, or powerful process simulators such as Hysys or Promax in the PI of NG processing, and
- a very limited number of publications about **the systematic simulation-based PI methods** while the publications about the PI technologies, such as membranes and pressure swing adsorption (PSA) are dominant.

The highlighted gaps indicate a clear need for approaching the PI in the NGD process via a systematic simulation-based method.

Hereinafter, the work is focused on the NGD particularly, and approaching the PI in this process via a systematic simulation-based method, that combines the **rated energy key driver** with a **powerful process simulator** to analyze and evaluate the potential PI and its fulfillment of the **process key specification**.

Before proceeding with the modeling and simulation of the studied case, a theoretical background about the NGD is presented.

Chapter 5 The natural gas dehydration process

The basic sequence of NG processing is shown in Figure 1. **Water, sulfur, and acid gases have to be eliminated from the stream** before proceeding with processing. The gas properties downstream of these modules allow the implementation of piping of less specification than those the upstream, which is vital from the economics perspective, especially if the processing would be far from the production field.

Phase separation is responsible to isolate the liquids of the mixture stream, but the NGD objective is the elimination of the associated water vapor from the separated gas phase. This will achieve a dew point less than the minimum operating temperature in any part of the system, downstream of the separation unit. Consequently, this avoids the condensation of water, which

- eliminates the potential hydraulic problems such as slugs which could be destructive for receiving facilities, and other types of flow that enhance erosion rates,
- prevents gas hydrates formation, which could plug the piping system and result in severe damage to the asset, and high risks to the operator, as a mechanical hazard, in addition to high toxicity in case of H_2S content,
- reduces electrochemical corrosion rates and fines, especially with the natural gas of sour and acidic nature,
- guarantees beneficial transportation capacity with higher caloric value, and
- provides a wider operation margin at the low temperature and high-pressure values, which is mandatory in the case of cryogenic processes.

The essential inputs for the design of a dehydration process are to define the nature of the gas which is being dehydrated, if it is sour or sweet, and to estimate or calculate the water content. Then, a designer can proceed to the selection of a dehydration method or constitute a combination of methods for natural gas dehydration.

4.1 Water content prediction

Estimating or defining the water content could be done via direct metering devices such as Impedance Sensors and hygrometers, or indirect methods such as correlations, equations of state (EOS), and charts. Most of the applicable methods are based on empirical data, and most of these methods are based on the McKetta-Wehe chart (1958) [24]. If the gas is acidic, it is essential to define the acidic composition ratio of the gas stream. The equation of state methods (EOS) are being used for water content calculation as well, taking into consideration that EOS methods face the same problem with the gas of acidic nature. EOS methods overestimate the content of water for the high acid gas concentration and pressures, in comparison with the empirical data [25].

4.2 Pipeline and process specification

The desired pipeline specification is affected mainly by the ambient conditions. As much as the ambient temperature is lower, the allowable water content is more restricted according to the applicable specification.

Knowing the nature of the gas, sweet or sour, pressure, and dew point, the water content of the wet gas (initial stage) could be defined, then the entire water removal [%] could be found:

$$Water\ removal\ [\%] = \frac{Initial\ water\ content - final\ water\ content}{Initial\ water\ content}$$

4.3 Dehydration methods

Figure 5 presents the categories and sub-technologies of natural gas dehydration methods.

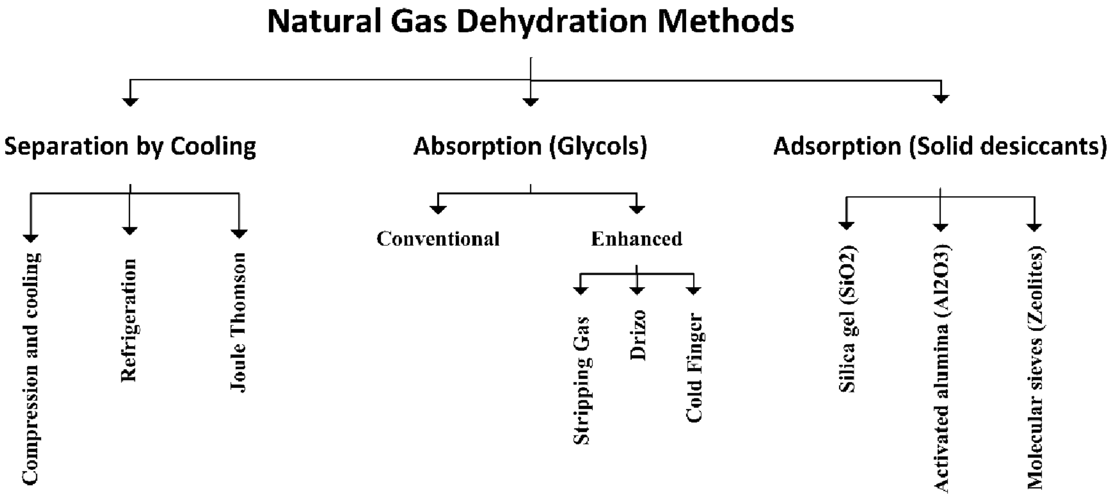


Figure 5 Natural gas dehydration methods

The natural gas dehydration process is selected based on the water dew point requirements. Helpful illustrations which define the ranges of applicability of each dehydration method could be found in the work of Netušil and Ditl [26], and Kemper [27], Figure 6.

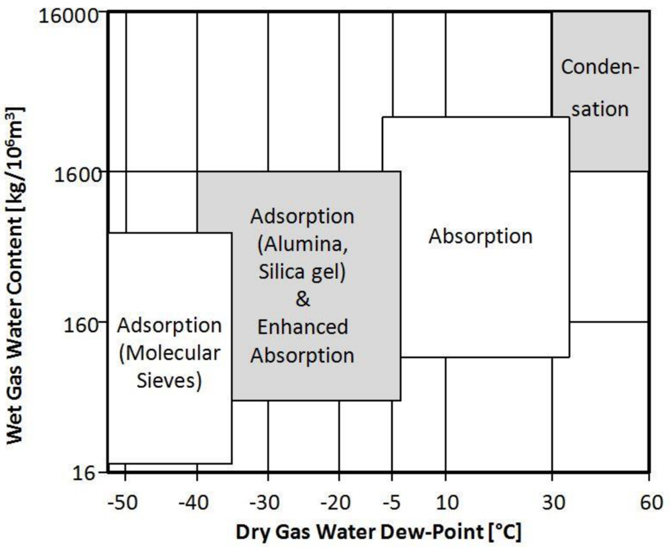


Figure 6 Natural gas dehydration methods due to water content [26]

In industry, there are three conventional methods for natural gas dehydration, direct cooling (refrigeration), absorption, and adsorption. Depending on the desired specification, a method or a combination of methods could be used.

- **Separation by cooling:** This method is very helpful in dehydrating the high-pressure NG streams with high water vapor content. It is based on condensing the water which will decrease the saturated vapor content of NG. The main problem of this method is the hydrate formation, which is prevented by injecting a polar solvent, such as monoethylen glycol (MEG) or methanol, as a hydrate inhibitor before cooling. The most applicable is the refrigeration method using Propane as a refrigerant.
- **Absorption**: **It is the most common method of dehydration**, especially with using glycol compounds as absorbents. This method has higher efficiency than direct cooling in the mid. range of dew point and water content. Monoethylene glycol (MEG) (So-called EG), Diethylene glycol (DEG), and Triethylene glycol (TEG) are the main glycol solvents for use in this method, especially TEG, which is very efficient due to higher boiling point, and fewer emissions losses. Tetraethylene glycol (T_4EG) has less loss at high contact temperatures but it is more expensive than TEG. The absorption unit includes two parts, contacting part (dehydration part) and the regeneration part. The main consumption of the regeneration is an energy consumption at the reboiler in the regeneration, in addition to solvent consumption, and stripping gas in some of the enhanced configurations of TEG units. BTEX (benzene, toluene, ethylbenzene, and xylene) is still one of the main problems of glycol dehydration units. Although TEG doesn't absorb hydrocarbons, it will remove a significant amount, up to 20% [1] of these heavy hydrocarbons that would be evaporated with the water at the regeneration. These VOCs (volatile organic compounds) must be incinerated, which will solve the harmful emissions problem, partially, but it is still a loss of energy via flaring, as well as another type of emissions. Using the absorption method can reduce the water content significantly, to be about 10 [pmmv], equivalent to dew point temperature -30 [^{o}C].
- **Adsorption**: For some processes such as LNG recovery, a very low dew point temperature of about -60 to -110 [^{o}C] has to be achieved, so further dehydration via adsorption is done, as the most efficient method for meeting the required inlet gas specification. The molecules of water vapor (adsorbate) adhere in an extremely thin film to the surfaces of solid bodies (adsorbent) with which they are in contact. The commonly used adsorbent in NGD is the solid one, so-called desiccants, and the most commercially are the zeolites. The adsorption dehydration system consists of, at least, two adsorption vessels, so-called molecular sieve contractors, and a gas regeneration heating unit. The adsorbers are packed with desiccants, and work in a batch-type process within a continuously operating facility. One adsorber is within the active phase (adsorption phase), while the other would be in the regeneration phase. The length of each cycle is decided according to the saturation when the mass transfer zone (MTZ) reaches the end of the bed, illustrated by breakthrough curves. The regeneration of the saturated contactor is the desorption of the adsorbate. This could be achieved by reducing the pressure, increasing the temperature, or both. A pressure-temperature swing process is used for regeneration, and the demands are energy consumption, and regeneration gas consumption which is a dry gas stream extracted downstream of the active adsorber.

Within this thesis, the Triethylene glycol (TEG) absorption unit was selected as a case study, to validate the methodology.

Chapter 6 Modeling approach

This work aims to develop a clear **systematic simulated-based method** that meets

- the PI drivers and process specifications, and
- easy and efficient utilization, that serves the **future design**, as well as the **current facilities** in operation.

Investigating the **mutual relation between** the **REC** and the **water content** specification represents the cornerstone of the proposed method.

- REC is a key driver and evaluation tool of PI, and
- the water content specification is a key input for NGD design.

The $REC_{Dehyd.}$ is used as an evaluation tool of the intensified solution that has to fulfill the product specification (water content). The $REC_{Dehyd.}$ consists of the equipment or process energy consumption ($REC_{equipment}$) and enthalpy loss ($Enthalpy_{vent}$).

$$REC_{Dehyd} = REC_{equipment} + Enthalpy_{vent}$$

The announced aim is approached by using a combination of two methods,

- a systematic method that recognizes unit intensification and extended process intensification, similar method was firstly suggested by Ponce-Ortega [10], and
- a concise framework for PI implementation in the O&G proposed originally by the author [19].

The established simulation-based method uses the powerful process simulator **ASPEN HYSYS**.

As a case study, the **absorption-based dehydration** by TEG in an existing gas plant is used.

The case study's primary data is prepared from the available documentation from the operator. A current state model is established, and the reference results are calculated.

In the second stage, the intensified solution of the NGD is structured as follows

- the PI of the core unit (core node (TEG unit)), with its independent variables,
- the PI of the extended unit including the integrated upstream and downstream.

Hereinafter, the case study of the existing gas processing facility is presented, simulated, and the results are discussed.

Chapter 7 Case Study

The studied facility is an existing gas processing plant of two parts,

- a gas gathering and initial processing station denoted hereinafter as (GGS), and
- a gas treatment plant, denoted as (GTP)

7.1 Process overview: Natural gas dehydration TEG unit

A simplified block diagram of the entire chain from wellheads to the final product, throughout the GGS, trunkline, and GTP, is shown in Figure 7.

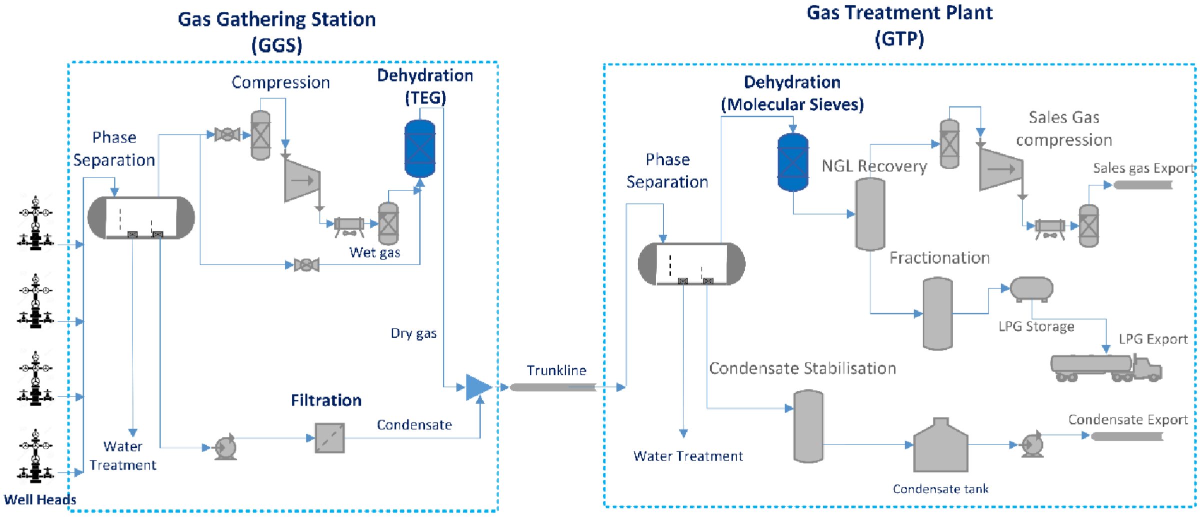


Figure 7 Gas processing facilities block diagram

The stream from WHs is transported to the GGS inlet manifold through flowlines. The 3-phase inlet stream consists of gas, condensate, and water. The liquids will be separated from the stream at the inlet 3-phase separator. Separated oily water will be treated at the oily water treatment unit. Condensate will be filtered of solids, then of water using a filter coalescer. The wet gas will proceed to the TEG dehydration unit. The carried-over liquids within the wet gas stream could be separated and recovered by 2-phase inlet separators of units, while the water vapor could be eliminated only by dehydration. Though, the major portion of water vapor will be absorbed in the first dehydration unit, the TEG unit.

The filtered condensate and dehydrated gas are mixed at the outlet of the GGS and transported through a trunkline of a 77 [km] length to the GTP, where another round of separation and dehydration takes a place. The dehydration unit at the GTP contains Molecular Sieves to remove the moisture by adsorption, which achieves a water content of 0.1 [ppmv], the required specification for the downstream cryogenic process, NGL recovery, and fractionation.

A preamble of the studied facilities is presented in Table 2.

Table 2 Primary data about the case study (Gas processing plant)

Plant	Gas Gathering and Treatment Plant
Production Capacity	Gas: 80 [MMSCFD]= 2.265x10^6 [Sm3/d], Condensate: 22.5 [m^3/d], about 141.53 [bbl/d]
Production phase	High-pressure stream at the inlet manifold
Fluids	Gas, condensate, water
Acid/Sour gas	No
Products	GGS outlet: Dehydrated gas and condensate mixture GTP: Sales Gas, LPG, Condensate
Production facilities	7 Wellheads, flowlines, gas gathering station (GGS), trunkline, and gas treatment plant (GTP).
Dry gas specification	GGS outlet: Dew point: < -5 [ºC] ~ 35 [ppmv] GTP Fractionation inlet: <-60 [ºC] ~ 0.1 [ppmv]

The wet gas at an approximate pressure and temperature of 87 [barg] and 40 [°C] enters the integrated scrubber of the gas dehydration contactor (105-C-001), where any entrained free liquid is removed before the gas flows on into the dehydration section of the contactor, Figure 8. The recovered liquids in the inlet scrubber are drained to Flare Drum in case of high pressure operating case, or GGS inlet separator in case of low pressure operating case Figure 7.

The TEG contactor has a structured packing design where the mass transfer takes a place. The lean TEG enters the contactor from the top with an approximate temperature of 50 [°C]. It gets equally distributed over the whole section of the column above the packed bed, then flows downward through the bed, absorbs the water of the upward gas flow, and leaves the bottom of the contactor as a rich TEG. The lean TEG inlet temperature is maintained at 5-10 [°C] above the wet gas inlet temperature. The TEG contactor is equipped with a high-efficiency demister that catches the entrained glycol droplets from the dehydrated gas stream before it leaves the top of the contactor. The dehydrated gas from the top of the contactor enters the Dry Gas/Lean TEG Heat exchanger (105-E-004), where the lean TEG is cooled to maintain the above-mentioned contact temperature difference. The dehydrated gas continues to be mixed with the dehydrated condensate, downstream of the condensate filter coalescer, then it is exported to the GTP through the trunkline, while the rich TEG is sent to the TEG regeneration unit.

The rich TEG, with some dissolved light hydrocarbons such as Methane and Ethane, leaves the bottom of the contactor (105-C-001) and the pressure will be reduced at the 105-LV-3017 to the app. 5-6 [barg], and flows through the reflux condenser (105-E-003), which is installed on the top of the still column (105-C-002) and intended to cool the vapors that leave the still column to the incinerator unit (140-X-001). This will reduce the TEG losses with the water vapor exhaust. The preheated rich TEG continues to the cold lean/rich glycol heat exchanger (105-E-001), where heat will be recovered from the lean TEG stream, this will help flash off the dissolved light hydrocarbons when the rich TEG gets into the flush drum (105-V-002), rather than to have them with the still column vapor exhaust later. In this facility, these light hydrocarbons are sent off to the flaring. The flush drum is equipped with a weir, to catch the liquid hydrocarbons, which are operation problematic if exist with the rich TEG, and drain them into the closed drain.

The rich TEG at the outlet of the flush drum is filtered and flows through the hot lean/rich glycol heat exchanger (105-E-002), where another portion of the heat is recovered from the hot lean TEG, and the rich TEG is preheated. This multistage heat recovery helps to reduce the reboiler duty (105-H-001). The rich TEG enters the still column (105-C-002) and flows downward through the packing to the direct-fire heated reboiler. The rich TEG is boiled at about 200-204 [°C], and the water vapor flows up through the packing of the still column to the reflux condenser (105-E-003) where it will cool down. The entrained TEG should not travel beyond the reflux condenser, as mentioned above, while the water vapor with the vapors of BTEX go out the top to the incinerator. To increase the purity of the TEG, the regeneration process is enhanced by a stripping column (105-C-003). When the lean TEG flows over the weir of the reboiler, it flows down the packing of the stripping column and gets in contact with the upward dry natural gas flow, so-called the stripping gas. To meet the equilibrium, the dry NG flow will drive out the traces of the water that could still exist within the lean TEG. The hot lean TEG will leave the bottom of the TEG surge drum (105-V-005) and goes through the heat exchangers (105-E-001,002 and 004) while the TEG circulation pump (105-P-003) increases the lean TEG pressure to a value higher than the contactor pressure.

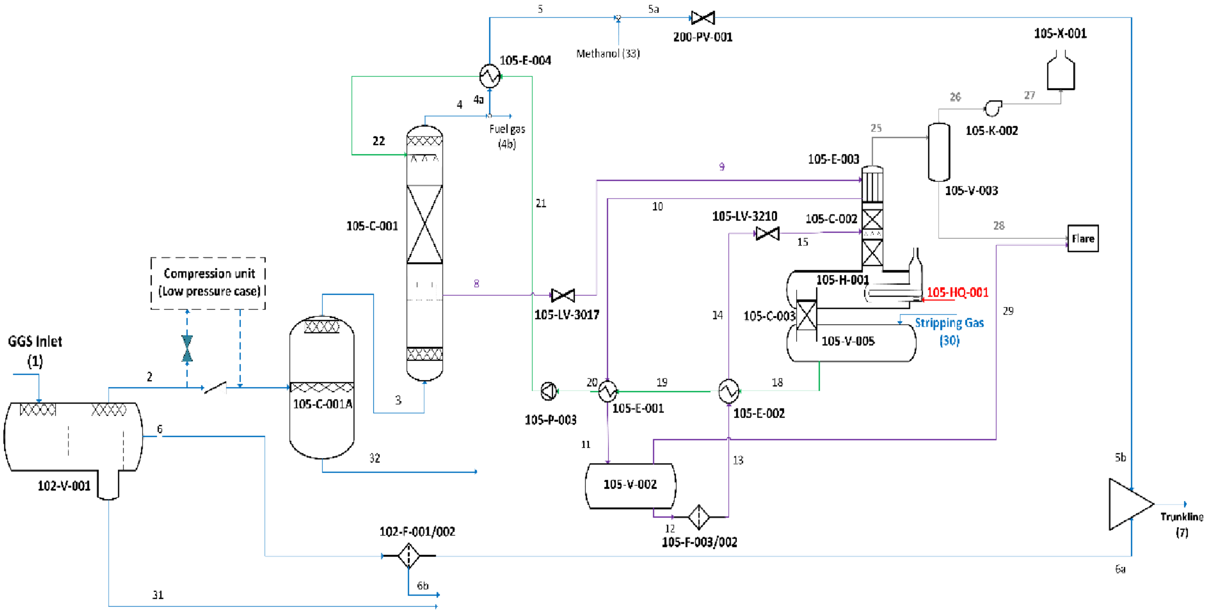


Figure 8 Gas Dehydration- TEG Unit

The efficiency of the absorption section is measured by the percentage of the water that is being removed from the wet gas, as a rule of thumb, it is 90-95%, while the efficiency of the regeneration section is measured with the achieved purity of the TEG. To define the required TEG purity for a specific dew point, the equilibrium water dew point chart is used [28]. The chart gives the equilibrium water dew point for different TEG purity over a range of contactor temperatures.

In the studied case, an equilibrium dew point of -5 [°C] in addition to a reserved safety margin (approach temperature) of -5 [°C] which is in total -10 [°C] could be obtained with a TEG of 99.0 [wt.%] at contactor temperature of 40[°C]. Using the stripping gas will enhance the purity. In addition to the minimum purity degree of the TEG, and the temperature difference between the lean TEG and the NG inlet temp at the contactor, the reboiler temperature is another operational limitation that has to be considered very carefully. The degradation temperature of the TEG is 206 [°C], so the reboiler temperature should not get to this temperature. Moreover, a margin has to be kept due to the hot surface considerations of the heating element. In other words, the lower the temperature that meets the required TEG purity degree, the better lifetime and fewer losses of the TEG at the reboiler.

The available document and data of the studied facilities include:

- Heat and material balance
- Equipment datasheets
- Process and instrumentation diagrams (P&IDs)
- Operation manuals

The simulation input data and all parameters are obtained from the above-mentioned facility documentation.

As indicated above, the facility includes a dehydration process of two stages, 1st stage is absorption-based dehydration by TEG at the GGS, and adsorption-based dehydration (deep dehydration) with molecular sieves at the GTP.

Hereinafter, the work is **focused on the absorption-based dehydration unit**, as a defined case study to validate the PI approach.

The PI of the studied unit is approached in terms of operational and asset modifications. The simulation is done via the process simulator **ASPEN HYSYS** as follows

- the simulation of the current status is presented, and the current case calculations are done as a reference, then
- the intensified solution is structured and simulated as follows:
- Intensification of the core unit (TEG unit), with its independent variables,
- Intensification of the adjacent upstream and downstream units, intensifies the wider or entire process.

7.2 Current state simulation results

The steady-state model of the facility is simulated via ASPEN HYSYS, Figure 8 and Figure 9.

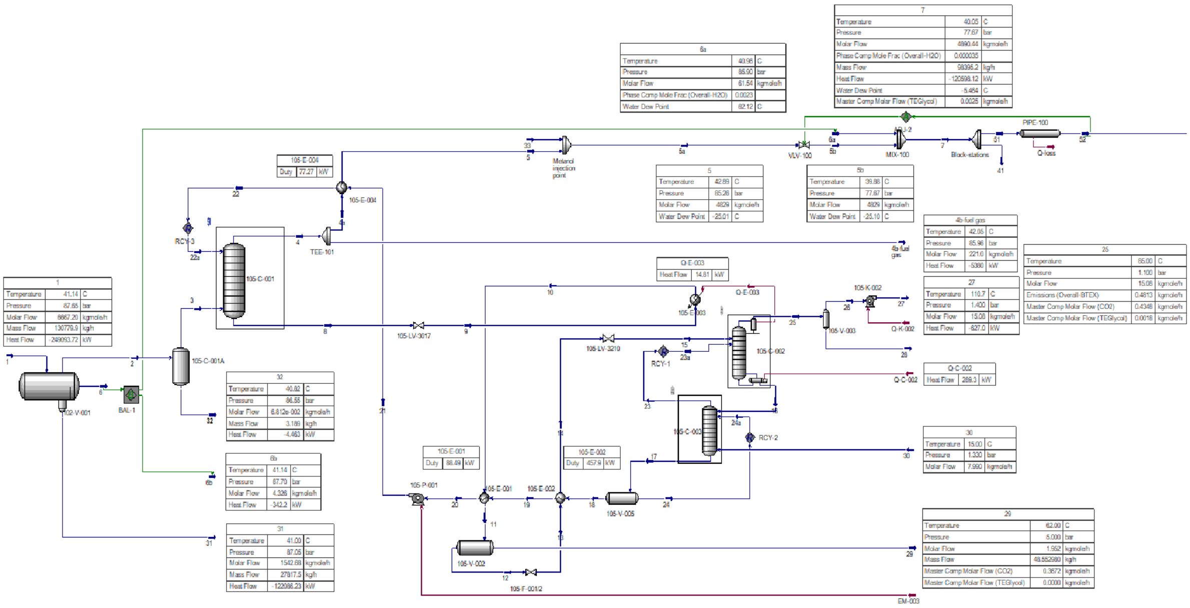


Figure 9 Case study simulated model

Table 3 Heat and material balance of the current state inlet-outlet streams

Main Stream Workbook and Rated Energy Consumption								
	1	**4**	**6b**	**32**	**30**	**25**	**29**	**7**
	Production separator gas **inlet**	TEG contactor dry gas **outlet**	Condensate Filter Coalescer water **outlet**	TEG contactor separator water **outlet**	Stripping gas **inlet**	TEG regeneration reflux cond. vapor **outlet**	TEG flush drum vapor **outlet**	Trunkline mixed gas-condensate (GGS **outlet**)
Temp.[C]	41.14	42.05	41.14	40.82	15	85	62	40.05
Press.[barg]	86.65	85.96	86.7	85.55	0.33	0.1	4	76.67
Molar Flow *[kgmole/h]*	6667.2	5050	4.33	0.068	7.99	15.08	1.95	4890.44
Mass Flow *[kg/h]*	130780	27818	78	3	150	322	49	98395
Liquid Volume Flow *[m3/h]*	319.97	-	0.079	0.004	0.445	0.629	0.11	279.26
Heat Flow *[kW]*	-249094	-122933	-342.2	-4.5	-199.3	-631.5	-71.8	-120598
Dew Point [ºC]	-	**-25.00**	-	-	-	-	-	**-5.46**
Reboiler energy consumption 105-HQ-001								**289.35 [kW]**
NGD vent and drain enthalpy (Heat flow loss) (streams 25+29)								**703.3 [kW]**
Other appliances' electrical consumption (motors) (considered fixed)								**23 [kW]**
Total Rated Energy Consumption $REC_{Dehyd.}$								**1015 [kW]**
Comp. Mole Fraction and Emissions								
H2O	0.23286971	**7.5E-6**	0.99789979	0.532687	0.0130387	0.428773411	0.005079883	**35.4E-06**
TEG	-	5.03E-07	-	-	-	119.3 E-06	4.24E-06	5.03E-07
CO_2 (Process)	0.02499675	0.0737626	0.00070007	0.0103396	0.0327974	0.028828383	0.188127235	0.032298227
BTEX	-	-	0.00E+00	2.81E-02	-	3.19E-02	2.05E-03	-
Total TEG loss (25+29+7)								0.0043 [kgmole/h]
Total CO_2 (Process) (25+29)								0.8017 [kgmole/h]
Total BTEX emissions (25) (BTEX in 29 is negligible)								0.4813 [kgmole/h]

7.3 Intensified solution simulation and results

As previously highlighted, the intensified solution is structured and simulated as follows:

- Intensification of the core unit (TEG unit), with its independent variables,
- Intensification of the adjacent upstream and downstream units, intensifies the wider or entire process.

7.4.1. Intensification of the core unit (TEG unit)

The intensification approach of the TEG unit is established on varying **four independent** parameters (variables) and defining the consequent impacts on the TEG unit outlet in terms of **product specification, energy consumption, and emissions**. The independent variables with the ranges are listed in Table 4. While varying a single independent parameter, the others are held at original operating values, which are the actual values in the existing facility.

Table 4 Studied cases of TEG unit operation

Case study	Operational parameter	Fixed (Actual operating parameters of the unit)	Investigated range	unit
Case 1	TEG circulation rate	39.83	5-40	[kgmole/hr]
Case 2	Stripping gas flow	7.99	2-16	[kgmole/hr]
Case 3	Stripping gas temperature	15	15-200	[^{o}C]
Case 4	Regeneration reboiler temp.	200	160-204	[^{o}C]

The sensitivity analysis of the unit independent variables' impacts on the PI approach is done, and the summarized results indicate that (Figure 10):

- The maximum dryness that could be achieved at the TEG unit with the studied cases is limited to 5.0-7.0 x10^{-6}.
- It can be noticed clearly that the water content curves are mostly leveled out in the upper rate of the investigated ranges. This differs from one parameter to another.
- In terms of reboiler power consumption, the stripping gas molar flow increase tends to be inefficient >8 [kgmole/hr], and entirely ineffective >11 [kgmole/hr]. The stripping gas temperature increase is entirely inefficient due to no effect on dehydration over the entire range while consuming energy for heating. The TEG circulation rate is partially inefficient >30 [kgmole/hr], and ineffective >40 [kgmole/hr]. The reboiler temperature is partially inefficient at >200 [^{o}C], and technically limited to 204 [^{o}C].
- The equivalent reboiler power consumption at a specific water content could be found by defining the working point on the curves of the investigated case or method. To define the required power for further dehydration using the same method, the working point slides on the curves, and the new equivalent power consumption could be defined.

The same could be used for a different method, and results could be compared to define the efficient method.

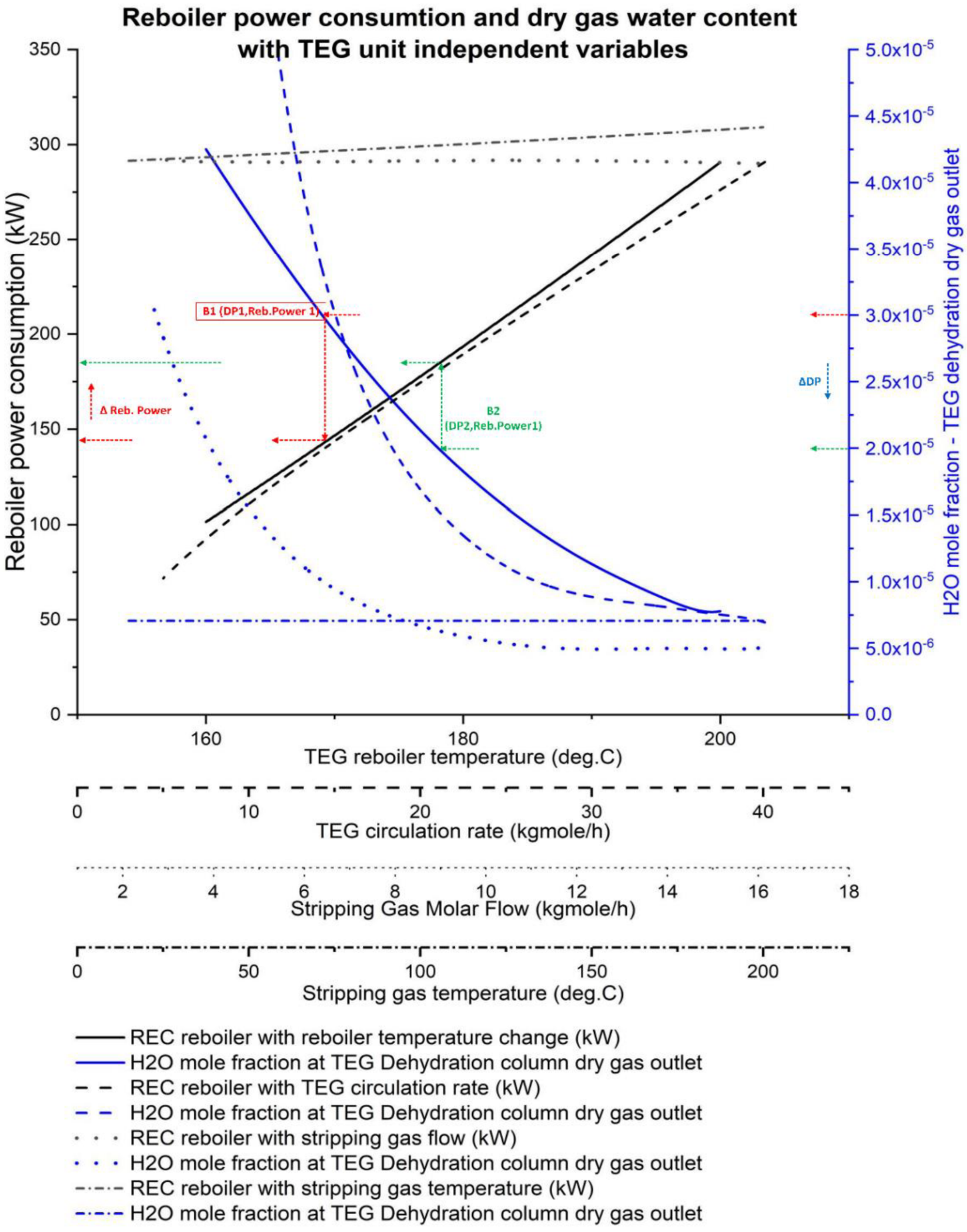


Figure 10 Reboiler power consumption and dry gas water content with TEG unit independent variables

TEG unit losses primarily consist of the condenser exhaust, and TEG flash drum released vapors. The greatest heat losses are accompanied by the stripping gas flow, Figure 11. The enthalpy changes at the exhaust due to dehydration degree, for a specific method, could be defined easily.

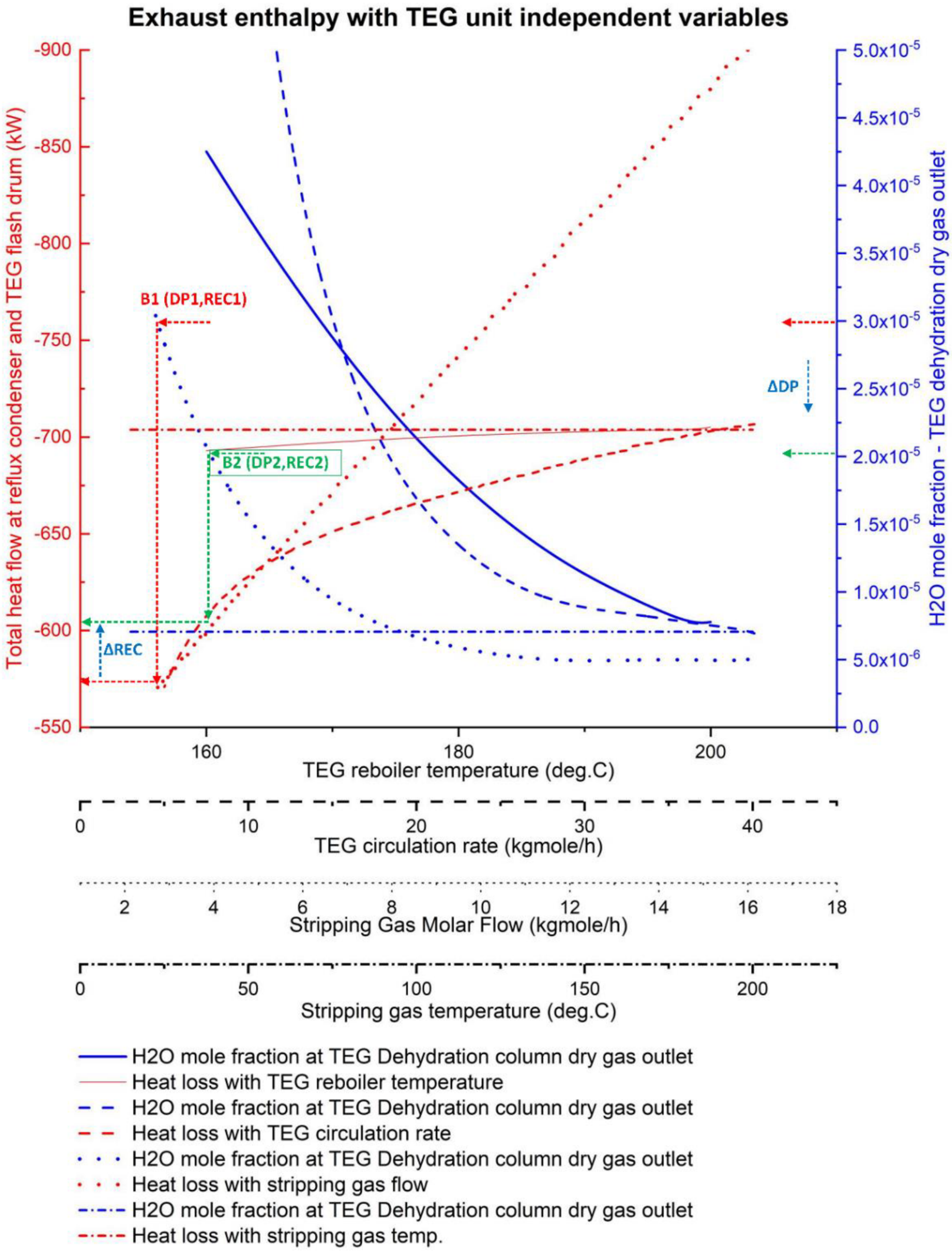


Figure 11 Exhaust enthalpy with TEG unit independent variables

- Referring to the current status simulation results in Table 3, it can be noticed that the gas is dehydrated **beyond** the dry gas specification (**dew point (DP) < -5 [ºC] ~ 35E-6 [ppmv]**). Stream 4 at the outlet of the TEG contactor has a **DP – 25 [ºC] ~ 7.5E-6 [ppmv]**. The extensive dehydration results in extra energy consumption and emissions.

- The obtained graphs in Figure 10 and Figure 11, help define the proper operating points to meet the required specification with some safety margin, save the extra OPEX, and other consequences resulting from the overdesign in an operational method.

- Based on the obtained simulation results, it was highlighted the effects of three independent variables on the NGD process in the TEG unit, **the TEG circulation, stripping gas flow rate, and regeneration reboiler temperature**. These three scenarios represent **three routes to shift** the current operating point **DP_0** (-25 [ºC]~ 7.5 ~ 7.5E-6 [ppmv]) to the optimized one **DP_x** (-10 [ºC] ~ 25E-6 [ppmv]), where x=1,2,3 according to the used variable (1: TEG circulation, 2: stripping gas flow rate, and 3: regeneration reboiler temperature). Taking into consideration that this new point keeps a safety margin of (-5 [ºC]) below the dry gas specification.
- The results of the intensified solution on the TEG unit are represented in Table 5.

Table 5 The intensified solutions impact the REC and emissions

Reference current state operating point **DP_0** TEG circulation =39.83 [kgmole/h] Stripping gas flow = 7.99 [kgmole/h] Reboiler temp.= 200 [ºC]			Scenario 1 TEG circulation @DP_1=16.46 [kgmole/h]		Scenario 2 Stripping gas flow @DP_2=3.3 [kgmole/h]		Scenario 3 Reboiler temp. @DP_3=172.8 [ºC]	
			DP_1	$\Delta_{0\text{-}1}$ %	**DP_2**	$\Delta_{0\text{-}2}$ %	**DP_3**	$\Delta_{0\text{-}3}$ %
Dew point (DP)	[ºC]	**-25**	**-10**	**-**	**-10**	**-**	**-10**	**-**
Water content	[ppmv]	**7.5**	**25**	**-**	**25**	**-**	**25**	**-**
Reboiler power consump.	[kW]	**289**	**153**	**-136 47%**	**292**	**+3 1%**	**161**	**-128 44%**
Enthalpy loss via venting	[kW]	**703**	**652**	**-56 8%**	**586**	**-122 17%**	**699**	**-9 1%**
Total REC*	[kW]	**1015**	**828**	**-187 18%**	**901**	**-114 11%**	**883**	**-132 13%**
BTEX (stream 25) **	[kgmole/h]	**0.4813**	**0.1485**	**-0.3330 69%**	**0.4730**	**-0.0080 2%**	**0.4713**	**-0.0100 2%**
CO_2 (stream 25 +29)	[kgmole/h]	**0.8017**	**0.5073**	**-0.2944 37%**	**0.6517**	**-0.1653 21%**	**0.8053**	**+0.0036 >1%**
TEG loss (stream 25 +29+7)	[kgmole/h]	**0.0043**	**0.0040**	**-0.0003 7%**	**0.0029**	**-0.0014 35%**	**0.0042**	**-0.0001 2%**

*: a fixed load of small motors = 23 kW
**: BTEX are calculated at the top of the reflux condenser outlet (stream 25) only. The BTEX emissions from the flash drum (stream 29) are negligible

The defined scenarios can reduce the REC by 11%-18%, BTEX emissions up to 69%, $CO_{2\text{-(process)}}$ up to 37%, and TEG loss reduction of about 35%, without compromising the product specification, and due to no CAPEX impacts, these scenarios are valid for both, future design, and current TEG units in operation.

7.4.2. TEG unit upstream block intensification (Pre-cooling)

The intensified solution upstream of the TEG unit includes the integration of a pre-cooling unit which enhances the separation by direct cooling, the first method of dehydration.

There are three common types of cooling units, air coolers, water coolers, and propane chillers. From an operation point of view, the cooling unit type and design depend on the location of the facility, compatibility with the annual ambient conditions, and the source of the cooling medium in case of water cooling. So, the air cooling systems are not feasible for a hot climate, considering that the selection and design inputs are considered in the worst case, which is the summertime, and the approximate approach temperature for design is 10 [^{o}C]. The cooling water systems are limited by the source of water, otherwise, a cooling system for the water cycle is needed, which means higher cost. The last method is the propane chilling process, which is feasible for all circumstances, but it has to be analyzed in terms of CAPEX and OPEX before deciding to integrate it with the TEG. Regardless of the pre-cooling method type, the other limit for consideration is the wet gas temperature, for efficient operation of the TEG unit, which is 25-40 [^{o}C]. So cooling below 25 [^{o}C] affects the TEG efficiency.

Considering the most feasible solution, the propane chilling process, Figure 12, the cooling cycle consists mainly of an evaporator, a compressor, a condenser, an expander, and an after-cooler separator to separate the condensed water. The main energy consumer in this cycle is the compressor. The integrated scrubber of the TEG contactor itself is used as an after-cooler separator. The suggested solution was simulated via the same proposed simulated-based method of REC that was used with the TEG, **and the only change is the process independent variable**, which is **Δt** in this case.

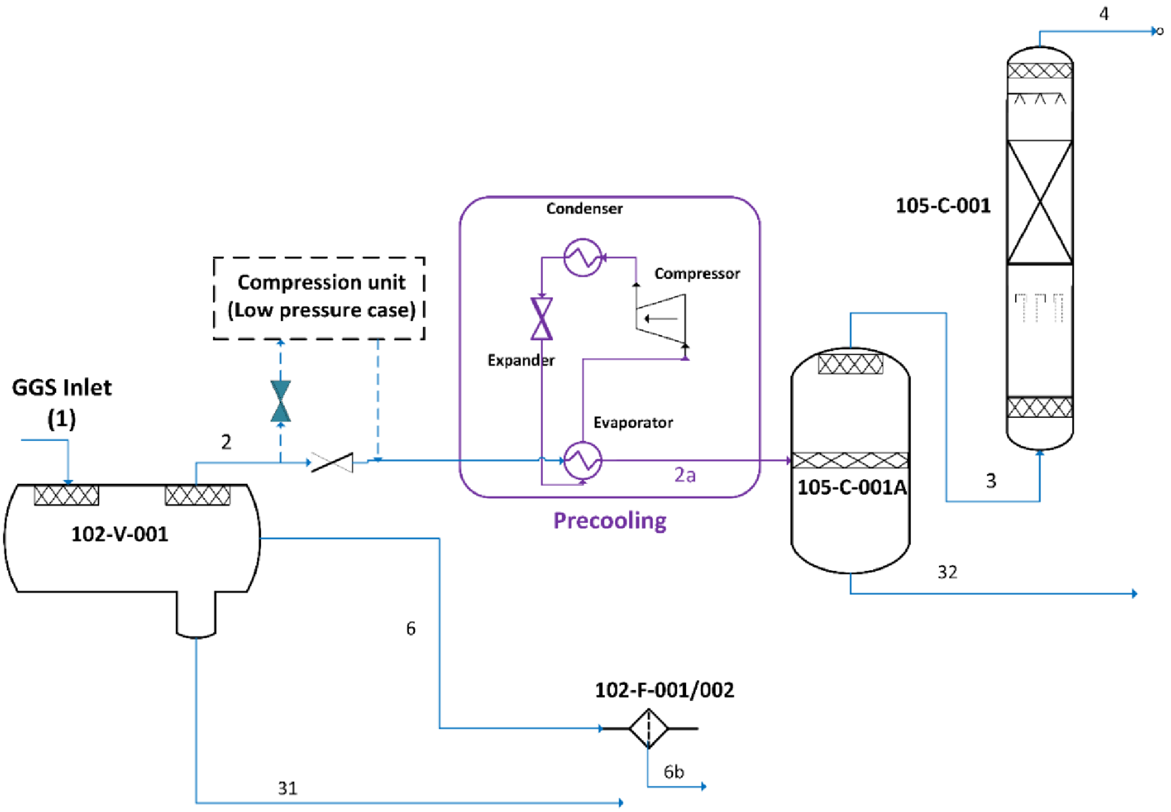


Figure 12 TEG unit pre-cooling solution

Figure 13 shows that the precooling helps separate the water over the precooling temperature range (41 to -15 [°C]) and the water content mole fraction in the dry gas is reduced to a limit value of approx. 3.7 x10^{-5}, but we are limited with the 25[°C]. Otherwise, another solvent has to be used. The REC including the power consumption of the compressor and the enthalpy loss at the separator drain increases considerably as far as we proceed with precooling. At the beginning of the range, the water mole fraction in the separator drain increases up to the pre-cooling temperature of 39.7 [°C], then starts to decrease. This is attributed to the condensation of the HC and confirmed in the heat flow increase at precooling separator liquid outlet.

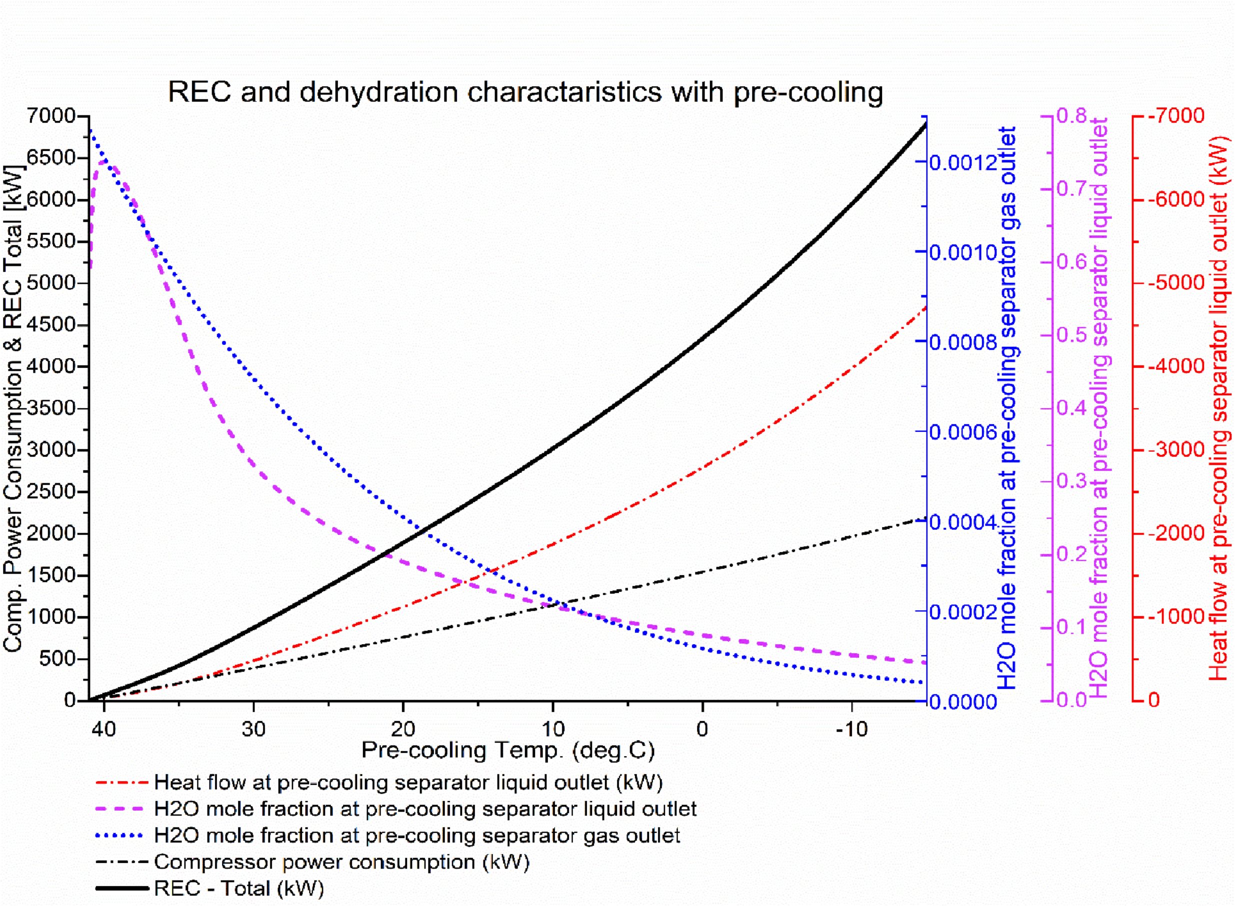


Figure 13 REC and dehydration characteristics with TEG precooling solution

7.4.3. TEG unit downstream block intensification (Mixing point)

The downstream block of the TEG is a simple mixer (Tee connection) that mixes the streams of dried gas and dried condensate to export them via one pipeline. The mixed condensate – gas pipeline itself is a common PI solution in the field of transportation. No intensification can be done at this mixer, but the simulation results of the current state drive further discussion about the input and output characteristics of the mixer. It was noticed that the dry gas downstream of the TEG unit has a dew point of -25.1 [°C], while the dew point downstream of the mixer is only -5.5 [°C]. The operator input data of the condensate stream is actual and obtained from the operator, and there was no simulation of the condensate processing itself, Figure 14.

The high content of water of 0.0023 [mole. fraction] within the condensate stream is clear, while this stream is supposed to be dry. This indicates a clear carry underwater with condensate. This water could be one or both of the following,

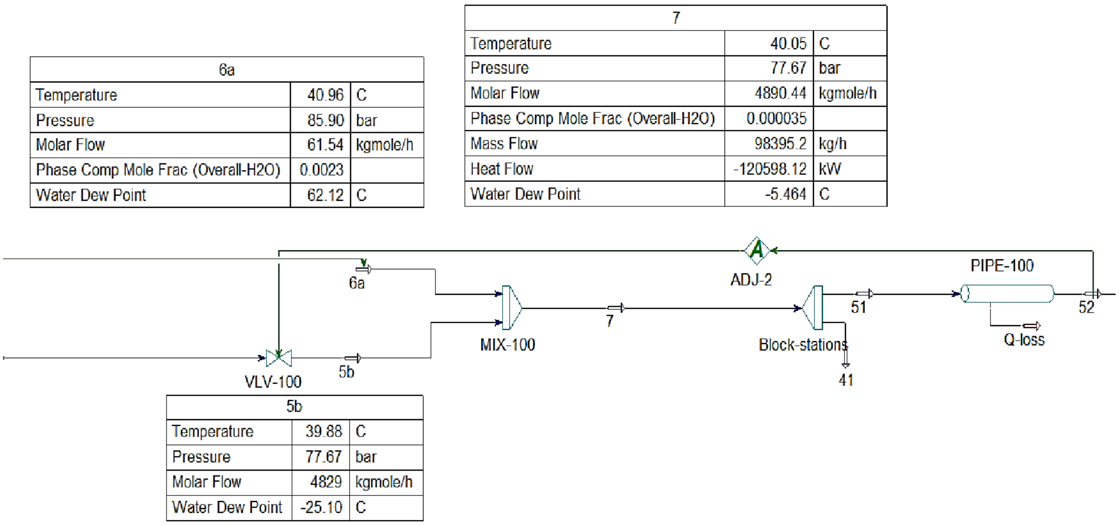
A) free water with condensate, which means very fine droplets of water with the condensate, or

B) dissolved saturated water with the condensate,

The filter coalescer can remove the free water only, but it is not able to separate the dissolved water. Separation of the dissolved water requires a liquid dehydrator (adsorption catalyst), which is of considerable high CAPEX and OPEX due to the regeneration process requirement.

In such a scenario the best is to keep the TEG unit with extended dehydration scope beyond the required dry gas specification (dew point), and the extra dried gas will be sufficient to overcome the compromising of the specification, which is caused by the water in the condensate. The other solution is to optimize the design of the separator internally to achieve better settling for the water and increase the efficiency of the separator.

The water in condensate problem is beyond the scope of this paper, and it is a complicated standalone topic that has to be solved separately.



6a		
Temperature	40.96	C
Pressure	85.90	bar
Molar Flow	61.54	kgmole/h
Phase Comp Mole Frac (Overall-H2O)	0.0023	
Water Dew Point	62.12	C

7		
Temperature	40.05	C
Pressure	77.67	bar
Molar Flow	4890.44	kgmole/h
Phase Comp Mole Frac (Overall-H2O)	0.000035	
Mass Flow	98395.2	kg/h
Heat Flow	-120598.12	kW
Water Dew Point	-5.464	C

5b		
Temperature	39.88	C
Pressure	77.67	bar
Molar Flow	4829	kgmole/h
Water Dew Point	-25.10	C

Figure 14 Dry gas and condensate mixer

To investigate this finding, further data about the composition of streams upstream and downstream of the condensate filtration were obtained. The mole fraction of water within the stream from the separator to the condensate filtration is 0.0630, and downstream the condensate filter coalescer is 0.0023. This means a filter efficiency of 96.3%, which is a high-quality filtration. So the solution could be one of the following:

- Design modifications on the separator unit to reduce the transferred water with the condensate stream.
- Replacing the condensate filter element with higher quality membrane filters.
- Implementation of some demulsification methods to reduce the water content within the condensate stream.

Chapter 8 Conclusions

The developed systematic method for process intensification of the natural gas dehydration indicated PI potentials on two levels:

- the core unit or core node (TEG unit), and
- the complex NGD unit with the integrated upstream and downstream.

The PI in the core unit (TEG unit) is achievable via three scenarios, each of them deals with one independent variable in the TEG unit, (1) the TEG circulation, (2) stripping gas flow rate, and (3) regeneration reboiler temperature. These three scenarios represent three routes to shift the current operating point to the optimized one.

This upgraded methodology has the following unique characteristics:

- It is a systematic simulated-based, that can be implemented easily and efficiently.
- The proposed scenarios are applicable for future design, as well as the existing units in operation.
- In the case of implementing this method for achieving the PI in the existing TEG units, no CAPEX have to be considered.
- This method provides a guide to the operator to approach the PI in an existing dehydration unit, by applying operational procedures.
- It is ready to extend and define the optimum balance between the three scenarios.
- The proposed method with the same approach applies to the extended unit, including the upstream and downstream adjacent units.
- The results of the extended unit case study indicate the benefits that could be obtained or losses that could happen, by implementing any dehydration solution upstream or downstream of the core unit.
- The implementation of the proposed method can be extended beyond the TEG unit and its adjacent upstream and downstream units. The same method applies to the entire process of dehydration, from separation to the LPG fractionation. The only needed input is the independent variable for each studied unit.

It is recommended to extend this work by studying the adsorption unit as well, and the independent variables, in this case, would be the water content on the inlet of the unit, and the stream temperature, pressure, and flow rate. Also, the condensate filtration and dehydration loop should be further investigated as it is an essential connection to the node of mixing, and affects the entire dehydration process in terms of PI drivers.

As could be noticed, our newly developed method can be considered as a general upgraded PI methodology useful for various types of intensification in the O&G. It has a wide range of applicability, as it is related to the REC that exists in any part of the process, and all the processes. So the same method can be used for approaching the PI in any other process by incorporating the specific independent variables of the studied process.

Nomenclature

Abbreviation	Definition
BTEX	Benzene, toluene, ethylbenzene, and xylene
CAPEX	Capital Expenses
DEG	Diethylene glycol
DP	Dew Point
DWC	Dividing Wall Column
EG	Ethylene glycol
EOS	Equation of state
GGS	Gas gathering station
GHG	Greenhouse Gas Emissions
GTL	Gas to Liquids
GTP	Gas treatment plant
HC	Hydrocarbons
LNG	liquefied natural gas
LPG	Liquefied Petroleum Gas
MEG	Monoethylen glycol
MMSCFD	Million std. Cubic Feet
NG	Natural gas
NGD	Natural gas dehydration
NGL	Natural gas liquid
O&G	Oil and Gas
OPEX	Operating Expenses
PI	Process Intensification
PO	Periodic Operations
ppm	Part per million
PRC	Processing Capacity
PSA	Pressure Swing Adsorption
PSE	Process Systems Engineering
REC	Rated Energy Consumption
SEC	Specific Energy Consumption
T_4EG	Tetraethylene glycol
TEG	Triethylene glycol
TSA	Temperature Swing Adsorption
VOCs	Volatile Organic Compounds

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