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# Deaerator Design Aspects and Troubleshooting

Abdullah Al Bin Saad, Prashant Sankarankandath

## BACKGROUND:

Steam is one of the most useful and vital utilities in many chemical process industries. It is the favored heating medium in process plants for several reasons:

- High content of latent heat associated with condensation.
- It is non-explosive.
- Given that it is generated from water, it is cheap.

Steam applications can be divided into the following categories:

- Recoverable usage:
  - Heating medium in heat exchangers to heat process fluid to desired temperature.
  - To spin turbines to generate power or drive rotating equipment.
  - Steam tracing to maintain the process the temperature at desired temperature or prevent freezing
- Non-recoverable usage:
  - Steam purging to avoid plugging in some services in relief valves
  - Steam stripping, such as in a distillation column, to reduce the partial pressure of the hydrocarbons as per Dalton's Law.
  - Addition of steam to the relief valve outlet piping to improve dispersion and reduce the flammability of certain chemicals, such as ethylene oxide.
  - Steam injection in flare for smokeless operation.
  - Steam ejectors
  - Steam reforming to produce Syngas.

Can steam be produced straight from raw water? is a possible query.

Of course, the response would be negative! We all know that the source of the water affects its quality. Water typically contains the following contaminants, for example

- Sand and silt.
- Iron
- Copper
- Silica
- Aluminum
- Calcium
- Magnesium
- Hardness
- Total dissolved solids
- Suspended solids and organic material
- Dissolved gasses

Some contaminants, such as silicates, which have a tendency to deposit on the steam turbines' rotor blades, can lead to scaling. Such deposits will throw off the rotor's balance, which will create vibration, which will eventually harm seals and shaft bearings. Additionally, additional pollutants like oxygen and carbon dioxide, which are present, promote corrosion. So generally, the raw water first needs to have primary treatment through filters to remove sand and silt. Then, this water can be sent to secondary treatment such as demineralization or hot lime softening to remove dissolved solids.

**Selecting technology for boiler feed water treatment is a complex activity and that's based on the feed water source and boiler specification. Hence, such activities shall be conducted by a water treatment expert.**



Here are some common treatment processes:

- Reverse Osmosis (RO)
- Softening.
- Chemical precipitation
- Deaeration

Before steam is produced in the boiler, dissolved gases (such as oxygen and carbon dioxide) must also be eliminated. This process is termed ((deaeration)) and it happens in an integral devise called a deaerator. (For a typical Steam plant, see Figure 1)

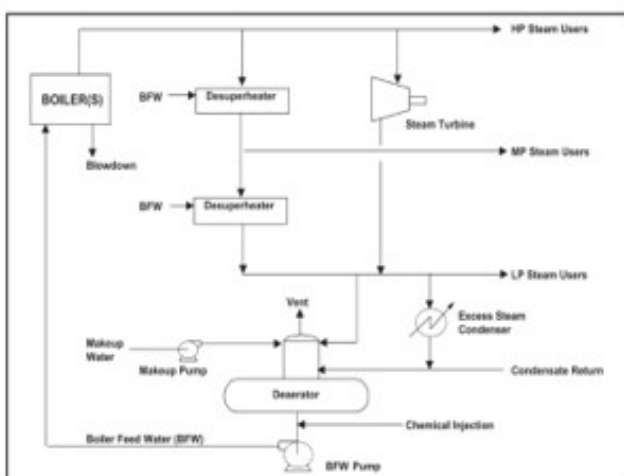


Figure 1- Typical Steam plant

This article will focus on deaeration principles, design aspects of deaerator system and common deaerator malfunction.

### DEAERATION PRINCIPLE

Industrial steam boilers are a huge investment and are considered as long lead items. As such, it is required to extend their life and keep their efficiency for as long as possible. The existence of oxygen in the boiler system can be a substantial problem due to its corrosivity at high temperature. Also, carbon dioxide which is produced from dissolved solids could lead to serious corrosion into downstream heat exchangers. That happens as carbon dioxide dissolves in condensed steam and produces formic acid.

The purpose of the deaerator is to remove dissolved gases from boiler feed water oxygen and carbon dioxide). Deaeration is The purpose of the deaerator is to remove dissolved gases from boiler feed water oxygen and carbon dioxide). Deaeration is built on two scientific concepts. The first scientific concept can be defined by Henry's Law.

**Henry's Law states that gas solubility in a solution decrease as the gas partial pressure above the solution decreases.**



Figure 2- O<sub>2</sub> Impact (Taken from Stork Vendor)

The second scientific concept that explain deaeration further is the relationship between gas solubility and temperature. Simply, gas solubility in a solution decreases as the temperature of the solution increases and approaches saturation temperature. (See Figure 3)

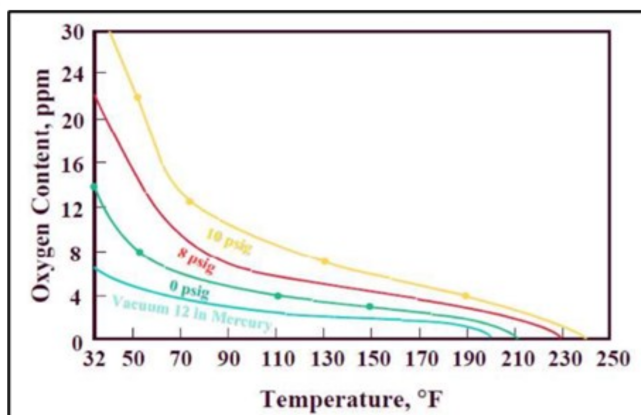


Figure 3- Solubility of oxygen in water (from Reference #3)

A deaerator uses both concepts to take away dissolved oxygen, carbon dioxide and other non-condensable gases from the boiler feed water. The feedwater is sprayed in thin films through spray nozzles into a steam allowing it to become quickly heated to saturation. Spraying feedwater in thin films rises the surface area of the liquid in contact with the steam, which enhance the mass transfer and results in more quick oxygen elimination and lower gas concentrations. The liberated gases are then vented from the deaeration section.

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## DESIGN ASPECTS OF DEAERATOR

A typical deaerator consists of two sections, stripping section for deaerating and heating and another section provides storage.

### Types

Generally, Deaerators are classified into two types as following:

#### Spray-Type

A spray-type deaerator is classically a single horizontal vessel which consists of two sections, deaeration section and a preheating section. The two sections are separated by a baffle. Low pressure steam passes into the deaerator through a sparger in the bottom of the deaerator. (See Figure 4)

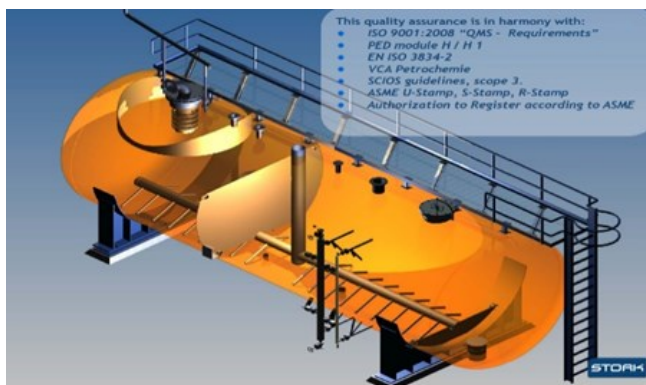


Figure 4- Spray-type deaerator (Taken from Stork Vendor)

The feedwater is sprayed in thin films over spray nozzles into the preheating section (1st section in above photo), where it is heated to saturated temperature to enable stripping out the dissolved gases in the subsequent deaeration section.

Then, the heated feedwater moves to the deaeration section where it is deaerated by the steam rising from the bottom sparger. The stripped-out gases of the water exit via the vent that is mounted on the top of deaerator.

#### Tray-Type

The typical tray-type deaerator has a vertical domed deaeration section, that may be horizontal in some cases (i.e big deaerator), mounted above a horizontal feedwater hold-up storage vessel.

Make-up feedwater enters the domed deaeration section over spray valves above the perforated trays and then flows downward through the holes in the trays. Low-pressure steam joins below the perforated trays and flows

upward through the perforations. Combined action of spray valves & trays guarantees very high performance because of longer contact time between steam and water.

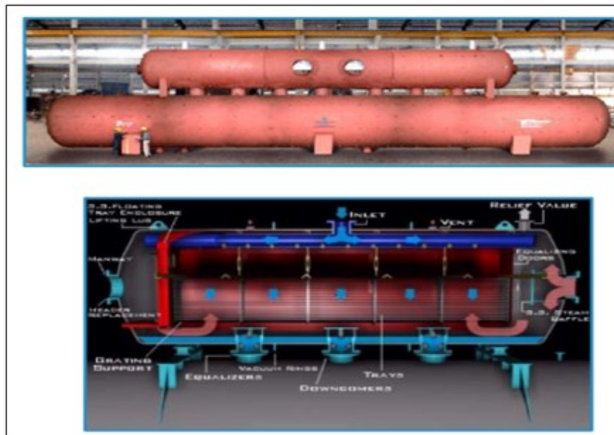


Figure 5- Tray-type deaerator (Taken from Stork Vendor)

The steam strips the dissolved gas from the feedwater and leaves through the vent valve. (See figure #5)

### Spray Type Vs Tray Type

	Spray Type	Tray Type
<b>Cost</b>	Lower	Higher
<b>Affected by solids or scale (1)</b>	No	Yes
<b>Load Variation (2)</b>	Can't operate well	Can operate properly

1. Scaling will lead to operating issues in tray type.
2. Tray-type copes well with load variation such as night, summer and with turbines that have extensive range of load. However, some vendors guarantees higher turn-down in special spray type such as STORK Spray Deaerator.

### Deaerator Performance

Deaerator shall be designed to reduce oxygen to 0.007ppm or less. Deaerators will eliminate free carbon dioxide. Chemical scavenging of oxygen is still enormously significant despite the apparent low levels achieved by physical means.

### Steam Consumption:

Steam Consumption could be calculated by means of applying basic form of the first law of thermodynamics:

$$\Delta H + \Delta E_K + \Delta E_P = Q - W_s$$

Equation can be simplified with following:

- 1-  $W_s$  = shaft work = 0 (as no moving part in Deaerator system).
- 2- Kinetic and potential energy ( $\Delta E_K, \Delta E_P$ ) = 0
- 3-  $Q = 0$  as deaerator is insulated.

Therefore, Equation will be as following:

$$\Delta H = \sum (\mathbf{H} \cdot \mathbf{M})_{out} - \sum (\mathbf{H} \cdot \mathbf{M})_{in}$$

H: Specific enthalpy (KJ /Kg)

M: Mass flow rate (Kg/h)

Let's take quick example to estimate Steam requirement for new deaerator with following design data:

Operating Pressure/Temperature:  
0.42 barg / 110°C

### Deaerator Sketch

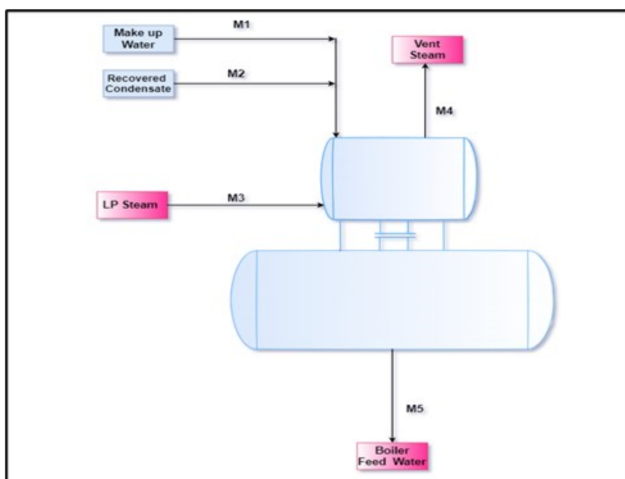


Figure5- Deaerator Sketch

### Deaerator Streams Table:

	Pressure	Temperature	Flow	Enthalpy
Stream /Unit	Barg	°C	Kg/h	KJ/Kg
Make up Water	4	30	71319	126.12
Recovered Condensate	4	96.7	618200	405.46
Low Pressure Steam	3.5	165	TBC	2781.43
Boiler Feed Water	0.42	110	TBC	461.32
Vent Steam	0.42	110	200	2691.3

TBC: To be calculated

Please be noted that this vent stream is minor and its value rises with the selected operating pressure and temperature of the deaerator (e.g. 50-200 kg/h at 105 °C, 1000kg/h at 150 °C).

However, Process engineers sometimes uses other approach to estimate vent steam same as rule of thumb:

**The vent stream may be assumed as 2% of the inlet steam to deaerator.**

For simplicity in this example, vent steam is assumed as 200 kg/h.

Boiler feed water and Steam flow rates shall be calculated. We have two equations (mass balance and energy balance) and two unknowns so degree of freedom is zero.

Hence, this example can be solved with following equations:

$$M_1 + M_2 + M_3 = M_4 + M_5 \quad (1)$$

$$M_1 \times H_1 + M_2 \times H_2 + M_3 \times H_3 = M_4 \times H_4 + M_5 \times H_5 \quad (2)$$

$M_1, M_2$  and  $M_3$  are knowns from Deaerator Streams Table, so equation (1) would be:  
 $M_5 = 689319 + M_3 \quad (3)$

Then, if we substitute equation (3) in equation (2), equation (2) would be:

$$M_3 = \frac{((M_1 \times H_1) + (M_2 \times H_2) - (M_4 \times H_4) - (689319 \times H_5))}{(H_5 - H_3)} \quad (4)$$

Now,  $M_3$  and  $M_5$  can be calculated simply from equation (4).

$$M_3 = 25380.17 \text{ Kg/h}$$

$$M_5 = 714699.17 \text{ Kg/h}$$

$M_1, H_1$ : Mass flowrate, Enthalpy of Make-up Water

$M_2, H_2$ : Mass flowrate, Enthalpy of recovered condensate

$M_3, H_3$ : Mass flowrate, Enthalpy of LP steam

$M_4, H_4$ : Mass flowrate, Enthalpy of vent steam

$M_5, H_5$ : Mass flowrate, Enthalpy of boiler feed Water



## CASE STUDY

The intention of this case study is to show impact of recovered condensate temperature on low-pressure steam requirement.

Before diving into case study, let's have quick overview of typical condensate system in chemical process industry (CPI).

Recovered condensate usually represent 80% to 90% of total inlet stream to deaerator. Hence, Temperature have more impact on low-pressure steam requirement than make up water.

Recovered condensate can be classified into two into following categories:

### Suspected Condensate:

Condensate comes from process heat exchanger where hydrocarbon can leak to condensate system. Such condensate shall be sent to condensate polishing unit where hydrocarbon is adsorbed on activated carbon.

### Clean Condensate:

Condensate comes from condensing steam turbine that use water-cooled shell and tube heat exchanger to condense its exhaust steam.

Cooling water leak to condensate system can increase silica that has bad impact on rotor blades of steam turbines as mentioned previously. Such condensate shall be sent to condensate polishing unit where cations /anions limits are restored by means of mixed bed column.

It is typically necessary to cool the condensate to nearby 50 °C to inhibit temperature degradation of the anion resins.

In such case, process engineer shall find a way to raise condensate temperature by means of heat recovery such routing condensate stream through Condensate in waste heat boiler. Such heat recovery will reduce steam requirement, fuel gas and boiler feed water power consumption.

Back to case study, HYSYS was utilized to realize steam requirement to deaerator at various temperatures.

The results are summarized in below table:

	Temperature (°C)	steam requirement (kg/h)
Case 1	50	77638.3
Case 2	55	72067.3
Case 3	60	66493.7
Case 4	65	60917.2
Case 5	70	55337.4
Case 6	75	49753.6
Case 7	80	44165.5
Case 8	85	38572.3
Case 9	90	32973.5
Case 10	95	27368.2
Case 11	100	21755.8

The below plot may demonstrate results in better way than previous table: \

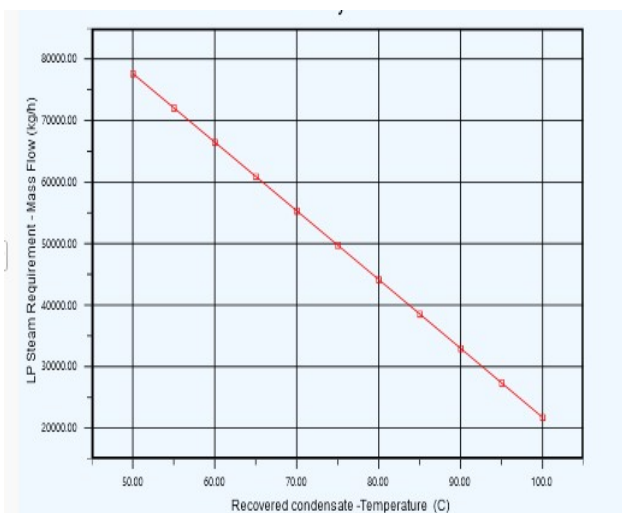


Figure 6- Steam requirements Vs Temperature of Condensate

The below tables show steam requirement reduction % based on temperature rise by 5 ° C:

	Temperature (°C)	steam requirement (kg/h)	Steam Requirement Reduction %
Case 1	50	77638.3	7.2%
Case 2	55	72067.3	7.7%
Case 3	60	66493.7	8.4%
Case 4	65	60917.2	9.2%
Case 5	70	55337.4	10.1%
Case 6	75	49753.6	11.2%
Case 7	80	44165.5	12.7%
Case 8	85	38572.3	14.5%
Case 9	90	32973.5	17.0%
Case 10	95	27368.2	20.5%
Case 11	100	21755.8	

If condensate is heated from 50 °C to 95 °C, steam requirement will reduce by 58%, which will decrease fuel gas and pump power consumption accordingly.

### COMMON DEAERATOR MALFUNCTION

Deaerators play a key role in ensuring a long and efficient equipment life. Mechanical deaeration is the primary means of removing dissolved gases from various condensate streams and make-up water streams.

Some of the essential factors required for deaerators to work efficiently are as outlined below:

#### Temperature:

Ensuring the entire water flow to the reaches the saturation temperature is vital to the performance of the deaerator. Dissolved gases are released from water at the saturation temperature.

#### Spraying/Mixing:

Good spraying or turbulence increases the contact area and promotes the release of gases.

#### Venting:

Adequate venting capacity plays a major role in the deaerator performance. The released gases should be continuously vented from the system.

#### Stable operating conditions:

Wide range of fluctuations in feed water flow rate and temperatures can affect the deaerator performance adversely. By creating, additional demands on steam control systems.

The following table lists some of the common

malfunctions encountered in typical deaerators and their possible causes

Malfunction	Possible cause
<b>High dissolved Oxygen in BFW</b>	Inadequate venting Very high delta T between deaerator temperature and BFW outlet  Internal channeling or damaged spray nozzles  Large variations in incoming water flowrates and temperatures  Air leakage through surface condenser for turbine
<b>Pressure fluctuations</b>	Heating steam control valve hunting or incorrectly sized
<b>Excessive vibration of deaerator or tank</b>	Blocked internals or damaged condenser tubes
<b>Low Outlet Temperature</b>	Incorrect Thermometer reading  Insufficient steam flow  Spray valves or internals malfunction



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## STORK DEAERATOR

Last but not least, we would like to present a technical comparison between conventional tray-type and STORK- Spray type. The below comparison table is handed by STORK vendor.

## ACKNOWLEDGMENT

We are grateful to STORK Company, world-leading designer and manufacturer specialty equipment (e.g. boilers, deaerators and burners, along with complex pipe spools), for providing some pictures and sharing some practical information about deaerators.

	Stork-type	Conventional tray-type
Layout	<p>Low total height, because of the single-vessel design.            Easy erection, minimum platforms, insulation, and piping.            Since the Stork design requires a specific steam compartment in the vessel above the water level, water levels must be a little lower than in the tray-type design, giving slightly less storage volume at the same geometric vessel volume.</p>	<p>Usually two-vessel design or dome-design. More piping, connection between vessels makes erection more complicated. More insulation and platforms needed.</p>
Operation	<p>During heating-up and filling deaerated water is available, saturation conditions in every part. No thermal stress as there are no temperature differences present. The operating range is approx. 1:30.            There is no pressure difference in the steam area.</p>	<p>The operating range is approx. 1:4.            Pressure differences top- and bottom section can arise.</p>
Safety	<p>Low susceptibility to earthquakes thanks to the application of internal deaeration instead of a superimposed deaerator dome. Single vessel with a minimum of components gives maximum safety.</p>	<p>Two-vessel design has drawbacks in robustness and earthquake-resistance.</p>
Maintenance & Spares	<p>No maintenance required, only gaskets for manholes and gaskets for sprayers are needed as spare parts to enable inspections.</p>	<p>Trays to be replaced after certain time of operating.            In case of unexpected high loads, risk of tray damage exists.</p>
Erection	<p>The erection is extremely easy. The deaerator can be mounted by local personnel, using the accompanying instructions for erection.</p>	<p>Erection more complex. If deaerators are placed inside a building, they are usually located on elevated areas. Because of the dome section, the building's roof must be higher with a tray-type design in such a case.</p>

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# TrayHeart

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# Flash Steam and Steam Condensates in Return Lines

Jayanthi Vijay Sarathy

In power plants, boiler feed water is subjected to heat thereby producing steam which acts as a motive force for a steam turbine. The steam upon doing work loses energy to form condensate and is recycled/returned back to reduce the required make up boiler feed water (BFW).

Recycling steam condensate poses its own challenges. Flash Steam is defined as steam generated from steam condensate due to a drop in pressure. When high pressure and temperature condensate passes through process elements such as steam traps or pressure reducing valves to lose pressure, the condensate flashes to form steam. Greater the drop in pressure, greater is the flash steam generated. This results in a two phase flow in the condensate return lines.

## General Notes

- To size condensate return lines, the primary input data required to be estimated is A. Fraction of Flash Steam and condensate, B. Flow Rates of Flash Steam & condensate, C. Specific volume of flash steam & condensates, D. Velocity limits across the condensate return lines.
- Sizing condensate return lines also require lower velocity limits for wet steam since liquid droplets at higher velocities cause internal erosion in pipes and excessive piping vibration. A rule of thumb, for saturated wet steam is 25 – 40 m/s for short lines of the order of a few tens of metres and 15 - 20 m/s for longer lines of the order of a few hundred metres.
- Condensate return lines work on the principle of gravity draining. To effectuate this, drain lines are to be sloped downward at a ratio of atleast 1:100.
- Proper sizing of stem condensate return lines requires consideration of all operating scenarios, chiefly start up, shutdown and during normal running conditions. During plant start up, steam is not generated instantly. As a result, the condensate lines would be filled with liquids which gradually turn two-phase until reaching normal running conditions. During shutdown

conditions, with time, flash steam in the lines condense leaving behind condensates due to natural cooling.

- Condensate return line design must also consider the effects of water hammering. When multiple steam return lines are connected to a header pipe that is routed to a flash drum, flash steam in the presence of cooler liquid from other streams would condense rapidly to cause a water hammer.

## Fraction of Flash Steam

Taking an example case, condensate flows across a control valve from an upstream pressure of 5 bara to 2 bara downstream. The saturation temperature at 5 bara is 151.84 °C & 120.20°C at 2 bara. The specific volume of water at 5 bara is 0.001093 m<sup>3</sup>/kg & 0.00106 m<sup>3</sup>/kg at 2 bara. The latent heat of saturated steam upon reaching 2 bara is 2201.56 kJ/kg. The % flash steam generated is estimated as,

$$h_{f,1} = h_{f,2} + \left[ \frac{\% \text{ Flash}}{100} \times h_{fg} \right] \quad (1)$$

Where,

$h_{f,1}$  = Upstream specific enthalpy [kJ/kg]

$h_{f,2}$  = Downstream specific enthalpy [kJ/kg]

$h_{fg}$  = Latent Heat of Saturated Steam [kJ/kg]

The upstream specific enthalpy,  $h_{f1}$  of saturated water at 5 bara is 640.185 kJ/kg and  $h_{f2}$  of 504.684 kJ/kg at 2 bara. The steam specific volume at 2 bara is 0.8858 m<sup>3</sup>/kg.

The fraction of flash steam is calculated as,

$$\% \text{ Flash} = \frac{[640.185 - 504.684]}{2201.56} \times 100 = 6.15\% \quad (2)$$

Therefore the condensate fraction is,

$$\% \text{ Cond} = 100 - 6.15 = 93.85\% \quad (3)$$



The steam volume is calculated as,

$$V_{Steam} = 0.8858 \times 0.0615 = 0.05448 \frac{m^3}{kg} \quad (4)$$

The condensate volume is calculated as,

$$V_{Cond} = 0.00106 \times 0.9385 = 0.000995 \frac{m^3}{kg} \quad (5)$$

### Condensate Return Pipe Sizing

To size the condensate return line, the bulk properties and mixture properties can be used to estimate the pipe size. It must be remembered that as the two-phase mixture travels through the pipe, there is a pressure profile that causes the flash % to change along the pipe length. Additionally due to the pipe inclination, a certain amount of static head is added to the total pressure drop.

To estimate the pipe pressure drop across the pipe length, a homogenous model for modelling the two phase pressure drop can be adopted. The homogenous mixture acts as a pseudo-fluid, that obeys conventional design based on single phase fluids characterized by the fluid's average properties.

The mixture properties can be estimated as,

$$\rho_h = \rho_L [1 - \varepsilon_h] + \rho_v \varepsilon_h \quad (6)$$

Where,

$\rho_L$  = Condensate Density [kg/m<sup>3</sup>]

$\rho_v$  = Steam Density [kg/m<sup>3</sup>]

$\varepsilon_h$  = Homogenous void fraction for a given steam quality [x] [-]

The homogenous void fraction [ $\varepsilon_h$ ] for a given steam quality [x] can be estimated as,

$$\varepsilon_h = \frac{1}{1 + \left[ \frac{u_v}{u_L} \times \frac{1-x}{x} \times \frac{\rho_v}{\rho_L} \right]} \quad (7)$$

The dynamic viscosity for calculating the Reynolds number can be chosen as the viscosity of the liquid phase or a quality averaged viscosity,  $\mu_h$ .

$$\mu_h = x\mu_v + [1 - x]\mu_L \quad (8)$$

The homogenous model for gravitational pressure drop is applicable for large drop in pressures and mass velocities < 2000 kg/m<sup>2</sup>.s, such that sufficient turbulence exists to cause both phases to mix properly and ensure the slip ratio ( $u_v/u_L$ ) between the vapour and liquid phase is ~1.0. For more precise estimates capturing slip ratios and varying void fraction, correlations such as Friedal (1979), Chisholm (1973) or Muller-Steinhagen & Heck (1986) can be used.

The total pressure drop is the sum of the static head, frictional pressure drop & pressure drop due to momentum pressure gradient.

$$\Delta P_T = \Delta P_{static} + \Delta P_{mom} + \Delta P_{fric} \quad (9)$$

The Static Head [ $DP_{static}$ ] is computed as,

$$\Delta P_{static} [bar] = \frac{H \times \rho_h \times g \times \sin \theta}{10^5} \quad (10)$$

Where,

H = Pipe Elevation [m]

$\theta$  = Pipe inclination w.r.t horizontal [degrees]

The pressure drop due to momentum pressure gradient [ $DP_{mom}$ ] is,

$$\frac{dP}{dZ} = \frac{d(m/\rho_h)}{dZ} \quad (11)$$

If the vapour fraction remains constant across the piping, the pressure drop due to momentum pressure gradient is negligible.

The frictional pressure drop is calculated as,

$$\Delta P_f = \frac{f \times L \times \rho_h \times V^2}{2D}$$

(12)

Where, DP = Pressure drop [bar]

f = Darcy Friction Factor [-]

L = Pipe Length [m]

$\rho_h$  = Mixture Density [kg/m<sup>3</sup>]

V = Bulk fluid Velocity [m/s]

D = Pipe Inner Diameter, ID [m]

$$Re = \frac{DV\rho_h}{\mu_h} \quad (13)$$

Where,  $\mu_h$  = Dynamic Viscosity [kg.m/s]

$\rho_h$  = Homogenous Density [kg/m<sup>3</sup>]

The Darcy Friction Factor [ $f$ ] depends on the Reynolds number follows the following criteria,

If  $Re \leq 2100$  ; Hagen Poiseuille's Equation

If  $Re \leq 4000$  ; Churchill Equation

If  $Re > 4000$  ; Colebrook Equation

The Laminar Flow equation also referred to as the Hagen Poiseuille's equation is,

$$f = \frac{64}{Re} \quad (14)$$

The Churchill equation combines both the expressions for friction factor in both laminar & turbulent flow regimes. It is accurate to within the error of the data used to construct the Moody diagram. This model also provides an estimate for the intermediate (transition) region; however this should be used with caution.

The Churchill equation shows very good agreement with the Darcy equation for laminar flow, accuracy through the transitional flow regime is unknown & in the turbulent regime a difference of around 0.5-2% is observed between the Churchill equation and the Colebrook equation. For Reynolds number up to ~4000,

$$f = 8 \left[ \left( \frac{8}{Re} \right)^{12} + \frac{1}{(A+B)^{1.5}} \right]^{1/12} \quad (15)$$

$$A = \left[ 2.457 \ln \left( \frac{1}{\left( \frac{7}{Re} \right)^{0.9} + 0.27 \frac{\epsilon}{D}} \right) \right]^{16} \quad (16)$$

$$B = \left[ \left( \frac{37,530}{Re} \right) \right]^{16} \quad (17)$$

The Colebrook equation was developed taking into account experimental results for the flow through both smooth and rough pipe. It is valid only in the turbulent regime for fluid filled pipes. Due to the implicit nature of this equa-

suitable accuracy for almost all industrial applications will be achieved in less than 10 iterations. For Reynolds number up greater than ~4000,

$$\frac{1}{\sqrt{f}} = -2 \log_{10} \left[ \frac{\epsilon/DH}{3.7} + \frac{2.51}{Re\sqrt{f}} \right] \quad (18)$$

### Homogenous Property Calculations

The two phase mixture flows through the condensate return line. The associated density and viscosity of flash steam and condensate at 2 bara and 120.2°C is,

$$\rho_v = \frac{1}{0.8858} = 1.129 \frac{kg}{m^3} \quad (19)$$

$$\rho_L = \frac{1}{0.00106} = 943.4 \frac{kg}{m^3} \quad (20)$$

$$\mu_v = 0.000229 \frac{kg}{m.s} \quad (21)$$

$$\mu_L = 0.0000128 \frac{kg}{m.s} \quad (22)$$

The homogenous void fraction [ $\epsilon_h$ ] for a slip ratio ( $u_v/u_L$ ) of 1.0, i.e.,  $u_v = u_L$ , and a steam quality [ $x$ ] of 6.15% is,

$$\epsilon_h = \frac{1}{1 + \left[ 1 \times \frac{1 - 0.0615}{0.0615} \times \frac{1.129}{943.4} \right]} = 0.9821 \quad (23)$$

The two phase homogeneous density is,

$$\rho_h = 943.4 \times [1 - 0.9821] + [1.129 \times 0.9821] \quad (24)$$

$$\rho_h = 18.014 \frac{kg}{m^3} \quad (25)$$

The two phase homogeneous viscosity is,

$$\mu_h = \frac{0.0615 \times 1.28}{10^5} + \frac{[1 - 0.0615] \times 2.29}{10^4} \quad (26)$$

$$\mu_h = 0.000216 \frac{kg}{m.s} \quad (27)$$

### Pressure Drop Calculations

The return condensate line from the control valve discharge is sloped at a ratio of 1:100 for gravity drain. The layout of the return condensate line is,

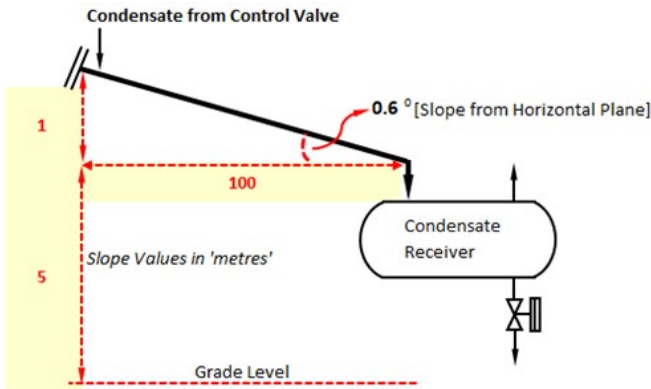


Figure 1. Condensate Return Line to Receiver

The condensate receiver operates at 1.1 bara pressure. The mechanical details of the piping for a flow rate of 1,000 kg/h, pipe size of 1.5", 100m length & pipe roughness of 45.2 mm is,

Table 1. Condensate Return Line Details

Parameter	Value	Unit
Mass Flow rate [m]	1000.0	kg/h
Volumetric Flow [Q]	55.51	m <sup>3</sup> /h
Pipe Length [L]	100	m
Pipe Roughness [ε]	45.2	μm
Pipe Outer Diameter [OD]	48.3	mm
Pipe SMYS [Carbon Steel]	30,000	psi
Pipe Design Pressure [DP]	7	bara
Pipe Wall Thickness [WT]	0.08	mm
Corrosion Allowance [CA]	1.0	mm
Calculated WT	1.08	mm
Selected WT	3.68	mm
Pipe Inner Diameter [ID]	40.94	mm

The pipe wall thickness chosen is based on ASME/ANSI B36.10M and is calculated based on the hoop stress created by internal pressure in a thin wall cylindrical vessel as,

$$WT = \frac{DP \times OD}{2 \times SMYS} = \frac{[7 \times 14.5] \times \left[ \frac{48.3}{25.4} \right]}{2 \times 30,000} \times 25.4 \quad (28)$$

$$WT = 0.08 \text{ mm} \quad (29)$$

Adding CA of 1 mm, the WT becomes 1.08 mm. Based on ASME/ANSI B36.10M, the selected WT is 3.68mm. The inner diameter calculated for the selected WT is 40.94 mm.

The condensate return line mixture fluid velocity is calculated as,

$$V = \frac{Q}{A} = \frac{4 \times \left[ \frac{1000}{18.01} \right] \times \frac{1}{3.600}}{\pi \times [0.04094]^2} = 11.7142 \text{ m/s} \quad (30)$$

The Reynolds number is estimated as,

$$Re = \frac{ID \times V \times \rho \hbar}{\mu \hbar} = \frac{0.04094 \times 11.7 \times 18.01}{0.000216} \quad (31)$$

$$Re \approx 39,971 \quad (\text{MS-Excel computed}) \quad (32)$$

Since the Reynolds number is much higher than 4,000, the flow is fully turbulent and the friction factor is calculated based on Colebrook equation. The friction factor is estimated as,

$$f = f_{\text{Colebrook}} = 0.0251 \quad (33)$$

The frictional pressure drop is now calculated using the Darcy-Weisbach expression as,

$$\Delta P_f = \frac{0.0251 \times 100 \times 18.01 \times 11.7^2}{2 \times 0.04094 \times 10^5} \quad (34)$$

$$\Delta P_f = 0.757 \text{ bar} \quad (35)$$

The slope angle is calculated as,

$$\theta = \left[ \text{Tan}^{-1} \left( \frac{1}{100} \right) \right] \times \frac{180}{\pi} = 0.6^\circ \quad (36)$$

The static pressure drop [ $DP_{\text{static}}$ ] becomes

$$\Delta P_{\text{static}} = \frac{18.01 \times 9.81 \times [(1+5) \times \sin(0.6^\circ)]}{10^5} \quad (37)$$

$$\Delta P_{\text{static}} = 0.000106 \text{ bar} \quad (38)$$

Therefore the total DP with negligible DP due to momentum pressure gradient [ $DP_{\text{mom}}$ ].

$$\Delta P_{\text{total}} = \Delta P_{\text{static}} + \Delta P_f \quad (39)$$

$$\Delta P_{\text{total}} = 0.757 + 0.000106 = 0.757 \text{ bar} \quad (40)$$

The condensate exit pressure is  $2 - 0.757 = 1.243$  bara which is higher than the receiver's operating pressure of 1.1 bara.



## REFERENCES

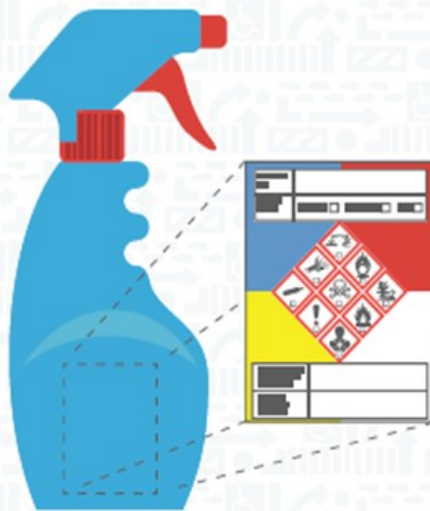
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Vijay Sarathy holds a master's degree in Chemical Engineering from Birla Institute of Technology & Science (BITS), Pilani, India and is a Chartered Engineer from the Institution of Chemical Engineers, UK. His expertise over 16 years of professional experience covers Front End Engineering, Process Dynamic Simulation and Subsea/Onshore pipeline flow assurance in the Oil and Gas industry. Vijay has worked as an Upstream Process Engineer with major conglomerates of General Electric, ENI Saipem and Shell.



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# Importance of Production Cost Models for Renewable Integration Studies in Developing countries

Mousumi Guha

## ABSTRACT

Renewable energy, in particular wind and solar, has experienced a large increase in installed capacity in recent years. Power system planning has evolved rapidly in recent years to keep pace with advancements in generation technologies, formation, or interconnection of larger and more complex grids, and increasing consumer expectations. Uniquely, this paper tries to evaluate the importance of a planning model for developing countries.

## INTRODUCTION

India has made significant progress in renewable energy integration in recent years, and the country has set ambitious targets to increase the share of renewable energy in its energy mix. As of 2021, India has a total installed renewable energy capacity of around 97 GW, which includes solar, wind, biomass, and small hydroelectric projects. One of the key drivers of renewable energy integration in India has been the government's policies and initiatives. The Indian government has implemented various policies and programs to promote the development and deployment of renewable energy projects, such as the National Solar Mission, which aims to install 100 GW of solar power by 2022. The government has also offered various financial incentives, such as tax exemptions and subsidies, to encourage private investment in renewable energy projects. Another important aspect of renewable energy integration in India is the development of grid infrastructure to support the integration of variable renewable energy sources, such as wind and solar. The Indian government has been investing in the development of grid infrastructure, such as the Green Energy Corridor project, which aims to strengthen the transmission system for renewable energy integration. However, there are still challenges to the integration of renewable energy in India, such as the intermittency of solar and wind power, and the need for energy storage solutions. These

challenges require continued investment and innovation to develop new technologies and solutions that can improve the reliability and efficiency of renewable energy integration. Hence, there is a need of a long-term planning model in order to understand the integration of renewables onto the grid.

## PRODUCTION COST MODELS (PCM)

### Economic dispatch model

Production cost models seek to minimize the total cost of satisfying electricity demand and ancillary services requirements by controlling commitment and dispatch of an entire fleet of generators while adhering to system-level constraints on transmission capacity and generator physical or operational limitations. Hence, the resulting dispatch schedules provide a least-cost economic dispatch solution for the overall system. In principle, allowing the PCM to optimize the system dispatch.

### Evolution of Power System Planning

Power system planning has evolved rapidly in recent years to keep pace with advancements in generation technologies, formation or interconnection of larger and more complex grids, and increasing consumer expectations. Load forecasting is an integral part of the planning process because it provides the bounds inside which the system must be planned. The traditional approach to power system planning is to ensure the system has adequate generation and transmission capacity to meet anticipated peak demand and annual or seasonal energy requirements.

## BRIEF OVERVIEW OF THE POWER SYSTEM

For our analysis, we are using Indian Power system as our study region. This paper references to NREL's study and highlights and emphasizes the need of production cost models in the developing countries. As of 2019,



India has an installed generation capacity of 357 GW, with coal and RE sources accounting for 194 GW (54%) and 78 GW (22%), respectively, and peak demand of 181 GW. India's peak demand is expected to increase from 181 GW in 2018–2019 and to 520 GW in 2036–2037, prompting the need for investments in generation infrastructure (CEA 2018b). Government targets and favorable economics could lead to an increasing share of generation capacity met with VRE technologies. Because VRE resources are not uniformly distributed in form or location, this could shift the mix and regional distribution of electricity supply.

### USING THE MODELING FRAMEWORK

Capacity expansion models must balance the need for detailed representation of the electricity sector with computational complexity. Planning tools vary significantly in their treatment of operating constraints, energy prices, demand projections, as well as temporal and geographic resolution. For systems such as that of India, where Variable renewable energy (VRE) technologies may play an increasing role in the future generation mix, the appropriate tool should capture the diversity of candidate VRE technologies and their applications, the location-dependent quality of these resources, and inherent uncertainty and variability in wind and solar generation. This model is based on a linear optimization program that minimizes the net present value of investment and operating costs subject to several constraints. The major constraints include balancing electricity supply and demand, resource supply limits, planning and operating reserve constraints, transmission constraints, and policy targets. These constraints are met considering a broad portfolio of conventional generation, renewable generation, storage, and transmission technologies. India model is implemented in the General Algebraic Modeling System (GAMS) programming language and is publicly available at <https://www.nrel.gov/analysis/reeds/>.

### Electricity Demand & Supply Dynamics

To capture anticipated growth in electricity demand, we create state-wise hourly demand profiles for each year over the planning period. Each with its own techno-economic parameters. Table 1 summarizes the generation technologies considered in the model.

Table 1: Generation Technology Candidates

Generation Technology Candidates		
Conventional	Subhead	Subhead
Combined-cycle gas turbine (CCGT) Gas	Distributed PV	BESS (4-hour)
CCGT liquified natural gas (LNG)	Hydro pondage	BESS (4-hour)
Combustion turbine (CT) gas	Hydro run-of-river	

Generation Technology Candidates		
Conventional	Subhead	Subhead
Cogeneration bagasse	Hydro storage	
Diesel	Onshore wind	
Subcritical coal	Utility PV	
Subcritical lignite		
Supercritical coal		

Simplifications are made in the representation of generation units to maintain a tractable optimization problem. Here we aggregate all units of the same technology within a BA, with the exception of wind and solar, which are aggregated by resource region. To capture differences in cost and performance of units of the same technology, we cluster units into "performance bins" based on their techno-economic parameters.

### Existing and Committed Generation Capacity

Input data for exogenously defined capacity include existing capacity, planned capacity additions, and planned retirements. Table 2 shows the planned additions and retirements through planning forecast period.

Table 2: Summary of Installed Capacity (GW) by Technology

VRE	Hydro	Nuclear	Thermal	Subhead
50	45	6.9	196.7	298.6

### Future Technology Options for Expansion

Future electricity supply needs can be met by any of the thermal, nuclear, or renewables-based technologies. The optimal mix of

technologies is based on several factors, including the cost of development, operation and maintenance costs, policy targets, and resource availability. The capital costs assumptions are sourced from public data of CEA. Table 3 shows the typical cost and lifetime parameters.

Table 3: Capital Cost and Plant Lifetime Assumptions for Generation Technologies

<i>Technology</i>	<i>Capital Cost (crore/MW)</i>	<i>Plant Lifetime (yrs)</i>
BESS	9.1	15
CCGT gas / LNG	4.7	55
Gas CT	4	55
Hydro	10	100
Nuclear	10.2	100
Subcritical Coal	6.5	25
Supercritical Coal	6.5	25
PV	5.5	30
Wind	6	24

For all technologies, both mature and emerging, there is a learning rate that results in reductions in capital costs over time as manufacturers and developers gain experience with the technology. We adopt the same learning rates used in NREL's 2018 Annual Technology Baseline "Mid" estimates.

The investment constraints represent policy, resource, or technical criteria that may influence investment outcomes. We impose three types of investment constraints on generation additions: (1) first year for endogenous capacity additions, (2) absolute growth limits, and (3) relative growth limits. The first year for endogenous capacity additions is the initial year when new capacity can be built based on economic criteria. Before the first year, only prescribed additions can be added.

The absolute growth limit represents the state-wise capacity limits on hydro, biomass, and waste heat recovery (WHR) technologies based on their estimated potential. Finally, we use relative growth and geographic diversity constraints to prevent unrealistic rates of capacity growth in any single year or location. All technologies except BESS are constrained with a 50% year-over-year limit of growth relative to installed capacity in the previous year. Renewable Resource Supply Curves uses supply curves for wind and solar to characterize the potential sites available for

development and directly evaluate the investments of these generation sources. These supply curves are estimated from detailed weather data, geospatial constraints, and economic assumptions.

These are combined with financial assumptions about technology capital costs, fixed operating costs, and grid integration costs (i.e., transmission upgrades) to calculate site-based levelized cost of energy (LCOE). Hourly profiles for each potential site are created to estimate generation, curtailment, and capacity credit for all wind and solar investments.

### System Operations

uses a reduced form-dispatch where generation technologies, rather than individual units, are dispatched to meet requirements for operating reserves and electricity demand in each time slice. This section presents the operational characteristics and constraints designed to capture the cost and performance characteristics of each technology type.

Model uses the variable operation and maintenance cost parameter to capture differences in unit cost and performance for existing and planned units. Within each Balancing area (BA), we cluster individual units into "performance bins" or groups of units with similar costs.

As the penetration of VRE and storage technologies increases, more-detailed representation of system operations becomes increasingly important in planning. The Model addresses this through simulations of time-synchronous operations to estimate curtailment for each capacity expansion solution.

The operating constraints represent technical and resource-based limits on how technologies may be dispatched. These include (1) seasonal limits on hydropower generation, (2) limits on gas fuel supplies, (3) minimum loading for CCGT gas, and (4) seasonal minimum loading limits.

### INTERPRETING THE MODELING RESULTS

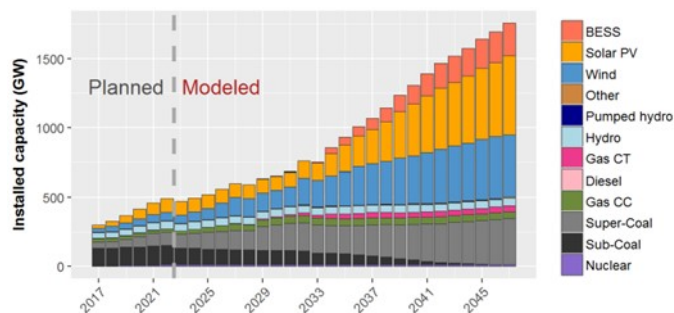
The result of model shows an example of India modeling to examines the development of the India power system to 2047 under a Base scenario.

#### Electricity Installed Capacity

In the Base scenario, the total installed capacity over the planning period increases from 299 GW in 2017 to 1,718 GW in 2047. Capacity additions and retirements are fixed based

on current plans through 2022. After that, the model optimizes the capacity mix in each year to achieve a least cost system. Figure 1 shows the total modeled capacity expansion under the Base scenario.

Figure 1: Total installed capacity, 2017–2047 in the Base scenario



Based on guidance from policies, all subcritical coal and diesel plants are retired by 2047. Most new investments are from supercritical coal, wind, solar PV and BESS technologies. After 2022, there are no prescribed additions, and all investments reflect economic, least-cost capacity additions. Gas CT plants have more generation dispatch flexibility and are better suited than gas CC plants to operate as peaking plants with very low utilization. Investments in wind, solar PV, and BESS account for most capacity additions after 2034; the fraction of installed capacity from solar and wind increases from 17% in 2017 to 58% in 2047. Supercritical coal and BESS also play a larger role in the future capacity mix, accounting for 19% and 13% of installed capacity in 2047 respectively.

In a future system with high penetrations of Renewable Energy (RE), capacity additions are driven by the coincidence of demand and RE generation rather than peak demand alone. By 2047, the system has surplus capacity during the peak demand months of July–September because high wind speeds mean more wind generation is available to meet peak demand in these months. New capacity is needed to meet peak demand during the moderate demand months of October and November, when wind generation is lower.

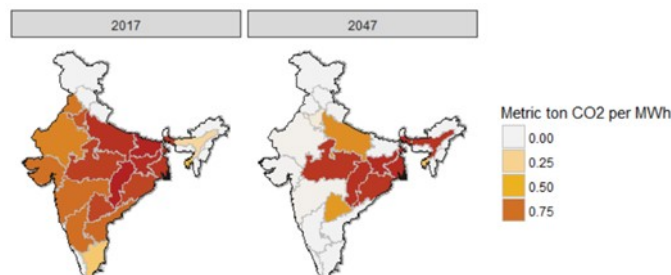
### Electricity Carbon Emissions

India has pledged a 33%–35% reduction in the emissions intensity of its economy from 2005 to 2030 (UNFCCC 2015). Reducing emissions from the electric power sector is a critical element of this goal. In the Base scenario, total emissions increase over the planning period as the amount of total electricity generated increases significantly. However,

the emissions intensity decreases 47%, from 0.76 metric tonnes of carbon dioxide per megawatt-hour in 2017 to 0.40 in 2047.

Carbon emissions from the production of electricity also become more concentrated in a few states. Figure 2 shows the variation in CO<sub>2</sub> emissions from the geographical variation.

Figure 2: Carbon emissions intensity from electricity production by state, 2017 and 2047



### CONCLUSIONS

The supply of electricity in India is poised to undergo significant changes over the coming decades. A system previously dominated by subcritical coal plants could rely increasingly on supercritical coal, wind, and solar technologies. In this analysis, we find 95% of electricity demand could be met by these three technologies by 2047. As electricity supplies become more concentrated in areas with strong variable renewable energy (VRE) resources, new interstate transmission capacity is needed to evacuate excess power to neighboring states. This concentration also has implications for carbon emissions, which become increasingly concentrated in a few Eastern Region states where coal remains cost-competitive with other technologies.

The results from this long-term assessment are pertinent for a variety of decision makers. For example, policymakers must establish the policy and regulatory frameworks needed to enable cost-effective investments and system operations. And the results can allow utilities, project developers, and financing institutions to anticipate system changes and mobilize necessary expertise and funding to realize their long-term vision. Finally, the evolution of the power system is of interest to the broader public who will be impacted by issues related to land use, electricity prices, quality of supply, emissions, and domestic jobs in the energy sector.

However, some assumptions are needed wherever data are incomplete or unavailable. While many of these assumptions are unlikely



### Today's production of hydrogen is via carbon-intensive processes, with use of hydrogen concentrated in the refining, ammonia, and methanol sectors

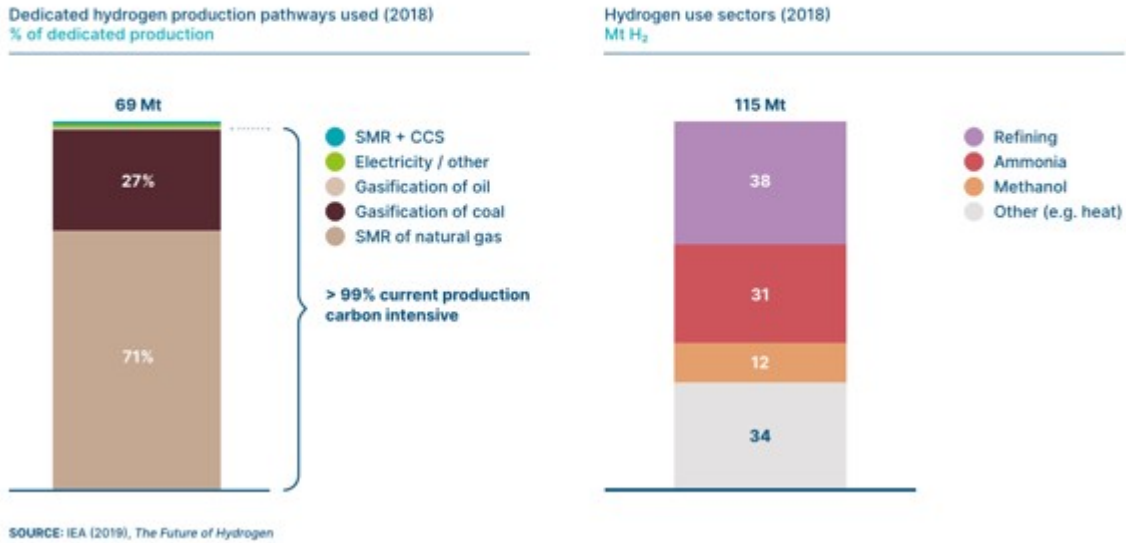


Figure 5 – Main Production Routes and Hydrogen Consumers (ETC Global Hydrogen Report, 2021)

conversion of syngas (CO + H<sub>2</sub>) in longer-chain hydrocarbons such as gasoline and other liquid fuel products, known as Gas to Liquids Technologies (GTL). The liquid hydrocarbons production can be carried out by direct syngas conversion, in Fischer-Tropsch synthesis reactions or through methanol production as intermediate product (Methanol to Olefins technologies).

Shown process in Figure 6 is based in the syngas gas generation from steam reforming of natural gas, this is the most common route, however, there are process variations applying syngas production through coal, biomass, or petroleum coke gasification route.

The process starts with syngas generation and, as aforementioned, the produced hydrocarbon chain extension is controlled in the Fischer-Tropsch synthesis step through the CO/H<sub>2</sub> ratio in the syngas fed to the FT reactors (beyond temperature and reaction pressure), following the produced hydrocarbons are separated and sent to refining steps as isomerization, hydrotreating, hydrocracking, catalytic reforming, etc. According to application of the produced derivative (Gasoline, Diesel, Lubricant, etc.).

Some side reactions can occur during the hydrocarbons production process, leading to coke deposition on the catalyst, causing

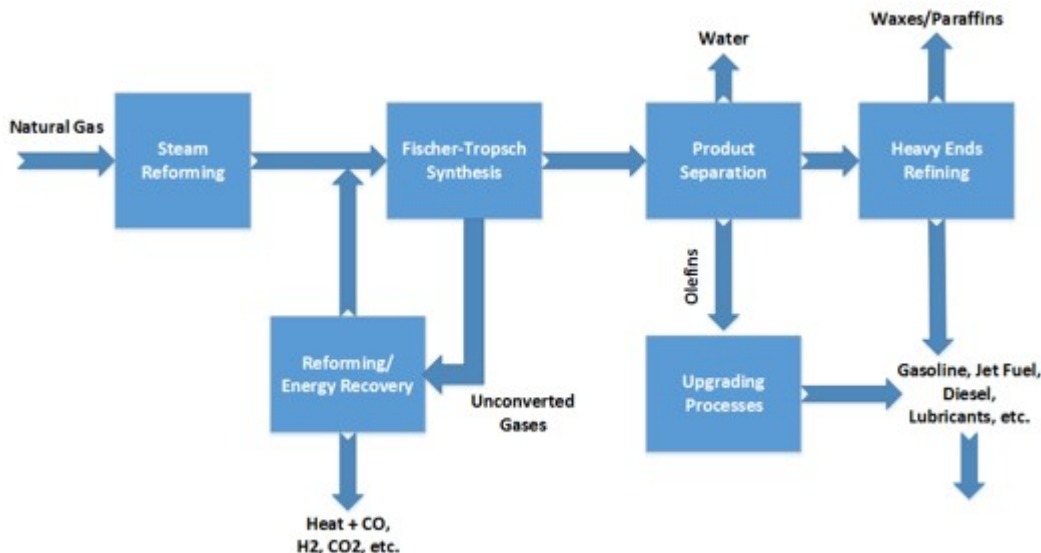


Figure 6 – Block Diagram to a Typical Fischer-Tropsch GTL Process Plant.



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# Burn is not the Only Way! Non-Energetic Derivatives as Route to Add Value to the Crude Oil

Dr. Marcio Wagner da Silva

## INTRODUCTION AND CONTEXT

The current scenario present great challenges to the crude oil refining industry, prices volatility of raw material, pressure from society to reduce environmental impacts and refining margins increasingly lower. The newest threat to refiners is the reduction of the consumer market, in the last years became common, news about countries that intend to reduce or ban the production of vehicles powered by fossil fuels in the middle term, mainly in the European market. Despite the recent forecasts, the transportation fuels demand is still the main revenues driver to the downstream industry, as presented in Figure 1, based on data from Wood Mackenzie Company.

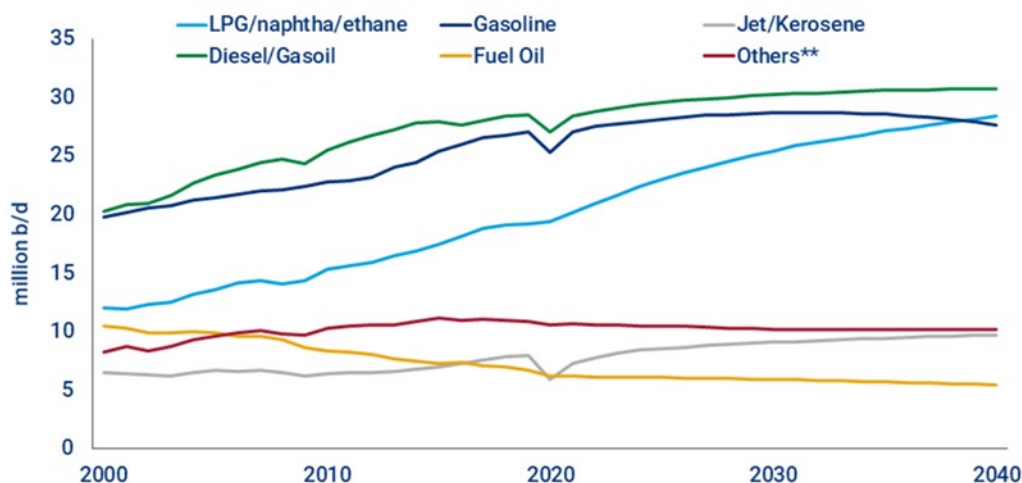
According to Figure 1, is expected a growing demand by petrochemicals while the transportation fuels tend to present falling consumption. Still according to Wood Mackenzie data, presented in Figure 2, due to the higher added value, the most integrated refiners tend to

achieve higher refining margins than the conventional refiners which keep the operations focused on transportation fuels.

NCM = Net Cash Margins

The improvement in fuel efficiency, growing market of electric vehicles tends to decline the participation of transportation fuels in the global crude oil demand. New technologies like additive manufacturing (3D printing) have the potential to produce great impact to the transportation demands, leading to even more impact over the transportation fuels demand. Furthermore, the higher availability of lighter crude oils favors the oversupply of lighter derivatives that facilitate the production of petrochemicals against transportation fuels as well as the higher added value of petrochemicals in comparison with fuels.

### Oil demand by product\*



\*Product-level demand is reported on a gross base including backflow.

\*\*Includes multiple products such as refinery gas, petroleum coke, bitumen, crude oil, non-specified other products, and backflow (negative figure).

Source: IEA, Forecast – Wood Mackenzie

Figure 1 – Global Oil Demand by Derivative (Wood Mackenzie, 2020)



On the other hand, non-energetic derivatives like petrochemicals and lubricating presents a growing consumer market. According to trend analysts and recent forecasts, the lubricants market size was valued at USD 165 billion in 2022 and will grow by compound annual rates around 3,0 % and can reach a total value of USD 188 billion in 2027. Figure 3 presents the growing trend for lubricants market by consumer sector. The high added value of lubricants in comparison with the transportation fuels accompanied by the trend of reduction in transportation fuels demand indicates an attractive alternative to refiners with adequate refining hardware to improve his revenues and the competitiveness in the downstream market.

Like others crude oil derivatives, the economic and technology development have been required the production of lubricating oils with higher quality and performance, moreover with lower contaminants content. In his turn, petrochemicals also present a significant growth to the next years, as presented in Figure 4.

Just the olefins market will rise a total value of US\$ 322 billion dollars in 2026 with a growing rate of 4,0 % in 2022 to 2027 period according to recent forecasts. Under this scenario, search for alternatives that ensure survival and sustainability of the refining industry became constant by refiners and technology developers. The maximization of non-energetic derivatives like lubricants and petrochemicals can offer a profitable alternative to refiners, according to the local market. Due to his similarities, better integration between refining and

petrochemical production processes appears as an attractive alternative. Although the advantages, it's important consider that the integration between refining and petrochemical assets increase the complexity, requires capital spending, and affect the interdependency of refineries and petrochemical plants, these facts need to be deeply studied and analyzed case by case.

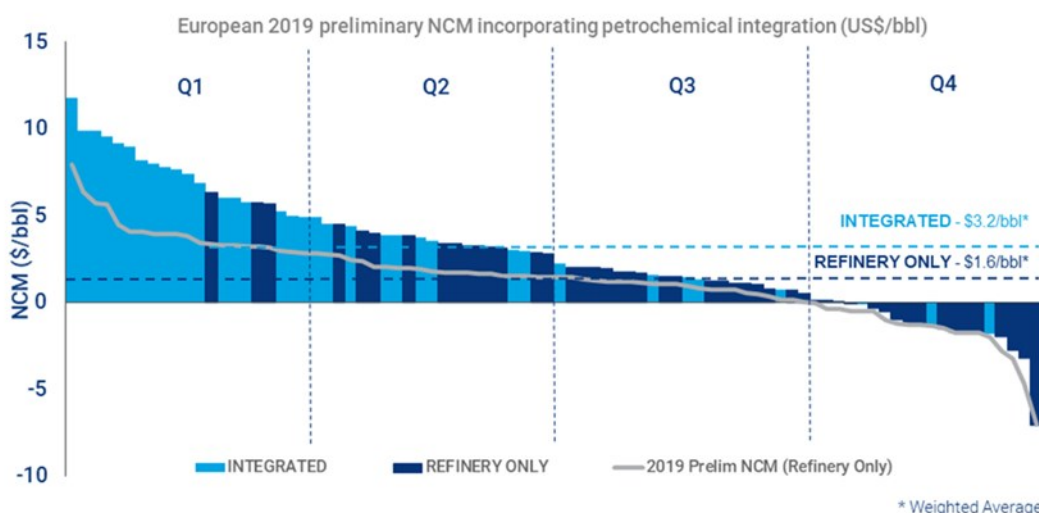
### HIGHER ADDED VALUE TO THE NAPHTHA – PETROCHEMICAL INTEGRATION CONCEPT

The focus of the closer integration between refining and petrochemical industries is to promote and seize the synergies existing opportunities between both downstream sectors to generate value to the whole crude oil production chain. Table 1 presents the main characteristics of the refining and petrochemical industry and the synergies potential.

As aforementioned, the petrochemical industry has been growing at considerably higher rates when compared with the transportation fuels market in the last years, additionally, represent a noblest destiny and less environmental aggressive to crude oil derivatives. The technological bases of the refining and petrochemical industries are similar which lead to possibilities of synergies capable to reduce operational costs and add value to derivatives produced in the refineries.

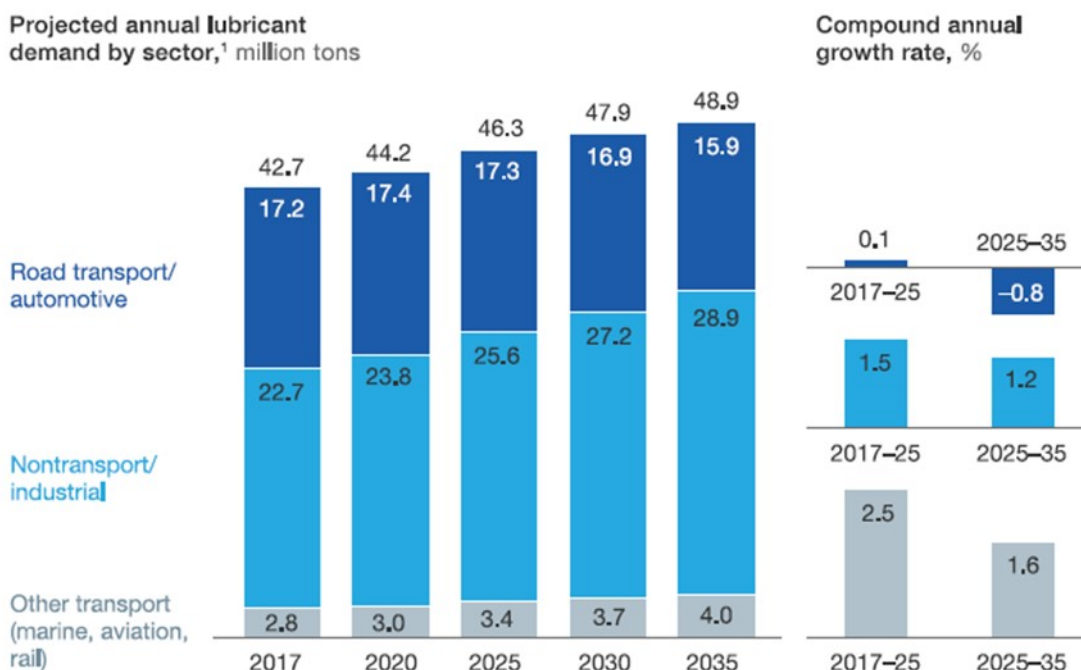
Figure 5 presents a block diagram that shows some integration possibilities between refining processes and the petrochemical industry.

### Petrochemical integration almost doubles the average European refinery net cash margin (NCM)



Source: Wood Mackenzie

Figure 2 – Refining Margins to Integrated and Non-Integrated Refining Hardware (Wood Mackenzie, 2020)

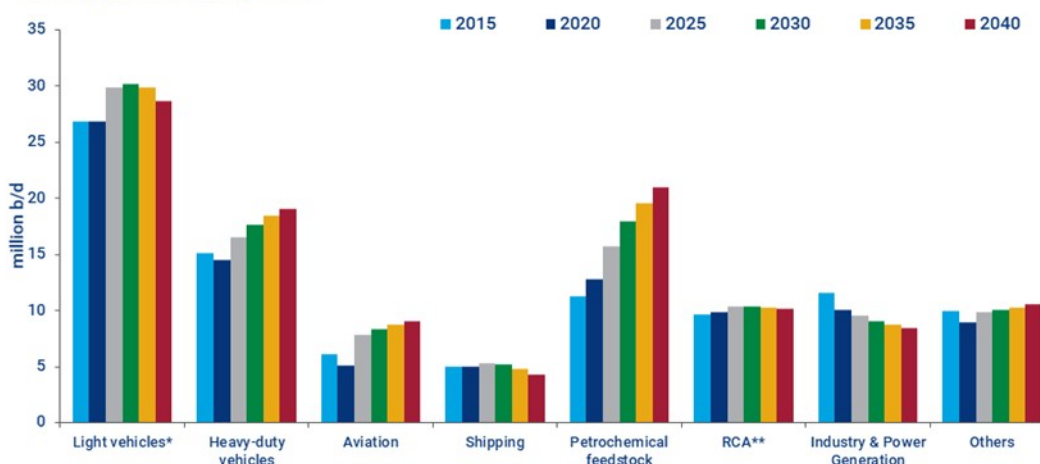


<sup>1</sup>Figures may not sum, because of rounding.

Figure 3 – Growing Trend in the Demand by Lubricants (McKinsey & Company, 2018)

### Petrochemicals feedstock leads demand growth in the long run – while fuel demand from light vehicles will start to fall

Global liquids demand by sector



Source: Wood Mackenzie Macro Oils Long Term Outlook H1 2020 \* includes two-wheelers \*\* Residential, Commercial and Agriculture \*\*\* includes non-energy use (other than petrochemical feedstock) and refinery fuel, etc.

Figure 4 – Growing Trend in the Demand by Petrochemical Intermediates (Wood Mackenzie, 2020)

Table 1 – Refining and Petrochemical Industry Characteristics

Refining Industry	Petrochemical Industry
Large Feedstock Flexibility	Raw Material from Naphtha/NGL
High Capacities	Higher Operation Margins
Self Sufficient in Power/Steam	High Electricity Consumption
High Hydrogen Consumption	High Availability of Hydrogen
Streams with low added Value (Unsaturated Gases & C2)	Streams with Low Added Value (Heavy Aromatics, Pyrolysis Gasoline, C4's)
Strict Regulations (Benzene in Gasoline, etc.)	Strict Specifications (Hard Separation Processes)
Transportation Fuels Demand in Declining at Global Level	High Demand Products

Process streams considered with low added value to refiners like fuel gas (C2) are attractive raw materials to the petrochemical industry, as well as streams considered residual to petrochemical industries (butanes, pyrolysis gasoline, and heavy aromatics) can be applied to refiners to produce high quality transportation fuels, this can help the refining industry meet the environmental and quality regulations to derivatives.

The integration potential and the synergy among the processes rely on the refining scheme adopted by the refinery and the consumer market, process units as Fluid Catalytic Cracking (FCC) and Catalytic Reforming can be optimized to produce petrochemical intermediates to the detriment of streams that will be incorporated to fuels pool. In the case of FCC, installation of units dedicated to produce petrochemical intermediates, called petrochemical FCC, aims to reduce to the minimum the generation of streams to produce transportation fuels, however, the capital investment is high once the severity of the process requires the use of material with noble metallurgical characteristics.

The IHS Markit Company proposed a classification of the petrochemical integration grades, as presented in Figure 6.

According to the classification proposed, the crude to chemicals refineries is considered the maximum level of petrochemical integration where the processed crude is totally converted into petrochemicals like ethylene, propylene, and BTX.

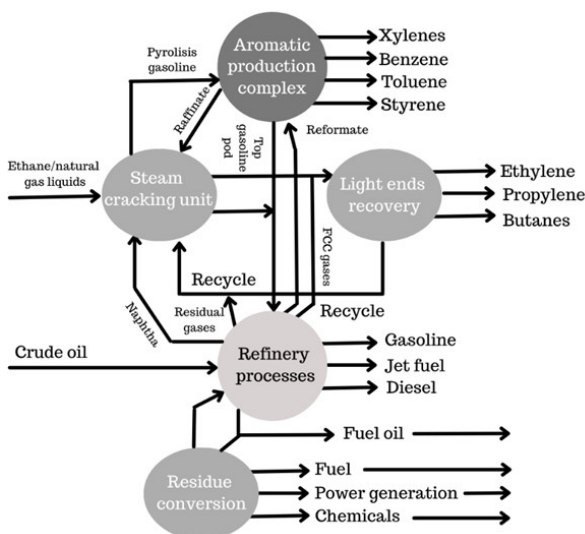


Figure 5 –Possible Synergies between Refining and Petrochemical Processes

### REACHING MAXIMUM ADDED VALUE - INTEGRATED REFINING SCHEMES

Historically, the refining industry growth was sustained and focused on transportation fuels, this can explain the profile of the traditional refining schemes. Nowadays, the downstream industry is facing with a trend of reduction in transportation fuels demand, followed by a growing demand by petrochemicals, this fact is the main driving force to promote the change of focus in downstream industry.

The growing market of petrochemicals have been led some refiners to look for a closer integration between refining and petrochemicals assets aiming to reach more adherence with the market demand, improve revenues, and reduce operation costs. To reach this goal, the refiners are implementing most integrated refining schemes as presented in Figure 7.

As presented in Figure 7, the integrated refining scheme rely on flexible refining technologies as catalytic reforming and fluid catalytic cracking (FCC) that are capable to reach the production of high-quality petrochemicals and transportation fuels, according to the market demand. A more integrated refining configuration allows the maximization of petrochemicals, raising the refining margins and ensures higher value addition to the processed crude oils. Another fundamental competitive advantage is the operational flexibility reached through the integrated refining configurations, allowing the processing of discounted and cheaper crude oils, raising even more the refining margins.

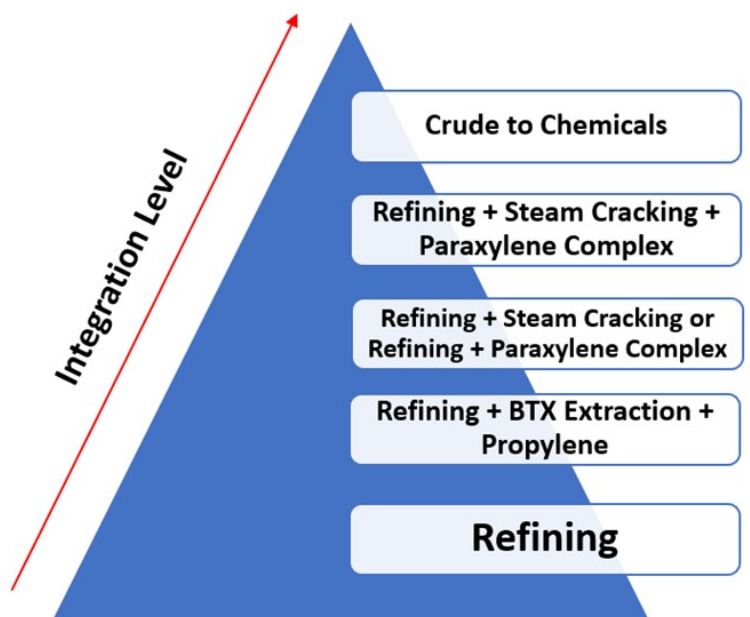


Figure 6 – Petrochemical Integration Levels (IHS Markit, 2018)





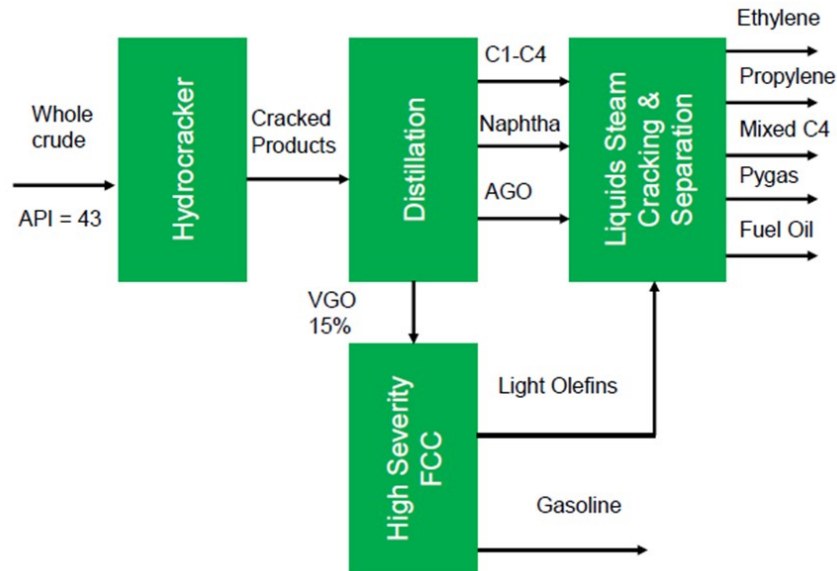


Figure 8 – Saudi Aramco Crude Oil to Chemicals Concept (IHS Markit, 2017)

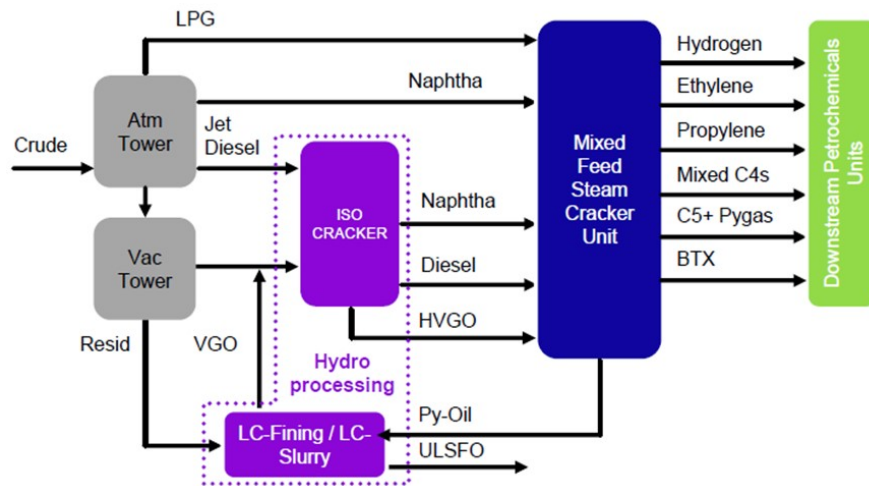
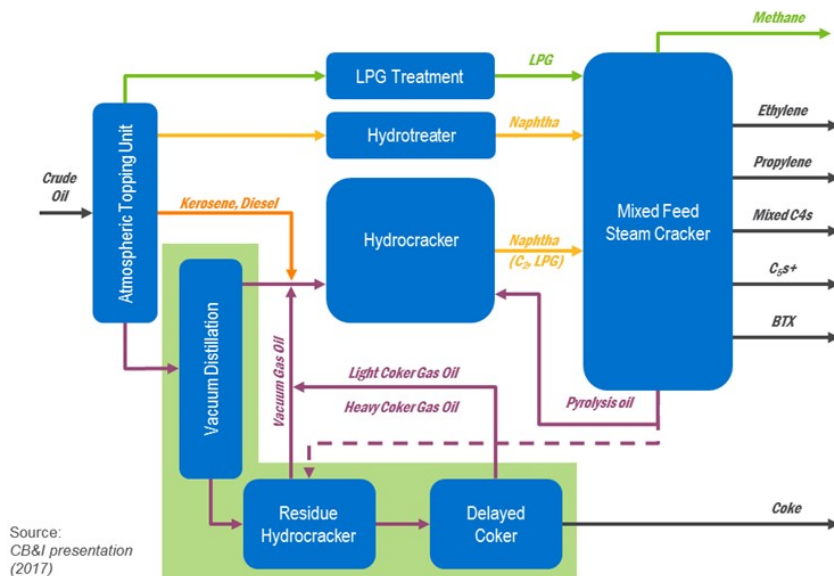


Figure 9 – Crude to Chemicals Concept by Chevron Lummus Company (Chevron Lummus Global Company, 2019)



Source: CB&I presentation (2017)

Figure 10 – Crude to Chemicals Concept by Chevron Lummus Company (Nexant Company, 2018)

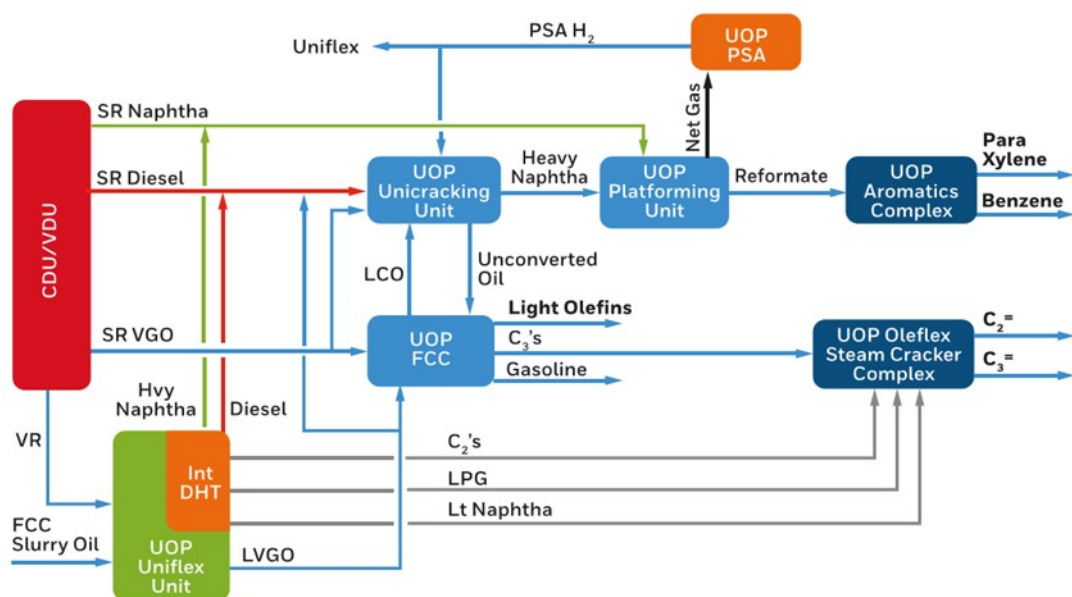


Figure 11 – Integrated Refining Configuration Based in Crude to Chemicals Concept by UOP Company.

As aforementioned, face the current trend of reduction in transportation fuels demand at the global level, the capacity of maximum adding value to crude oil can be a competitive differential to refiners. Due to the high capital investment needed for the implementation that allows the conventional refinery to achieve the maximization of chemicals, capital efficiency becomes also an extremely important factor in the current competitive scenario as well as the operational flexibility related to the processed crude oil slate.

### THE LUBRICANT PRODUCTION ROUTES – ANOTHER PROFITABLE WAY TO ENSURE PARTICIPATION IN A GROWING MARKET

The first step in the lubricant production process is vacuum distillation of atmospheric residue obtained like bottom product in the atmospheric distillation processes. For vacuum distillation units dedicated to producing lubricating fractions the fractionating needs a better control than in the units dedicated to producing gasoils to fuels conversion, the objective is to avoid the thermal degradation and to control distillation curve of the side streams, a typical arrangement for vacuum distillation unit to produce lubricating fractions is presented in Figure 12. A secondary vacuum distillation column is necessary when is desired to separate the heavy neutral oil stream from vacuum residue.

In lubricating production units based on the solvent route the following steps are basically physical separation processes with the objective to remove from the process streams the components which can prejudice the desired

properties of base oils, mainly the viscosity index, and chemical stability.

Figure 13 shows a block diagram corresponding to the process steps to produce base lubricating oils through solvent extraction route.

As aforementioned, in the vacuum distillation step, the fractionating quality obtained between the cuts is critical for these streams reach the quality requirements like flash point and viscosity. After vacuum distillation step the side cuts are pumped to aromatic extraction unit and the vacuum residue is sent to propane deasphalting unit.

The Propane deasphalting process seeks to remove from vacuum residue the heavier fractions which can be applied as lubricating oil. The Propane deasphalting units dedicated to producing lubricating oils apply pure propane like solvent because this solvent has higher selectivity to remove resins and asphaltenes from deasphalted oil.

In the aromatic extraction step, the process streams are put in contact with solvents selective to remove aromatics compounds, mainly polyaromatics. The main objective in remove these compounds is the fact that they have low viscosity index and low chemical stability, this is strongly undesired in lubricating oils. As the nitrogen and sulfur compounds are normally present in the polyaromatic structures, in this step a major part of sulfur and nitrogen content of the process stream is removed. The solvents normally applied in the aromatics extraction process is phenol, furfural, and N-methyl pyrrolidone.



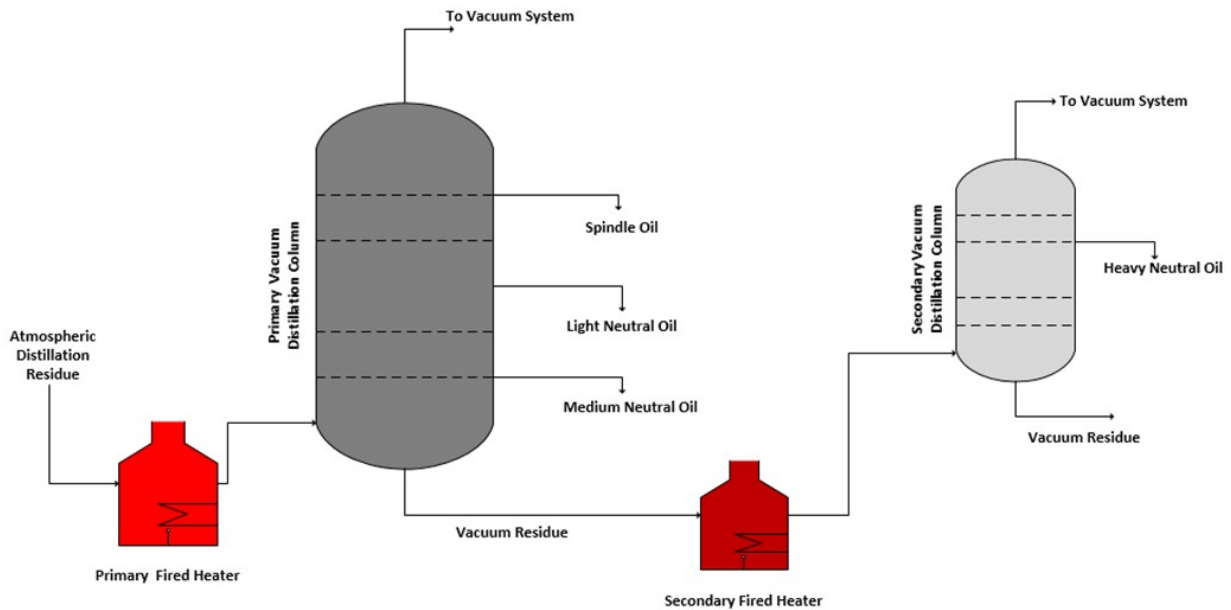


Figure 12 – Typical Arrangement for Vacuum Distillation Process to Lubricating Oil Production

The subsequent step is to remove the linear paraffins with high molecular weight through solvent extraction. This step is important because these compounds prejudice the lubricating oils flow at low temperatures, a typical solvent employed in the solvent dewaxing units is the Methyl-Isobutyl-Ketone (MIK), but some process plants apply toluene and/or methyl ethylketone for this purpose.

After paraffins removing, the lubricating oil is sent to the finishing process, in this step are removed heteroatom's compounds (oxygen, sulfur, and nitrogen), these compounds can give color and chemical instability for the lube oil, furthermore, are removed some remaining

polyaromatic molecules. Some process plants with low investment and processing capacity apply a clay treatment in this step, however, modern plants and with higher processing capacity use mild hydrotreating units, this is especially important when the petroleum processed have higher contaminants content, in this case, the Clay bed saturates very quickly.

The paraffins removed from lubricating oils are treated to removing the oil excess in the unit called wax deoiling unit, in this step, the process stream is submitted to reduced temperatures to remove the low branched paraffins which have low melting point. Like the

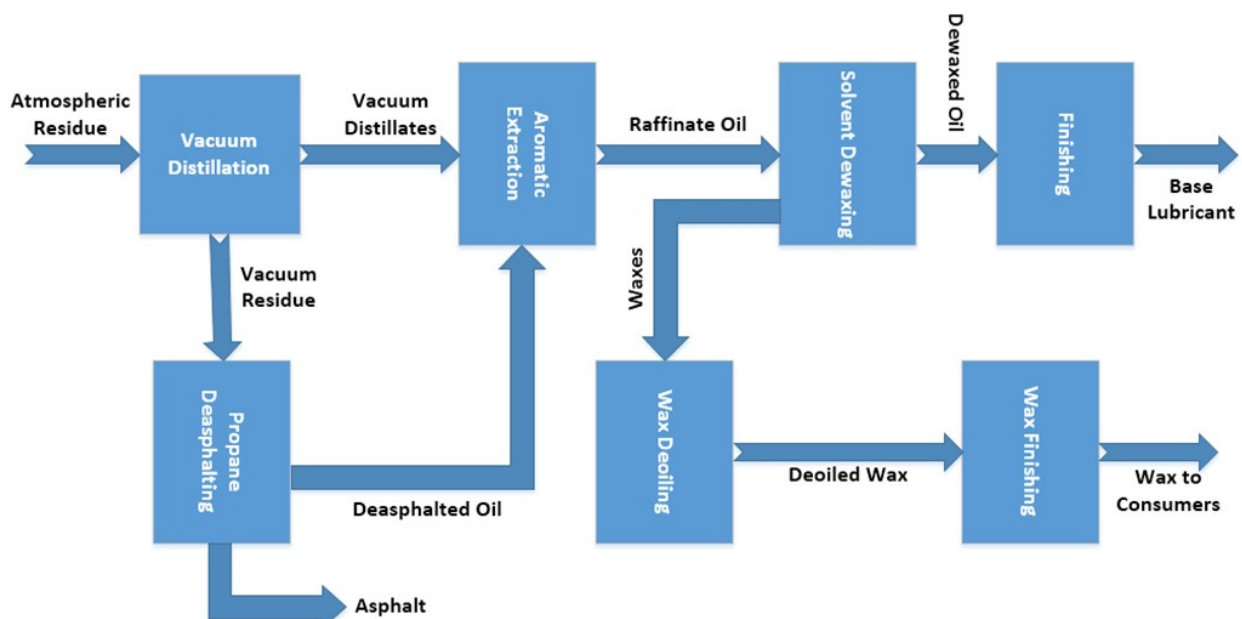


Figure 13 – Processing Scheme for Base Lubricating Oil Production through Solvent Route

lubricating oils, the subsequent step is a finishing process to remove heteroatoms (N,S,O) and to saturate polyaromatic compounds, in the paraffins case generally, is applied a hydrotreating process with sufficient severity to saturate the aromatic compounds that can allow to reaching the food grade in the final product. As cited earlier, the solvent route can produce group I lubricating oil, however, lube oils employed in severe work conditions (large temperature variation) need be had higher saturated compounds content and higher viscosity index, in this case, is necessary apply the hydro-refining route.

### PRODUCING HIGH QUALITY LUBRICATING OILS – THE HYDROPROCESSING ROUTE

In the lubricating oil production by hydro-refining, the physical processes of the solvent route are substituted by catalytic processes, basically hydrotreating processes. Figure 15 shows a block diagram of the processing sequence to produce base lube oils through hydro-refining route.

In this case the fractionating in the vacuum distillation step has more flexibility than in the solvent route, once that the streams will be cracked in the hydrocracking unit, so another distillation step is necessary.

After the vacuum distillation and propane deasphalting steps, the process streams are sent to a hydrotreating unit, this step seeks to saturate polyaromatic compounds and remove contaminants like sulfur and mainly nitrogen which is a strong deactivation agent for the hydrocracking catalyst.

In the hydrocracking step, the feed stream is cracked under controlled conditions and chemical reactions like dehydrocyclization, and aromatics saturation occur which give to the process stream the adequate characteristics to the application as lubricants. The following step, hydroisomerization, seeks to promote isomerization of linear paraffins (which can reduce de viscosity index) producing branched paraffins.

After the hydroisomerization the process stream is pumped to hydrofinishing units to saturate remaining polyaromatic compounds and to remove heteroatoms, in the hydrofinishing step the water content in the lube oil is controlled to avoid turbidity in the final product.

In hydrotreating units dedicated to produce lubricant, one of the focus of the hydrotreating process is to reduce the concentration of long chain paraffin, to achieve this goal is applied a specific catalyst beds containing dewaxing catalysts (ZSM-5). One of the most known hydrodewaxing technology in the market is the MSDW™ process, commercialized by ExxonMobil Company. A basic process flow diagram for MSDW™ process is shown in Figure 16.

HDF = Hydrofinishing

Another available hydrodewaxing technology is the Isodewaxing™ process, developed by Lummus Company, this process is shown in Figure 17.

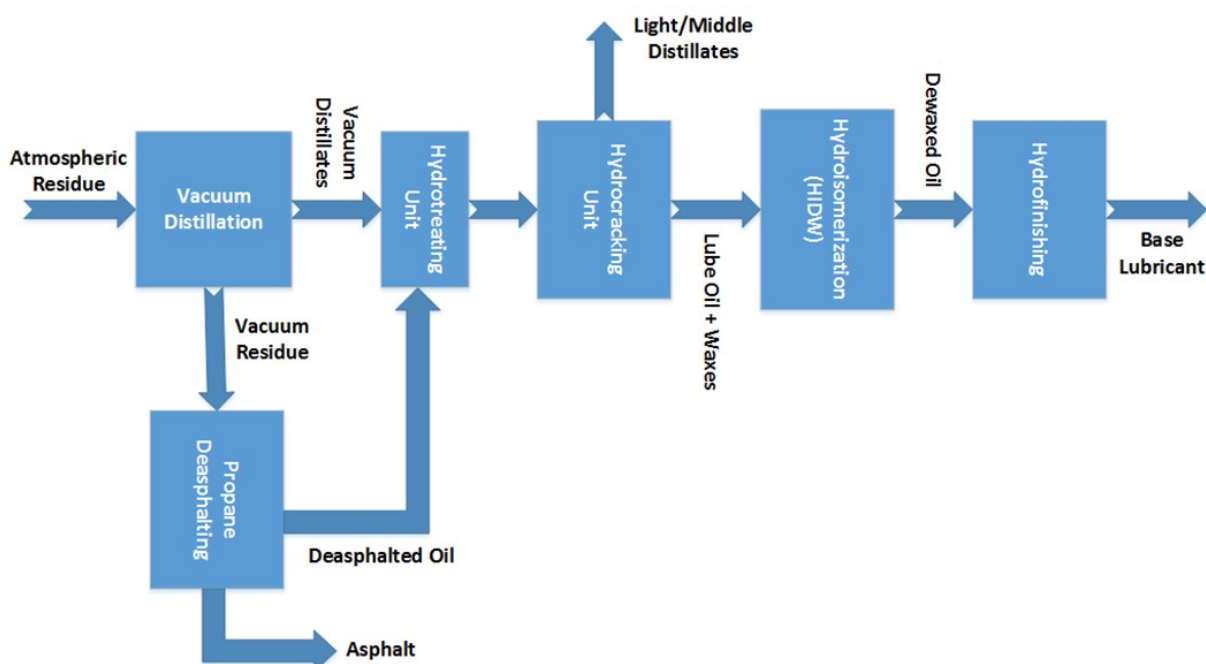


Figure 15 - Processing Scheme for Base Lubricating Oil Production through Hydrorefining Route

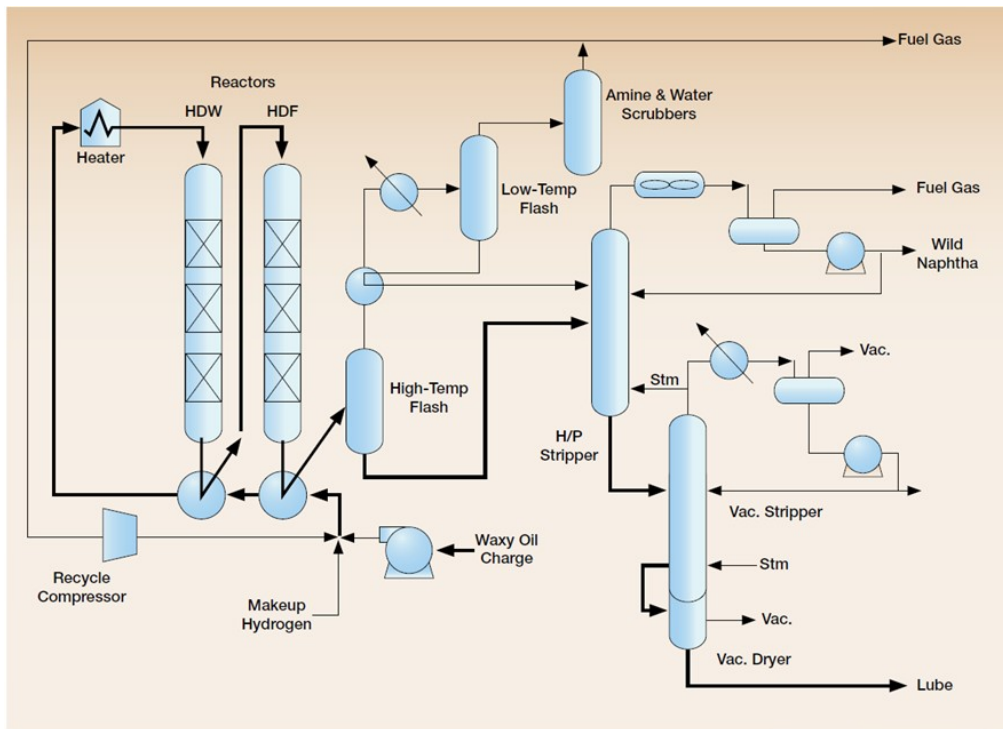


Figure 16 – Basic Process Flow Diagram for MSDW™ Dewaxing Technology by ExxonMobil Company (ExxonMobil Website).

#### Process Flow Diagram

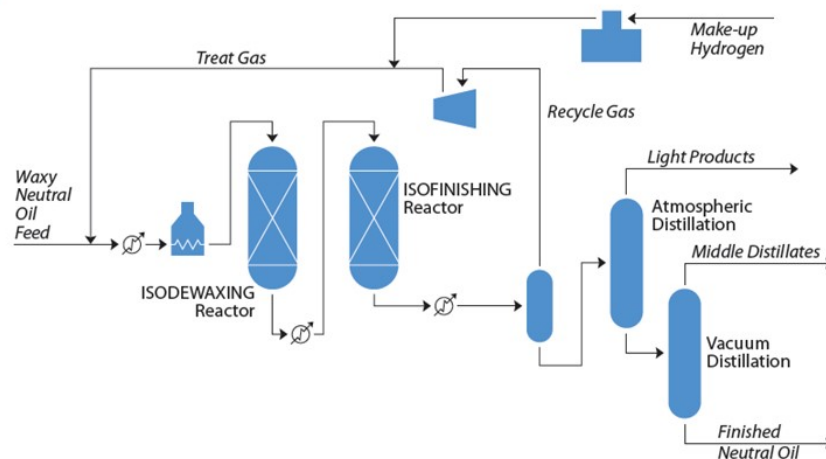


Figure 17 – Basic Process Flow Diagram for the Isodewaxing™ technology by Lummus Company.

At this point is important to quote that the main quality requirements of the lubricating oils are put under control through the following processes:

- Viscosity – The viscosity of the lubricating oil is controlled in the distillation step, managing the cuts in the crude distillation units or in the distillation columns after hydrocracking units;
- Viscosity Index (VI) – This variable is controlled in the hydrocracking step through the reduction in the aromatics content;
- Saturates – Another parameter that is adjusted in the hydrocracking step, through reduction of aromatics;
- Pour Point – This quality requirement is controlled in the hydrodewaxing step, through the reduction of waxes content.

Despite the high capital spending involved in the hydroprocessing route, it's possible to achieve better quality, higher added value, and products with growing demand against the production of Group I lube that presents contraction demands. In this scenario, is expected which refiners relying on exclusively solvent routes, lose market share forcing re-vamps of the existing lubricating production units or the exit from the market.



## SOLVENT ROUTE X HYDROREFINING ROUTE – KEEPING COMPETITIVE

As aforementioned, comparing the lubricant production routes can be observed that the hydro-refining route gives more flexibility in a relation of the petroleum to be processed. As the solvent route apply basically physical processes, is necessary to select crude oils with higher content of paraffins and low contaminants content (mainly nitrogen) to the processing, which can be a critical disadvantage in geopolitical instability scenario. The main disadvantage of the solvent route, when compared with the hydrorefining route, is that the solvent route can produce only Group I lubricating oil, this can limit his application to restricted consumer markets, which can reflect in the economic viability. Figure 18 presents a forecast to the market share evolution to different kinds of base oils in the market.

According to the data from Figure 18, is expected a significant reduction in the demand by Group I base oils, leading to a great competitive loss to refiners relying on base oil production exclusively through solvent routes.

Another solvent route disadvantage is the solvents applying which can cause environmental damage and needs specials security requirements during the processing, production of low value-added streams like aromatic extract is another disadvantage.

As advantages of the solvent route over the hydro-refining route can be cited lower capital investment and the fact that the solvent route produces paraffins which can be directed to

the consumer market like products with higher added value.

### Conclusion

As discussed above, the production of non-energetic derivatives can ensure high economic results to refiners once these derivatives present higher added value and growing market. The synergy between refining and petrochemical processes raises the availability of raw material to petrochemical plants and makes the supply of energy to these processes more reliable at the same time ensures better refining margin to refiners due to the high added value of petrochemical intermediates when compared with transportation fuels. Another advantage is the reduction of risks of transportation fuels oversupply, facing the current scenario of demand reduction and restriction of fossil fuels. It's important to consider that integrated processes lead to higher operational complexity, however, given current and middle term scenarios to the refining industry, better integration between refining and petrochemical processes is fundamental to the economic sustainability of the downstream industry. Again, it's important to understand the transitive period faced by the downstream industry and maintain competitive operations with the current focus in transportation fuels while the transition to petrochemicals is prepared in a sustainable manner aiming to keep economic sustainability and competitiveness in the downstream market.

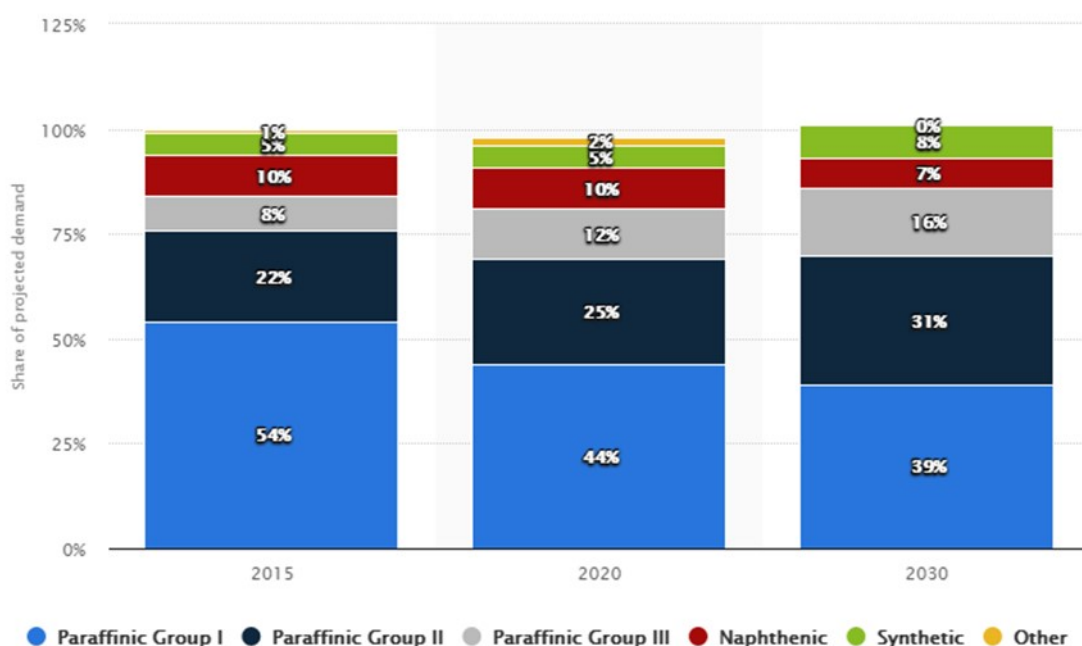


Figure 17 – Basic Process Flow Diagram for the Isodewaxing™ technology by Lummus Company.

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## AUTHOR



Dr. Marcio Wagner da Silva is Process Engineer and Stockpiling Manager focusing on Crude Oil Refining Industry based in São José dos Campos, Brazil. Bachelor's in chemical engineering from University of Maringa (UEM), Brazil and PhD. in Chemical Engineering from University of Campinas (UNICAMP), Brazil. Has extensive experience in research, design and construction to oil and gas industry including developing and coordinating projects to operational improvements and debottlenecking to bottom barrel units, moreover Dr. Marcio Wagner have MBA in Project Management from Federal University of Rio de Janeiro (UFRJ), in Digital Transformation at PUC/RS, and is certified in Business from Getulio Vargas Foundation (FGV).

# Rock Bottom View:

## Isn't Denial of Climate Change Really a Nod to Continued Inflation?



Ronald J. Cormier, *Engineering Practice* Contributing Author

Extreme weather events worsened by climate change is a hidden cause of inflation, threatening to push up already high prices of everything from food and clothing to electronics. Severe weather events, like hurricanes, wildfires and droughts, devastate entire communities while costing billions to rebuild. It also affects industry, from energy to transportation and agriculture, leading to a significant rise in food costs for millions.



"If we ignore it and don't do anything about climate change, it will become a staggering cost. And it will have a huge impact not only on grocery bills, but many other aspects of our ordinary lives," said Suzi Kerr, chief economist at the Environmental Defense Fund.



Corn (and wheat above) waits to be harvested on land leased by Tempe Farming Co., Thursday. The Colorado River has been a go-to source of water for cities, tribes and farmers in the U.S. West for decades. However, climate change, drought and increased demand are taking a toll. The U.S. Bureau of Reclamation is expected to declare the first-ever mandatory volume cuts from the river for 2022-2023.

### The Big Picture.....

- Climate change is capable of devastating entire U.S. industries, especially agriculture.
- Farmers in Florida are facing that reality after multiple hurricanes have damaged the state's citrus farms.
- As the pandemic has shown, disruption to supply chains and workers' productivity drives up the cost of doing business. And one way or another, (smaller size store portions and packaging, but without lower price, usually) companies pass those costs onto consumers.
- Workers facing more strenuous conditions tend to command a higher wage, Solomon Hsiang, a professor of public policy at UC Berkley, says. And if companies have to pay more to protect them or install new equipment like air conditioning in warehouses, someone's got to pay and at the end of the day that someone is usually the consumer. Finally, when people take longer breaks to recover from heat exhaustion, or leave 15 minutes early, for example, lost productivity adds up day after day, Carleton said.
- Long-lasting heat waves like the ones in the U.S. and China are expected to become more commonplace — just as global inflation is leading to a slowdown of economic growth. Climate disasters have cost North America \$415 billion, much of it due to wildfires and hurricanes.



**Why it matters:** Heavy rainfall, flooding, heat waves and droughts erode agriculture yields, infrastructure, and workers' ability to stay on the job — all of which lead to supply-chain breakdowns and worker shortages.

**Driving the news:** Our society for now still seems comfortable labelling these critical events, “as 50, or 100, or 500 year occurrences”, though in reality atmospheric anomalies keep coming with more and more regularity, and of more biblical magnitude. Chip and solar panel factories in one of China's key manufacturing regions just shutdown, as the country tries to ration power during a 60-year record heat wave.

- Dairy and meat prices in Europe are rising even higher as droughts destroy lands meant for grazing and growing grain for feed.
- In the U.S., wheat fields in Kansas, Oklahoma, Nebraska and cotton harvests in Texas have also been withering due to drought.
- And in California, production of processed tomato products earlier suffered due to a lack of rain (many of the same fields now freezing under near-spring snowfall) while workers are starting to walk off the job at an Amazon delivery hub partially in protest of heat exhaustion.
- Destruction from historic rains and floods in the Northeast, North Carolina, Europe and South Korea demonstrates how ill-equipped our infrastructure is to withstand climate change impacts — and how difficult it is for communities to rebuild, let alone get back to work.

***Climate change isn't viewed as a major contributing factor for high prices just yet, but as severe weather events increase in frequency and devastate industries that contribute to the U.S. economy, experts warn it increasingly will be if temperatures keep rising.***

Treasury Secretary Janet Yellen said, while speaking in North Carolina last year, that climate change can manifest itself in “acute, weather-related supply shocks,” that create sharp reductions in capacity and raise prices for consumers.

The Environmental Protection Agency (EPA) has also warned that climate change can and will disrupt food availability, reduce agricultural productivity and interrupt food delivery. EPA warned that, “spikes in food prices after extreme events are expected to be more frequent in the future.” It's a reality that Florida is currently experiencing firsthand after Hurricane Ian hit the state and resulted in higher prices for frozen orange concentrate orange juice by more than 5 percent and could have long lasting impacts with at least 75 percent of Florida's citrus belt under threat of heavy flooding.

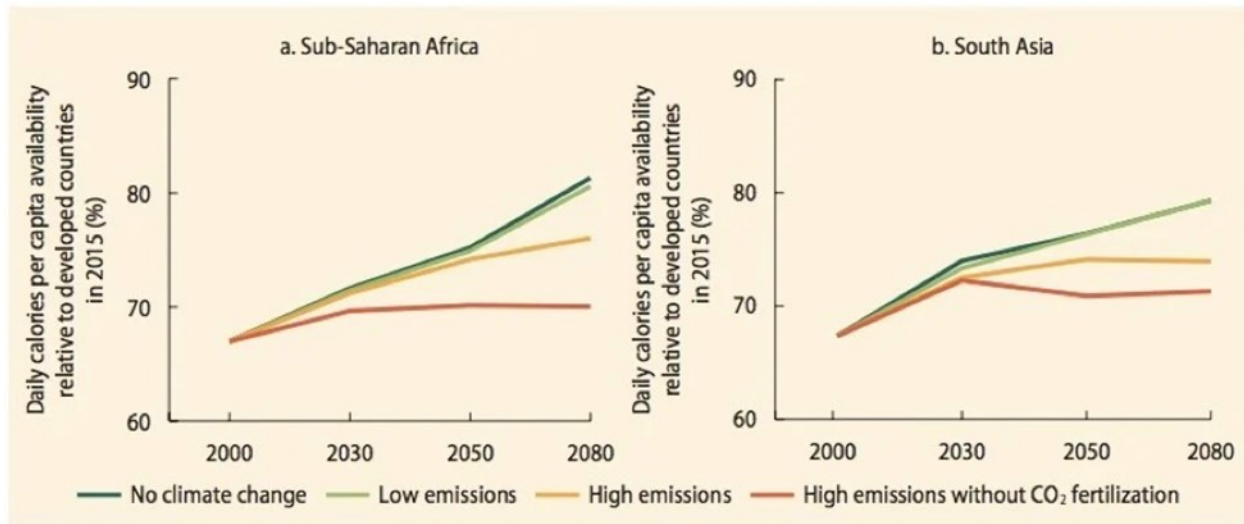


Workers in the Philippines helping fishermen after a typhoon. (Photo: Ted Aljibe/Getty Images)

Though current see-saw record snowfall and rain may alter long-term outcomes, California is another. The U.S. Department of Agriculture (USDA) has noted in 2023 that U.S. orange production is expected to drop 13 percent to the lowest level in 55 years. Poor results are due to the affected fruit set, the stage where a flower turns into a berry — driven by California's severe drought.

Maladaptation of U.S. corn and soybeans to a changing climate is also a quantifiable phenomenon. Long-run adaptation of U.S. corn and soybean yields to changes in temperature and precipitation were quantified over 1951–2017. Results show that although the two crops became more heat- and drought-tolerant, their productivity under normal temperature and precipitation conditions decreased. Over 1951–2017, heat- and drought-tolerance increased corn and soybean yields by 33% and 20%, whereas maladaptation to normal conditions reduced yields by 41% and 87%, respectively, with large spatial variations in effects.

Changes in climate are projected to reduce average corn and soybean yields by 39–68% and 86–92%, respectively, by 2050 relative to



Source: Havlik et al., forthcoming.

Note: Results are based on simulations from the Global Biosphere Management Model (GLOBIOM) in a scenario with large population growth and little economic growth.

### Climate Change Can Significantly Reduce Food Availability In Poorer Regions

2013–2017 depending on the warming scenario. After incorporating estimated effects of climate-neutral technological advances, the net change in yield ranges from (–)13 to 62% for corn and (–)57 to (–)26% for soybeans in 2050 relative to 2013–2017. This analysis uncovers the inherent trade-offs and limitations of existing approaches to crop adaptation. Concerns about the impact of climate change on agriculture have led to a growing interest in adapting crops to the increased frequency of harmful weather events such as extreme heat and drought.

Numerous advances have been made in crop cultivars and management to enhance their stress tolerance to extreme climate conditions. These advances include new breeding technologies (e.g., marker-assisted selection genomic selection and gene-editing) and improved practices. However, some studies find that current breeding programs are not preparing crop cultivars sufficiently for climatic variability and others find that crop cultivars adapted to extreme climate conditions might perform worse under other conditions. For instance, productivity of heat-resistant plants could be reduced under normal temperatures and drought-resistant cultivars can perform worse than conventional ones when sufficient water is available.

Studies analyzing the adaptability of heat and drought tolerance traits through laboratory and field experiments do not provide systematic evidence of the extent to which crops are becoming more resilient overall to climate conditions or whether the directions of climate-neutral technical change and climate adaptation efforts are synergistic or conflicting.

These severe weather events are happening at a time when the price of goods is especially high, with food prices in the U.S. rising 11.4 percent over the past 12 months — the largest annual increase since May 1979. That's along with record high prices for electricity, housing, gas and a broad range of other products. Climate change's current role in driving up the prices of goods and services is relatively tolerable, but if we ignore it and don't do anything about climate change, it will become a staggering cost.

Climate change will have a huge impact not only on grocery bills, but many other aspects of our ordinary lives. Climate change is expected to continue, causing all sorts of severe weather events. The U.S. West has been in a long-running drought since 2020, which is expected to continue, unless current enormous snowfall can correct outcomes without overflowing into the Pacific Ocean.

As well, research from the journal *Nature Communications* also found that hurricanes have increased in frequency and destructiveness over the past 150 years, with climate change considered a major factor. Even Federal Reserve Chairman Jerome H. Powell said last year during the Green Swan conference that climate change risks the world economy and that, "there is no doubt that climate change poses profound challenges for the global economy and certainly the financial system."

### What Does It All Mean?....

Understanding the economic impact of climate change is critical, as an analysis by Columbia University's Climate School noted climate disasters have cost North America \$415 billion,

much of it due to wildfires and hurricanes. Every degree Celsius that the Earth warms, there's an estimated 5 to 15 percent decrease in overall crop production. That will hit American farmers who are likely to struggle to maintain their fields and adapt to changing weather conditions — causing prices to increase. Increased costs may also come in the form of lost wages and medical bills, as a warming climate adds to the risk of waterborne and food borne diseases and allergies. Columbia estimated temperature extremes are projected to cause the loss of two billion labor hours each year by 2090, resulting in \$160 billion of lost wages.

Congress has taken action against climate change and current inflation, most recently through the Inflation Reduction Act (IRA), which includes provisions to mitigate climate change through a host of different measures, such as tax credits for energy production and investments in technologies including wind, solar and geothermal energies.

IRA also includes a new program to reduce methane emissions from oil and gas by offering grants and loans to help companies that reduce their emissions while charging fees to those with excess emissions. Kerr believes that the Inflation Reduction Act is a “game changer” and carries strong potential to reduce energy costs in the U.S. and could set

an example for the rest of the world about what's possible when addressing climate change.

So by looking past the problems, denial of climate change really is a nod to continued inflation. Hard, recurring data proves so. If our future existence on Earth could be limited only to inconvenience, we would be getting off lightly. Especially as scientists, engineers, mathematicians, and those charged with innovating for the future, real quantifiable data is undeniable. **Hence, we treat this critical change phenomena accordingly; we must be change agents for at least a minimally livable planet.**

Until next time, we at EPM will keep an eye on the issues that matter, embracing the unpredictable and encouraging professional opportunities to encourage the path forward. From this old porch at Rock Bottom Ranch in Central Texas, y'all take care.

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### ***GTC Vorro - a full-service provider for Turn-key H<sub>2</sub>S Removal Service***

As a full-service provider of turn-key H<sub>2</sub>S removal service, GTC Vorro is a problem solver across all regions and capacities of sulfur, upstream and downstream.

In addition to our environmental services, GTC Vorro offers licensed technology to address flare reduction, energy reduction and specialty chemicals.

For more information, email us at [cfink@gtevorro.com](mailto:cfink@gtevorro.com).



#### **GTC VORRO**

**Environmental Services &  
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Houston, TX 77079





6. *Green Swan Conference, 2022*, comments by Jerome Powell
7. *Maladaptation of U.S. corn and soybeans to a changing climate*, Scientific Reports, volume11, Article number: 12351 (2021), Chengzheng Yu, Ruiqing Miao & Madhu Khanna
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