



Dead end approaches for high-sulfur fuels

Refiners' time window shrinks – they need to act

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Executive summary

Demand switch to low-sulfur fuels has been uneven across the globe, but environmental and engine regulations are pressing sulfur specs to extremely low limits. Refiners need to act accordingly since there will not be place to sink high-sulfur fuels anymore.

Demand for ultra-low-sulfur on-road fuels rose more than a decade ago in regions on the forefront. Late-comers are pushing towards this tendency and will catch up sooner or later; marine fuel is also playing its part on a global scale. Pressure is rising on refiners and their capacity to almost eliminate sulfur from their products.

1. Environmental drive from multiple angles

Energy-related emissions, and from oil combustion in particular, have been facing stricter and geographically broader limitations for the past decade, and the tendency keeps accelerating.

Pressure is not only coming from populations with greater environmental awareness, preaching for a world of clean energy and clean fuels, but also from environmental institutions and governments, which are following population demand.

This rise in environmental concern has supported many initiatives in the land mobility sector, such as:

- Fuel efficiency of on-road fleets: driven mainly, but not only, by engine and powertrain efficiency and vehicle bodywork design
- Installation of cleaner-fuel urban transportation systems and interurban corridors
- Growing penetration of electric vehicles (EVs) supported by subsidies: still incipient but threatening petroleum products demand almost exclusively in certain regions
- Changes in mobility behavior (car-sharing, car-pooling): mostly promoted in metropolitan areas, with the aim of alleviating on-site emissions and traffic congestion

In addition, other petroleum-fuel-demand segments have seen “dirty” products such as fuel oil, the largest destiny of refinery sulfur, displaced by natural gas, which reduces its market size and price. This fact also affects the share of petroleum products in the global energy matrix.

More than 98 MM BPD¹ (million barrels per day) of refined products are consumed in the world, and said consumption keeps growing at around 1 percent annually. Increasing share of natural gas and non-traditional renewable energy sources, plus the strong trend of increasing the use of electricity, have been moderating petroleum products’ demand growth and will continue to do so. This is such that, contrary to what we have believed for decades, peak oil will come from the demand side instead of from the supply side.

¹ According to the EIA (US Energy Information Administration)

² EGR: exhaust gas recirculation

³ SCR: selective catalytic reduction

Although difficult to predict, both the potential displacement of up to 3 MM BPD of oil products globally by 2030 due to EVs and the availability of larger naphtha volumes of feedstock from the petroleum upstream will challenge refining capacity and product mix, deepening expected relative shortage of diesel.

This EV penetration will, however, be uneven across the globe and more aggressive in countries where bans on sales of fossil fuel cars have been announced. However, these announcements are meant to be effective from 2025 to 2040, and fossil fuel vehicle fleet replacement will take some years to be significant, and challenge mainly gasoline consumption.

Those 98 MM BPD of oil products will continue to have a market, but a large portion of them will need to be much “cleaner” than today to be tradable.

On-road vehicles: stricter limits for ~40 MM BPD

Regulation for reduced emissions is driving development of more demanding automotive engine technology and playing a preponderant role in the push for clean fuels. The impact is immediate for the countries or regions where the engines are produced locally (i.e., Euro V/VI). However, sooner than later, when late-comers discontinue production of less restrictive engines, they will need to adjust their fuel quality regardless of local regulation. Even though regulators are the ones redefining local specs on fuels, it ultimately is the adoption of new engine technology that requires low sulfur fuel to operate in working conditions.

For instance, for diesel-fueled vehicles, the chosen systems for gas exhaust treatment are EGR² and SCR³, the latter of which requires regular urea refills. The major difficulty for this treatment is the trade-off between NOx and particulate matter emissions. To help this equation, the fuel needs to be almost clear of sulfur, a state known as ultra-low sulfur. Otherwise, engine corrosion and catalyst fouling occur, and the soot (particulate matter) increases in volume.

In addition to this technical-based demand, there is also a commercial drive, which means changes in tendency according to what customers demand.

In order to fully eliminate or reduce sulfur from oil products, new refinery units need to be installed. However, these units emit significant greenhouse gases, so in the end, it is a trade-off between greenhouse gases at refineries (which, in some cases, are located close to cities) and contaminant gases and particles spread over the cities and roads.

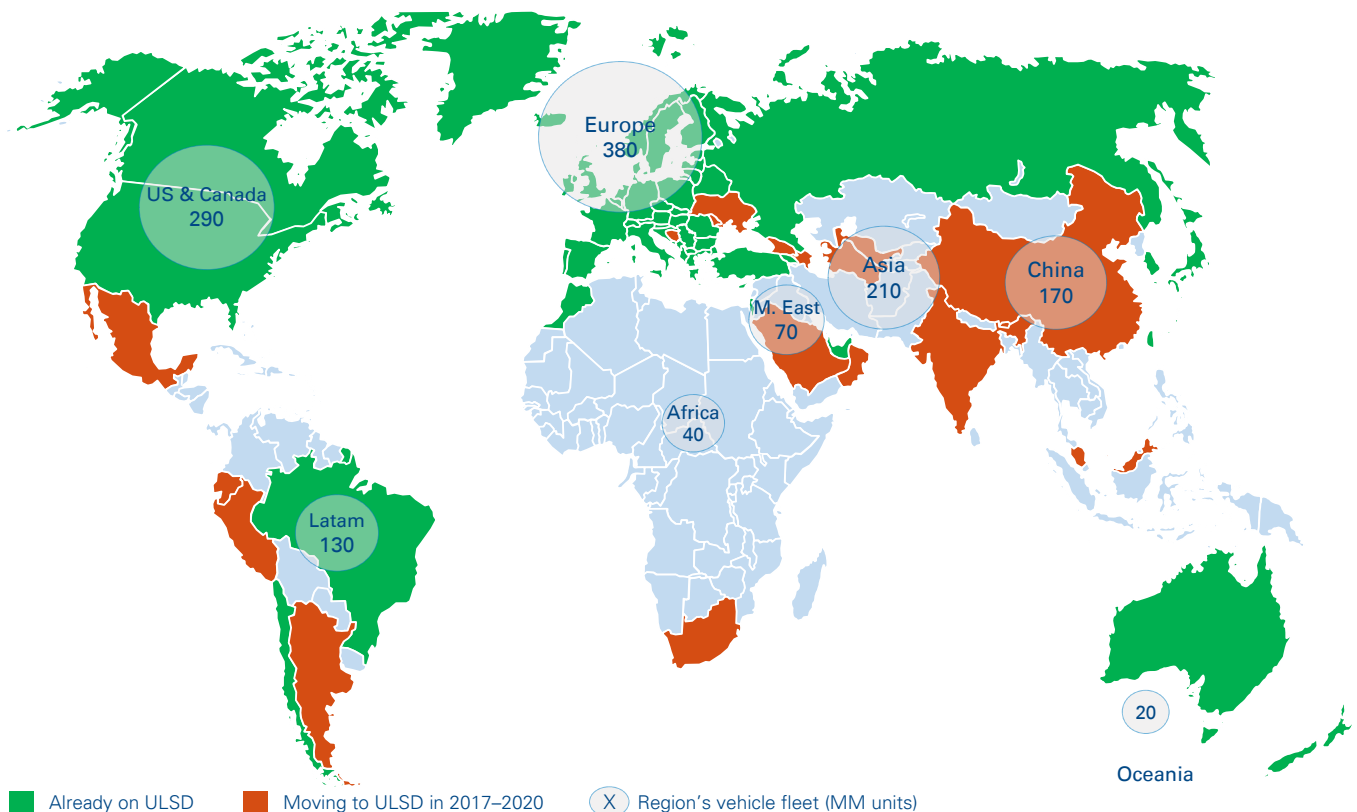
Local regulations are distributed unevenly across the globe, and while some regions have been operating exclusively on ultra-low-sulfur fuels for more than a decade, lagging regions still offer markets for high-sulfur ones. These regions (mostly Asia, Africa, the Middle East and Latam) have been and still are playing the role of “sulfur sink.” However, the clock is ticking for them, as the era of high-sulfur fuel is running its course.

Marine fuel: ~4 MM BPD subject to IMO regulations

In October 2016 a global regulator, the International Marine Organization (IMO) committee, set January 1, 2020 as the starting date for the new MARPOL⁴ regulation. This regulation limits marine fuel sulfur levels to 0.5 percent (m/m – mass over mass) in marine fuels outside the already-much-stricter emission control areas (ECAs). Current marine fuel regulation demands a maximum of 0.1 percent sulfur content inside ECAs and 3.5 percent outside them.

Moreover, international marine trade is expected to continue growing at a 3–4 percent annual rate, as international trade usually surpasses GDP growth and about 90 percent of world trade is transported by ship.

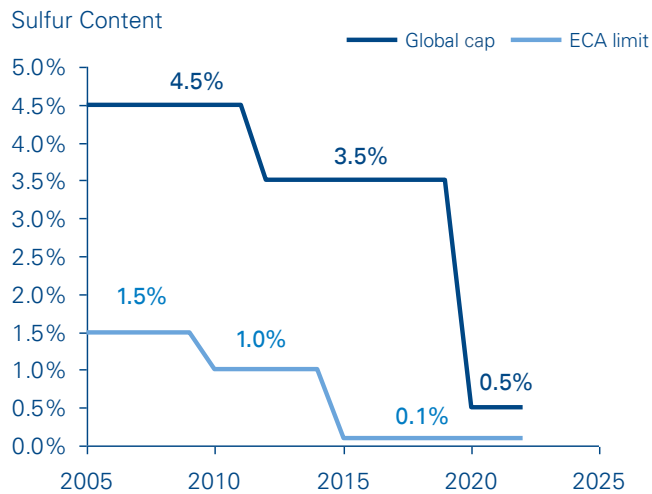
Figure 1: Local sulfur specs for on-road diesel



Source: Arthur D. Little

4 MARPOL: Marine Pollution, the International Convention for the Prevention of Pollution from Ships

Figure 2: Marine fuel sulfur content limit – percent of m/m



Source: IMO, Arthur D. Little

Fuel oil (the major destiny of refinery sulfur) finds about 40 percent of its market as a marine fuel (~3 MM BPD), which means this oil product will be severely restricted. However,

even though its use for propulsion in the sea may be very limited, high-sulfur residues are withstanding and dodging reconfiguration in some places where there are still captive markets for industrial use and power generation with lighter specs than marine fuel. Nevertheless, both uses will get incremental participation of natural gas and renewable sources, motivated to some extent to meet with Paris Agreement⁵ commitments.

Industrial use and power generation: ~ 12 MM BPD still dodging regulations

The industrial and power generation sector, which is not as strictly regulated as mobility fuels, has been adjusting the sulfur content of what it burns unevenly across the globe. These have been the places of disposal for high-sulfur fuels. However, sooner or later, the SOx emission limits will reach larger, stationary engines, and even if some are located far from urban centers, the industrial and power sector will no longer be able to burn the amount of sulfur it burns today.



5 Paris Agreement: signed in 2015, committed almost 200 countries to reducing greenhouse emissions so as to limit global average temperature to 2°C above pre-industrial levels

2. Refining segment under challenge

Any refinery product ends up with some content of sulfur because it is naturally present in crude oil. In the distillation of crude oil, sulfur components are dragged down to the largest (or, more accurately, higher-boiling-point) hydrocarbons. This is why the heavier the product is, the sourer it is, for any given processed crude oil.

In order to reach ultra-low-sulfur specs, even the lightest streams require some kind of treatment. Then each stream requires different treating severities depending not only on which refinery process unit it is coming from, but also on how sour the input crude oil is.

With the exception of some regions with recent light oil discoveries, especially unconventional oil, crude oil is not getting any lighter or sweeter for the majority of resource basins, which would imply greater challenges to reach specs.

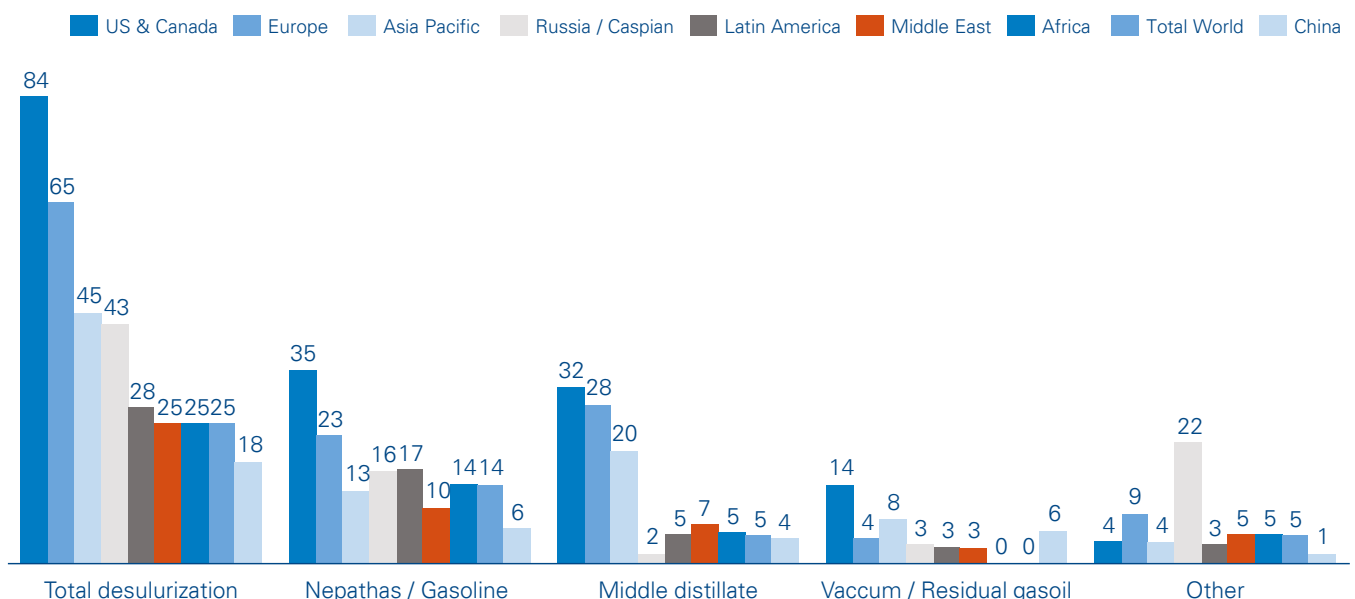
Even taking into account the growing participation of shale oil and condensates, we estimate that 2035 oil production will be

an average of 1.3 percent sulfur versus the current ~1.2 percent. In other words, the industry will have around 5 MM tons of sulfur to remove from oil products annually to reach today's sulfur specs.

Regulation shows an uneven geographical pattern, and so does treating capacity in refineries to convert "dirty" fuels into clean ones. Regions with 100 percent clean fuels demand have developed enough capacity to treat full-range streams coming out of both distillation and conversion units. In contrast, late-comers show low desulfurization capacity and will eventually need to increase this; however, such developments carry no ease.

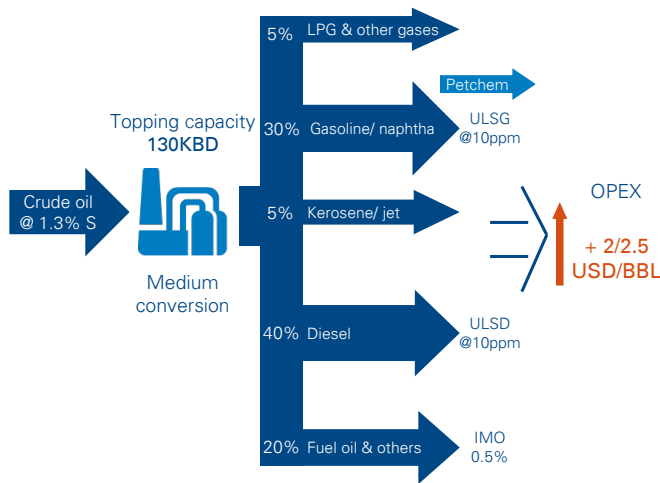
For instance, a world-average-size refinery (130 KBD) with medium conversion capacity – having average-quality crude oil as feedstock – placed in a market with ULS on-road fuels and IMO-compliant marine fuel will have to remove around 200 tons of sulfur per day to comply with product-quality requirements. The unit cost for removing would be around 2–2.5 USD/BBL (of refining capacity) in additional OPEX plus CAPEX.

Figure 3: Desulfurization capacity as a percentage of crude distillation capacity (KBD/KBD* 100 percent)



Source: European Patent Office, Arthur D. Little analysis

Figure 4: Impact of desulfurizing on refining cost sample



Source: Arthur D. Little analysis

For non-deep-conversion refineries, the fuel oil market has been acting as a sulfur sink, as they have found demand in segments or regions for products with up to and over 3 percent sulfur content. This sulphur-heavy products market will shrink drastically by 2020, when IMO regulations take place.

Key prerequisites to pursue a profitable investment in a refinery are scale and conversion capacity. In a capital-intensive industry facing volatile (and thus sometimes tight) margins, scale is key to secure long-term sustainability, let alone to invest in treatment capacity.

Current scale and refining configuration across the globe is such that, in many cases, further investment will hardly be economically feasible.

Marine fuels will have to be desulfurized or blended with lower-sulfur fuels to enable them to meet the new specifications, but the incorporation of new shipping technology will play a role as well, especially exhaust gas scrubbers and built-in LNG systems.

Fuel oil has been centrally involved in marine propulsion since the early 20th century, and its application is now being challenged. Both demand for refined products and crude oil refining throughput will continue growing, and consequently, fuel oil production will too.

Since the majority of current marine fuel oil does not meet the 2020 standards, low-sulfur fuel oil and other distillates such as MDO⁶ will see its demand increased.

The current global sulfur average content in HSFO⁷ is above 2.5 percent, and with the new regulation, at least 80 percent of it will have to be removed, or some way will need to be found to dilute it with very-low-sulfur-content fuels.

Economics for residue desulfurization favors investment in large-scale refinery units instead of on-board vessel scrubbers, and we expect that this fact, combined with the additional demand for ultra-low-sulfur on-road fuels, will drive refiners' investments: desulfurization or extra conversion capacity. The timing for adapting vessels for onboard scrubbing is shorter than that for a refinery, so refiners should react first. They cannot wait to see how much the shipping segment will facilitate the regulation compliance by itself.

We foresee a key role for refiners in adapting themselves and the shipping industry as fuel price-takers with relative reluctance to invest for compliance.

Tight economics for desulfurization

Desulfurization economics are tight due to CAPEX and margin impact:

- Since a market for sour products still exists, price spread between sour and clean products is relatively small. Also, to some extent low-utilization-rate refineries in some regions would be willing to purchase high-sulfur streams at discounted prices, hydrotreat them and sell ultra-low-sulfur-quality fuel, charging only the variable cost plus a low margin for the transaction.
- New treatment units need to be built, refineries' hydrogen supplies usually fall short, and new production units are required, as well as extra investment, feedstock and energy to run them.
- A world-scale diesel hydrodesulfurization unit's (i.e., 60 KBPD) expected CAPEX is around 4–8 MM USD/KBPD. However, a large number of refineries have small-scale streams, so they will require relatively small-scale and very expensive units (in terms of USD/BPD).
- Operating costs are significant, around 1–1.5 USD/BBL; desulfurization is utility-demanding and its hydrogen consumption is intensive.
- Costs are highly sensitive to units' severity, natural gas – both for fuel and hydrogen production – local price and availability, plus other utilities' availability (i.e., cooling water and chemicals).

6 MDO: marine diesel oil
7 HSFO: high-sulfur fuel oil

- OPEX plus CAPEX present value add up to 2–3 USD/BBL for each barrel of the treated stream.

Some factors favor economics of desulfurization investment decisions:

- Logistics sometimes levers the economic equation: In cases for which international trade is possible, an alternative to industrial reconfiguration may be to export sour products and import cleaner ones. Then the savings on logistics expenses provide a return on the investment. So the more isolated the refinery position is, the stronger the lever to payback investments. Said trading opportunities are real, but only temporal since high-sulfur markets keep shrinking every day and are increasingly distant.
- Conversion also helps the economy. Extra distillate volumes cracked and upgraded from heavier products leverage refinery crack spread, and, if conversion is hydro-based, cracked products end up being fully or at least partially desulfurized.
- In cases in which ultra-low-sulfur specs are a novelty, rushing the imminent industrial reconfiguration could bring commercial advantages over local competitors that have to import and blend – at least for a window of time until they catch up.

Estimating CAPEX depends on both regional and local factors, plus the existing configuration in the refinery. Heavy impact factors are:

- Existence of non-hydrotreated existing streams
- Existing treatment capacity and its severity; most of the time units can be revamped to meet specs at high capital-efficiency
- Hydrogen balance: hydrogen-deficit refineries will incur in new H₂ plants with both significant CAPEX and OPEX. Naphtha-reforming units can partially supply the H₂ circuit, but generally run short of supplying the whole hydrodesulfurization demand
- Ancillary plants: such as amine and sulfur plants, intimately related to regulation of on-site emissions

- Refinery scale
- Engineering and construction cost, highly dependent on local capacity and availability
- Location and infrastructure factors
- Capital cost (especially for high-country-risk-premium locations)

Whether to go for deeper conversion or just desulfurization is often a dilemma: operating hydrocrackers in high severity can secure ultra-low sulfur quality and an increased middle-distillate yield, which leverages the economics if supplying a distillate-deficit market. However CAPEX may be a deal-breaker when compared to current refinery value for these kinds of units.

Worldwide, transportation demands 40 MM BPD of gasoline and diesel, out of which around 25 MM BPD are not hydrotreated; to do so with world-scale units would require 100–110 Bn USD. Additionally, huge investments for ancillary units would be incurred.

Some projects only reach feasibility with the inclusion of deeper conversion or upgrading units (i.e., reforming, alkylation/polymerization or isomerization). Furthermore, desulfurizing naphtha streams come at an implicit cost besides the explicit OPEX and CAPEX; said cost is the RON (octane) loss due to olefin saturation in the hydrogenation process. This limits the blending into the high-grade gasoline unless there is a subsequent upgrading process.

In either case, these types of projects should be analyzed against an acid “do-nothing” case, in which a pseudo-catastrophic scenario is being presented; this implies that some kind of reaction from the refiners’ side is mandatory, and every month counts to maintain the competitive position. On top of that, company value (or at least its downstream business unit) will be wrecked if the enterprise is to stop refining and evolve into a trading company, giving away its refining margin value.

The real question, in most cases, is not of whether to invest, but of the optimal industrial reconfiguration (i.e., finding the proper balance between producing and trading) and the right pace and timing to execute optimal projects.

3. Finding the proper route and timing for compliance

Typical desulfurization challenges on main refinery streams

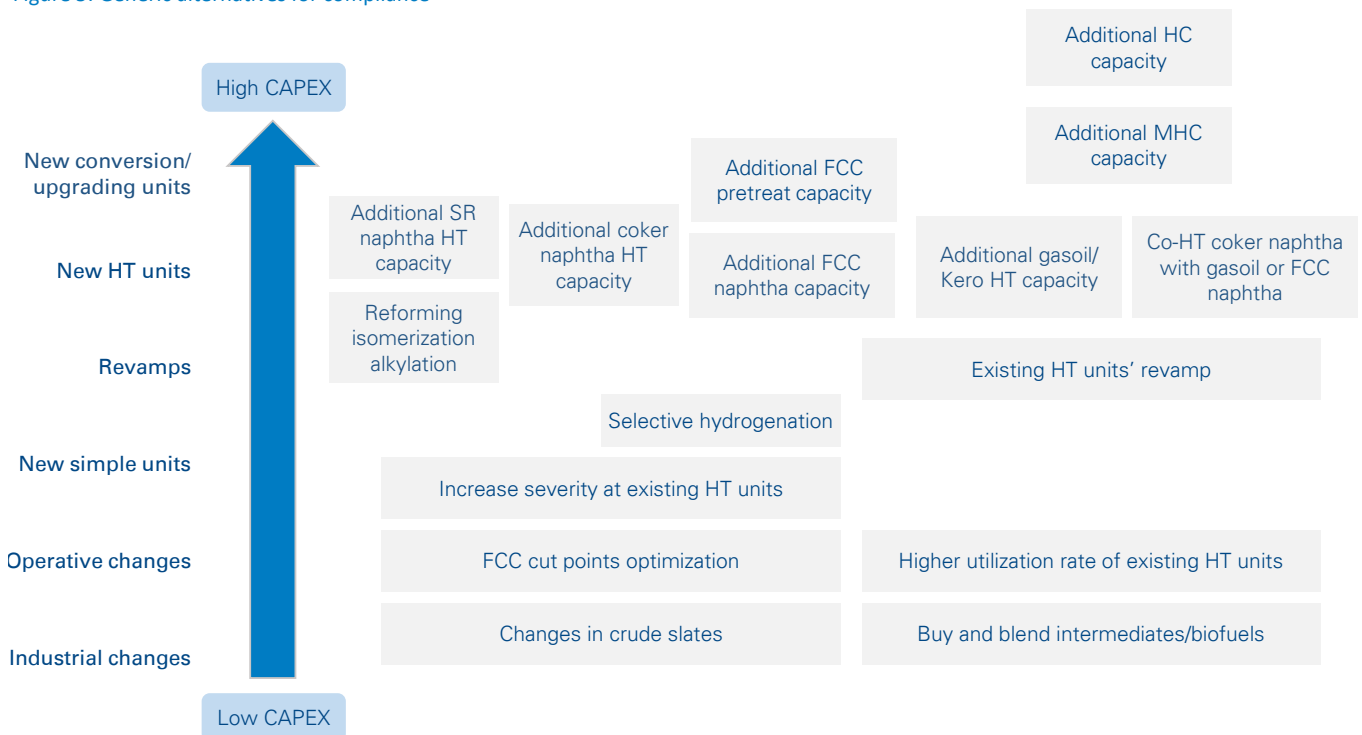
Some streams are typically difficult for refiners facing industrial desulfurization reconfiguration and forcing them to incur high-CAPEX sums:

- Straight-run naphtha: Highly dependent on crude sweetness, but usually requires some mild treatment and finally upgrading to be blended into the gasoline pool to reduce their impact.
- FCC naphtha: As a major sulfur contributor to gasoline pools, these streams have no other option than to be treated, with an exception in countries where second-grade quality accepts some sulfur content. Since the desulfurization

process has the collateral effect of reducing the octane number of the treated stream, octane loss is a major issue for these streams and creates limitations for them as a premium gasoline blending component.

- There is a global tendency to use selective hydrotreatment, minimizing RON loss in the light fraction (mostly mercaptans).
- A heavy fraction may end up in the diesel pool if it has too much of a refractory nature (aromatics such as benzothiophenes).
- Coker naphtha: Typically high sulfur, silica and conjugated diolefin content streams. This means such streams have to be hydrotreated, but not before tackling diolefins (foul

Figure 5: Generic alternatives for compliance



Source: Arthur D. Little

treatment reactors) and silica (deactivates/damages catalysts).

- Kerosene: In aviation fuel blending, aromatic and naphthalene content are limited, but sulfur spec is rarely limited. Treating the kerosene topping stream will depend on the crude chemistry nature; hydrocracked streams are usually compliant enough to blend into the jet pool (with the necessary additives), although sometimes it is convenient to divert part of them into the diesel pool.
- Topping gas oil: Light fractions frequently present no major challenge, but have to be hydro-treated either way, and severity will depend on the processed crude nature.
 - Heavy fractions usually do not meet diesel distillation specs and need further conversion, or are degraded into the fuel oil pool.
 - The same happens to heavy cycle oil and heavy coker gas oil.
- Light cycle oil/light coker gas oil: Two must-be-treated streams; their dirty nature may result in not even being compliant enough for the soon-to-be-extinguished 2,500ppm diesel oil. Treatment is usually severe for these streams.

- Residue: With quite a negative refining spread, the challenge of stricter regulations, and the very high cost of hydrotreatment, its opportunity cost is decreasing and making refiners reassess their refinery conversion upgrade projects.

Major considerations for re-configurations

No two refineries are alike, especially if considering their market, geographical positions and access to capital. Each reconfiguration should be carefully analyzed, taking into account its singularities and factors, such as:

- Market demand for every type and quality of fuel
- Local market-specific pricing and margin challenges and opportunities
- Technical restrictions
- Logistics limitations
- Country legislation and environmental restrictions
- Access to capital and its cost
- Company corporate strategy

4. Refiners' versus shippers' struggle

How to close the marine specs gap?

Even though the new regulation involves some major challenges, the solutions for these should be expected to come as a combination of the following approaches:

- Inland/refinery fuel blending to meet specifications
- Greater use of MDO/MGO
- Greater use of non-refined oil products
- Inland fuel oil desulfurization
- Ship onboard desulfurization

Thus, the dilemma is clear and, in the end, it will be a struggle between refiners and shippers, since each approach requires actions being taken by different players and all approaches imply investment and higher operational costs (or the use or sacrifice of high-value products) to comply with the upcoming specifications.

Refiners' perspective

The marine fuel scenario will erode the current competitive position of those refineries processing sour crudes with low residue conversion and limited desulfurization capabilities. For them, it will be tougher to produce compliant marine fuel: residues are already facing negative spread versus crude, and it is unlikely that clean residue production will repay capital cost for hydrotreatment.

Nowadays, non-hydrotreated-residue producers struggle to allocate their output in nearby markets and will be forced to compete in a shrinking high-sulfur-fuel market, which means even further price penalization. As a result, blending higher quantities of distillates for fuel oil production appears to be a temporary alternative, but there will be reluctance to sacrifice middle distillates by diverting them to the fuel oil pool.

Vessel owners' perspective

- Shippers should expect compliant marine fuel prices to rise, but increased prices will become common across the shipping industry.
- MDO and blended 0.5 percent sulfur fuel will be the easiest options to resort to. However, since their price premiums

will be high, shippers will probably think about retrofitting vessels.

- Scrubber installations in both new and existing ships will be increasingly considered as an alternative to continue burning non-compliant, low-demand and cost-efficient high-sulfur fuels.

On the one hand, scrubbers are a relatively fast-adapting technology and may enjoy temporary advantages when compliant fuel prices suffer a major rise.

On the other hand, equipment is expensive (up to 4 MM USD CAPEX, depending on the vessel) and voluminous, taking up a portion of the cargo capacity, and requires regular discharge of residues at reception facilities. Installation feasibility will also depend on the type of vessel. Furthermore, with a proper scrubber and feed-quality combination, SOx emission can be maintained under permitted levels but may not be sufficient for NOx and PM emissions.

LNG-fueled vessels, together with LNG-ready ones (or retrofitted), are a viable approach to the challenge but would initially have fairly low penetration in the shipping industry.

LNG is a competitive fuel alternative and will reduce freight costs compared to low-sulfur fuels. However, LNG equipment is also expensive (around 5 MM USD CAPEX, depending on the vessel) and large, again taking up a portion of cargo capacity. Another hindering factor for LNG-fueled vessels deployment is the need for LNG terminal structures at ports which are yet to be extensively developed. That is why we only foresee feasibility on ships navigating well-defined and usual routes where LNG infrastructure can be warranted on end-to-end ports. This may be the case for routine container ships and some bulk cargo ones, yet it will be mild penetration.

It is worth mentioning that retrofitting vessels (scrubbers or LNG) is only technically and economically feasible in a small portion of vessels, since it depends on the existing vessel's technology, design, scale, age, consumption, etc.; for the other significantly large part of the fleet, the only option is to run on clean fuels.

Methanol will have quite limited penetration. It faces similar challenges to those of LNG as it needs a retrofit and port infrastructure to be massively spread. It carries, however, the major safety upside of not having to be stored and handled at

high-pressure and cryogenic temperatures; another advantage is that it can be produced from renewable sources. Nevertheless, methanol price is usually higher than that of LNG and its energy density lower, which means more space is required for fuel storage.

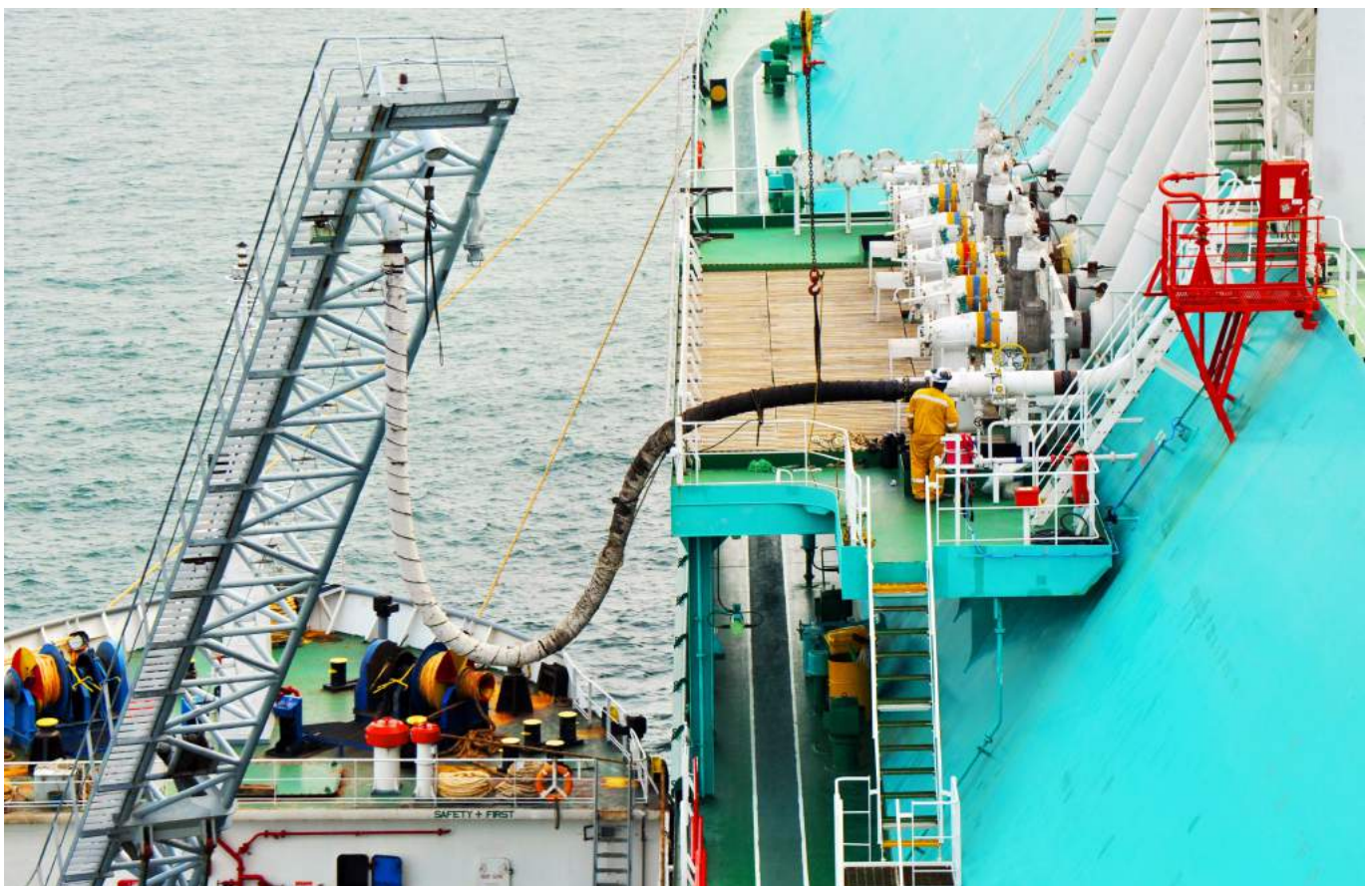
Running on biodiesel is another option which will have short diffusion: even though it is produced from renewable sources and can adapt to diesel engines, its major setback is that the price is even considerably higher than that of ULSD, let alone compliant residuals.

Biomass is sometimes brought into question as an alternative to residual fuels. This fuel faces several major barriers: it has limited availability at all ports, price is not always competitive (if available), energy density is substantially lower than that of liquid/gas fuels (which implies larger volume for fuel storage), and biomass has significant emissions with regard to particulate matter (depending on its source).

Electric ships have been catching attention lately, and some projects are under way. Major drawbacks for this technology are the initial cost of batteries and engines, plus the operational limitations of the shorter range and charging time.

Outcome of the refiners' versus shippers' struggle

All above-mentioned solutions for ship owners are costly in terms of initial investment and face the short-scale challenge of investing in one ship at a time, with virtually zero effect worldwide. Solutions with no investment involved end up running on expensive fuels. Nonetheless, retrofitting a vessel is a faster process than reconfiguring refineries, and shippers are taking a spectator role to some extent, watching for outcomes before reacting.



Insights for executives

- Worldwide tendency to move to ultra-low-sulfur fuels – uneven among regions, especially time-wise
- Demand for clean on-road fuels coming from engines; fuel regulators mostly playing a messenger role
 - Engines' technology does follow an environmental agenda
- Marine fuel regulations limiting marine fuels' sulfur content to 0.5 percent outside the ECA in 2020 will set greater challenges to refiners rather than shippers
- Residual fuels may still find a non-marine-fuel market, but for a very limited time
- Price spreads between clean and dirty fuels are relatively low, and both CAPEX and OPEX are significant for fuel treatment, thus economics are tight
- Investment may be phased and part of it minimized with some trading activities in the short run
- Scale is key to leverage reconfiguration projects' economics; many refineries will have serious competitive positions and survival challenge
- Environmental trend has already eroded present value of global refining business. Refinery value may be protected by identifying optimal actions and investments, but every month counts for survival – company value could be more eroded than expected
- Transformation formulas should be tailor-made since a combination of operational adjustment and new units may be the fittest solution. In some cases new conversion and upgrading units, rather than only hydrotreating, can bring the most profitable return on investment

How can Arthur D. Little support the key players?

- Feedstock supply, valuation and strategy
- Refining industrial, commercial, supply and trading strategy
- Desulfurization configuration design and feasibility
- Upgrading conceptual design and feasibility
- Long-term demand-supply trends for petroleum products

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Refiners' time window shrinks – they need to act

Arthur D. Little

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