

Economic and environmental versatile technologies in refining

Case study on the dewaxing of fuels and lubes using porous zeolites reveals the merits of efficient chemical conversions and reduced energy consumption

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Innovation in the refining and chemical industries has enormous potential to overcome the environmental challenges of today's society. Yet, innovation can only be widely adopted once both environmental benefits and economic merit can be achieved. The chances of achieving such a win-win in this sector may be maximised when focusing on versatile technologies; that is, those that find application independent of the feedstock.

Versatile innovations often have a higher technology readiness level, find a wider and more secure market, and do not face supply and demand complications, which may make them faster to commercialise. In addition, whereas the need for energy conservation is widely embraced, the potential environmental impact of improving the efficiency of chemical conversions and the more efficient use of chemicals is less widely recognised. Herein, we highlight the value of an economic and environmental win-win through a case study on the dewaxing of fuels and lubricants using advanced porous zeolites.

Innovation in today's society

An impressive amount of game-changing and environmentally driven technology does not make it to fruition, often due to excessive costs. Today, in order to bring an innovative product/service to the market, it must follow the governing principles of this market. This implies that the company adopting the innovation should, ultimately, be able to generate a profit.

For example, say a typical refinery may combust 10 wt% of its crude to form CO₂. The technology to capture the emitted fossil-derived CO₂ sounds attractive for both funding and allocating subsidies. Yet, even if an impressive 30% of the emitted CO₂ can be reduced, the capture and utilisation of the CO₂ will in most countries today pose an inhibitive cost. In contrast, as illustrated in the following case study, investing in more efficient hydrocracking or dewaxing may instigate the same reduction in CO₂ emissions, while also presenting an attractive business case. Yet, such innovations are often passed over for investment or subsidies due to the fossil origin of the feedstock.

Accordingly, when investing in innovation for combating the environmental crisis, the underlying challenge may not just be technological, but also economic, political, and

societal, which begs the question: How can we make environmental benign technologies profitable? Will this be possible under the current macroeconomic markets? Should we still invest in technologies suitable for fossil-derived streams? Should we continue to strive for more growth and positive compound annual growth rates (CAGRs)?

Answering such quasi-philosophical questions is obviously beyond the scope of the article. Yet, herein, an innovative trajectory to enable the environmental and economic win-win is highlighted for the refining and chemical industry, regardless of the nature of the feedstock used.

Versatile innovations

A significant part of innovations in the refining and chemical industry steer towards replacing fossil-based oil feedstock with those derived from biomass or CO₂. Yet, in most projections, the majority of fuels and chemicals remain derived from petroleum for decades to come due to a variety of challenges.

For example, the conversion of CO₂ to fuels and chemicals requires an order of magnitude more energy than refining petroleum. Moreover, the availability of suitable amounts and forms (such as concentration and pressure) of CO₂ feedstock is not trivial. Similarly, for biomass-derived feedstocks, numerous challenges emerge, including available locations to cultivate them, the potential for accelerated deforestation, and competition with food-based agriculture. It is easy to imagine that for a Capex-driven industry such as the refining and chemical industries, many of these risks pose a serious liability, making investing in innovations in specific-feedstock technologies risky.

Instead, a versatile technology in the refining and chemical industry implies that it can be exploited independently of the feedstock used and accordingly poses a much safer investment. This relates to processes after the initial conversion of the feedstock, on the way towards the fuels, base chemicals, or fine chemicals. Importantly, the relative amount of versatile technology increases as we move further upstream from refining towards base chemicals and finally fine chemicals (see **Figure 1**). Additionally, when the switch from fossil towards circular feedstocks occurs, these versatile technologies can be readily applied and will be even more advanced by that time.

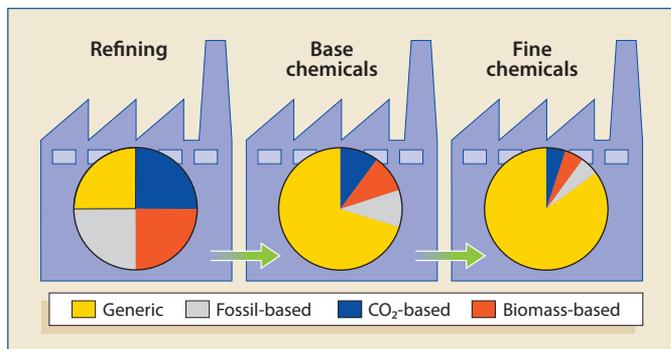


Figure 1 Scheme to illustrate the relative abundance of versatile technologies in the refining and chemical industry

Hence, versatile innovations offer a high technology-ready level, a wide and secure market, and face fewer supply and demand complications, and may therefore be faster to implement and commercialise. Yet, despite this major advantage, versatile technologies have been described as less attractive to financial investors and less eligible for governmental subsidies, simply because they can also be used to process fossil-derived streams.

Efficiency of production and usage

Efficiency and related innovations are intuitively related to the amount of energy or time that is used to deliver a certain product or service. And, indeed, there is ample room in the refining and chemical industry to lower emissions by, for example, a more efficient use (and recovery) of heat.¹

Yet, lesser known is the efficiency of the use of a product. For example, the use of a more porous type of plastic.² In this case, fewer emissions and less feedstock are consumed, simply because less product would be needed to exert a certain function. Similarly, by enhancing the catalytic efficiency of a chemical conversion, fewer emissions are emitted per unit operation, and at the same time, more valuable product is yielded.

As illustrated in the following discussion, the energy savings from product usage and chemical conversion can be sizable, especially when multiple steps are concerned, which is typical in the refining and chemical industry. In

contrast to energy savings of a single step of conversion, benefits in product yields or reduced product consumption directly impact the entire supply chain.

Zeolite catalysts

One of the most dominant influences on the efficiency of conversion for versatile conversions are porous solids, specifically zeolites. Zeolite catalysts have demonstrated a hegemonic role for several decades already, being used on a massive scale to decrease (cracking) or increase (alkylation) the size of molecules, or by rearranging molecules (such as isomerisation), in processes such as fluidised bed catalytic cracking (FCC), hydrocracking, dewaxing, and aromatics conversions.

Zeolites have developed a dominant position based on their high surface area, stability, and acid strength, which in turn is due to their regular/crystalline pores being in the size range of individual molecules (ca. 0.5 nm, **Figure 2**). Accordingly, configurational constraints enable unprecedented selectivities towards desired products. Moreover, being aluminosilicates, zeolites are made from abundant materials, and their synthesis is relatively safe, environmentally friendly, and scalable.

The design of zeolites has progressed impressively since their discovery as catalysts in the 1960s. It accordingly seems hard to believe that there is room to improve these materials. Yet, with enhanced understanding, new ways have emerged to push the envelope.

Potential of superior porous zeolite catalyst

Besides giving rise to the many attractive properties, the narrow intrinsic zeolite properties also impose significant access (molecule cannot enter) and transport (molecule stuck in traffic) limitations. These limitations mean that the performance of standard zeolites can often be considered sub-optimal and can therefore be subject to sizable improvement.

Mesoporous zeolites complement the intrinsic zeolitic micropores with a secondary network of larger pores in the size range of 2–50 nm. The ‘mesopores’ enhance access to the zeolite micropores and alleviate molecular traffic jams, resulting in sizable catalytic benefits, as demonstrated in virtually any reaction involving a hydrocarbon.

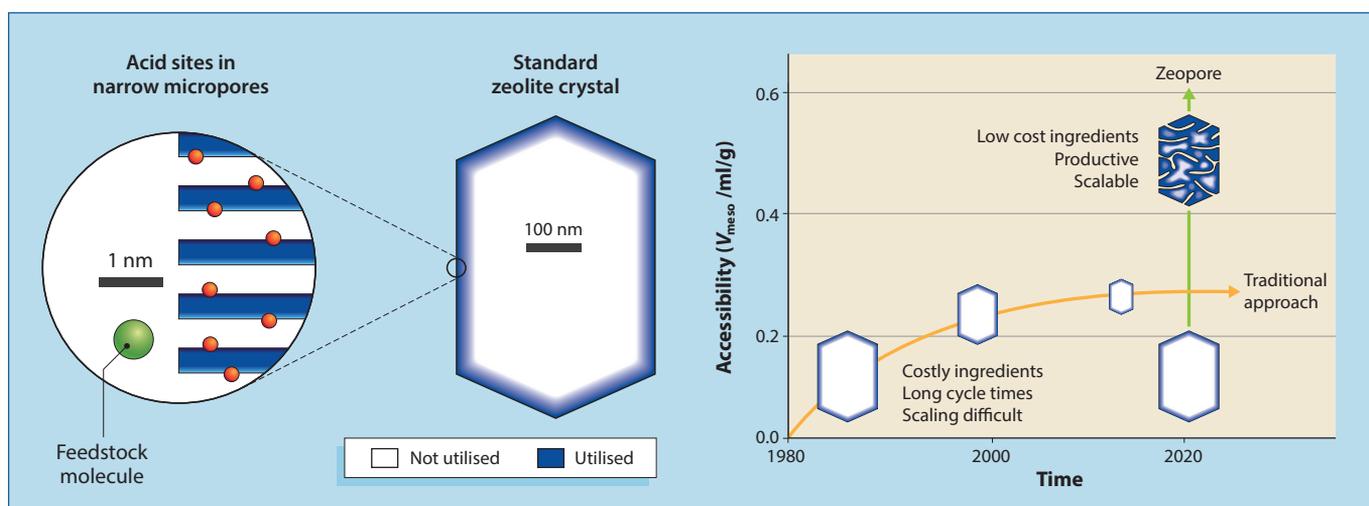


Figure 2 (left) Visualisation of the narrow pore inside zeolite crystals; **(right)** Traditional vs Zeopore's approach to increase accessibility in zeolites

Overview of productivity, efficiency, and CO₂ profile of middle distillates derived from different feedstocks

Aspect	Crude oil		CO ₂		FOGs	
	Standard	Zeopore	Standard	Zeopore	Standard	Zeopore
Energy of feedstock sourcing GJ/ton feedstock		2 ^a		10 ^h		7 ⁱ
Energy of conversion GJ/ton feedstock		5 ^{a,c}		80 ^d		6 ^f
Selectivity to middle distillates and/or olefins, %	90 ^c	93 ^e	80 ^d	83 ^e	65 ^f	68 ^e
Selectivity to undesired byproducts, %	10	7 ^e	20	17 ^e	35	32 ^e
Energy input GJ/tonproduct ^j	8	8	113	108	20	19
Byproducts CO ₂ value ton CO ₂ /ton product ^k	0.4	0.2	0.8	0.7	1.7	1.5
CO ₂ upon burning the SAF ton CO ₂ /ton product	3.2 ^b	3.2 ^b	0	0	0	0
Total: CO ₂ ton/ton product	3.6	3.4 (-4%)	0.8	0.7 (-15%)	1.7	1.5 (-12%)

a) Energy density of oil: https://en.wikipedia.org/wiki/Tonne_of_oil_equivalent

b) CO₂ formation upon combustion of fuels or oils: <https://climate.mit.edu/ask-mit/how-can-burning-one-ton-fuel-create-more-one-ton-co2>. Here, assumed to be 3.2 ton CO₂ for oil, middle distillates, and byproducts for simplicity.

c) Efficiency of fossil oil refinery: <https://pubs.acs.org/doi/10.1021/es501035a>

d) Efficiency of CO₂ to methanol to SAF: 10.1021/acssuschemeng.4c03939.

e) Zeopore increases yields to middle distillates by 3 wt% at the expense of undesired byproducts, being mixtures of lights such as ethane, propane, and naphtha.

f) Efficiency of FOGs to SAF: <http://dx.doi.org/10.1016/j.biortech.2016.05.090>

g) Efficiency of producing fossil-based oil: <https://theworld.org/stories/2013/08/15/energy-costs-oil-production>

h) Efficiency of CO₂ capture: <https://doi.org/10.1016/j.cej.2024.154421>

i) Efficiency of producing FOGs: <http://dx.doi.org/10.1016/j.biortech.2016.05.090>

j) Energy of conversion + feedstock sourcing normalised to yield of middle distillates + olefins.

k) Energy of combustion of waste products normalised to yield of middle distillates + olefins.

Table 1

Yet, despite the clear catalytic superiority of accessible zeolites, their industrial adoption has remained hampered due to excessive cost and technical challenges of manufacture. Accessible zeolites are often systematically linked to a synthesis that features copious amounts of expensive ingredients, low productivity, hard-to-scale operations, and/or inhibitive safety or environmental impacts.

Within this domain, Zeopore has designed and manufactured high-quality, highly tunable, and accessible mesoporous zeolites, attaining proof of concept in versatile applications such as FCC, hydrocracking, and dewaxing (Figure 2), as well as with feedstock-specific circular applications, such as methanol-to-olefins, waste plastics, and biomass conversions.

Case study on dewaxing

Dewaxing relates to the improvement of cold flow properties, making fuels and lubricants more processable and compliant with regulations. Dewaxing by hydro-isomerisation using a specific type of unidirectional zeolites is often the method of choice, as these zeolites can lower cold-flow properties by branching linear alkanes without losing precious feedstocks through undesired cracking to undesired byproducts, such as naphtha.

Dewaxing serves as an insightful case study, as it is a versatile application that has already been used at an industrial scale for decades, and its use is foreseen to significantly

grow when fuels and lubrications are derived from circular feedstocks (see **Figure 3**). Unsurprisingly, next to dewaxing, other versatile reactions, such as the reforming of lights and cracking of heavies, both zeolite-catalysed, will also remain of paramount importance.

With this domain, accessible zeolites have already been applied, typically engineered by decreasing the crystal size, an approach that is relatively costly and also has plateaued in effectiveness. Here, Zeopore offers a fundamentally different approach, using strictly low-cost and scalable methods, reaching any desired level of accessibility (Figure 2).

In dewaxing, superior accessible zeolites enable further maximisation of the yield of desired output, at the expense of undesired lights (such as light byproducts). Zeopore has attained several proof-of-principle results, yielding, on average, 3 wt% more middle distillates. This represents a value to the refiner of 500 USD/kg of mesoporous zeolite. Therefore, many times more than the cost of the innovation, and accordingly represents an attractive business case.

The impact of a 3 wt% increase in middle distillate product at the expense of light byproducts is studied for three potential cases where dewaxing can be applied: the dewaxing of streams from crude oil, CO₂, and fatty acids, oils, and greases (FOGs), as shown in **Figure 4**. Today, each method has its limitations: whereas the processing of crude oil is already highly efficient, it is not circular. CO₂-derived middle

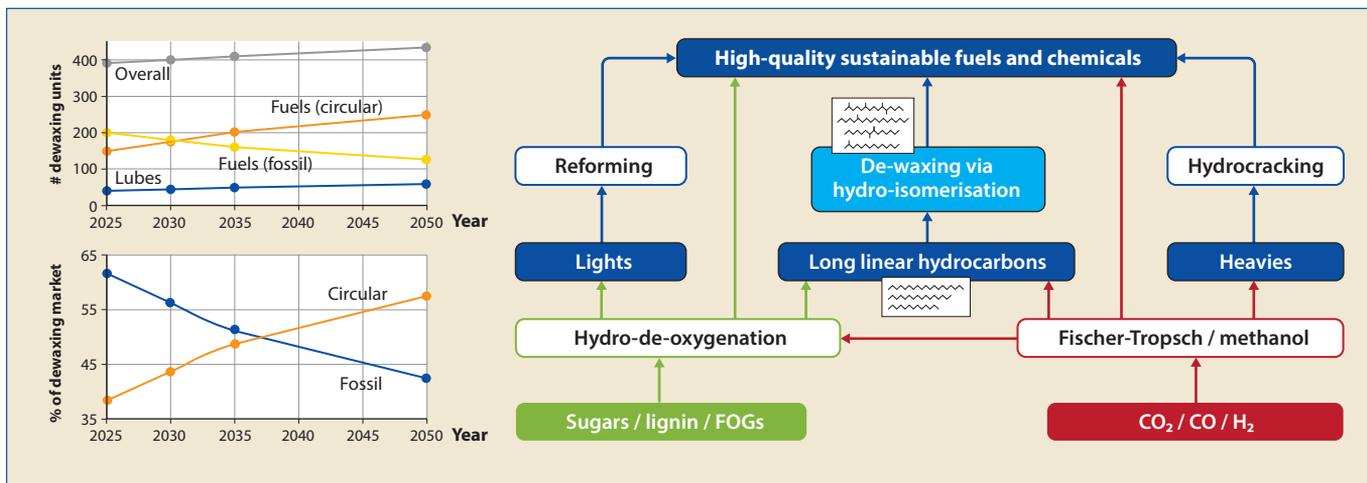


Figure 3 (left) Market trends in dewaxing; **(right)** Schematic flow chart highlighting the increased need for dewaxing in the circular domain. Feedstock-dependent conversions in green and red, versatile feedstock-independent conversions in blue

distillates are circular, yet come at an enormous energy input. For FOGs, the energy input is more similar to crude oil; however, the losses to byproducts are higher.

In the established refining of crude oil, the 3 wt% benefit to middle distillates relates to more than a 40% reduction in formed byproducts (see **Table 1**). Within the following analysis, such byproducts are burned off for heat recovery and are therefore directly related to CO₂ formation. Yet, despite the large reduction in byproducts, the overall benefit remains ca. 3 wt%, as product middle distillates form the prime source of CO₂ formed.

In circular applications, the benefit per ton of middle distillates is similar, about 0.1 to 0.2 ton CO₂ per ton of middle distillates. However, unlike the case for fossil-based fuels, the burning of middle distillates does not count as CO₂ emissions. Accordingly, the CO₂ reductions via the improved selectivity are much higher, about 10-15%.

It is assumed here that the increased energy requirement for the relevant conversions is entirely provided by net-zero sources, which may be challenging for the conversion of CO₂ due to its very high energy consumption. Again, the increased selectivity to desired products via enhanced refining using superior zeolite catalysts reduces the energy requirement per ton of end product by 4-5%.

When these benefits are related to the total number of suitable dewaxing units (250) with an average capacity of 100,000 barrels per day (bpd), the savings amount to

roughly 200 million tons CO₂ per year, about 5% of the total yearly CO₂ output in the refining and chemical industry. Similar-sized benefits may be attained using this type of superior zeolites in hydrocracking, FCC, and aromatics conversions. Hence, from this relatively simple high-level analysis, one can appreciate the sizable impact of a versatile innovation, both in the future and today.

Summary and outlook

Innovation of environmentally benign, versatile technologies in the refining and chemical industry is attractive, as they are relatively easy to implement and have a higher chance of profitability, now and in the future. More importantly, the author believes such feedstock-independent innovations merit support from venture capital and governmental subsidies. This support, in combination with promising business cases and positive environmental impact, should increase technology readiness levels (TRLs), lowering the risks involved in commercialisation. Only then can chances to have the technology successfully and widely adopted be maximised in the relatively conservative and Capex-heavy refining and chemical industry.

Zeopore is currently commercialising its dewaxing technology, as well as other applications such as hydrocracking and FCC³, where similarly attractive business cases can be combined with significant environmental impact. Together with its partners, the company is now quantifying not only the business cases but also the environmental impact of its innovations throughout the supply chain. Operations have been successfully and efficiently scaled up towards the ton-scale, predating the focus on making strategic alliances to facilitate innovations as effectively, broadly, and efficiently as possible.

References

- 1 See example www.QPinch.com
- 2 See example www.voidtechnologies.com
- 3 D. Verboekend, Maximising hydrocracker performance and middle distillate production, *PTQ Catalysis 2025*, pp.53-57.

Danny Verboekend is a founder and CSO of Zeopore Technologies. He is engaged in the strategic development of novel materials using strictly low-cost and scalable manufacturing routes, for established and novel (circular) catalytic applications.

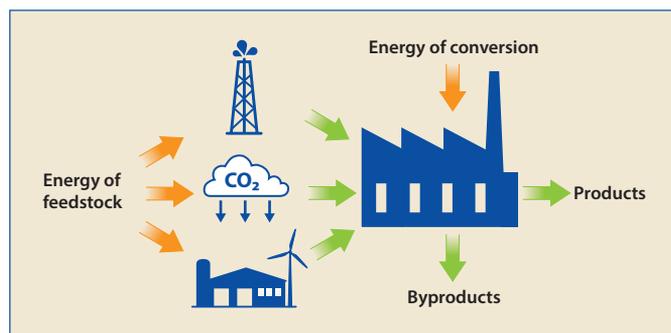


Figure 4 Simplified overview of required energy and obtained product streams in the conversion of crude oil (top), CO₂ (middle), and biomass (bottom) feedstocks to middle distillates

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