



# Hybrid separation technologies for minimizing energy use in petrochemical processes

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**Abstract.** Separation operations in petrochemical processing account for a significant portion of total energy consumption due to the large-scale handling of multi-component mixtures with close physicochemical properties. Conventional distillation, while technically mature and widely adopted, is thermodynamically intensive and under growing pressure to reduce energy use and associated emissions. Hybrid separation technologies - characterized by the integration of two or more unit-operations (e.g., membranes, distillation, adsorption, heat integration) - offer promising routes for energy minimization by leveraging the strengths and compensating for the weaknesses of individual processes. This review assesses recent advancements in hybrid separation systems, discusses industrially relevant petrochemical applications, and highlights energy savings potential along with implementation challenges and future prospects.

**Key Words:** energy efficiency, heat integration, membrane-distillation hybrids, process intensification.

**Introduction.** Petrochemical processing relies heavily on separation operations such as distillation, extraction, adsorption, and membrane techniques to isolate products including olefins, aromatics, and hydrogen. Traditional distillation columns often operate near azeotropic or close-boiling compositions, demanding high thermal duty and resulting in large energy footprints. As energy costs rise and decarbonization becomes imperative, process intensification strategies - including hybrid separation systems - are emerging as critical enablers for energy efficiency. Hybrid systems combine conventional and non-conventional technologies to reduce thermal duty, exploit waste heat, and improve separative performance beyond what each technique can achieve independently.

**Energy challenges in petrochemical separation.** Distillation, especially for light hydrocarbons (e.g., propylene/propane), represents one of the highest energy-consuming unit operations in refineries and petrochemical plants due to the need for high reboiler duty and numerous theoretical stages to achieve purity targets (Blahušiak et al 2016; Park et al 2017; Park et al 2017; Luo et al 2024). Technologies such as dividing-wall columns and mechanical vapor recompression have been demonstrated to reduce energy use through improved internal heat integration and reduced vapor flow requirements. In crude distillation units, advanced configurations and heat recovery networks can reduce energy consumption by 15-30% relative to conventional designs, primarily through reduced reboiler duty and enhanced thermal efficiency (Mathew et al 2022; Nogaja et al 2022; Uthman et al 2025).

## Hybrid membrane-distillation configurations

**Membrane assistance in distillation.** The combination of membrane separation with distillation has been extensively studied as a hybrid approach to reduce the reliance on thermal separation alone. When properly configured, membranes can perform partial

component separations that alleviate the load on distillation columns. For example, membrane-distillation hybrids for propylene/propane separations using olefin-selective zeolite membranes demonstrate markedly lower energy consumption compared to standalone distillation. Configurations where membranes precede or replace distillation columns show that both energy consumption and membrane area requirements vary strongly with feed composition and membrane characteristics, but generally outperform conventional columns for high-purity separations.

**Pervaporation-distillation hybrids.** Pervaporation - where selective transport through a membrane is driven by partial vaporization - is another hybrid partner to distillation (Chia & Sorensen 2023; Chia et al 2023; Thi & Tóth 2024, 2025). Integrated pervaporation-distillation systems with heat integration have been experimentally shown to reduce energy consumption by approximately 24% compared to pressurized distillation, while improving energy efficiency by nearly 32% under certain feed conditions (Zong et al 2021). The use of low-temperature residual streams to cool distillation overhead vapors further enhances thermal coupling between steps.

**Advanced hybridization with heat integration.** Beyond purely combining separation mechanisms, hybrid systems often incorporate advanced heat integration to recycle thermal energy across process steps (Yang et al 2019; Wang et al 2021; Duan & Li 2025). Heat pump-assisted systems, when paired with membrane units, can significantly lower operating costs and energy usage relative to distillation-only processes. Such configurations can capture and reuse low-grade heat that would otherwise be wasted, effectively boosting the overall efficiency of separation trains (Li et al 2019; Yang et al 2019; Shaulsky et al 2020; Wang et al 2021; Şulgan et al 2023; Zhang & Xian 2024; Pérez et al 2025). Techno-economic analyses show that hybrid systems integrating carbon molecular sieve membranes with heat pumps can reduce operating costs by up to ~69% and improve total cost savings relative to conventional designs when membrane selectivity and permeance are favorable (Park et al 2019, 2021).

**Hybrid adsorption-membrane systems.** Adsorption processes such as pressure swing adsorption can be hybridized with membrane units to enhance selectivity and reduce energy demand for gas separations. In petrochemical applications, adsorption can pre-concentrate target components or remove impurities prior to membrane or distillation steps, thereby lowering the energy penalty associated with deep separations. Although specific data for petrochemical compound separations are less widely reported in the literature than for gas treatment (e.g., hydrogen purification), analogous concepts from industrial gas separations illustrate the potential of integrating adsorptive steps to manipulate process equilibria and reduce energy burdens.

**Drivers of energy efficiency in hybrid systems.** Hybrid separation technologies deliver energy benefits through several mechanisms:

- thermal load redistribution: hybrid systems allow separation duties to be shared between thermal and non-thermal processes, reducing the demand for high-grade heat;
- heat recovery and integration: reusing waste heat within the separation train reduces utility consumption and lowers net energy input;
- selective component removal: membranes and adsorbents can selectively remove difficult-to-separate species, reducing the stages required in downstream distillation;
- process intensification: combining multiple functions into a single unit or network improves mass and energy transfer rates, reducing equipment size and heat requirements.

**Implementation challenges and limitations.** Despite demonstrated energy savings in pilot and simulation studies, hybrid systems face several practical challenges:

- material limitations: membrane and adsorbent performance (selectivity, permeance, stability) under aggressive petrochemical conditions can limit applicability and lifetime;

- capital and integration costs: advanced materials and complex integration networks can entail higher upfront costs compared to conventional distillation, delaying payback in some configurations;
- process control complexity: hybrid systems require sophisticated control schemes to manage interactions between disparate unit operations and maintain separative targets.

**Future directions.** Future research should prioritize:

- development of robust membranes and hybrid materials with enhanced selectivity and thermal stability suitable for petrochemical feeds;
- advanced heat integration strategies that reuse waste heat more effectively at different temperature levels;
- hybridization with reactive separations (e.g., reactive distillation) to combine reaction and separation in a single step;
- digital and model-based optimization to dynamically optimize hybrid system performance and energy consumption.

**Conclusions.** Hybrid separation technologies represent a promising strategy to reduce energy consumption in petrochemical processes by integrating multiple separation mechanisms and leveraging heat integration. Studies on membrane-distillation and heat pump-assisted systems show quantifiable energy advantages over conventional sequences. While industrial adoption is still emerging, ongoing advances in membrane materials, process design, and integration engineering position hybrid separation as a cornerstone of future energy-efficient petrochemical processing.

**Conflict of interest.** The author declares that there is no conflict of interest.

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