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Review paper

Distillation-Centered Decarbonization of Petroleum Refineries: Energy Optimization of Crude and Vacuum Distillation Units

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Abstract: The petroleum refining sector is a major industrial energy consumer, with crude and vacuum distillation representing important sources of thermal and utility demand. This review examines distillation-centered decarbonization of petroleum refineries, focusing on the Crude Distillation Unit (CDU) and Vacuum Distillation Unit (VDU) as interconnected components of the refinery energy system. The study evaluates a hierarchy of interventions, beginning with operational optimization and thermodynamic integration, followed by crude preheat-train fouling mitigation, direct waste-heat recovery, heat upgrading, process electrification, and digital optimization. Particular attention is given to Pinch Analysis, heat-exchanger-network optimization, waste-heat boilers, Organic Rankine Cycles, absorption heat pumps, Mechanical Vapor Recompression, fired-heater optimization, steam and vacuum-system improvements, Advanced Process Control, and digital twins. The review further considers how CDU/VDU interventions interact with refinery fuel gas, steam networks, hydrogen recovery, downstream conversion units and refinery-wide energy management. The review compares technology maturity, implementation constraints, and indicative techno-economic characteristics to distinguish brownfield-ready measures from options requiring major retrofit or infrastructure changes. Reported performance values are treated as context-dependent ranges because achievable savings depend on crude quality, refinery configuration, baseline efficiency, throughput, utility prices and retrofit scope. The review concludes that near-term refinery decarbonization is best approached through an integrated sequence of demand reduction, heat recovery, operational control, and selective hardware modernization, with electrification and low-carbon hydrogen. Through a synthesis of industrial case studies from major operators including Sinopec, ExxonMobil, Shell, and TotalEnergies, this manuscript shows that a holistic distillation optimization strategy can yield energy savings of approximately 15–25% and significantly reduce Scope 1 and 2 emissions. The analysis concludes that while electrification and novel separations offer long-term pathways, rigorous thermal integration and digital optimization constitute the essential, commercially viable bridge to the low-carbon refinery of the future.

Keywords: Petroleum Refining, Distillation Optimization, Industrial Decarbonization, Waste Heat Recovery, Process Electrification, Energy Efficiency, Heat Integration, Digital Twins.

1. Introduction

The global energy landscape is undergoing a profound structural transformation, driven by the dual imperatives of meeting rising energy demand and mitigating the catastrophic risks of anthropogenic climate change. Despite the accelerated deployment of

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renewable energy technologies and the electrification of transport, petroleum-derived fuels and petrochemical feedstocks continue to underpin the global economy. Consequently, the petroleum refining sector remains one of the largest stationary sources of greenhouse gas (GHG) emissions and industrial energy consumption [1-3]. According to recent data from the International Energy Agency (IEA), the refining sector accounts for approximately 6–8% of total global industrial energy consumption [4]. In 2024, global energy-related CO_2 emissions continued to rise, with natural gas-related emissions increasing by approximately 2.5% or 180 Mt CO_2, highlighting the broader challenge of decarbonizing process heat and industrial fuel combustion [1]. This trend highlights a critical paradox: while downstream fossil-fuel consumption drives global emissions, upstream production and refining are massive, energy-intensive industrial operations that must be decarbonized to meet net-zero targets [3, 5].

Refining energy intensity is not uniform; it is heavily concentrated in specific thermal and separation processes. Refineries are complex, integrated industrial cities comprising diverse processing units, yet the fundamental separation process, distillation, dominates the energy profile. Separating crude oil into fractions based on boiling points is inherently thermodynamically inefficient in its conventional configuration. It requires large thermal energy inputs to vaporize liquid hydrocarbons, only to reject a significant portion of that heat during condensation and product cooling [6, 7]. As the industry grapples with stricter environmental regulations, carbon pricing mechanisms such as the EU ETS, and increasing investor pressure for Environmental, Social, and Governance (ESG) compliance, the decarbonization of refining operations has transitioned from a peripheral corporate social responsibility metric to a central strategic imperative for operational license and economic survival [8]. The Crude Distillation Unit (CDU) and Vacuum Distillation Unit (VDU) are the primary processing units in any refinery and process 100% of incoming crude oil. Together, these units account for a staggering share of the site-wide energy bill. Comprehensive energy audits and academic literature consistently suggest that distillation processes account for approximately 30–50% of a refinery's total energy consumption [9, 10]. The CDU alone is typically the largest single energy consumer on site, driven by the massive thermal duty required by the atmospheric fired heaters to raise crude oil to approximately 350–370°C, and the subsequent steam or reboiler duties required for fractionation [11-13].

The CDU's operational efficiency has disproportionate ripple effects across the entire refinery complex. Because the CDU feeds all downstream conversion units (e.g., Fluid Catalytic Crackers, Hydrocrackers, Reformers), inefficiencies or instabilities in the CDU propagate downstream. A suboptimal separation in the CDU can lead to off-specification intermediate streams, requiring downstream units to operate at higher severities to correct boiling point gaps or remove contaminants, thereby compounding energy waste [14]. Furthermore, the VDU, which processes the atmospheric residue, operates under high vacuum and high temperature, adding significant steam demand for ejector systems and fuel gas demand for vacuum furnaces. Therefore, focusing decarbonization efforts on these "front-end" units offers the highest leverage for site-wide emission reductions [14, 15]. In the discourse of industrial decarbonization, significant attention is often lavished on deep decarbonization technologies such as Carbon Capture and Storage (CCS) and the switch to alternative feedstocks like biofuels or green hydrogen. While these are undoubtedly critical for long-term emissions elimination, they often entail high capital expenditures (CAPEX), significant infrastructure dependencies, and technological maturity risks that may delay widespread implementation [16].

In contrast, distillation-centered energy optimization presents a suite of "no-regrets" measures, technologies, and operational strategies that are relatively mature and, depending on site-specific conditions, may offer practical near-term deployment opportunities. Distillation optimization addresses the root cause of emissions and energy demand rather than merely treating the symptom (CO_2) [17]. By reducing the thermal energy required for separation, refiners can immediately lower their fuel consumption and Scope 1 emissions [18]. This review posits that a holistic optimization of distillation systems is the most effective near-term pathway for refineries to reduce emissions while preparing for a deep-decarbonized future. This approach aligns with the Energy Efficiency First principle, which argues that demand reduction must precede supply-side decarbonization to minimize the scale and cost of the required renewable energy infrastructure.

The primary objective of this review is to bridge the gap between theoretical process integration research and practical industrial implementation. Unlike general reviews of refinery efficiency, this work specifically targets the CDU/VDU complex, providing a granular analysis of how specific technologies interact within the distillation envelope.

The novelty of this review lies in its distillation-centered decision framework rather than in treating individual technologies as independent solutions. The analysis links thermodynamic optimization, crude preheat-train performance, fouling mitigation, fired-heater and steam-system efficiency, waste-heat valorization, and digital control within the CDU/VDU envelope, while explicitly considering their interactions with refinery-wide utility systems and downstream conversion units. The review also distinguishes technology maturity from retrofit practicality by considering Technology Readiness Level (TRL), implementation difficulty, brownfield compatibility, operational risk and indicative economic characteristics. Emerging options such as Mechanical Vapor Recompression, heat-integrated distillation and crude-selective membrane fractionation are therefore assessed against established measures rather than presented as standalone alternatives. This scope distinguishes the present work from broader refinery-decarbonization reviews by focusing on how optimizing the distillation energy system can provide a practical near-term foundation for deeper refinery decarbonization.

1.1 Review Methodology

This manuscript uses a rigorous narrative review methodology to provide a critical, synthesized, and comprehensive overview of the state of the art in refinery distillation decarbonization. This approach integrates diverse evidence streams, from fundamental thermodynamic studies to industrial case reports, enabling a holistic understanding of the subject. We used a comprehensive search strategy to identify high-quality literature at the intersection of petroleum refining, thermodynamics, and decarbonization. The search prioritized literature published between 2010 and 2025 to ensure relevance to the current energy transition context, while also including foundational works establishing the principles of distillation thermodynamics.

We conducted a systematic literature review using major scientific and engineering databases. We collected peer-reviewed journal articles from Scopus and Web of Science to ensure comprehensive coverage of high-quality research in chemical engineering, energy, and sustainability. Relevant articles were further sourced from ScienceDirect, with particular emphasis on established journals such as Applied Energy, Journal of Cleaner Production, and Energy Conversion and Management. In addition to academic publications, the review incorporates authoritative technical reports and industrial documentation from international agencies (e.g., IEA, EIA, Concawe) and technology licensors (KBC, Jacobs, Honeywell UOP) to capture practical and industrial perspectives. The review applied explicit inclusion and exclusion criteria to maintain analytical focus and depth. The review concentrated on studies addressing energy optimization and decarbonization of crude distillation units and vacuum distillation units, with particular emphasis on heat integration, fouling mitigation, waste heat recovery, and thermal efficiency enhancement within refinery distillation systems. We also considered techno-economic evaluations and lifecycle assessments of decarbonization technologies directly applicable to distillation operations. In contrast, generic energy-efficiency studies that did not explicitly consider the complex thermodynamic and operational interdependencies characteristic of petroleum refining were excluded. Similarly, studies focusing exclusively on downstream petrochemical units, such as steam crackers or polymerization processes, were omitted unless they provided directly transferable insights into crude or vacuum distillation heat integration networks.

Following screening and selection, the identified literature was systematically synthesized and organized into four overarching thematic domains reflecting the dominant decarbonization pathways for refinery distillation, as schematically illustrated in Figure 1.

1. Thermodynamic Optimization: Pinch analysis, heat exchanger network synthesis, and exergy analysis.
2. Hardware Modernization: Advanced column internals, high-efficiency fired heaters, and vacuum system upgrades.
3. Waste Heat Valorization: Technologies for upgrading low-grade heat, including Organic Rankine Cycles (ORC), Absorption Heat Pumps (AHP), and Mechanical Vapor Recompression (MVR).
4. Digital Transformation: The role of Advanced Process Control (APC), Artificial Intelligence (AI), and Digital Twins in maintaining optimal operating points.

This thematic structure provides a coherent analytical framework for the subsequent sections of the review, enabling systematic comparison of technological options, identification of synergies and trade-offs, and articulation of future research and industrial implementation priorities.

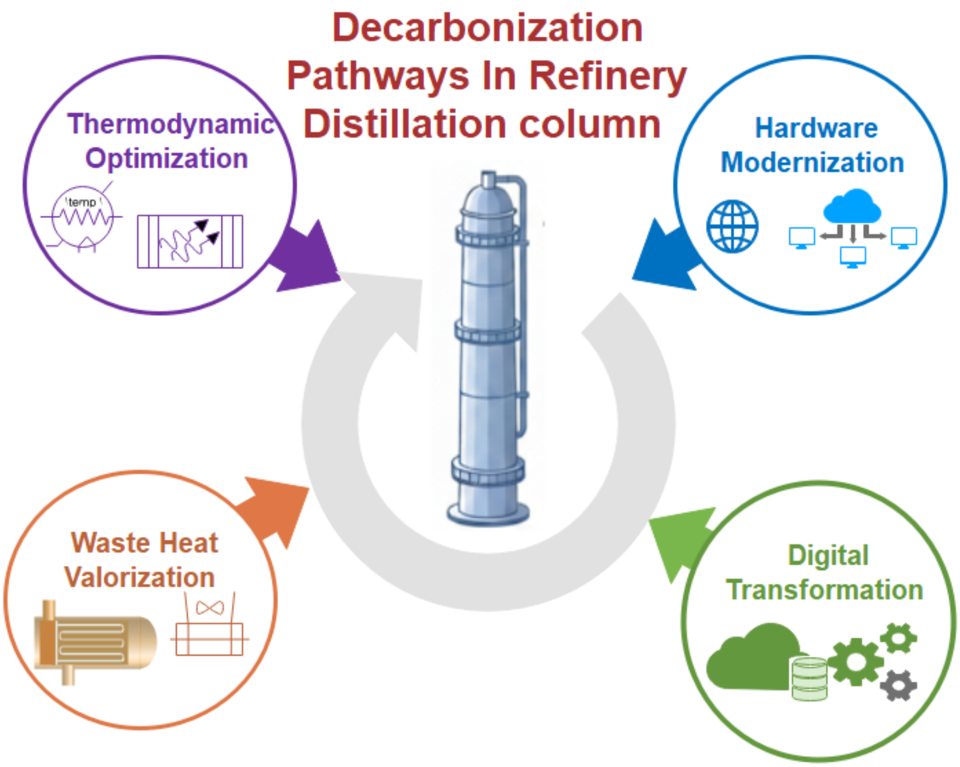

Figure 1. Decarbonization pathways for Refinery Distillation, highlighting energy efficiency measures, advanced process control, digitalization, fuel transition strategies, renewable integration, and carbon capture technologies.

2. Carbon Footprint and Energy Intensity of Refinery Distillation Units

To effectively decarbonize, one must first quantify the baseline energy consumption and carbon footprint of distillation operations [14]. The energy intensity of petroleum refining is driven by the thermodynamic requirements of separating complex hydrocarbon mixtures, a process that is inherently energy-intensive because of the phase changes involved [19].

2.1 Energy Consumption Breakdown in Distillation Column

In a typical complex refinery, energy is consumed primarily in the form of fuel gas (for fired heaters), steam (for stripping, heating, and vacuum generation), and electricity (for pumps, compressors, and fans)[14, 20, 21]. Fuel gas primarily powers direct-fired heaters; steam is required for stripping, heating, and vacuum generation; and electricity drives pumps, compressors, and air-cooling systems. In this energy landscape, the Crude Distillation Unit (CDU) and Vacuum Distillation Unit (VDU) have consumption profiles fundamentally different from those of conversion units such as fluid catalytic crackers or hydrocrackers, because they rely on large-scale thermal separation rather than reaction-driven processing [22].

Direct fuel combustion in fired heaters represents the single largest source of energy demand in distillation units. The atmospheric heater in the CDU and the vacuum heater in the VDU consume substantial fuel to raise crude oil temperatures to the required flash-zone conditions, typically 350–380 °C for atmospheric distillation and 390–420 °C for vacuum distillation. According to data reported by the U.S. Department of Energy, fired heaters collectively account for approximately 64 % of total refinery fuel consumption [23]. In the CDU, this energy input provides both the sensible heat required to raise the crude oil to its boiling range and the latent heat needed for partial vaporization and effective fractionation [4]. A significant fraction of this thermal energy is ultimately lost through stack gases and air-cooled heat exchangers, underscoring the importance of waste heat recovery (WHR) strategies, as illustrated in Figure 2.

Steam systems constitute another major component of energy use in crude and vacuum distillation. In the CDU, stripping steam is injected at the column bottom and into side strippers to reduce the partial pressure of light hydrocarbons, thereby enhancing vaporization and improving separation efficiency. In the VDU, steam plays a dual role by supporting hydrocarbon stripping and driving ejector systems that establish and maintain the deep vacuum conditions required for low-temperature vaporization of heavy fractions. Overall, steam generation and utilization account for approximately 30 % of total refinery fuel consumption, reflecting both direct process requirements and inefficiencies associated with steam production and distribution [23]. Although thermal energy dominates the overall energy balance, electricity consumption in distillation units remains significant and is increasing in relative importance. Electrical power is required for crude charge pumps, desalter circulation, reflux pumping, vacuum system auxiliaries, and large banks of air-cooled heat exchanger fans. The electrical load has further intensified with the implementation of more stringent environmental regulations, including advanced emission control systems such as wet gas scrubbers and enhanced wastewater treatment units, which impose additional pumping and auxiliary power demands [24]. As a result, electricity use in CDU and VDU operations represents an increasingly relevant target for efficiency improvement and decarbonization.

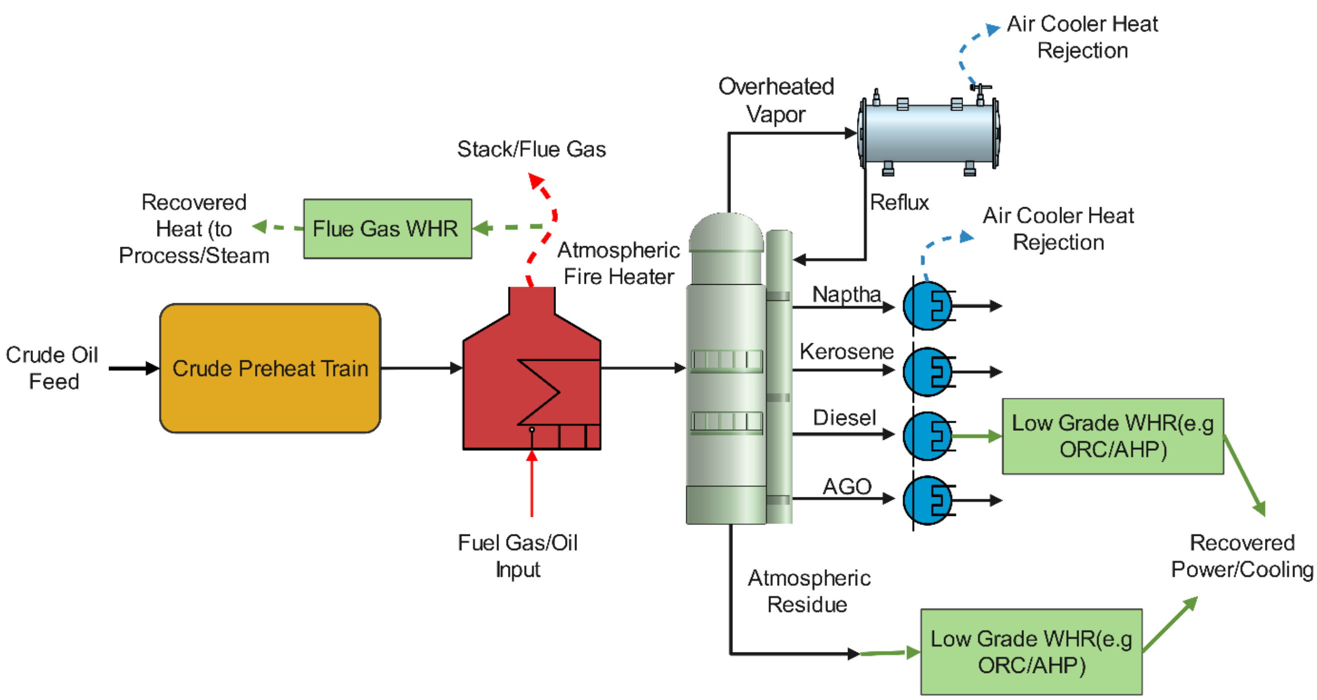

Figure 2. Energy Flow Diagram of a Typical CDU showing losses to air cooling and stack gases

Table 1. Typical energy consumption distribution in a refinery distillation complex.
Source: Synthesized from Ref. [4].

Energy Vector	Primary Consumers in CDU/VDU	Approximate Share of Unit Energy
Fuel Gas/Oil	Atmospheric Heater, Vacuum Heater	60–70%
Steam	Stripping Steam, Ejectors, Reboilers	20–30%
Electricity	Desalter, Feed Pumps, Reflux Pumps, Air Coolers	5–10%

2.2 CO_2 Emission Sources and Fuel-Related Drivers in Refinery Distillation

Refinery CO_2 emissions are conventionally classified into direct emissions (Scope 1) arising from on-site fuel combustion for process heat and steam generation, indirect emissions (Scope 2) associated with purchased electricity, and process-related emissions. In crude and vacuum distillation units, Scope 1 emissions overwhelmingly dominate the emissions profile due to the extensive use of fired heaters and steam systems required to achieve phase separation of complex hydrocarbon mixtures [25]. The specific carbon intensity of a distillation unit is strongly influenced by the fuels used in fired heaters and auxiliary steam boilers. Most refineries rely on a combination of internally generated refinery fuel gas (RFG) and natural gas, with some facilities, particularly older or regionally constrained installations, still utilizing residual fuel oil, petroleum coke, or coal. These fuels differ substantially in their carbon intensity and associated environmental impacts [26].

Solid and heavy liquid fuels exhibit the highest specific CO_2 emissions per unit of thermal energy supplied. Coal has the highest carbon intensity and, although many Western refineries have largely phased it out, it remains relevant in certain regions. Residual fuel oil also exhibits high carbon intensity and contributes not only to CO_2 emissions but also to elevated particulate matter and sulfur oxide releases. In contrast, natural gas has a lower direct CO_2 emission factor per unit of energy than coal, petroleum coke, or residual fuel oil and is therefore often considered a transitional fuel [26, 27]. Historically, switching from higher-carbon fuels to natural gas has been one of the more accessible measures for reducing combustion-related emissions. However, recent International Energy Agency data show that global CO_2 emissions associated with natural-gas use continue to rise [1]. This broader trend underscores that fuel switching alone is insufficient to deliver deep decarbonization of refinery distillation [14].

In addition to fuel selection, the nature of the crude slate exerts a decisive influence on the carbon footprint of distillation. Heavier and sour crudes require higher furnace outlet temperatures, increased stripping steam rates, and more energy-intensive downstream processing, thereby increasing the embedded emissions of the distillation step. Consequently, emissions from distillation units are not only a function of fuel choice but are intrinsically linked to process thermodynamics and separation inefficiencies, which are examined in the following section.

2.3 Thermodynamic Efficiency Gaps in Conventional Distillation

From a Second Law of Thermodynamics perspective, conventional distillation is inherently inefficient. The thermodynamic efficiency of typical industrial distillation columns is often estimated to be below 10–15% when compared to an ideal reversible separation process [12]. This fundamental inefficiency explains the high energy demand and, consequently, the large carbon footprint of crude and vacuum distillation units. The inefficiency of distillation arises primarily from irreversible entropy generation within the column and the manner in which thermal energy is supplied and rejected. One major source of exergy destruction is the entropy of mixing that occurs on trays or packing, where liquid and vapor streams of different compositions and temperatures are repeatedly contacted. This remixing effect, while essential for mass transfer, results in significant losses of useful work potential.

A second major contributor is thermal degradation. In conventional distillation systems, heat is supplied at the highest temperature level either in the furnace or reboiler and rejected at the lowest temperature level in the overhead condenser. As a result, high-quality thermal energy is degraded into low-grade waste heat that is ultimately dissipated to cooling water or ambient air without performing useful work. This temperature mismatch between heat addition and rejection represents a fundamental thermodynamic penalty of conventional column design.

Energy benchmarking should complement, rather than replace, thermodynamic analysis when evaluating refinery distillation performance. The Energy Intensity Index (EII) is widely used to compare refinery energy performance after accounting for differences in process complexity and operating configuration, and Solomon-based benchmarking provides a practical peer-comparison framework for identifying performance gaps. For CDU/VDU optimization, EII trends can serve as a plant-level performance indicator, while unit-level energy balances identify where fuel, steam, or electricity is consumed. Exergy analysis adds a second layer of decision support by distinguishing the quality of energy losses. A high-temperature furnace loss, for example, has greater exergy significance than an equivalent quantity of low-temperature cooling loss. Combining EII benchmarking with exergy analysis and Pinch Analysis therefore provides a stronger basis for prioritizing projects: benchmarking identifies the performance gap, exergy identifies the quality and location of thermodynamic losses, and Pinch Analysis identifies feasible heat-recovery opportunities.

Bridging this thermodynamic efficiency gap is the central challenge in distillation optimization and decarbonization. Technologies aimed at reducing exergy destruction such as intermediate reboilers and condensers, heat-integrated distillation columns, and advanced heat recovery schemes seek to bring practical distillation systems closer to the ideal reversible separation limit. These concepts form the basis for many of the decarbonization pathways discussed in subsequent sections.

3. A Distillation-Centered Framework for Refinery Decarbonization

Given the inherently high energy demand and thermodynamic inefficiencies of crude and vacuum distillation, effective decarbonization requires a structured and prioritized approach rather than the ad hoc deployment of individual technologies. Isolated retrofits frequently yield suboptimal or short-lived benefits if implemented without regard to process fundamentals and system-wide interactions. To address this challenge, this paper proposes a distillation-centered decarbonization framework that systematically prioritizes interventions by thermodynamic impact, cost-effectiveness, and ease of implementation. The framework is explicitly aligned with the dominant sources of emissions identified in Section 2 and is designed to maximize achievable CO_2 abatement while minimizing operational disruption and capital intensity. Rather than focusing solely on fuel substitution, the framework emphasizes demand-side reduction and internal heat utilization as prerequisite steps for deep decarbonization.

3.1 Energy Management Hierarchy for CDU/VDU Operations

The proposed framework follows a hierarchical energy management philosophy, progressing from low-cost, high-impact measures to more capital-intensive solutions. This sequencing is critical to maximizing return on investment and ensuring that higher-order decarbonization technologies are not oversized or misapplied.

The first and most fundamental step is the reduction of energy demand through operational excellence. This involves minimizing the energy required to meet product specifications by optimizing reflux ratios, avoiding excessive over-refluxing, reducing slop and off-spec production, and ensuring that column internals and heat exchangers operate at their intended efficiency. In practice, operators often maintain conservative operating margins to guarantee product quality, but these margins can create significant, unnecessary energy penalties if not rigorously monitored and optimized [11, 18]. Once energy demand has been minimized, the second step focuses on heat recovery through process integration. At this stage, waste heat from hot product and pump-around streams is systematically recovered and reused to preheat the crude feed. Pinch analysis and heat-exchanger-network optimization are central tools in this step, enabling the identification of economically and thermodynamically favorable heat-recovery opportunities within the CDU/VDU system [28, 29]. The third step addresses waste heat that cannot be reused directly because of temperature mismatches or process constraints. Industrial heat pumps can upgrade such low- to medium-grade heat, or Organic Rankine Cycle (ORC) systems can convert it to electricity [30-32].

The final step in the hierarchy involves decarbonizing the remaining energy supply. After demand reduction and heat recovery opportunities have been exhausted, residual energy requirements can be met through lower-carbon energy sources. These include switching from high-carbon fuels to natural gas or hydrogen and, where technically feasible, electrifying heaters and auxiliary systems using low-carbon or renewable electricity. Positioning fuel switching and electrification as the final step avoids masking underlying inefficiencies and ensures that low-carbon energy is used as effectively as possible [33].

3.2 Key Pillars of the Distillation-Centered Decarbonization Framework

The practical implementation of the proposed framework rests on three interdependent pillars: operational excellence, thermal integration, and hardware modernization. Operational excellence forms the foundation of distillation decarbonization and relies on rigorous monitoring, advanced control, and digital decision-support tools to ensure that units operate close to their design efficiency [34, 35]. Particular emphasis is placed on minimizing over-refluxing, a common operational practice adopted to safeguard product specifications, as well as optimizing stripping-steam rates in both atmospheric and vacuum columns. Even modest improvements in these parameters can reduce furnace and reboiler duties [34, 35]. Thermal integration represents the most impactful design and retrofit opportunity within crude distillation units. Maximizing heat recovery from hot product streams such as atmospheric residue, diesel, and pump-around circuits to preheat the incoming crude feed has long been recognized as a cornerstone of energy-efficient CDU design. Well-integrated heat exchanger networks not only reduce fired-heater duty but also improve overall process stability and controllability. Hardware modernization complements operational and integration measures by addressing inherent equipment inefficiencies. Examples include replacing steam-ejector systems with liquid-ring or hybrid vacuum pumps in VDUs, upgrading fired heaters with enhanced heat-transfer surfaces and advanced combustion control, and adopting intensified separation technologies such as dividing-wall columns for suitable separation tasks [36-38].

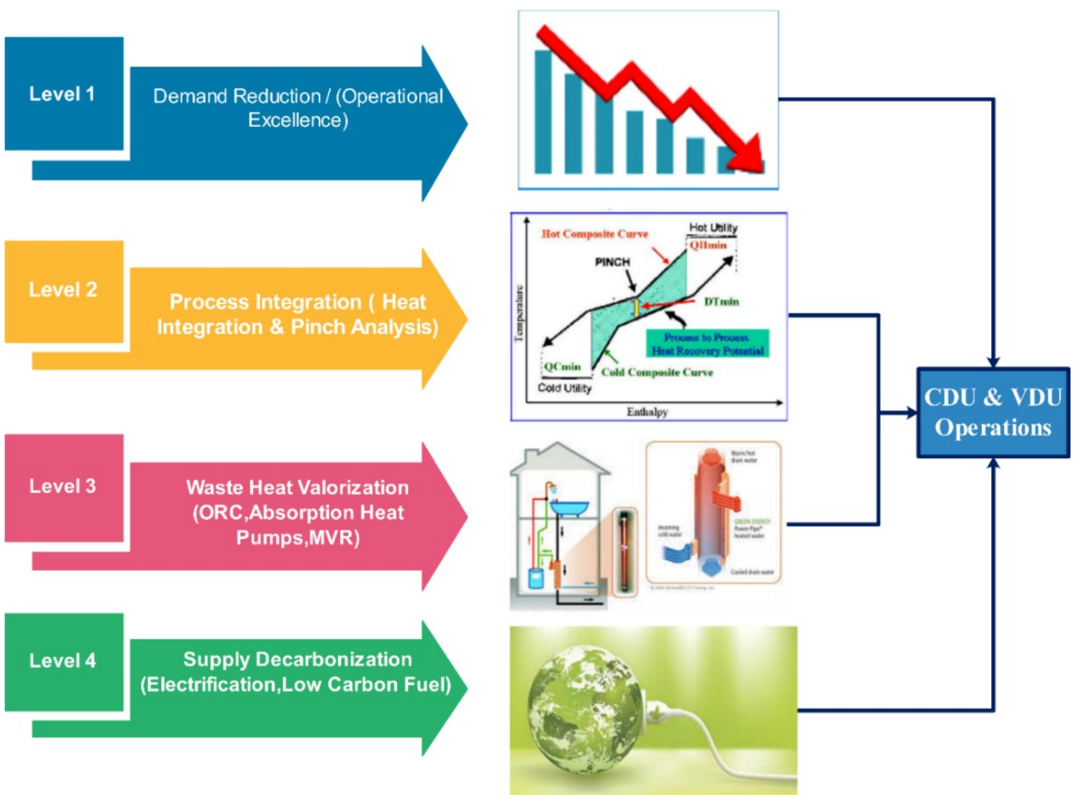

Figure 3. Energy Flow Diagram of a Typical CDU showing losses to air cooling and stack gases

The practical implementation of refinery decarbonization technologies is governed not only by technological maturity but also by the constraints of existing brownfield infrastructure. Operational optimization, fouling monitoring, combustion optimization, and advanced process control generally require limited physical modification and can often be implemented with relatively low disruption. In contrast, major heat-exchanger-network modifications, waste-heat recovery systems, Mechanical Vapor Recompression, and process-heater electrification may require significant plot space, electrical or utility infrastructure, equipment modification, and planned turnaround periods. Existing heat-exchanger configurations, hydraulic and pressure-drop limitations, equipment age and condition, and available temperature driving forces can restrict otherwise attractive heat-integration opportunities. In addition, refinery configuration and crude flexibility must be maintained because modifications optimized for a specific crude slate may reduce operational flexibility when feed characteristics change. Reliability, process safety, maintainability, and the refinery's maintenance philosophy must also be incorporated into technology selection, since additional equipment and control complexity may introduce new maintenance and availability requirements. Consequently, the technologies discussed in this review should not be regarded as universally deployable; their practical suitability must be established through site-specific engineering assessment considering retrofit requirements, operational continuity, safety, reliability, and maintenance constraints.

Although the CDU and VDU are the primary focus of this review, their optimization cannot be evaluated independently from the refinery-wide energy network. Reducing furnace duty decreases refinery fuel-gas demand and may alter the balance between refinery fuel gas, imported natural gas, steam generation, and cogeneration. Similarly, changes in stripping-steam demand affect the high-, medium-, and low-pressure steam headers and can influence utility-boiler loading and power generation. Hydrogen recovery from refinery fuel gas can simultaneously reduce combustion of a high-value fuel-gas component and offset part of the hydrogen requirement of hydrotreating units. At the process level, improved CDU fractionation can reduce the severity required in downstream FCC, hydrocracking and hydrotreating operations, whereas aggressive heat recovery that restricts flexibility may create hydraulic or temperature constraints elsewhere in the refinery. Accordingly, the proposed hierarchy should be implemented through refinery-wide energy optimization rather than as a sequence of isolated CDU/VDU projects.

3.3 Waste Heat Recovery and Valorization Strategies in Distillation Units

The technologies reviewed in this work should not be interpreted as mutually exclusive alternatives. Their relative value depends on the temperature level and availability of waste heat, the existing heat-exchanger network, column configuration, electricity and fuel prices, carbon intensity of purchased electricity, refinery complexity and the extent of brownfield constraints. Direct heat recovery and operational optimization generally have the lowest implementation risk because they reduce utility demand without fundamentally changing the separation mechanism. Waste-heat-to-power systems such as ORC become attractive when recoverable heat cannot be economically reused within the process, whereas absorption heat pumps are more suitable when low-grade heat can be upgraded to a useful steam or heating level. MVR can provide large energy reductions where the column vapor conditions and compressor pressure ratio are favorable, but its applicability to crude distillation is more constrained than for narrow-boiling separations. Electrification offers deeper emissions reductions only when low-carbon electricity is available, and the refinery can accommodate the required electrical capacity. Digital technologies are best regarded as enabling layers that sustain the performance of physical retrofits rather than substitutes for thermodynamic improvements.

3.3.1 Direct Waste Heat Recovery from Distillation Furnaces

Crude and vacuum distillation units represent the thermal core of a refinery and are among the largest consumers of fuel due to the high temperatures required to achieve fractionation. A substantial fraction of this thermal energy is rejected with flue gases from atmospheric and vacuum heaters, which typically exit the stacks at temperatures ranging from 350 °C to 490 °C. These exhaust streams constitute one of the most attractive and underutilized sources of recoverable waste heat in refinery operations [30]. A proven and widely deployed strategy for capturing this energy involves the installation of waste heat boilers (WHBs) downstream of CDU and VDU heater stacks. WHBs recover sensible heat from flue gases and convert it into useful steam, most commonly low-pressure (LP) steam that can be integrated into the refinery steam header. Industrial implementations show that waste heat boilers installed downstream of refinery heater stacks can recover substantial sensible heat from flue gases and generate useful low-pressure steam for integration into the refinery steam network, depending on heater duty, excess air levels, and exhaust gas temperature [9, 23, 30].

The successful integration of WHBs requires careful consideration of flue-gas-side pressure drop, fouling propensity, and combustion stability. Excessive pressure drop can adversely affect natural or forced draft operation, necessitating close coordination with stack design, induced-draft fans, and combustion air control systems. To ensure reliable long-term operation, WHBs are typically equipped with soot-blowing or online cleaning systems to mitigate fouling from particulates and unburned hydrocarbons present in heater exhaust gases. Integration with furnace firing control systems is also essential to maintain safe operating margins and stable combustion [11]. The generation of LP steam from recovered waste heat directly displaces steam produced in utility boilers, thereby reducing refinery fuel consumption and operating costs. Reported industrial case studies indicate daily fuel savings on the order of several thousand MMBtu, translating into significant operating expenditure reductions. From a system-level perspective, this displacement can improve key energy performance indicators, including the Energy Intensity Index (EII), by reducing fired-heater and utility-boiler fuel demand in well-integrated refinery energy systems [9, 23, 30].

Beyond energy efficiency improvements, WHB-based heat recovery delivers meaningful decarbonization benefits. Reduced firing in utility boilers translates directly into lower Scope 1 CO_2 emissions, with annual reductions on the order of tens of kilotons reported for large-scale refinery applications. Importantly, these benefits are achieved without altering product slates or unit throughout making WHBs a technically mature decarbonization option with potentially favorable economics where suitable waste-heat sources and steam-system integration are available for CDU and VDU systems.

3.3.2 Waste Heat-to-Power Conversion Using Organic Rankine Cycles

While direct steam generation represents the most efficient use of high-temperature waste heat, significant quantities of low- and medium-grade heat remain unavailable for direct reuse in many distillation units. The Organic Rankine Cycle (ORC) has emerged as a mature and commercially proven technology for converting such low-grade waste heat into electricity [39].

In a CDU context, suitable heat sources include hot overhead vapors, kerosene and diesel pump around streams, and sections of the crude preheat train where heat is ultimately rejected to air coolers. Unlike conventional steam Rankine cycles, ORC systems employ organic working fluids with low boiling points, such as pentane, butane, or refrigerants including R245fa. The working fluid is vaporized in an evaporator using waste heat, expanded through a turbine to generate electricity, and subsequently condensed and recycled [40]. The selection of working fluid is a critical design variable. Recent studies demonstrate that hydrocarbon mixtures, such as isobutane–butane blends with tailored composition ratios, can better match the temperature glide of distillation heat sources, improving thermal coupling and maximizing power output. ORC systems are particularly well-suited for heat sources in the range of 80–150 °C, which are abundant in CDU overhead systems and pump-around circuits [41]. From an economic perspective, the viability of ORC installations is strongly dependent on heat source temperature and local electricity prices. For heat sources above approximately 70 °C, reported payback periods range from 2 to 4 years under favorable market conditions [41]. The levelized cost of electricity generated by ORC systems is increasingly competitive with grid electricity, particularly when accounting for avoided cooling-duty costs, such as reduced power consumption by air cooler fans.

3.3.3 Heat Upgrading via Absorption Heat Pumps

Unlike ORC systems, which convert waste heat into electricity, absorption heat pumps (AHPs) upgrade low-temperature waste heat to more useful temperature levels. AHPs operate through thermochemical cycles, most commonly employing lithium bromide–water ($LiBr/H_2O$) as the working pair [12]. In these systems, waste heat drives the separation of the refrigerant (water) from the absorbent (LiBr), and the subsequent recombination releases heat at an elevated temperature. In refinery distillation units, AHPs can recover waste heat from CDU overhead systems or product streams in the 100–120 °C range to generate low-pressure steam or preheat boiler feed water [42]. Case studies in industrial process heating have shown that absorption heat pump integration can substantially reduce steam consumption by upgrading low-temperature waste heat into useful process heat [43, 44]. AHPs act as heat multipliers and typically exhibit coefficients of performance significantly greater than unity. Large-scale industrial deployments, such as those reported in the Daxie petrochemical complex, have recovered megawatt-scale waste heat to produce process steam, achieving annual energy savings equivalent to several thousand tons of coal.

3.3.4 Mechanical Vapor Recompression and Distillation Electrification

Mechanical Vapor Recompression (MVR) represents a transformative heat-integration and electrification strategy that fundamentally alters the energy input mechanism of distillation. MVR operates on a heat-pump principle, in which overhead vapor from a distillation column is mechanically compressed, raising its pressure and saturation temperature. The compressed vapor is then routed to the reboiler, where it condenses and transfers its latent heat to vaporize the bottoms stream [45-47]. This configuration can eliminate a substantial fraction of external steam-reboiler and overhead-condenser duties by recycling thermal energy internally, with electricity supplied to the compressor. The achievable energy reduction is strongly application-specific and should not be extrapolated directly to conventional CDU/VDU operation.

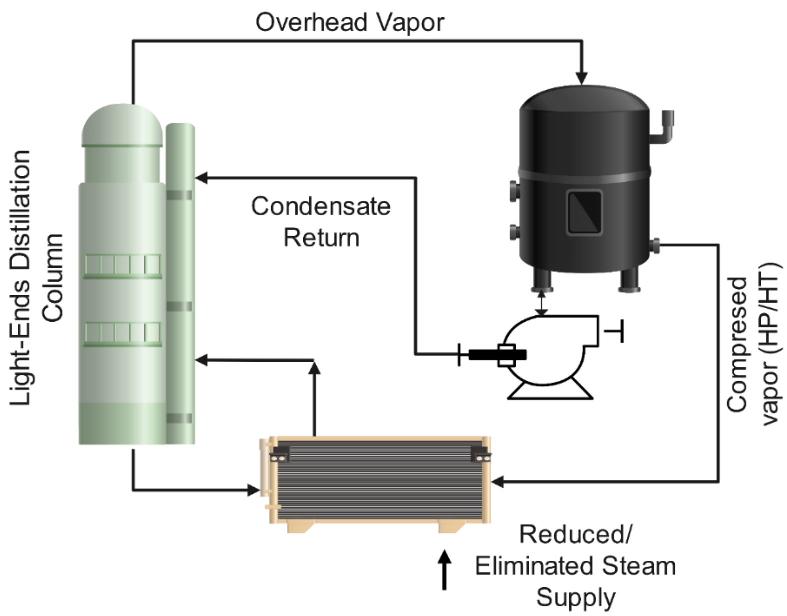

Figure 4. Mechanical Vapor Recompression (MVR) integrated into a light-ends splitter

Table 2. Comparison of waste heat recovery technologies in distillation.
Source: Derived from Ref. [41].

Technology	Heat Source Temp (°C)	Output Vector	TRL	CAPEX Intensity	Payback (Years)
ORC (Organic Rankine Cycle)	80–200	Electricity	9	High	2–4
Absorption Heat Pump (AHP)	90–150	LP Steam / Heating	9	Medium	3–5
MVR (Light Ends)	Overhead Vapor	Reboiler Duty	9	High	3–6
MVR (Crude/Atmospheric)	Overhead/Side Vapor	Reboiler Duty	5–7	High	>5
Open Loop Heat Pump (CompriVAP)	Waste Steam	Process Steam	7–8	Medium	2–5

3.4 Heat Integration and Crude Preheat Train Optimization

The Crude Preheat Train (CPHT) represents the recuperative core of the crude distillation unit (CDU) and plays a decisive role in determining overall furnace fuel consumption. It comprises an extensive network of shell-and-tube heat exchangers that recover sensible heat from hot product streams, including atmospheric residue, gas oil, kerosene, and pump-around streams, and transfer it to the incoming crude oil before it enters the atmospheric furnace [22, 28, 29]. Because furnace duty is directly dependent on the coil inlet temperature (CIT), maximizing heat recovery within the CPHT is a central strategy for reducing refinery fuel demand and associated emissions.

3.4.1 Pinch Analysis and Heat Exchanger Network Retrofit

Pinch analysis is a thermodynamic methodology for identifying minimum process energy requirements and for designing or retrofitting heat exchanger networks (HENs) to maximize internal heat recovery [28, 29]. The approach is based on hot and cold composite curves representing process heating and cooling demands. The point of minimum temperature difference between these curves, known as the pinch point, identifies the principal thermodynamic bottleneck and provides design rules for minimizing external utility consumption.

Application of pinch analysis to refinery crude distillation can reveal substantial heat-recovery potential. In one CDU retrofit study, approximately 45% of the existing heating and cooling utility load was identified as potentially recoverable under the maximum-recovery scenario [28]. By optimizing minimum temperature approaches, rearranging exchanger duties, and improving heat recovery from high-temperature streams such as atmospheric and vacuum residue, refiners can increase furnace coil inlet temperature and reduce firing rates [28, 29]. In a separate multicolumn distillation study, combining driving-force-based sequencing with thermal pinch analysis produced an overall energy saving of 48% relative to the conventional sequence [6].

3.4.2 Fouling Mitigation: The Silent Energy Thief

The fouling response of a crude preheat train is strongly dependent on crude quality and crude-blending practice. Light, low-viscosity crudes generally impose lower hydraulic resistance and may provide greater heat-recovery flexibility, whereas heavy or highly acidic crudes can increase furnace duty, stripping-steam demand, and deposition risk. Crude compatibility is particularly important because blending chemically incompatible crudes can destabilize asphaltenes and accelerate deposit formation [48, 49]. Calcium-containing species, including calcium salts, can also contribute to deposits, while inadequate desalter performance can increase the transport of salts and water into downstream exchangers [49]. Corrosion products may further interact with organic deposits, making fouling a coupled heat-transfer, corrosion, and hydraulic problem rather than a simple loss of U-value. For this reason, fouling mitigation should combine crude compatibility assessment, desalter optimization, deposit characterization, online monitoring of heat-transfer coefficient and pressure drop, and predictive cleaning based on the economic trade-off between additional furnace firing and exchanger-cleaning downtime [48, 49].

As crude oil is heated through the preheat train, asphaltene destabilization, chemical reactions, inorganic deposition, and other mechanisms can form insulating deposits on exchanger surfaces, degrading the overall heat-transfer coefficient while increasing hydraulic pressure drop [48-50]. This degradation forces the atmospheric furnace to compensate by increasing fuel firing to maintain target outlet temperatures, thereby increasing fuel consumption, CO_2 emissions, and operating costs. Crude-preheat-train fouling is therefore a major source of refinery energy inefficiency and maintenance burden [48, 49].

To address this challenge, researchers have developed both hardware- and software-based mitigation strategies. Researchers have investigated low-fouling and self-cleaning exchanger concepts to sustain heat-transfer performance and extend operating periods between cleaning interventions [50]. Chemical antifoulant injection remains a widely used mitigation strategy, particularly near the hot end of the preheat train where deposition tendencies are greatest. More recently, monitoring models and digital twins have been used to quantify fouling progression and support economically optimized exchanger-cleaning schedules [51, 52].

3.5 Fuel Gas and Off-Gas Management for Emission Reduction

Refinery fuel gas, commonly referred to as still gas, is generated as a byproduct of distillation, cracking, and reforming operations and constitutes a critical energy stream within the refinery energy system. Efficient management of this internally generated fuel is important for both energy efficiency and emissions control [53].

3.5.1 Valorization of Still Gas

Refinery fuel gas typically contains a variable mixture of hydrogen, methane, ethane, propane, and other light hydrocarbons. Optimizing the balance between direct combustion and recovery of valuable components is therefore an important operational and economic consideration [53]. A key opportunity lies in hydrogen recovery, because hydrogen entering the fuel-gas header can instead be recovered for process use where technically and economically justified. Pressure swing adsorption or membrane separation can reduce the amount of valuable hydrogen combusted as fuel and help stabilize the remaining fuel-gas composition [53].

Fuel-gas composition variability directly affects heating value and the Wobbe Index, potentially contributing to furnace instability and inefficient combustion if not properly controlled. Fuel-gas management and blending control can therefore support more stable combustion and lower excess-air operation, improving thermal efficiency and reducing stack losses [53].

3.5.2 Flare Minimization

Flaring represents a total loss of recoverable energy and is a major source of CO_2, NO_x, and visible emissions. While flaring is fundamentally a safety mechanism, routine and continuous flaring is increasingly targeted under refinery decarbonization and zero-emission initiatives. Flare gas recovery units (FGRUs) compress low-pressure flare streams and recycle them into the fuel gas system, converting waste energy into useful fuel while reducing emissions and improving site energy efficiency.

3.6 Fired Heater Efficiency and Combustion Optimization

Atmospheric and vacuum fired heaters are among the largest single energy consumers in a refinery. Their thermal efficiency depends on combustion completeness, excess-air levels, and the extent of flue-gas heat recovery [4, 9, 36].

3.6.1 Combustion Air Preheating

Preheating combustion air using hot flue gases via air preheaters (APHs) is a well-established strategy for reducing fuel consumption, yet it remains under-optimized in many installations. By recycling sensible heat from stack gases back into the combustion process, the fuel required to reach the desired flame temperature is reduced. A widely accepted rule of thumb suggests that every 20 °C reduction in stack temperature corresponds to approximately a 1% increase in heater efficiency. Heater efficiencies of approximately 90–92% have been reported under optimized operating conditions. The primary constraint to further heat recovery is the acid dew point of flue gases, below which sulfur oxides condense as sulfuric acid and cause corrosion. Advances in corrosion-resistant materials, such as glass-lined or polymer-coated tubes, combined with improved control strategies, now allow operation closer to these limits with reduced risk [30, 36].

3.6.2 Excess Air Control and Oxygen Trim

Maintaining the correct fuel-to-air ratio is critical for efficient combustion. Excessive air unnecessarily heats nitrogen, which exits through the stack, carrying valuable energy. Automatic oxygen-trim systems adjust combustion air in real time to maintain appropriate excess-oxygen levels. In a published case study of an atmospheric-distillation furnace at an Iranian refinery, combined air preheating and excess-air reduction increased modeled furnace efficiency from 63% to 89%, with a reported payback period of approximately 0.9 years [54].

3.6.3 Electrification of Process Heaters

Electrifying process heaters offers a transformative pathway for deep decarbonization. While electric heating technologies are mature for many applications, large-scale high-temperature electrification of distillation remains constrained by electrical-infrastructure requirements, equipment design, and power carbon intensity and availability. Hybrid configurations can provide a transitional pathway where low-carbon electricity is available while maintaining operational flexibility [55, 56].

3.7 Steam System Optimization in Distillation Operations

Steam is a critical utility in distillation operations, serving functions such as stripping, reboiling, and vacuum generation. Consequently, optimization of steam generation, distribution, recovery, and process use can have a direct impact on overall refinery energy efficiency [9, 23].

3.7.1 Reboiler Optimization and Condensate Recovery

Inefficient condensate removal in steam reboilers reduces effective heat-transfer area and can induce operational problems such as water hammer. Proper condensate management and steam-control strategies improve both thermal performance and reliability. In addition, excessive reflux ratios are frequently used to maintain conservative product-quality margins, increasing reboiler steam consumption. Advanced process control can support operation closer to specification constraints and thereby reduce unnecessary reflux and reboiler duty [34, 35].

3.7.2 Vacuum System Modernization: Ejectors versus Vacuum Pumps

Vacuum distillation requires low absolute pressure to vaporize heavy residues while limiting thermal cracking [57]. Multi-stage steam ejectors are widely used because of their simplicity and robustness, but they consume motive steam. Liquid-ring vacuum pumps and hybrid vacuum systems provide alternative configurations for suitable services. In a modeled mini-refinery vacuum unit, replacement of the existing steam-ejector-based vacuum system with a liquid-ring-vacuum-pump-based system was estimated to reduce vacuum-system operating costs by 78% [37].

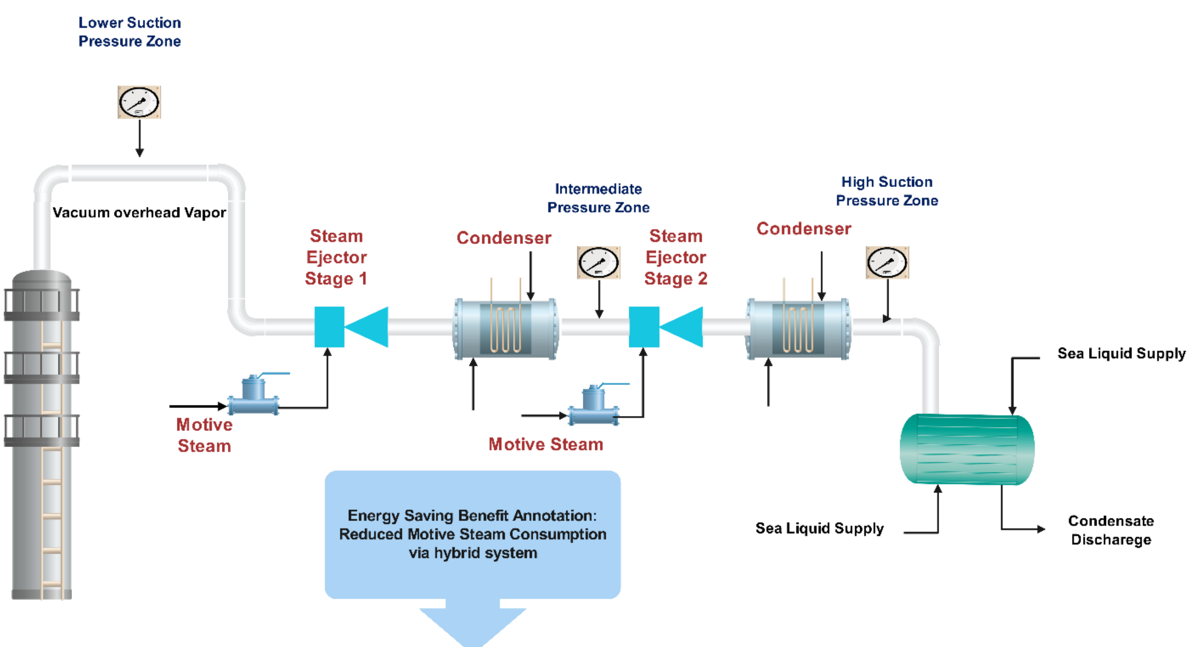

Figure 5. Hybrid Ejector–Liquid Ring Vacuum Pump system for VDU

4. Digitalization and Advanced Process Control for Decarbonization

The contemporary refinery is increasingly evolving into a digitally enabled asset, where advanced analytics, automation, and artificial intelligence function as the "software layer" that optimizes the performance of energy-intensive "hardware" systems such as distillation columns, heat exchanger networks, fired heaters, and steam systems. Digitalization enables real-time monitoring, optimization, and decision-making, thereby transforming static design efficiencies into sustained operational performance. In the context of refinery decarbonization, digital tools are indispensable for minimizing energy consumption, reducing emissions variability, and unlocking latent efficiency gains that cannot be achieved through equipment modifications alone.

4.1 Advanced Process Control (APC)

Advanced Process Control, most commonly implemented using Model Predictive Control (MPC), is a mature digital technology in refinery operations. APC predicts process behavior using dynamic models and continuously optimizes manipulated variables such as flow rates, temperatures, pressures, and reflux ratios subject to operating and safety constraints [35, 58-60]. In crude distillation, APC can support operation closer to product-quality and equipment constraints while reducing process variability and avoiding unnecessarily conservative operating margins [35].

Recent APC frameworks increasingly incorporate soft sensors and machine-learning-based inferential models. These virtual analyzers estimate difficult-to-measure product properties from readily available process measurements, reducing dependence on delayed laboratory analyses and enabling tighter real-time control [61, 62]. When models are appropriately validated and maintained, this can reduce product giveaway, excessive safety margins, and unnecessary energy use.

4.2 Digital Twins for Energy Optimization and Predictive Maintenance

A digital twin is a virtual representation of a physical asset or process that is updated using operational data. Digital twins may be physics-based, data-driven, or hybrid in nature and can support monitoring, simulation, optimization, and predictive maintenance [52, 63]. In refinery distillation, such approaches are particularly relevant to energy-intensive subsystems such as crude preheat trains and heat-exchanger networks. By modeling exchanger fouling and heat-transfer degradation, a digital twin can support condition-based cleaning decisions and help sustain heat-recovery performance over the operating cycle [51, 52].

Beyond energy optimization, digital twins can support early identification of abnormal equipment or process behavior and enable proactive maintenance and operational adjustments [52, 63]. Their economic value is application-specific. In one documented North American refinery case, an integrated digital twin of the heat-exchanger network monitored fouling and optimized cleaning decisions, with estimated savings exceeding USD 2 million per year [51]. Such examples demonstrate the potential of digital twins to support both energy-efficiency and asset-management objectives when high-quality plant data and appropriate models are available [51, 52, 63].

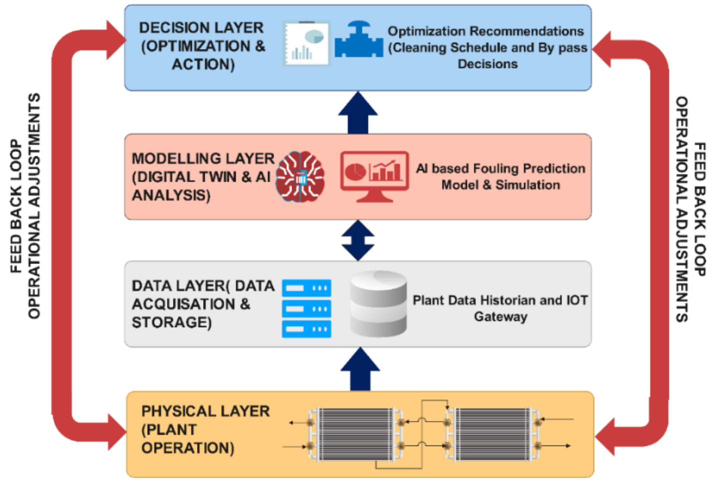

Figure 6. Digital Twin Architecture for Crude Preheat Train Fouling Management

4.3 Role of Digitalization in Integrated Decarbonization Strategies

When deployed in isolation, individual digital solutions deliver incremental efficiency gains. Their broader decarbonization value increases when APC systems, digital twins, energy-management systems, and plantwide optimization platforms are integrated into a unified digital architecture. Such integration can enable closed-loop energy optimization and site-wide tracking of performance and emissions indicators [64-67]. In this framework, digitalization acts as an enabling layer for physical retrofit measures such as heat integration, fired-heater upgrades, and steam-system optimization rather than as a substitute for thermodynamic improvements [64-67].

Advanced digitalization tools are increasingly deployed in refining and petrochemical operations to enhance energy efficiency, operational reliability, and economic performance, as summarized in Table 3. Advanced Process Control (APC), particularly Model Predictive Control (MPC), is widely used for multivariable constraint handling and optimization in process operations [35, 59, 60]. By dynamically adjusting manipulated variables while respecting process constraints, APC can enable operation closer to optimal limits and reduce unnecessary energy use.

Soft sensors (inferential models) provide real-time estimates of difficult-to-measure properties, such as product composition or quality indicators, from readily available process measurements [61, 62]. These models can reduce reliance on laboratory analyses and support tighter process control, reduced product giveaway, and lower recycle or reprocessing requirements. Digital twins extend process monitoring and optimization by combining models with plant data. In refining applications, they can support fouling monitoring, simulation, and heat-exchanger-network performance optimization; documented refinery cases demonstrate measurable operating-cost benefits [51, 52].

Artificial intelligence (AI) and machine learning (ML) techniques are increasingly applied for anomaly detection, fault diagnosis, predictive maintenance, and process optimization in industrial systems [68-70]. These data-driven approaches can identify patterns and deviations that are difficult to capture using conventional monitoring alone. Their deployment nevertheless depends on data quality, model maintenance, interpretability, integration with existing control systems, and cybersecurity considerations [60, 69, 71].

Table 3. Digital and AI-Based Optimization Tools in Refining

Tool	Application	Energy/Cost Benefit	References
APC (Model Predictive Control)	Reflux optimization, constraint pushing	3–10% energy savings (application-dependent)	[35, 59, 60]
Soft Sensors (Inferential)	Real-time property prediction (RON, Flash)	Reduced product giveaway and reprocessing	[61, 62]
Digital Twin	Fouling monitoring, rigorous simulation	Documented refinery savings > USD 2 million/year	[51, 52]
AI/Machine Learning	Anomaly detection, predictive maintenance	Avoided unplanned shutdowns	[68-70]

5. Industrial Case Studies and Lessons Learned

Although modeling and theoretical assessments consistently indicate a substantial potential for decarbonization within refining and petrochemical systems, the most compelling evidence of feasibility, techno-economic viability, and long-term sustainability is derived from real-world industrial deployments. Unlike simulation-based studies, which are often constrained by idealized assumptions, industrial case studies incorporate operational variability, equipment limitations, and economic constraints, thereby providing a more accurate representation of achievable performance improvements at scale. In recent years, major refining companies have increasingly adopted integrated approaches that combine advanced energy management systems, process digitalization, heat integration strategies, and low-carbon technologies to reduce energy intensity and greenhouse gas emissions systematically [18]. These implementations demonstrate that meaningful decarbonization can be achieved not through isolated technologies, but through coordinated system-level optimization across the entire refinery value chain.

Energy management systems enable continuous monitoring and benchmarking of utility consumption, allowing operators to identify inefficiencies and prioritize improvement measures. When combined with digitalization tools such as advanced process control, soft sensors, and digital twins, they can improve operational visibility and decision-making. In parallel, heat-integration techniques, including pinch analysis and waste-heat recovery, are widely used to reduce external utility demand by maximizing internal energy reuse [28-30]. These strategies are particularly relevant to distillation and fired-heater operations, which are among the most energy-intensive parts of a refinery.

Collectively, these industrial implementations provide strong empirical evidence that decarbonization in refining is not only technically feasible but also economically attractive when approached through integrated system optimization. The following case studies highlight how leading refining companies have successfully deployed these combined strategies, achieving substantial reductions in both energy consumption and carbon emissions while maintaining operational reliability and economic competitiveness.

5.1 Sinopec: Enterprise-Wide Energy Management through SMES

Sinopec Zhenhai Refining & Chemical Company (ZRCC) implemented an energy-management framework that integrated the Sinopec Management of Energy System (SMES) with an ISO 50001-based energy-management system. The implementation included an energy-management information system and systematic monitoring and management of energy performance. The case illustrates how structured energy-management practices and digital information systems can be combined to support continuous energy-efficiency improvement in a large refining and chemical complex [72].

5.2 ExxonMobil: Global Energy Management System (GEMS)

ExxonMobil has adopted a fleet-wide approach to energy efficiency through its Global Energy Management System (GEMS). The system benchmarks performance, identifies opportunities, and transfers energy-management practices across facilities. ExxonMobil reported that the GEMS approach identified energy-efficiency improvement opportunities of approximately 15–20% relative to early-2000s baselines. The associated program also reported approximately USD 1.6 billion in energy-efficiency investments since 2006 and cumulative greenhouse-gas reductions exceeding 12 million tonnes of CO_2 equivalent, a scale described as comparable to removing about 2.5 million passenger vehicles from the road [73].

5.3 Shell Pernis: The Refinery as an Integrated Energy Hub

Shell's Pernis refinery in Rotterdam is being transformed toward an integrated energy and chemicals park, with decarbonization measures that include energy efficiency, low-carbon products, green hydrogen, and carbon capture and storage [74, 75]. The site also supplies residual process heat to Rotterdam's district-heating network; the Pernis residual-heat initiative has been reported to serve approximately 16,000 households [76]. Shell's broader Pernis decarbonization strategy includes green-hydrogen production and increased carbon capture through the Porthos project [74]. Together, these initiatives illustrate how a refinery can interact with surrounding energy infrastructure while reducing both on-site and system-level emissions [74-76].

5.4 TotalEnergies: Green Hydrogen Integration for Refining

TotalEnergies is pursuing low-carbon and renewable hydrogen as a route to decarbonize hydrogen consumption at its European refineries. The company has announced long-term green-hydrogen supply arrangements with Air Products and projects involving RWE, including supply for the Leuna refinery [77]. Although hydrogen substitution does not directly reduce the thermal duty of crude and vacuum distillation units, it can reduce the carbon intensity of downstream hydrotreating and upgrading operations that are closely coupled to distillation. Green-hydrogen integration is therefore a complementary refinery-decarbonization pathway [78, 79].

6. Future Perspectives and Research Needs

Future research should move from technology-specific performance claims toward refinery-wide, multi-objective optimization. A useful framework would simultaneously minimize energy consumption, CO_2 emissions, and operating cost while constraining product quality, crude flexibility, reliability, and process safety. Such models should couple CDU/VDU heat-exchanger networks with steam systems, refinery fuel gas, hydrogen networks, cogeneration and downstream conversion units. Scenario analysis should also account for electricity-carbon intensity, fuel and carbon prices, renewable intermittency and changing crude slates. This system perspective is particularly important when comparing electrification and MVR with conventional heat recovery because the environmental benefit of electrification depends on electricity carbon intensity and availability.

While optimizing existing assets offers immediate, cost-effective emissions reductions, achieving deep decarbonization targets will ultimately require disruptive technologies that fundamentally alter separation mechanisms and energy flows within refineries. Several emerging concepts show promise but remain at varying stages of technological readiness.

6.1 Heat-Integrated Distillation Columns (HIDiC)

Heat-Integrated Distillation Columns (HIDiC) improve thermodynamic efficiency by transferring heat internally between the rectifying and stripping sections, often using vapor compression to create the required temperature driving force [47]. Pilot-scale work on multicomponent petroleum distillation has demonstrated more than 50% lower energy consumption than the corresponding conventional-distillation simulation under the reported operating conditions [80]. Despite this potential, application to large crude-oil fractionation services remains challenging because of scale, mechanical complexity, controllability, and fouling concerns [47, 80].

6.2 Membrane-Based Crude Oil Fractionation and Hybrid Separation Systems

Membrane-based separations offer the possibility of reducing the latent-heat demand associated with conventional thermal fractionation. Recent polyimine membranes incorporating shape-persistent units such as triptycene have demonstrated rapid and selective transport of multicomponent and industrially relevant hydrocarbon mixtures together with improved resistance to swelling and plasticization [81]. More recent work has demonstrated direct crude-oil pre-fractionation using mesoporous polyacrylonitrile membranes. Process simulations in that study indicated potential reductions of 31.6% in energy use, 20.7% in cooling-water demand, and 37.6% in CO_2 emissions relative to conventional atmospheric distillation [82]. These advances support the broader concept of membrane-based pre-fractionation integrated with conventional distillation, although membrane durability, fouling, stage-cut performance, and scale-up remain key implementation challenges [81-83].

6.3 Dividing Wall Columns (DWC)

Dividing-wall-column (DWC) technology integrates multiple separation sections within a single shell and reduces remixing of intermediate streams. Conventional DWCs can provide energy and investment-cost reductions of around 30% relative to conventional multicolumn sequences for suitable separations, while more complex multiple-DWC configurations may offer still larger savings [38]. DWCs are well established in chemical and petrochemical applications, and reported applications include naphtha-processing services [84, 85]. Their extension to broad-boiling crude-oil fractionation remains more challenging because of feed complexity, operating flexibility, and control requirements [38, 84].

7. Conclusions

Decarbonization of petroleum refineries represents a complex, multi-dimensional challenge, with crude and vacuum distillation units occupying a central role due to their dominant energy consumption. As demonstrated in this review, no single technology offers a universal solution. Instead, meaningful emissions reductions require a layered and integrated strategy spanning operational optimization, equipment retrofits, digitalization, and long-term process transformation. In the short term, refiners can achieve immediate and cost-effective immediate efficiency and emissions-reduction gains, with their economic attractiveness depending on site-specific conditions gains by maximizing heat integration through pinch analysis, mitigating fouling in crude preheat trains, and deploying advanced process control and AI-based optimization tools. Over the medium term, modernization of vacuum systems and deployment of waste heat recovery technologies offer additional reductions. In the long term, electrified heating, advanced separation technologies, and green hydrogen integration will be essential as power grids decarbonize and technologies mature. The refinery of the future will not merely process crude oil; it will function as a highly integrated, digitally optimized, low-carbon energy hub. The technologies required for this transition already exist. The defining challenge lies not in innovation alone, but in execution, integration, and sustained operational discipline.

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No generative AI or AI-assisted tools were used to create, modify, or enhance any figures or graphical materials in this work.

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