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An overview and perspective

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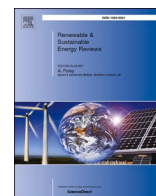
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Electrification of distillation for decarbonization: An overview and perspective

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ABSTRACT

Distillation remains the leading and most frequently adopted technique for the separation and purification of condensable mixtures in numerous industries. However, the inherently poor thermal efficiency of distillation requires a large amount of thermal energy, making it the chief factor in total process energy usage and a significant emitter of carbon dioxide due to the combustion of fossil fuels. To address this issue, electrification has arisen as a popular approach to reduce carbon emissions in different processes by primarily replacing the energy source with electricity derived from renewable energy resources. This review is designed to thoroughly explore the electrification concept in decarbonizing distillation and present a detailed analysis and summary of the cutting-edge technologies used in various distillation operations. The focus is on creating electrified distillation processes and their associated utility systems, making use of a range of power-to-heat and intensification strategies, to achieve simultaneous carbon reduction and energy savings. With the increasing variety of operating environments that incorporate renewable power, this review additionally encompasses the control and operation aspects to ensure efficient management of electrified distillation processes. To further delve into the advantages of incorporating electrification into distillation, this work proposes future directions from the viewpoints of technological advancement, design optimization, operation, and real-time scheduling of electrified distillation processes. Furthermore, this review highlights the enormous potential of electrification in dramatically lowering carbon emissions and promoting sustainable practices in the distillation industry.

1. Introduction

In the face of escalating climate crises and their pervasive impacts on global ecosystems, economies, and societies, the imperative quest for decarbonization has never been more pronounced. Decarbonization, the strategic reduction of carbon dioxide emissions through the adoption of clean energy, efficiency measures, and innovative technologies, stands at the forefront of global efforts to mitigate climate change and foster a sustainable future [1,2]. Presently, it is estimated that 70 % of the energy used in process industries is attributed to the utilization of fossil fuels [3]. The industrial sector alone is responsible for nearly 27 % of

global greenhouse gas emissions, with chemical industries (22 %), iron and steel production (27 %), and cement production (11 %) being the top contributors [4]. Distillation is an energy-intensive thermal separation technology widely employed across process industries. It accounts for 60 % of energy used in all separation technologies [5], 40–60 % in chemical and refining industries [6], and approximately 3 % of the global energy use [7]. Despite the high energy consumption, distillation operation is still heavily relying on the combustion of fossil fuels and thus contributing significantly to carbon emissions. Hence the reliance on fossil fuels for energy poses a substantial hurdle to achieving broader decarbonization goals.

The industry sector can adopt several technologies to achieve

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Abbreviations

A-DWC	Azeotropic dividing wall column
ASU	Air separation unit
BF	Bottom flashing
CDU	Crude distillation unit
CGCC	Column grand composite curve
CIP	Compressor inlet preheating
COP	Coefficient of performance
CV	Controlled variable
DPTCD	Different pressure thermally coupled distillation
DWC	Dividing wall column
EB/SM	Ethylbenzene/styrene monomer
ED	Extractive distillation
EDC	Extractive distillation column
E-DWC	Extractive dividing wall column
FP	Feed preheating
GCC	Grand composite curve
HAD	heterogeneous azeotropic distillation
HIDiC	Internally heat integrated distillation column
HPAD	Heat pump-assisted distillation
HPC	High-pressure column
IHE	Intermediate heat exchanger
IR	Intermediate reboiler
KC	Kalina cycle

LPC	Low-pressure column
MD	Membrane distillation
MED	Multi-effect distillation
MPC	Model predictive control
MV	Manipulated variable
MVR	Mechanical vapor recompression
ORC	Organic Rankine cycle
PCS	Precompressor splitting
PDC	Preconcentration distillation column
PI	Process intensification
PID	Proportional-integral-derivative
PSD	Pressure-swing distillation
PSE	Process systems engineering
PtH	Power-to-heat
RD	Reactive distillation
R-DWC	Reactive dividing wall column
RES	Renewable energy sources
SHRT	Self-heat recuperation technology
SRC	Solvent recovery column
SSC	Side stream column
TAC	Total annual cost
TCD	Thermally coupled distillation
THF	Tetrahydrofuran
TRL	Technology readiness level
VC	Vapor compression

decarbonization, such as electrification combined with low-carbon electricity, the use of low-carbon fuels like hydrogen or bio-based feedstocks, and CCUS (carbon capture, utilization and storage) [8]. These techniques can be jointly implemented to enable the complete decarbonization of the chemical or other industrial sectors. Among them, electrification has drawn attention for its efficacy in decarbonizing process industries, thanks to the swift proliferation of renewable energy sources (RES) providing economically competitive alternatives to fossil fuel-generated electricity [9]. Global photovoltaic or wind power capacity has seen a surge, with costs expected to continue dropping until 2030, making the construction of photovoltaic or wind power stations more cost-effective than coal power plants in most situations [10]. Furthermore, the International Renewable Energy Agency [11] forecasts that by 2050, renewable power generation could meet 80 % of the global electricity demand, with photovoltaic and wind power generation making up half of the total output.

Given the promising outlook of low-carbon electricity generation, process electrification paired with low-carbon electricity could become an efficient method of decarbonization [12]. The International Energy Agency [13] suggests that electrification could become a leading pathway towards net-zero carbon emissions by 2050, contributing to a roughly 20 % reduction in total CO₂ emissions. Renewables-powered electrification is expected to be dominant, spurred on by the fast expansion in the use of wind and solar energy. The concept of process electrification and its compatibility with renewables has been explored thus far. Barton [14] proposed using green electrons instead of carbon-based fuels for chemical synthesis by incorporating renewable energy. Bühler et al. [15] suggested several strategies for electrifying industrial sites based on integrating heat pumps and electric heaters. Wiese and Baldini [16] developed an industrial sector conceptual model, stating that electrification is a feasible option for reducing fossil fuel usage. However, electrifying the process industry poses challenges and calls for more in-depth case studies due to the heterogeneity of the processes compared to transport and household sectors.

While harnessing low-carbon electricity shows potential for making distillation carbon-neutral, directly replacing fossil fuels with electricity sourced from the power grid or RESs is currently not cost-effective

without modifying the existing thermal distillation setups. Process intensification (PI) offers a solution by reducing energy use and carbon emissions through the transformation of traditional thermal distillation processes into electrified versions [17]. Therefore, achieving distillation decarbonization necessitates leveraging the combination of electrification and intensification. The discipline of process systems engineering (PSE) plays a critical role in this endeavor by addressing the corresponding interplay between process electrification and intensification. This is done through the development of a systematic procedure for process systems design, optimization, and operation [18,19]. Fig. 1 illustrates the symbiosis of process electrification with PI and PSE. Although the route to decarbonizing distillation through electrification is straightforward, there exists a gap in research on how to adapt distillation processes and related site utility systems to facilitate their coordination and mutual integration, utilizing PI and PSE methodologies.

Despite the vast literature on energy-efficient distillation, most review articles have focused on distillation system integration and intensification, paying less attention to electrification and the interplay between the distillation system and the site utility system [6,20,21]. To effectively decarbonize various distillation systems, this review paper provides a systematic analysis of electrification and intensification strategies from a PSE perspective, discussing application in different distillation systems from energy, economic, and carbon abatement perspectives. Understanding distillation systems and the associated site utility systems is necessary for achieving distillation electrification. Therefore, the modification and retrofitting of traditional utility systems and potential layouts for electrified distillation schemes are also discussed. Moreover, as renewable power is variable and intermittent, efficient power backups are critical to addressing the intermittency of renewable power supply and are an integral part of operation of electrified distillation systems. Control strategies are included to aid in better process operation [22]. Meanwhile, the related real-world implementations and policy implications are mentioned. In general, this review article emphasizes electrified distillation design, control, and its associated utility system, summarizing the state-of-the-art technologies toward carbon neutrality.

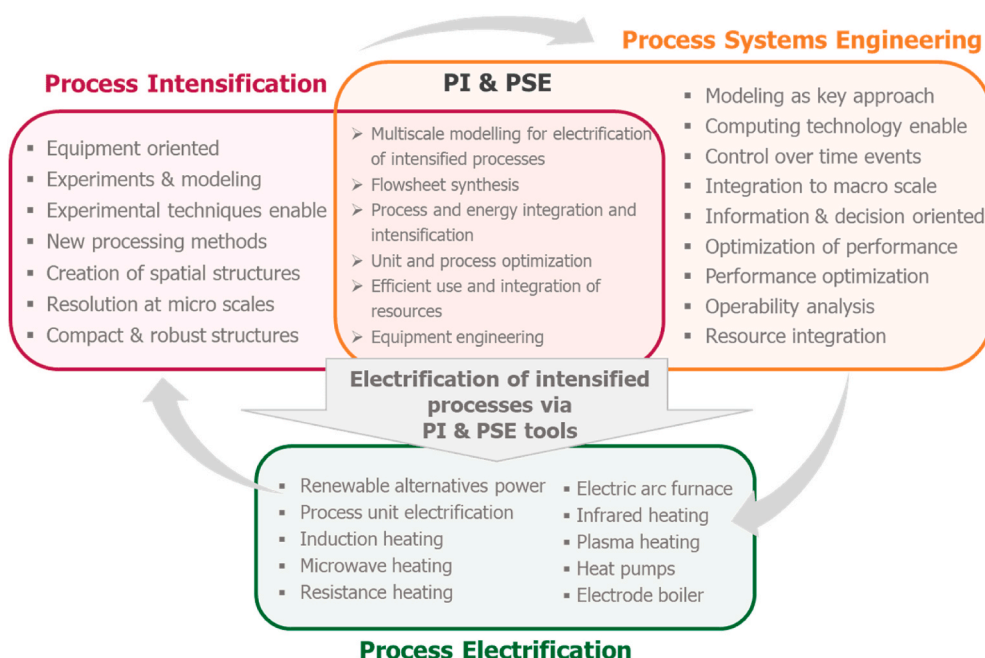


Fig. 1. Symbiosis of process electrification with PI and PSE.

The structure of this paper comprises 8 sections. Section 1 gives the research background and the importance of decarbonization. Section 2 deals with process electrification of distillation, including research scope, energy supply, thermodynamic analysis, and techno-economic evaluation. Section 3 introduces the electrification and intensification technologies from the perspectives of principles and applications. Section 4 introduces the state-of-the-art design of electrified distillation processes. Section 5 reviews the existing control structures of electrified distillation. Section 6 summaries the real-world implementations and policy implications. Section 7 lists future perspectives of electrification of distillation. Finally, Section 8 concludes the findings and prospects for future research priorities.

2. Electrifying distillation for decarbonization

2.1. Process electrification with low-carbon electricity

The US Energy Information Administration [23] stated that about 20 % of energy requirements on-site in the chemical sector is attributed to electricity, with the bulk of energy (80 %) originating from heat derived from combustion, predominantly from fossil fuels. Within the sector, "process energy", which powers heating/cooling, electrochemical reactors, and machine-driven tools, comprises 89 % of the total electricity. The residual 11 % of electricity usage, termed "non-process energy", fuels systems such as HVAC (heating, ventilation and air conditioning), lighting, and transportation. The prospect of employing low-carbon electricity to power distillation processes has been gaining attentions, due to its potential role in process decarbonization. Nonetheless, the primary hurdle lies in the necessity to design and control distillation processes to accommodate electric power use. The ways to utilize low-carbon electricity are broadly categorized into three levels [4].

Level 1 In industrial applications that are already electrified, the substitution of fossil fuel-based electricity with renewable alternatives like wind or solar power can take place. This replacement can be achieved in both process energy and non-process energy within industrial contexts.

Level 2 Electrifying process units that make use of low-temperature heat, such as distillation units traditionally driven by thermal

energy. However, some distillation processes like crude distillation units (CDUs) necessitate high-temperature heat. Beyond distillation, commercially viable options such as electrode boilers and compressors exist that can generate steam or pressurize streams using electricity.

Level 3 The electrification of units requiring high-temperature heat or having large capacity needs. Units such as electric furnaces [24, 25], steam reformers [26,27], and steam crackers [28,29] fall under this category. However, electrifying these units can be challenging due to the requirement for a steady and high-amperage power supply, predominantly or exclusively sourced from RESs. This could entail a substantial electrical storage infrastructure and significant capital expenditures.

This review primarily focuses on the level 2 of process electrification.

2.2. Scope of electrification of distillation

In this review, the electrification of distillation is defined as the implementation of power-to-heat (PtH) and/or PI technologies to either substitute or minimize the use of fossil fuel-based heat in distillation processes. The two main categories of electrification are direct and indirect [30]. Direct electrification refers to the transfer of electricity into heat within the process directly. It can also be achieved by applying an electric field [31] or microwaves [32,33] inside the distillation column. In contrast, indirect electrification utilizes alternative feedstock and green fuels like hydrogen, ammonia, methane, and methanol. These are produced from renewable electricity and/or nitrogen/captured CO₂ to power the process indirectly. Presently, the indirect method confronts obstacles in terms of economic feasibility and technological readiness [34], hence it is not considered in this review.

The prevalent concept of direct electrification merely focuses on substituting thermal heating with electric heating, not taking into account PI. However, adopting electric heating may entail high capital costs compared to traditional combustion-based technologies, given the capital-intensive nature of electrification technologies [35]. While a straightforward electrification replacement may work for basic process systems, it might fall short for complex distillation systems that offer multiple possibilities for heat and work integration to attain energy and

cost savings [36]. In such scenarios, advanced distillation structures can be used to seek suitable heat integration opportunities and reduce overall energy demand [37]. Therefore, the design of electrified distillation systems should consider both the energy supply structure (utility system) and the process integration/intensification opportunities.

The scope of this review mainly includes the implementation of PTH and PI technologies in distillation systems. The potential synergy of blending electrification and intensification is underscored to maximize the benefits of decarbonization. As the heat integration in a distillation system depends on the specific case, emphasis is on standalone distillation systems. Situations where energy is supplied from other units (e.g. reactor) or heat discarded that could be used downstream are not considered. The state-of-the-art advancements in electrification and intensification for various separation tasks are extensively discussed and analyzed.

2.3. Energy provision for electrified distillation processes

Stable energy supply is crucial to ensure continuous operation in distillation processes. Traditional site utility systems can maintain stability through fossil fuel combustion. However, the variable and intermittent nature of RESs creates hurdles for stable energy supply. The majority of electrified distillation processes cannot readily adapt their production loads to fit a variable power supply, as significant changes in column throughput can lead to inefficiency and unstable operation. Therefore, it is crucial to operate distillation columns with consistent energy demand, which calls for the allocation and management of power between renewable energy supply and demand sides. This underscores the necessity for new utility systems, specifically designed to stabilize renewable energy supply and convert renewable power into the required energy forms and quantities for electrified distillation systems.

Fig. 2 depicts a superstructure of utility systems for electrified distillation, where electricity is the sole energy source. Three types of production can be distinguished based on the power supply source: (1) islanded production, where the electrified distillation system is directly coupled with RES such as solar and wind; (2) grid-only production, which relies on steady power supply from the power grid; and (3) hybrid production, which primarily utilizes power from RES with a grid connection serving as (cheap) backup power. The determination of these production types is dependent on the local availability of the RES. To achieve a high penetration of RES in electrified distillation processes,

types (1) and (3) are preferred over using electricity from the power grid, as the latter causes significant carbon emissions, whereas type (2) could be adopted in a future scenario where the grid is fully decarbonized. Therefore, it is essential to incorporate additional on-site energy storage units in the utility system to address the variability and intermittency of renewable power. These on-site energy storage units enable excess power to be stored temporarily and released to the distillation system as needed.

Although electricity storage is critical to accommodating renewable energy fluctuations, full storage of excess electrical energy using state-of-the-art battery technologies can be costly. To reduce the overall storage cost, part of the excess electrical energy can be stored as thermal energy, which is easier and less expensive to store. The stored thermal energy can be regenerated using a working fluid to provide heating for distillation reboilers. While the use of thermal energy storage may lower the overall energy efficiency of the electrified system, there is an opportunity to reduce costs by simultaneously optimizing the storage ratio of electrical and thermal energy and the configuration of electrified distillation. In this case, conventional thermal reboilers could remain in electrified distillation systems, and the required thermal energy is produced from power using various PTH technologies [38]. The optimal design of the utility system for electrified distillation should consider both electrical and thermal energy storage options, as well as the corresponding quantities of energy required for possible configurations of electrified distillation designs.

The new utility system design for electrified distillation involves the integration of various technologies for both electricity and thermal storage. These storage systems comprise electrochemical energy storage, such as Li-ion batteries and supercapacitors. In addition, innovative Carnot energy storage systems such as compressed air energy storage, liquid air energy storage, and pumped thermal energy storage can be employed due to their low cost, large capacity, and high safety performance. Thermal energy storage can be accomplished by latent heat storage in rocks/tanks and sensible heat storage using phase change materials and thermal oil. The supplied electricity can be utilized to power electrically driven columns, compressors, and refrigeration systems for cooling. The supplied heat can be used to derive thermal-driven columns and generate steam for stripping, and the residual heat can be recovered and used for power generation through a Rankine cycle. Table 1 summarizes the available electricity and heat storage technologies [39,40]. Both the electricity storage and thermal storage systems

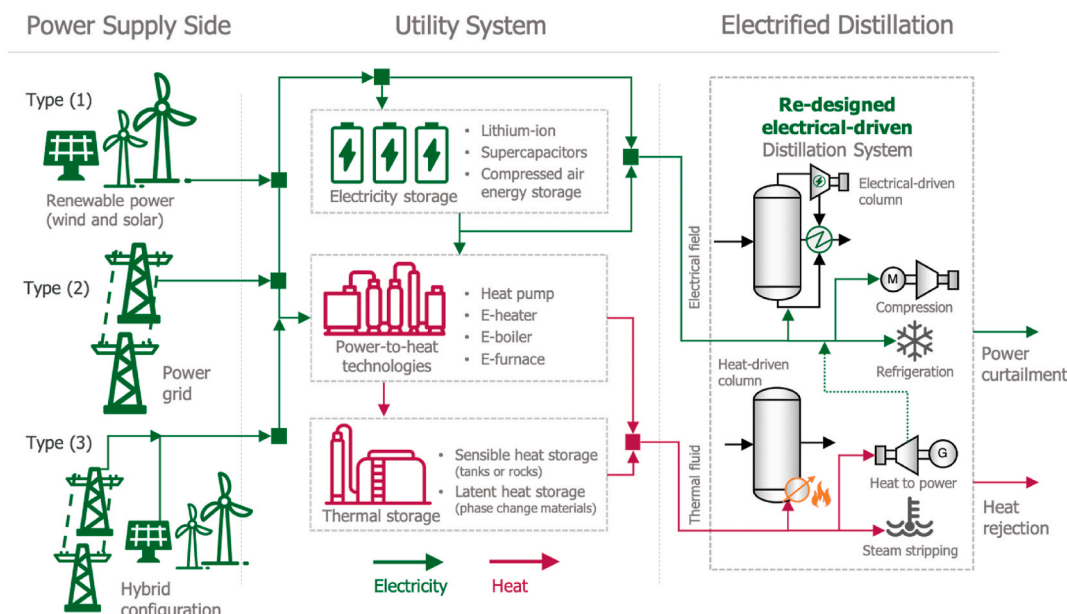


Fig. 2. Superstructure of the utility system for electrified distillation processes.

Table 1

A summary of state-of-the-art electricity and thermal energy storage technologies.

Type	Storage efficiency	Response time	Relative cost
Electricity storage [39]			
Li-ion battery	75–95 %	<1/4 cycle	High
Redox flow batteries	65–85 %	<1/4 cycle	High
Supercapacitors	90–95 %	<1/4 cycle	High
Compressed air energy storage	65–70 %	Minutes	Medium
Liquid air energy storage	45–70 %	Minutes	Relatively low
Pumped thermal energy storage	48–75 %	Minutes	Relatively low
Thermal storage [40]			
Sensible heat storage	70–90 %	Seconds	Medium
Latent energy storage	80–90 %	Seconds	Medium
Thermochemical storage	70–80 %	Minutes	High

work synergistically to provide electricity and thermal energy to electrified distillation systems.

2.4. Thermodynamic perspective of decarbonization by electrification

Conventional distillation column relies on the application of heat in the form of steam to the reboiler. Typically, steam is generated by utilizing different fossil fuels like coal, fuel oil, or natural gas, resulting in carbon emissions. Fig. 3 shows a typical energy balance in a boiler that generates steam from fossil fuel combustion to the end users. The overall systems efficiency is around 56–75 % [41–43]. Therefore, the carbon footprint associated with the generation of steam, denoted as c_{steam} , can be estimated as:

$$c_{\text{Steam}} = c_{\text{Fuel}} / \alpha \quad (1)$$

where α is the overall efficiency of steam generation boiler [41]. Table 2 lists the values of c_{Fuel} and c_{Steam} for various fuels [44].

Considering the use of grid-only for power supply in distillation processes, Fig. 4a shows the carbon intensity of 80 national grids in 2022 [45]. The first, second and third quartiles correspond to carbon intensities of 193, 350 and 489 gCO₂e/kWh, respectively. The detailed list of carbon intensity of electricity in different countries or areas is given in Fig. 4d. Therefore, unless utilizing a local grid with remarkably low carbon intensity, there is limited incentive to replace steam heating with electric heating. Instead, transitioning from high carbon fuel like coal or fuel oil to low carbon fuel such as natural gas appears to be a more feasible approach to reducing carbon emissions in steam generation for utility systems. This change would only require modifications to the

Table 2

Carbon intensities for different fossil fuels.

Fuel	c_{Fuel} (gCO ₂ /kWh)	$c_{\text{Steam}} (\alpha = 0.65)$ (gCO ₂ /kWh)
Coal (All types)	328	505
Fuel oil	253	389
Natural gas	181	278

utility system, while leaving all distillation operations unaffected.

A utility system generally supplies high-, medium- and low-pressure steams. The saturation temperatures, pressures and specific enthalpy of some typical steam conditions are listed in Table 3 [46]. Based on this Table, the reboiler temperature should not exceed 240 °C to allow for heat transfer.

The available work or exergy supplied by condensing 1 unit of steam heating in a reboiler at temperature T_R is calculated by multiplying the Carnot factor:

$$\mathcal{A} = \left(1 - \frac{T_0}{T_R} \right) \quad (2)$$

where $T_0 = 300\text{K}$ is a reference temperature of the environment. Therefore, the carbon intensity of available work $c_{\mathcal{A}}$ supplied by steam heating in the reboiler is given by:

$$c_{\mathcal{A}} = \frac{c_{\text{Steam}}}{\left(1 - \frac{T_0}{T_R} \right)} \quad (3)$$

Fig. 4b illustrates the carbon intensity of available work supplied to the reboiler through steam generated by natural gas, with respect to the reboiler temperature. Due to the Carnot factor $(1 - T_0/T_R)$ the use of electrical work to replace available work done by steam heating offers advantages from the viewpoint of carbon emissions, and this persists even when transitioning to low carbon fuels such as natural gas and in the presence of nearly all existing grids. Therefore, the carbon emissions per unit of available work from steam heating are significantly higher than those of almost all existing grids. Exceptions may arise only in scenarios where the reboiler temperature exceeds 200 °C and the grid carbon intensity is exceptionally high. Therefore, replacing fossil fuel combustion by direct grid electricity might be beneficial from the perspective of decarbonization.

Another way to explain the above conclusions is through the utilization of vapor recompression heat pump, which is a commonly adopted method for replacing reboiler heating with electricity. Heat pumps have the potential to achieve high coefficients of performance (COP) with the range of 4–5. Consequently, when the COP is 4, only 0.25 units of electricity are required for one unit of reboiler heat. The reduction in carbon intensity achieved through heat pump-assisted distillation

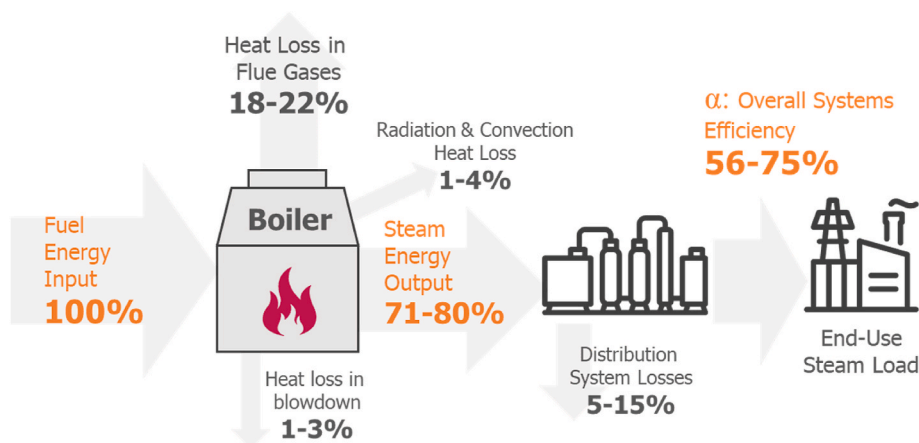


Fig. 3. Typical energy balance in a boiler.

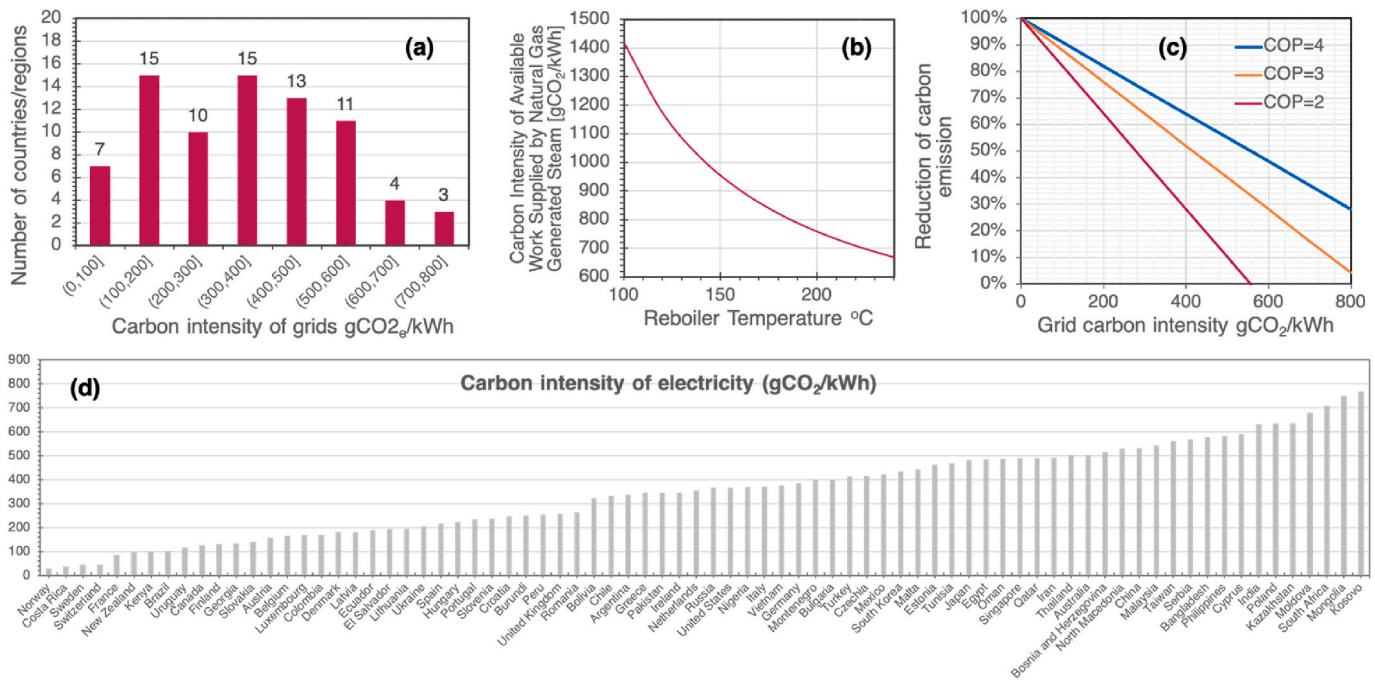


Fig. 4. (a) Distribution of carbon intensities of national grids in 80 countries or areas; (b) Carbon intensities of available work supplied to reboilers through steam generated by natural gas; (c) Potential of carbon emission reduction through heat pump electrified distillation compared to natural gas steam generation and reboiler heating at different grid carbon intensities; (d) Detailed list of carbon intensity of electricity in different countries or areas.

Table 3

Saturation temperature, pressure and specific enthalpy for steam utility.

Steam grade	Pressure (bar)	Temperature (°C)	Specific enthalpy (kJ/kg)
High-pressure steam	42	254	1691
Medium-pressure steam	11	184	1985
Low-pressure steam	6	160	2065

(HPAD), compared to conventional distillation, can be approximated as:

$$\gamma = \left(1 - \frac{c_{grid}}{c_{steam} \cdot COP} \right) \times 100\% \quad (4)$$

Fig. 4c estimates γ with $c_{steam} = 278$ gCO₂/kWh at different COPs and grid carbon intensities. It can be shown that substantial reductions in carbon emissions can be achieved when compared to reboiler heating using steam generated from natural gas, even in scenarios involving low COPs and grids with moderate carbon intensities.

Thus, the advantage of electrification of distillation derives mainly from the low thermodynamic efficiency of heat supplied to the reboiler. Replacing the condenser-reboiler configuration of simple distillations with a heat pump is a promising pathway towards achieving zero emissions in the distillation sector. HPAD is a well-established technology with relatively low risks. Moreover, it capitalizes on the sustainable progress of grid power as non-fossil and renewable fuels become more prevalent in the energy mix. However, it is important to note that replacing existing columns may present challenges due to space limitations, high investment costs, and operational considerations. Hence, it is crucial to thoroughly study retrofitting designs and control strategies, rather than solely focusing on grassroots designs, in order to encourage the implementation of more demonstration plants.

2.5. Techno-economic analysis of decarbonization by electrification

In this section, a case study based on grid-only power supply is investigated to illustrate the techno-economic aspect of decarbonization

by electrification.

Chaniago et al. [47] used HPAD to replace one of five conventional distillation columns in a solvent recovery process of a semiconductor plant. The reboiler heat requirement of 408.6 kW is reduced to 90.2 kW of electrical work. This means the COP of heat pump is 4.53. Assuming the steam required was generated by coal with a carbon intensity of 505 gCO₂/kWh (Table 2), the carbon emission would be 206 kgCO₂/h. In contrast, using natural gas would result in emissions of 114 kgCO₂/h. With electricity, assuming a carbon emission factor of 500 gCO₂/kWh and a mechanical efficiency of 75 %, the emissions would decrease to 60 kgCO₂/h.

In terms of operating costs, assuming a coal calorific value price of 0.2327 USD/(5500 kcal), the cost for the steam required for distillation provided by coal would be 14.87 USD/h. Using natural gas, with a calorific value price of 0.697 USD/(5500 kcal), the cost would be 44.55 USD/h. Based on a green electricity price of 0.20 USD/kWh [48], the energy cost for HPAD would be 18.04 USD/h, which is more expensive than coal but cheaper than directly replacing natural gas boilers to produce steam.

If the carbon reduction operation cost is calculated, the cost is increased by 18.04 - 14.87 = 3.17 USD/h, and the actual carbon reduction is 146 kgCO₂/h, so the carbon reduction operation cost is around 0.0217 USD/kgCO₂. The actual cost should also include the annualized investment cost of incorporating a low-carbon power system and adding a compressor. However, it is accepted that the use of low-carbon electricity coupled with heat pump assistance is a very economical carbon reduction strategy. In this case study, the steam capacity used in the discussed distillation column is about 870 kg/h (using high-pressure steam), indicating a relatively small scale. However, the benefits are more pronounced in large-scale distillations (e.g. crude distillation), which will be discussed later in Section 4.

3. Electrification and intensification technologies

3.1. Electrification technologies

This section starts by outlining a range of PtH technologies suitable

for the electrification of distillation processes, then subsequently, providing an in-depth analysis of more practical electrification solutions that utilize heat pumps, which are notable for their higher technology readiness level (TRL). Furthermore, it is important to acknowledge that in certain studies, HPAD is classified under the categories of PI. However, in this context, they are considered as methods of electrification.

3.1.1. Power-to-heat technologies

PtH or electric heating, as an approach for process electrification, presents numerous benefits including high availability, rapid startup periods, and a minimal turndown ratio [49]. Electric process heating uses either electric currents or electromagnetic fields to heat a material. There are two main types of electrification techniques: direct and indirect heating. Direct heating techniques heat the workpiece directly by: (1) running an electrical current through the material, (2) inducing an electrical current (also known as "eddy current") into the material, or (3) stimulating atoms or molecules within the material via electromagnetic radiation such as microwaves. Indirect heating uses one of these direct heating methods to heat an intermediary element or susceptor which then transfers heat to the workpiece via conduction, convection, radiation or a combination thereof [49]. In addition, PtH technologies such as heat pumps can help reconfigure the distillation process diagram, eliminating certain indirect heating needs including those related to the distillation reboiler. These aspects will be elaborated upon in subsequent sections. However, it is noteworthy that specific functionalities within an electrified distillation system may still require indirect heating, such as using steam as a heat carrier or deploying steam for stripping in petroleum fractionators or during the startup process for purging purposes.

There is a broad range of PtH technologies available for substituting thermal energy with electricity, but industrial adoption is constrained by factors like low TRL and practical limitations. At least 8 PtH technologies have been verified at a laboratory scale, including induction heating, electric arc furnace, infrared heating, plasma heating, microwave heating, heat pumping, resistance heating, and electrode boilers. Table 4 provides an evaluation of the feasibility of replacing conventional heat sources with electrified alternatives, based on characteristics such as heating type, working temperature, and efficiency.

Electric heaters (e-heater), electrode boilers (e-boiler), and heat pumps are already being utilized at an industrial scale in processing industries, achieving a TRL of 9. These technologies are leading the charge in electrification of distillation. Other electrification technologies

like infrared heaters (TRL 7–8), electric ceramic kilns (TRL 5–6), and microwave heaters (TRL 4–5) require additional research and development to establish and commercialize their viability [50].

In traditional utility systems reliant on fossil fuels, process heating is usually accomplished through direct heating from furnaces or by indirect heating via steam. High-grade steam, generated from boilers or hot process streams, is used for power generation, while low-grade steam is utilized for lower temperature process heating. This method, known as combined heat and power (or cogeneration), is usually fully exploited to meet the power demands within a plant. Over the years, grand composite curves (GCCs) have been extensively used as a practical method for selecting and efficiently allocating utilities among available options [37]. GCCs provide an overall representation of the energy requirement at the plant level, helping to identify the most suitable strategy for electrified heating. Kim et al. [60] suggested using GCCs to determine the best placement of electrified heating in industrial energy systems. They proposed that electric furnaces (e-furnace) could be considered for providing heat at relatively high temperatures, while electrode boilers or electric heaters could be used in temperature ranges where steam is typically employed. Implementing an electric heater would prevent steam from being used by the plant, while electrode boilers could be employed when steam is required for the process. Additionally, heat pumping can be explored when the temperature gap between the heat source and heat sink stream is not considerably large.

A distillation column can be viewed as a heat engine that produces separation instead of work [61], and an inefficient heat engine presents an opportunity for efficient heat pumping. Normally, a distillation column is powered by high-temperature heat in the reboiler, with the degraded heat being collected at a lower temperature in the condenser. Although substituting the steam reboilers with electric heaters or electrode boilers minimizes the modification required for the current processes, it does not improve the overall energy efficiency. Conversely, heat pumps can be implemented as a means of electrification, leading to savings in both hot and cold utilities at the expense of additional electric compression work. With the aid of heat pumps, the energy collected at low temperatures in the condenser can be elevated to higher temperatures, thereby mitigating undesirable heat degradation. Historically, heat pump implementation has been studied within the context of process integration rather than process electrification [37]. However, considering that heat pump removes process heating at the expense of electric power, it should be regarded as a technology of electrification.

3.1.2. Mechanical heat pump-assisted distillation

While distillation is recognized for its relatively low thermodynamic efficiency, it requires the input of high-quality energy in the reboiler to carry out the separation [62]. Simultaneously, a comparable amount of heat at lower temperature is expelled in the condenser. To mitigate the usage of valuable utilities along with associated carbon emissions, different types of heat pumps have been successfully integrated with distillation [63,64]. These heat pumping systems can be categorized into two main types: mechanical and absorption heat pumps [65]. The latter uses a separate closed-loop fluid system to transfer the heat up the temperature scale by means of the heat of mixing without consuming electricity. Hence, current developments in mechanical heat pumps, which are electrically powered vapor recompression types, are given particular consideration. Fig. 5 demonstrates three types of mechanical heat pump systems: mechanical vapor recompression (MVR), bottom flashing (BF), and closed cycle vapor compression (VC) [66,67]. These configurations utilize an expansion valve and a compressor to modulate the condensation and/or boiling processes, permitting the heat discarded in the overhead condenser to be repurposed for heating the bottom reboiler. Kiss et al. [68] introduced a unique selection framework for energy-efficient distillation technologies, emphasizing specifically heat pumps. Besides the commonly used mechanical heat pump, they also contemplated compression-resorption and absorption heat pumps, which leverage absorption equilibrium to bolster energy

Table 4
PtH technologies for electrification.

PtH technology	Heating type	Working temperature	Efficiency
Induction heating	Direct heating	100–2500 °C [51]	90 % [52]
Microwave heating	Direct heating	100–1300 °C [51]	85 % [53]
Resistance heating	Direct/indirect heating	200–1800 °C [51]	~100 % [49]
Electric arc furnace	Direct/indirect heating	1200–3000 °C [51]	40–75 % [54]
Infrared heating	Indirect heating	300–2600 °C [51]	30–70 % [55]
Plasma heating	Indirect heating	1600 °C in application for waste treatment [56]; 2000 °C in application for metal processing [57]	80 % [57]
Heat pump	Indirect heating	20–160 °C [58]	COP 5.7–6.5 (for 30 °C temperature life); COP 2.2–2.8 (for 70 °C temperature life) [58]
Electrode boiler	Steam generation	100–350 °C as superheated steam	99 % [59]

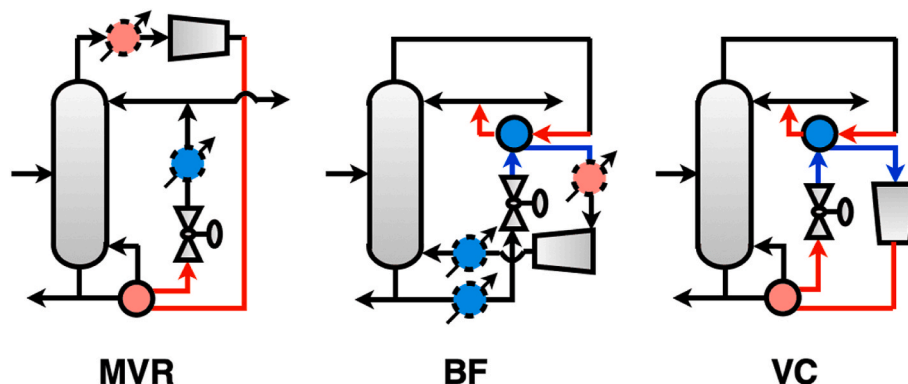


Fig. 5. Diagrammatic representation of the distillation assisted by mechanical heat pump.

efficiency [69].

In the MVR method, the overhead vapor is compressed to a higher temperature, allowing its latent heat to be utilized for bottom boiling. The high-pressure condensate is then expanded through a throttling valve to provide reflux and distillate. During the compression/expansion cycle, a fraction of the saturated vapor/liquid might be condensed/ flashed, requiring the use of an auxiliary heater/cooler to preheat/condense the stream. Due to its benefits, including a simplistic structure, compact size, ease of design and operation, lower initial capital outlay, and circumvention of working fluid-related issues, MVR has become a widely adopted and favored application of heat pumps in distillation. This review focuses on MVR-assisted distillation to uncover potential pathways for further advancements.

In the BF approach, the bottom saturated liquid is expanded to cool down the overhead vapor in the condenser. After passing through the throttling valve, the liquid undergoes vaporization, resulting in a two-phase mixture. The vapor fraction increases with higher pressure reduction in the valve, particularly when there is a significant difference in boiling point temperatures between the components being separated. Compared to a purely liquid stream, a partially evaporated stream has less latent heat of vaporization. An optional pre-throttling cooling can be employed by throttling a subcooled liquid, leading to a stream with a lower vapor fraction compared to a saturated liquid and thereby providing more latent heat. If the stream exiting condenser contains liquid, an optional preheater is added to ensure complete vaporization before supplying the stream to the compressor [70]. Additionally, the superheated vapor exiting the compressor can be cooled to saturated vapor in an optional cooler before entering the distillation column. It has been observed that the BF method is not efficient when there is a significant difference between the overhead and bottom of the column. However, it proves to be energy-efficient for mixtures with close-boiling points and when the bottoms product serves as a good refrigerant, as evidenced in separations such as ethylene/ethane [71], propylene/propane [72], and i-butane/n-butane [73].

In the closed-cycle VC method, the selection of a suitable working fluid is crucial and is affected by the drawbacks associated with the chosen working pair. This closed system approach is typically preferred when the fluid in the column is corrosive or does not function well as a refrigerant [74].

Heat pumps play a dual role in decarbonizing distillation processes. Firstly, direct electrification using renewables can substitute fossil fuels for industrial heat, thereby reducing carbon emissions. Secondly, distillation systems integrating heat pumps have the potential to save energy if a high COP can be achieved. To determine whether the use of a heat pump is appropriate for a specific distillation task, Pleşu et al. [75] proposed a simple criterion equation:

$$COP = \frac{Q}{W} \approx \frac{T_C}{T_R - T_C} \quad (5)$$

where Q is the reboiler duty, W is the work provided, and T_R and T_C are temperatures (in K) of the reboiler and condenser, respectively. A Q/W ratio exceeding 10 strongly advises the use of a heat pump. A ratio falling between 5 and 10 requires a more comprehensive evaluation. If the ratio is below 5, using a heat pump might not yield substantial benefits. Vapor recompression distillation is particularly apt for separating species with close-boiling points, as such separations lead to reduced compressor power input [76]. Also, mechanical heat pumps are well-suited for retrofitting existing distillation columns [77]. To conclude, the integration of heat pumps with distillation processes can reduce the needed heat input and enable electrification.

3.1.3. Self-heat recuperation-assisted distillation

The primary focus of employing mechanical heat pumps in distillation is the collection of latent heat, as opposed to sensible heat. To overcome this constraint and permit simultaneous circulation of both latent and sensible heat for heating and cooling thermal processes, Kansha et al. [78–80] proposed the idea of self-heat recuperation technology (SHRT). This technology recycles and reuses the heat from the effluent stream (gas and/or vapor) for the heating of the feed stream, without requiring additional heat, by compressing the effluent stream using compressors. Only mechanical work or electricity is required in this process.

SHRT-assisted distillation can be viewed as an upgraded version of the fundamental MVR. Matsuda et al. [81] developed SHRT-assisted distillation with a case study of aromatic separation. Fig. 6 shows a comparison between conventional heat recovery measures with two revised cases that incorporate SHRT. In the conventional case, feed preheating (FP) is used to recover heat from the overhead and bottom streams. However, due to temperature difference limitations, total recovered energy is restricted. In the SHRT-assisted cases, two compressors are installed in the overhead vapor line to recirculate heat at an elevated temperature, enabling greater energy recovery. An economical case was also developed, utilizing a single compressor that treats all overhead vapor, which is then divided between the reboiler and the feed heater. As a result, all the heat is recirculated within the process without the need for external heat, necessitating only electric power for the compressors. Therefore, SHRT implementation facilitates process electrification.

In addition to the elementary SHRT-assisted distillation setups, various refined structures have been suggested to optimize energy usage. Christopher et al. [82] introduced SHRT-assisted distillation with compressor inlet preheating (CIP). The overhead vapor preheating supplies some of the heat necessary for the reboiler, lessening the energy required by the compressor to compress the vapor. This method enhances the utilization of excessive sensible heat. Moreover, if the latent heat from the pressurized vapor is not entirely used in the reboiler and leaves as a two-phase mixture, a flow splitter known as pre-compressor splitting (PCS) is recommended to separate a portion of the vapor prior

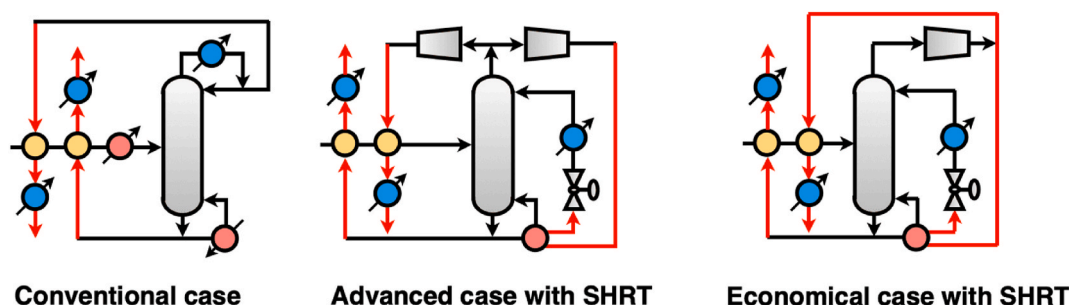


Fig. 6. Conventional heat recovery case and advanced cases with SHRT.

to it entering the compressor [71]. By optionally merging PCS, CIP, and FP, an appropriate process superstructure can be formulated, as depicted in Fig. 7. This SHRT-assisted distillation signifies an upgraded process compared to the economical case in Fig. 6. All these SHRT-assisted distillation concepts play a crucial role in the realm of process electrification.

3.1.4. Internally heat-integrated distillation column

The application of mechanical heat pump enables the internal heat integration of separate rectifying and stripping columns, forming an internally heat-integrated distillation column (HIDiC) [83–85]. Fig. 8 shows a schematic representation of various HIDiC systems. In this manner, the overhead vapor from the stripping column is compressed and then introduced into the bottom of the rectifying column, thereby facilitating internal heat transfer between the two column sections through stage-by-stage heat exchange. The rectifying column, operating at a higher pressure, admits its bottom liquid and the column feed into the top of the stripping column. A throttling valve equalizes the pressure of the liquid stream recycled from the rectifying column with that of the stripping column. The top of the rectifying column outputs light product vapor or condensed liquid, while the bottom liquid of the stripping column is the heavy product. Due to the heating and cooling, the vapor flow rate within the HIDiC is highest around the feed stage and gradually decreases towards the end, leading to a gradual change in the cross-sectional area. Furthermore, Kansha et al. [86] developed a combined HIDiC and SHRT process, which enables the analysis of energy input/output and recirculation of process heat through pressure changes, resulting in further energy consumption reduction. In certain studies [87–89], the idea of "different pressure thermally coupled distillation" (DPTCD) has been used. DPTCD diverges from the stage-by-stage heat integration seen in conventional HIDiC; it solely integrates the condenser of high-pressure rectifying section with the reboiler of low-pressure stripping section. In this context, DPTCD can be regarded as a particular form of HIDiC.

Even though HIDiC is anticipated to deliver promising energy-saving performance, instances have been recorded where this arrangement results in higher energy consumption [90]. In a comparative

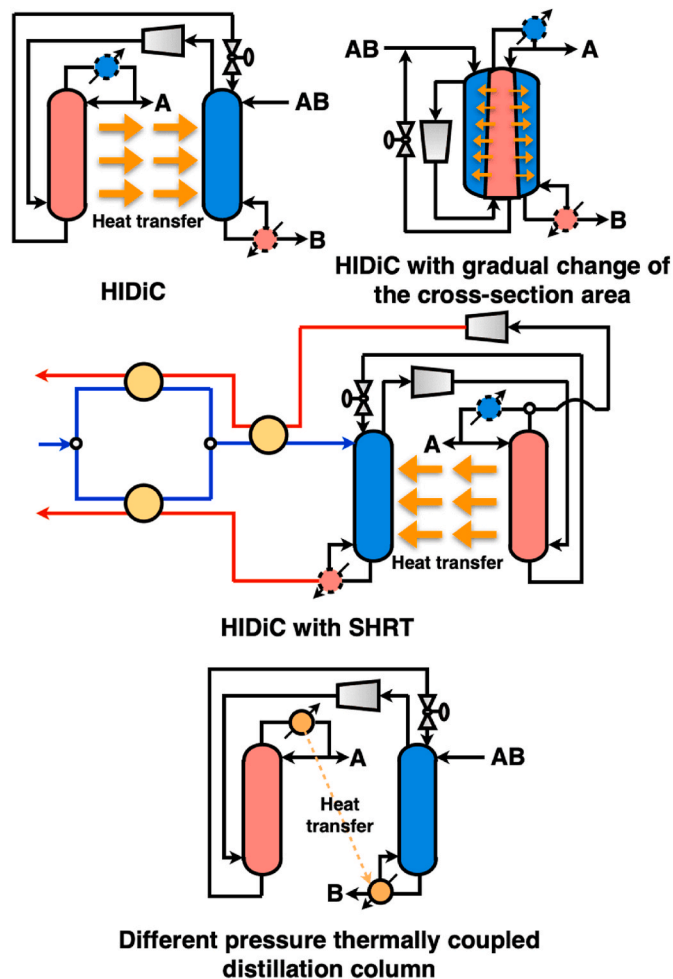


Fig. 8. A schematic representation of various HIDiC systems.

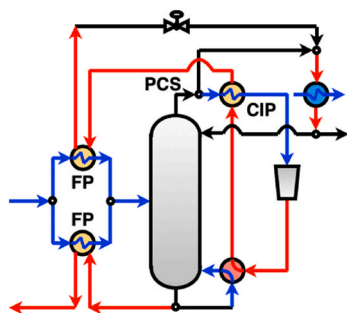


Fig. 7. A SHRT assisted distillation process superstructure with PCS, CIP, and FP.

optimization study, Harwardt and Marquardt [91] deduced that both MVR and HIDiC outperform conventional column in economic feasibility for close-boiling mixtures, with MVR being more cost-efficient than HIDiC. From a dynamics and control perspective, Fukushima et al. [92] showed that despite HIDiC having a more intricate structure and slower dynamics than the conventional case, comparable control performance can be achieved given the design of an appropriate control system. Nevertheless, due to challenges in design, construction, and operation, HIDiC sees limited use in industrial applications. Wakabayashi et al. [93] created the first commercial application of HIDiC technology, strategically applying heat exchangers to selected stages in the rectifying and stripping sections.

3.2. Intensification technologies

PI aims to drastically reduce the energy consumption and processing costs in the chemical processes by leveraging the synergistic effects of multifunctional phenomena at different time and space scales, enhancing mass, heat, and momentum transfer rates [17,19,94]. The successful execution of process electrification should incorporate a blend of PI strategies, with the goal of crafting compact, easy-to-operate, energy-efficient, and cost-effective configurations [21]. HPADs, as referenced earlier, are generally perceived as external intensification techniques, given that they necessitate a supplementary auxiliary heat pump without altering the inherent distillation structure itself [6]. Beyond heat pumps, another avenue for PI involves internal modifications to the topology of distillation configurations [95–97]. These internal intensification approaches encompass multi-effect distillation (MED), thermally coupled distillation (TCD), dividing wall column (DWC), and side stream column (SSC). When chemical reactions are involved, the integration of reaction and distillation gives rise to reactive distillation (RD), which has been recognized as one of the most successful examples of PI. The integration of these PI methods with electrification initiatives is of utmost importance.

3.2.1. Multi-effect distillation

MED involves the integration of high-pressure column (HPC) condensers and low-pressure column (LPC) reboilers. This method proves particularly advantageous when retrofitting existing plants where the objective is to minimize heat consumption without needing substantial column replacements [98–100]. Fig. 9 illustrates various ternary distillation configurations with MED, which can be arranged in either forward or reverse heat integration modes. These layouts are based on direct and indirect sequences as well as the prefractionator configuration. Cui et al. [101] developed an enumeration-based synthesis framework for binary separation with MED. The results indicated that MED can achieve energy savings ranging from approximately 30 to 60 %. Owing to its energy-saving advantages, MED has seen extensive use across various sectors such as cryogenic air separation [102], seawater desalination [103], biofuel refining [104], and other chemical purifications involving both zeotropic and azeotropic systems.

3.2.2. Thermally coupled distillation

TCD involves restructuring the conventional distillation column by eliminating a condenser or reboiler unit, as depicted in Fig. 10. The TCD offers advantages in mitigating or eliminating the issue of remixing within the system. Numerous studies have showcased the energy-saving potential of TCD compared to conventional direct and indirect distillation sequences. Such energy savings can reach up to 30 % for mixtures

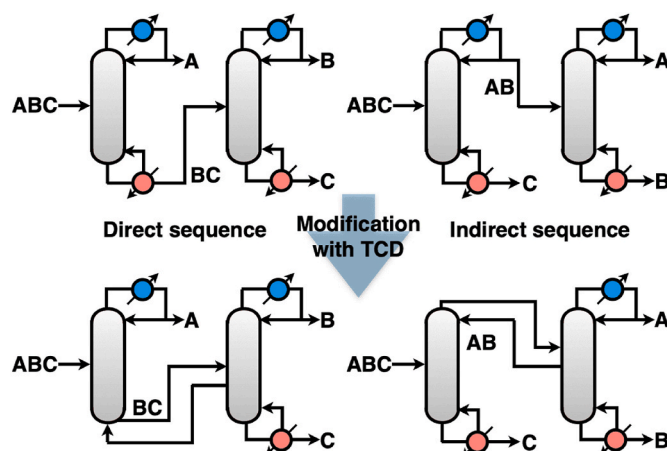


Fig. 10. Ternary distillation systems modified with TCD.

with low or high content of the intermediate component [105–109].

3.2.3. Dividing wall column

A DWC is a distillation column that incorporates vertical partition walls to create distinct separation sections. This design allows for the separation of multicomponent mixtures in a more efficient and cost-effective manner. Numerous studies have explored DWC, showcasing its potential for considerable energy savings. For ternary and multicomponent mixtures, DWC can provide up to 30 % savings in capital investments and up to 40 % in energy costs [110]. In addition to its application in zeotropic mixtures, DWC has been successfully merged with reactive [111,112], extractive and azeotropic distillations [113] to create specialized configurations known as reactive DWC (R-DWC), extractive DWC (E-DWC), and azeotropic DWC (A-DWC), as shown in Fig. 11.

Furthermore, beyond these three-product setups, various four-product DWC configurations have also been developed [114–118], as shown in Fig. 12. These DWC designs may utilize single or multiple partition walls to achieve the desired separation objectives.

3.2.4. Liquid-only side stream column

The use of liquid-only transfer streams is an alternative PI technique that offers several advantages. In the SSC configurations, the thermal coupling between the two columns is achieved through the transfer of liquid streams instead of vapor streams, as depicted in Fig. 13 [119]. Research by Ramapriya et al. [120] has shown that the SSC configuration requires the same overall minimum vapor requirement as the TCD

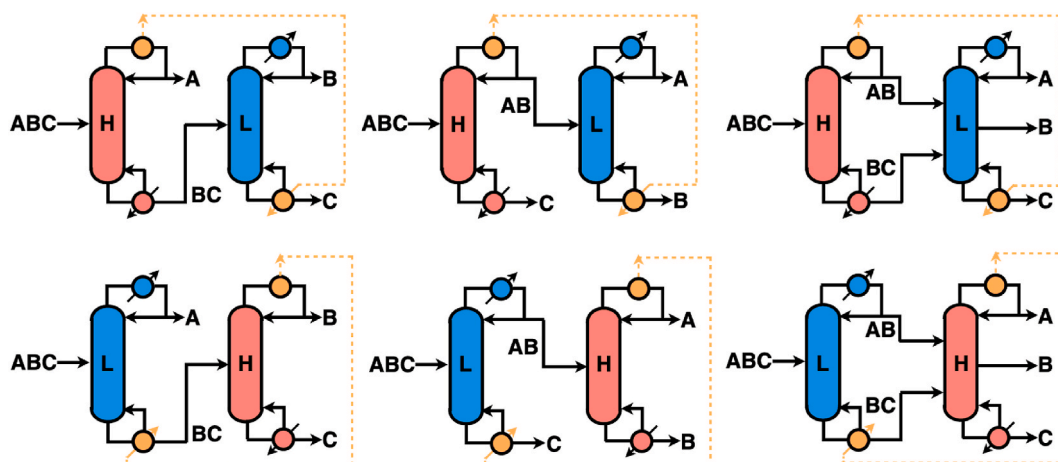


Fig. 9. Ternary distillation systems with MED.

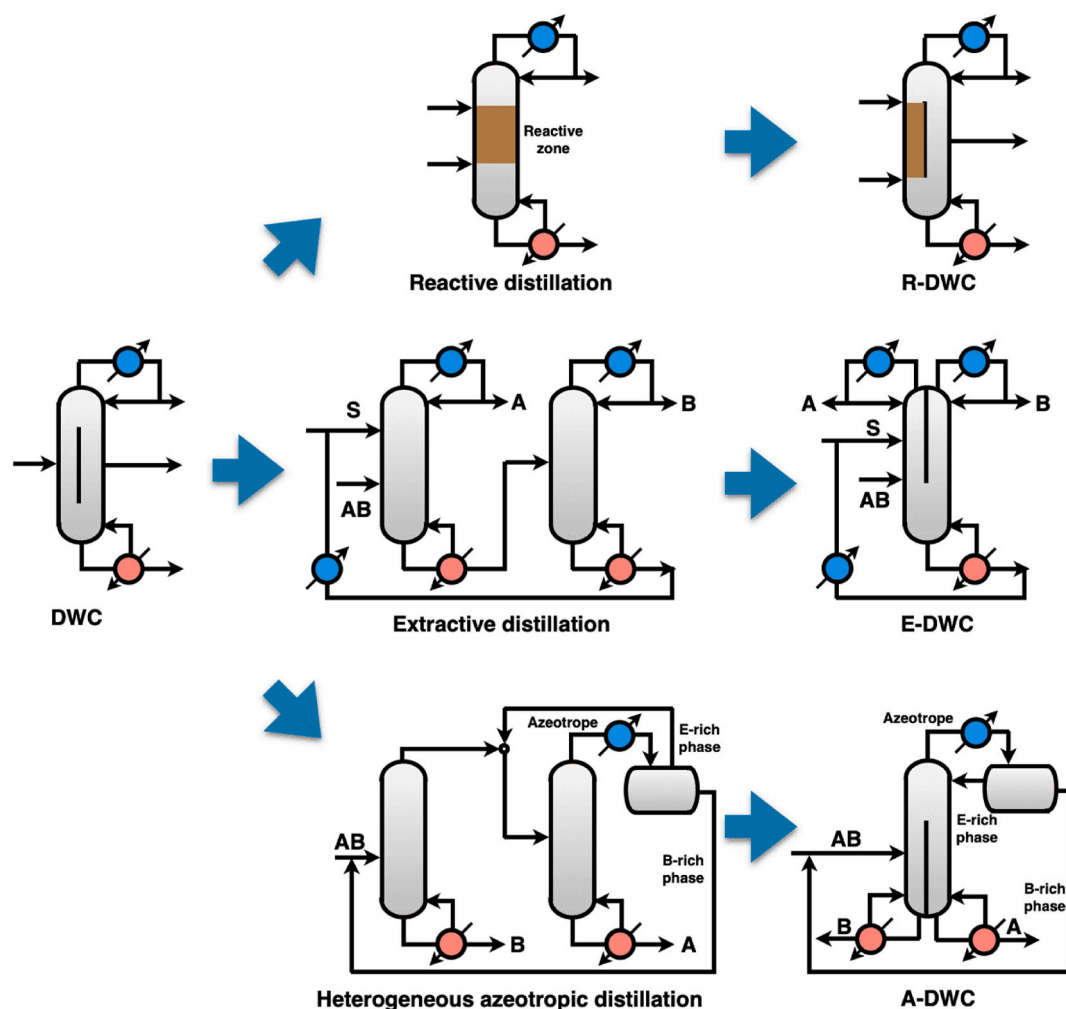


Fig. 11. Combining DWC with reactive, extractive and azeotropic distillations.

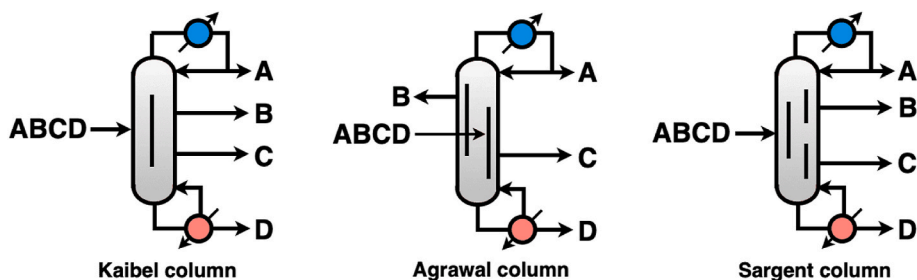


Fig. 12. Four-product DWCs: Kaibel, Agrawal, and Sargent columns.

configuration. Furthermore, the liquid-only SSC configuration can be synthesized as a modified DWC with side streams. SSC configurations have been reported to provide similar energy requirements and total annual cost (TAC) as compared to the direct or indirect configurations [121]. Compared to the TCD and DWC, the SSC offers two additional degrees of freedom, namely the side-draw flow rate and side-draw location. It also provides better control performance since it avoids the loss of control degrees of freedom that occurs in TCD and DWC when combining reboilers or condensers [122,123]. Overall, the SSC configuration presents an attractive alternative for PI in distillation processes.

3.2.5. Reactive distillation

The coalescence of reaction and separation within RD offers savings

in cost and energy by improving the selectivity and yield of reaction through simultaneous operation in a single apparatus [124,125]. RD brings economic benefits compared to traditional systems that feature distinct reaction, separation, and recycle phases, especially in the case of reversible reactions constrained by chemical equilibrium and vapor-liquid equilibrium restrictions. Nonetheless, the applicability of RD is limited by the need for compatibility between the reaction and separation conditions, particularly in terms of pressure and temperature. Therefore, a critical challenge in the design and operation of RD is to ensure that the optimal operating windows for reaction and separation coincide and overlap within a feasible pressure and temperature range [126]. When such alignment is not achievable, one practical solution is to employ a column with a side reactor configuration [127,128].

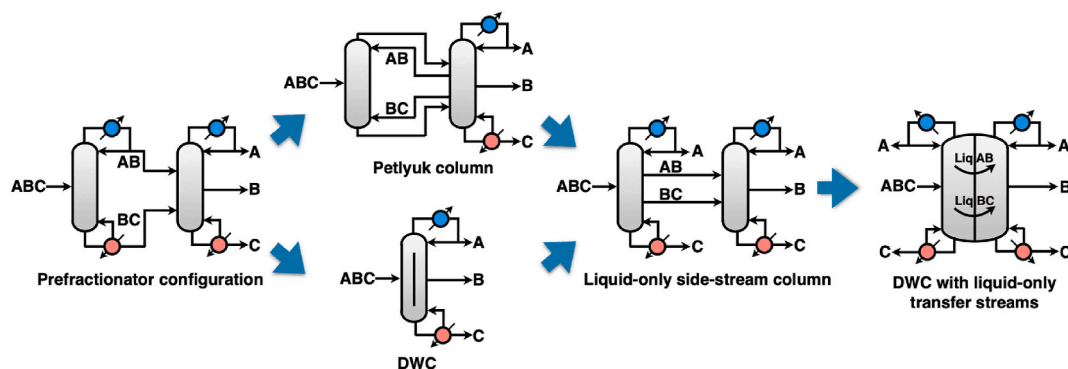


Fig. 13. Distillation configurations with liquid-only transfer streams.

Hussain et al. [129] presented guidelines that offer insights into the applicability of a side reactor configuration for a wide range of conventional or RD processes. Fig. 14 displays these configurations, showing the structural variances between the two methods.

4. Design of electrified distillation processes

This section reviews and examines different electrified systems designed for zeotropic, azeotropic, and reactive distillations. The main focus of this section is on modifying distillation processes, with limited attention given to the associated site utility systems.

4.1. Electrified zeotropic distillation

Separating multicomponent zeotropic mixtures by simple distillation column (one column separates two products) can result in a large number of possible distillation sequences. For a five-component mixture, there are 14 possible sequences, this number increases significantly to 4862 for a ten-component mixture [130]. Identifying the optimal distillation sequences represents a classic problem in process synthesis. However, this section does not primarily address the selection of distillation sequences. Instead, the focus is given to intensified distillation configurations, such as DWC. The discussion initially covers binary, ternary, and quaternary distillation processes, and then proceeds to examine high-temperature petroleum fractionators and cryogenic air separation.

4.1.1. Binary separation

Distillation exploits the difference in boiling points of the liquids involved. The separation can be classified into close-, middle-, and wide-boiling based on the boiling point difference, although these categories are not strictly defined. Electrification of distillation processes, especially when incorporating heat pumping, is particularly beneficial for separating close-boiling species, resulting in a high COP as illustrated in Eq. (5).

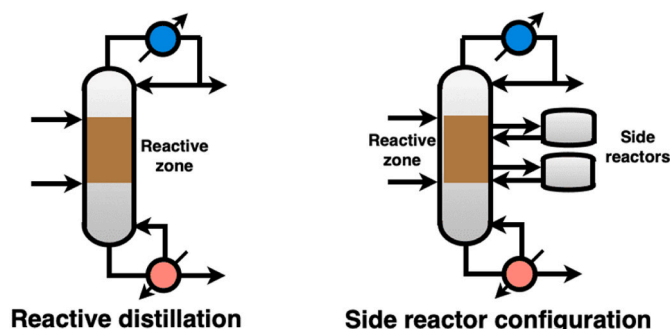


Fig. 14. Reactive distillation and side reactor configurations.

Numerous studies have delved into close-boiling binary distillation, investigating various electrification methods as covered in Section 3.1. One notable example is the work by Li et al. [131], where an electrified distillation process was developed for separating close-boiling ethylbenzene/styrene monomer (EB/SM). The normal boiling points of EB and SM are 136.2 and 145.7 °C, respectively. Conventional distillation column consumed 3819 kW of low-pressure steam. By optimizing the process superstructure of Figs. 7 and 15 shows the optimal SHRT-assisted distillation. The GCC analysis indicated that all the required heat was circulated within the system, with electrical power being the sole resource used. The COP for the heat pump is $(3941 + 170)/444 = 9.26$, which indicates a substantial decarbonization benefits. When examining the conventional distillation process powered by natural gas, carbon emissions are quantified at 1062 kgCO₂/h. In contrast, an electrified distillation process, considering the current grid electricity carbon intensity of China at 530.85 gCO₂/kWh, results in carbon emissions of 235.7 kgCO₂/h. This represents a carbon emission reduction of 77.8 %. Furthermore, as the grid transitions to low-carbon electricity sources, the potential for carbon reduction increases even more.

For the efficient electrification of middle- or wide-boiling distillation systems, an essential factor is to boost the COP of the heat pump by minimizing the temperature difference between heat sources and sinks. A pragmatic approach is to incorporate intermediate heat exchangers (IHEs), in which the intermediate reboiler (IR) is frequently used. Indeed, IHEs can be advantageous even in a common column as they can be operated using less expensive heating or cooling utilities [132,133]. Agrawal and Herron [134,135] provided guidelines for the optimal arrangement of IHEs from an economic perspective. Another method is to compress side vapor streams using a heat pump. In some cases, both IHEs and side streams may need to be utilized in conjunction with the heat pump. Lynd and Grethlein [136] proposed various techniques for electrifying wide-boiling systems via MVR, as depicted in Fig. 16. These methods have been proven effective in diminishing the temperature difference between heat sources and sinks, thereby enhancing the overall energy efficiency. It is worth noting that the heat pumps can be of the closed-cycle VC type, as demonstrated by Björn et al. [137]. As a practical method, the tool of column grand composite curve (CGCC) can be used to simultaneously identify the temperature difference of heat sources and sinks, the allocated stage number of IHE, and the approximate amount of energy consumption [138].

In addition to single-stage compression, multi-stage compression systems can be effectively implemented in certain cases. Shenvi et al. [139] developed a multi-stage vapor recompression scheme with IHEs for a binary distillation column, as presented in Fig. 17. Several alternative configurations of MVR have also been explored to conduct a comparative analysis with the HIDiC design. The authors concluded that there is no universally optimal heat integration scheme for all cases, and the most energy-efficient approach may vary depending on the specific circumstances. Additionally, electrification efforts are occasionally

Table 5

Summary of studies on process intensification and electrification of binary distillation.

System	Intensification technique	Electrification technique	Main remarks	Reference
Methanol/water	MED	MVR with IR	A hybrid design combining MED and MVR to achieve energy saving based on the tool of CGCC.	[140]
Ethanol/water	FP	MVR	Conducting exergetic, environmental, and economic impact of the electrification of a bio-refinery plant.	[141]
Bioethanol/water	FP	SHRT	A pilot scale plant was test and show the SHRT save considerable amount of energy consumption.	[142]
Ethane/ethylene	PCS and pre-throttle cooling	MVR and BF	BF outperforms MVR, and together with a pre-throttling cooler it provides the minimum TAC.	[71]
Propane/propene	FP and CIP	MVR and SHRT	MVR can eliminate the need for reboiler steam, and SHRT utilizes the remaining sensible heat to preheat the feed and compressor inlet stream in MVR.	[82]
Ethylbenzene/styrene	FP	VR and MVR with IHEs	Designing an isomer splitter to remove small amounts of low boilers.	[143]
i-Butane/n-butane	FP	MVR and SHRT	Proposed electrical-driven process saves 67.19 % operating cost compared to the conventional column.	[144]
n-Heptane/i-butanol	FP	MVR	Compared to a conventional refrigerated distillation system, the proposed high-pressure arrangement with MVR and heat integration can reduce TAC and CO ₂ emissions by 18.10 % and 75.01 %, respectively.	[145]

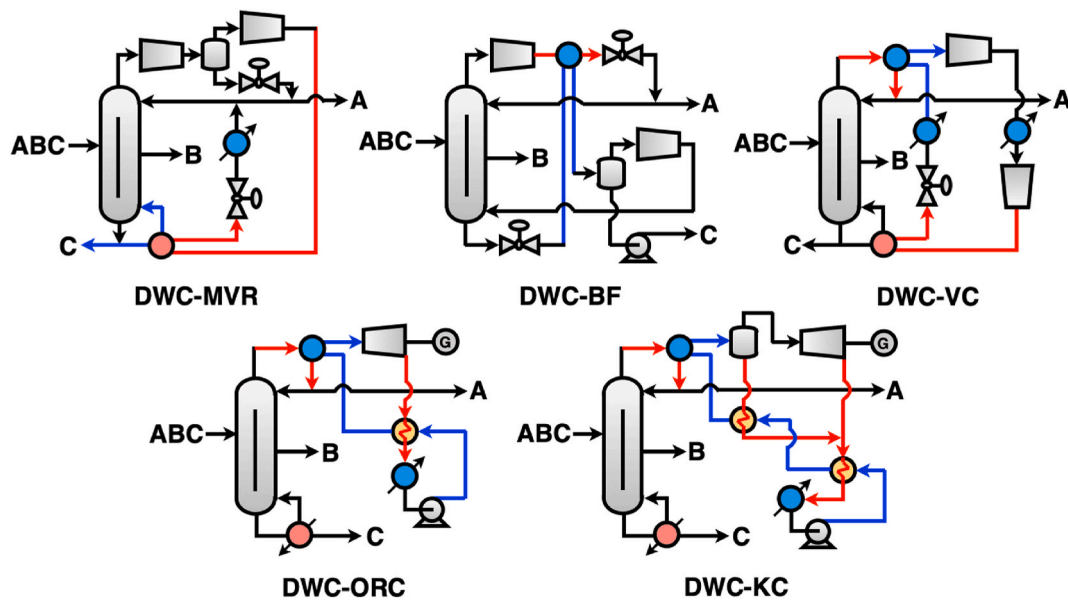


Fig. 18. A schematic representation of electrified DWC systems.

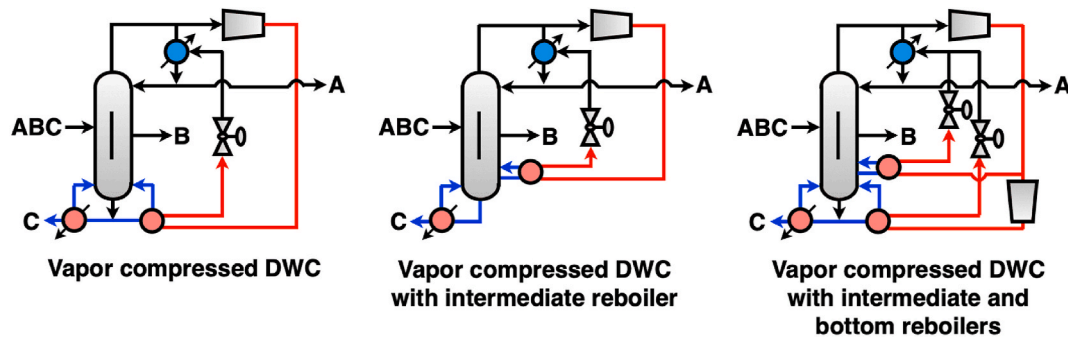


Fig. 19. A diagram of electrified DWC systems with intermediate and bottom reboilers.

minimal modifications to a conventional DWC design. Alongside the works mentioned above, Table 6 provides an overview of other relevant studies focusing on intensification and electrification of ternary distillation processes. These processes generally save energy consumption and associated carbon emissions compared to their corresponding benchmark designs.

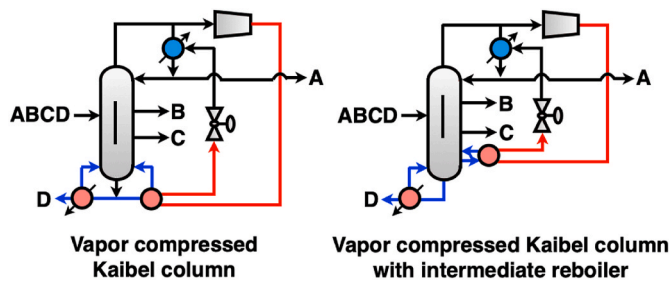
For quaternary distillation, Kaibel column is a prominent PI

approach saving approximately 40 % energy consumption compared to the conventional column [148,149]. To electrify the Kaibel column, vapor compression heat pump can be employed. Qian et al. [150] proposed two intensified Kaibel column configurations by integrating MVR and IR, as illustrated in Fig. 20. The results confirm that operating cost as well as carbon emissions can be substantially reduced.

Table 6

Summary of studies on process intensification and electrification of ternary distillation.

System	Intensification technique	Electrification technique	Main remarks	Reference
1,3-butadiene from crude C4 cut	DWC	MVR	Compared to BASF baseline, heat pump-assisted DWC can reduce energy consumption and TAC by approximately 55 % and 30 %, respectively.	[151]
Ethylene dichloride purification	DWC	MVR	The completely electrical-driven process reduces 83.7 % operating cost compared to the baseline of SSC.	[152]
Acetic acid purification	DWC	MVR	The electrical-driven DWC reduces 85.8 % of operating cost compared to the benchmark SSC.	[152]
n-pentane/n-hexane/n-heptane	DWC	MVR with IR	The electrical-driven process reduces 61.3 % of operating cost compared to the benchmark SSC.	[152]
Three ternary systems with different ESI (ease of separation index)	DWC	MVR with or without IR	Using the CGCC to determine the type of phase withdrawn from the side product stage and locate the intermediate heat exchanger regions.	[153]
Benzene/toluene/xylene	DWC and ORC	MVR	The authors evaluated several processes with energy, exergy, economic and environmental analysis, showing the cascade utilization of steam can effectively increase the economic benefit and decrease energy consumption of DWC with the large temperature difference between top and bottom.	[154]
(1) i-pentane/n-pentane/n-hexane; (2) benzene/toluene/ethylbenzene	DWC	(multistage) MVR with or without IR	Using the tool of CGCC, simulation results in two separation cases show that the proposed electrified process can largely improve the energy-saving performance of DWC.	[155]
C1/C2/C3 cuts	FP	BF	Compared to the conventional direct sequence distillation, the electrified process reduces energy requirement and TAC by 40.3 % and 20.7 %, respectively.	[156]
Ethanol/water/ethylene glycol	DWC	Side vapor MVR	Utilizing the latent heat of a vapor stream from an intermediate tray, the compression ratio can be reduced. Overall, the proposed electrified process achieves high advantages in energy and economics.	[157]

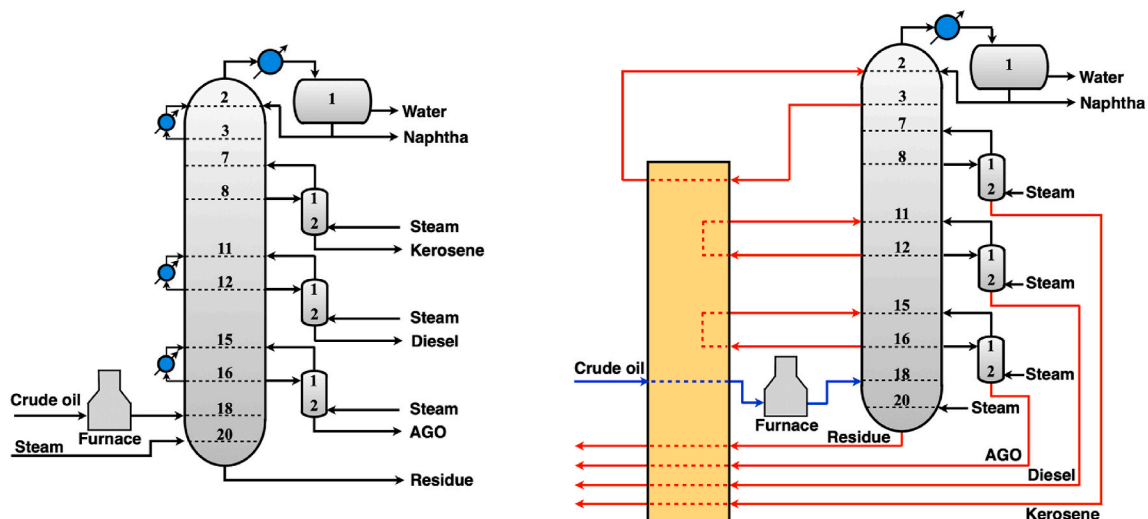
**Fig. 20.** A diagram of electrified Kaibel column with intermediate and/or bottom reboiler.

4.1.3. Crude oil distillation

The CDU in a petroleum refinery is notably large-scale and energy-intensive, accounting for approximately 30–40 % of the total energy usage [158]. To decrease both energy consumption and carbon

emissions, various improvement measures have been proposed, including alterations in operating conditions, heat exchanger networks, and stage locations [159,160]. The CDU employs techniques not commonly seen in typical distillation, such as pump-arounds, side strippers, and steam injection [161]. Fig. 21 shows the flow diagram of conventional atmospheric distillation column with and without heat integration. In a heat-integrated CDU, the crude oil is preheated by the product streams and pump-around circuits before entering the atmospheric furnace [162]. Apart from process optimization without altering the main column structure, an important PI measure for CDU involves developing innovative distillation sequences to reduce energy consumption [163,164]. In this regard, Mathew et al. [165] developed new distillation configuration options that uses 15 % less energy and produces 16 % less CO₂ emissions than their conventional industrial counterparts, exemplified by separating a light crude feedstock of ExxonMobil.

The current commercial CDUs primarily require large amounts of high-temperature heat. If the thermal-furnace is replaced by electric

**Fig. 21.** A flow diagram of conventional CDU and heat-integrated CDU.

furnace, the electrification would be very difficult as it falls under the level 3 mentioned in Section 2.1. However, by modifying the process, easy-to-implement electrification can be achieved. In this context, Kansha et al. [166] incorporated a SHRT into the CDU, as shown in Fig. 22. This innovative design featured four distillation modules and five compressors, with the entire process heat being recuperated within each module without additional heat input, falling under the level 2 of process electrification. Eventually, the whole process was able to be fully powered by electricity. However, it is important to highlight that this electrified process required compressors capable of operating at high temperature and handling heavy oil vapor. Taking an example of 795 m³/h (standard liquid volume) crude oil feedstock, 174.86 MW was required for the furnace without heat recovery. When considering heat integration, the total energy required for thermal- and electrical-driven CDUs was 50.67 and 26.29 MW, respectively. This was equivalent to a 48 % energy reduction when using electrification instead of heat. However, this reduction was unsatisfactory when taking into account primary energy calculated by power generation efficiency, which was 36.6 % according to the Japanese energy saving law. Considering the natural gas as the fuel in the furnace, the carbon emissions are 14.09 ton-CO₂/h. Based on the current Japanese grid carbon intensities of 0.483 ton-CO₂/MWh (Fig. 3d), the carbon emissions of the electrified CDU are 12.70 ton-CO₂/h. The carbon reduction is 9.87 %. If the carbon intensity of electricity is reduced to 0.085 ton-CO₂/MWh in France, which is dominated by nuclear power, the carbon emissions are reduced to 2.23 ton-CO₂/h, so the carbon emission savings are 84.17 %. From

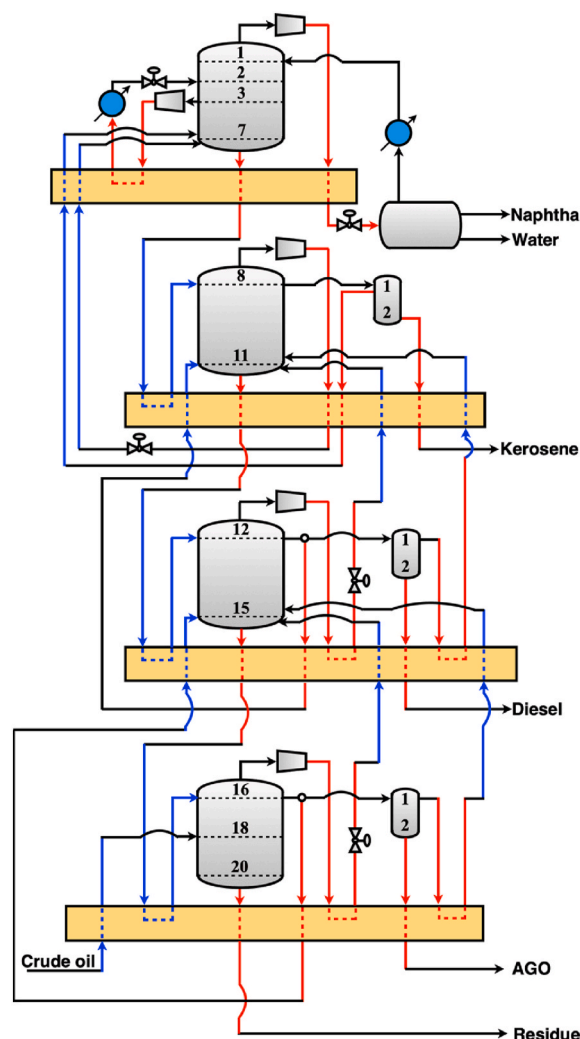


Fig. 22. A flow diagram of electrified CDU.

this analysis, it can be seen that the carbon reduction of distillation column electrification can keep up with the times with the low-carbon power supply, and has the potential for deep carbon reduction. Nevertheless, if low-cost zero-carbon electricity becomes available in the future, the decarbonization advantages of the electrified CDU should be taken into full consideration.

4.1.4. Cryogenic air separation

Although various separation technologies have been developed for oxygen production, air separation unit (ASU) by cryogenic distillation is the only commercially available technology for large scale industrial applications [167]. The process is characterized by its high electricity consumption and can be categorized as an electrified distillation process, thanks to the heat integration that eliminates the need for external thermal energy. Clearly, heat integration via MED has been implemented to save on energy usage. With the implementation of various heat integration methods, the ASU exhibits multiple resulting configurations, with the double-column configurations being the popular choice. The energy consumed by the ASU process mainly comes from the power required by the air feed compressors. The electricity-intensive ASU can serve as a method for energy storage because ASU can feasibly adjust its operational load to adapt to variations in the electricity supply. Therefore, it has become a feasible way of energy storage with the increased penetration of renewable energy sources in the energy systems. The ASU itself, or in possible combination with liquid air energy storage technology, can help to stabilize the electricity grid by participating in a range of demand response programs and contribute to the integration of renewable energy sources into the energy system [168]. As a result, additional economic benefits can be gained from electricity price arbitrage if the ASU is operated in line with the electricity demands.

To ensure optimal operation of ASUs in the face of time-varying electricity markets, flexible operation is essential. This involves adjusting production rates and storage amounts of cryogenic liquids, which can be facilitated through an integrated liquefaction cycle operated during off-peak electricity periods. The resulting electrical energy can be stored as liquids, and reused either internally, to provide cold energy to assist in column operation or electricity to assist in air compression, or externally, to support grid peak shaving and improve profitability. One example of this approach is the integrated ASU with cryogenic energy storage framework proposed by Zhang et al. [169], which leverages a cryogenic energy storage system to generate electricity by vaporizing liquid oxygen and nitrogen. This enables the electricity to be used internally within the ASU or sold to the electrical grid, depending on prevailing market conditions. Caspari et al. [170] presented an innovative ASU with an integrated liquefaction cycle and liquid assist operation to enhance its flexibility, as demonstrated in Fig. 23. The steady state design and optimization showed that the electricity demand can be varied over a large range from 3.5 to 28 MW without violating operational constraints by changing the oxygen and nitrogen production rates. Such a wide operational range offers great opportunities for the ASU to be actively and flexibly integrated into the fluctuating electricity markets. In addition, a new large-scale application of ASU is oxy-combustion power plants. That is, using oxygen instead of air as the oxidant in fossil fuel-based power plants. This way the produced furnace stack gases have low nitrogen and high carbon dioxide concentrations. Thus, ASU integrated with oxy-combustion is a potential method for economical sequestration of greenhouse gas [171].

4.2. Electrified azeotropic distillation

Azeotropes are characterized by having the same compositions in both vapor and liquid phases [172]. This trait means that simple distillation is insufficient for achieving a complete separation, given the lack of relative volatility differences in components to be separated. Consequently, when dealing with azeotropic mixtures, it is essential to

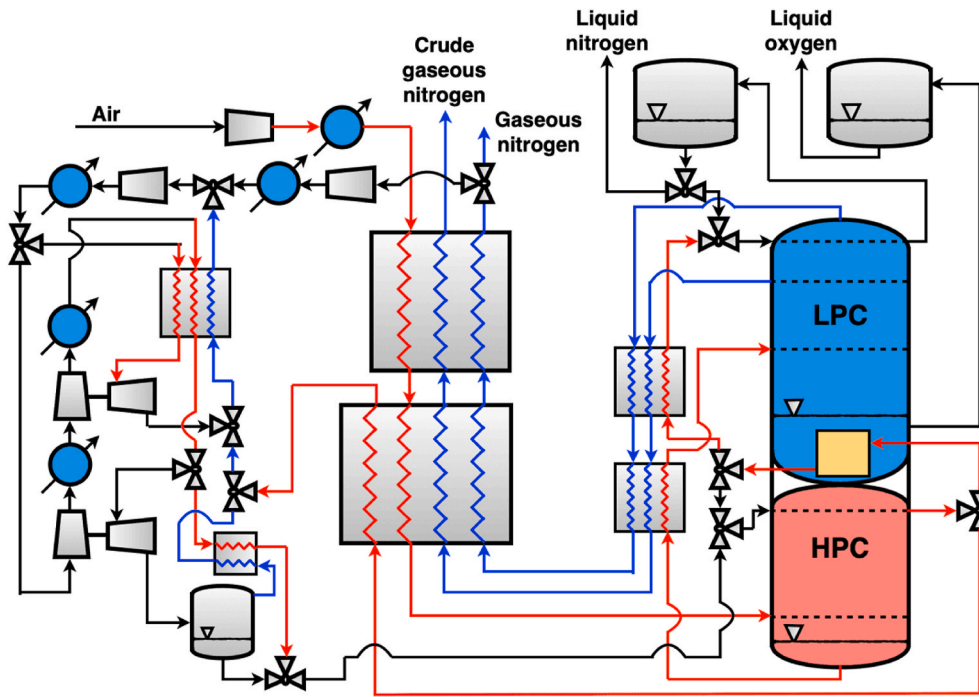


Fig. 23. Process flowsheet of ASU with integrated nitrogen liquefaction cycle.

identity the presence of distillation boundaries that render simple distillation impracticable.

Azeotropes result from the non-ideal phase equilibrium triggered by

molecular interactions between dissimilar chemical components. If these molecules display repulsive forces, the resultant azeotrope will have a minimum-boiling point and can be either heterogeneous or

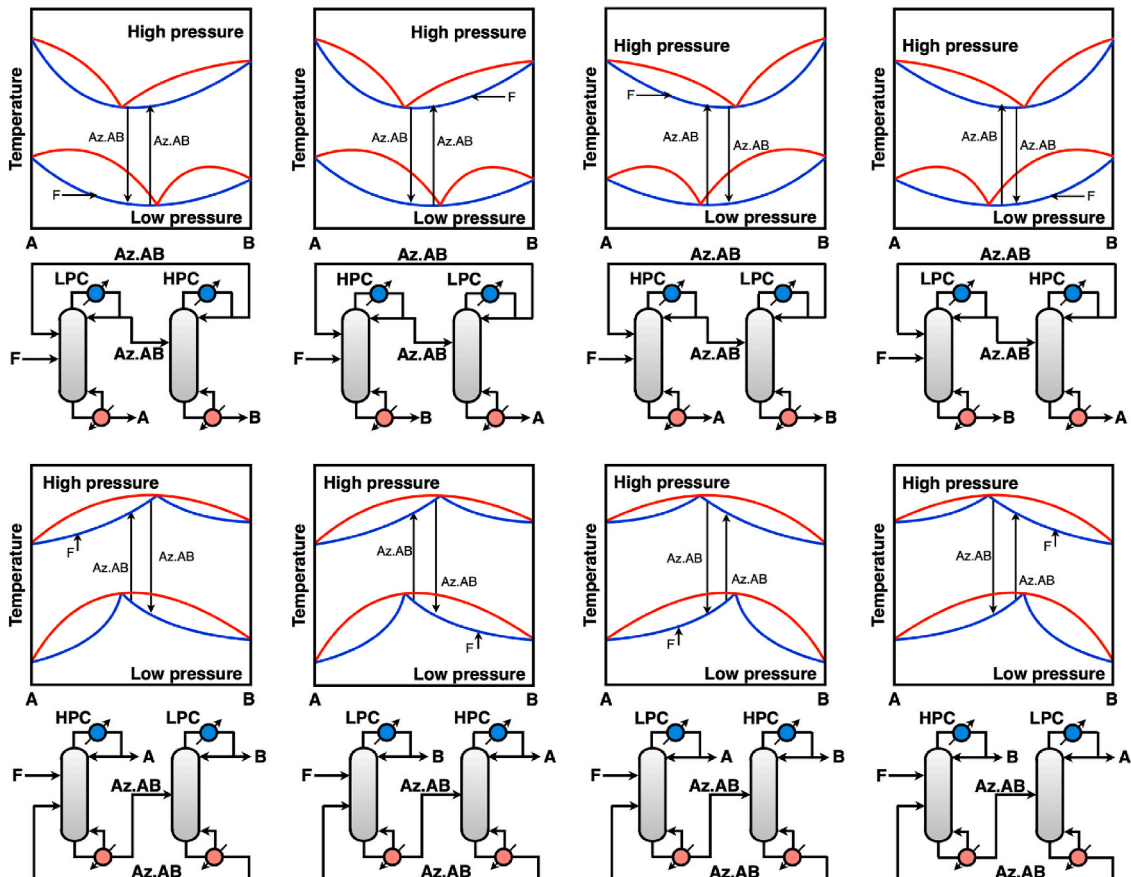


Fig. 24. The classification of PSD configurations for separating pressure-sensitive homogeneous binary azeotropes.

homogeneous. Conversely, if the molecules exhibit attractive forces, the azeotrope will have a maximum-boiling point [173]. Given the distinct physical properties of azeotropes, specific measures for azeotropic distillation are required for their separations.

Heterogeneous azeotropes can be easily separated by utilizing liquid-liquid phase separation in a decanter without the need for a third component. In contrast, the separation of homogeneous azeotropes can be accomplished using various methods such as pressure-swing distillation (PSD), heterogeneous azeotropic distillation (HAD), and extractive distillation (ED). These sections will review the electrification of azeotropic distillations.

4.2.1. Pressure-swing distillation

PSD is a widely employed and efficient method for separating pressure-sensitive azeotropic mixtures. Notably, PSD can achieve pure products without the need for introducing a third component, distinguishing it from ED and HAD. Liang et al. [174] provided an all-encompassing review of PSD, ranging from molecular-level azeotropic phenomena to process-level design and control. While PSD can be applied to separate mixtures with multiple azeotropes, binary systems are used for demonstration. Fig. 24 showcases a classification of various PSD arrangements for separating binary azeotropic systems with distinct feed compositions and thermodynamic properties. If cases where the azeotrope is minimum-boiling, it is extracted from the top and the product streams are obtained from the bottom. In contrast, for maximum-boiling azeotropes, the desired products are derived from the top, and the azeotrope is recycled from the bottoms.

Several studies have focused on MED (either partial or full heat integration) between the HPC and LPC to save energy [175–177]. However, depending on the boiling point difference between products and azeotropes, electrification by MVR can sometimes result in greater

energy savings compared to heat integration [178–180]. Moreover, like zeotropic distillation, the SHRT can also be applied to PSD to recover both latent and sensible heat. In the study conducted by Xia et al. [181], the PSD of a minimum-boiling azeotrope consisting of isopropyl alcohol/diisopropyl ether was investigated. The authors found that PSD-SHRT offers greater energy savings and TAC than PSD-MED. Similarly, Cui et al. [182] proposed PSD-SHRT for separating both minimum- and maximum-boiling azeotropes, specifically tetrahydrofuran (THF)/water and acetone/chloroform. Fig. 25 shows the schematic diagrams of these PSD-SHRT superstructure with PCS, CIP, and FP. Fig. 26 presents a numerical case study showcasing the PSD-SHRT for the separation of acetone/chloroform. The GCC demonstrated that all the heat required for the process is circulated within the system, with the only power consumed being electrical power. In many cases, it is frequently observed that the compressed overhead vapor is inadequate to meet the necessary reboiler duty. In such situations, an electric heater or electrode boiler can be employed to compensate the remaining duty requirement, achieving a fully electrical-driven process.

Table 7 lists relevant works considering different types of electrification on PSD of binary separation. In addition, PSD can be employed for the separation of systems containing multiple azeotropes. In such cases, residue curve maps, distillation boundary analysis and isovolatility curves are utilized to identify the most suitable PSD sequences [183]. Once the fundamental PSD process is established, electrification measures can be subsequently applied.

4.2.2. Heterogeneous azeotropic distillation

HAD involves the addition of a third light entrainer, which carries one of the components overhead in a column and forms two liquid phases in a decanter, permitting the crossing of a distillation boundary. By taking advantage of minimum-boiling azeotropes and liquid-liquid

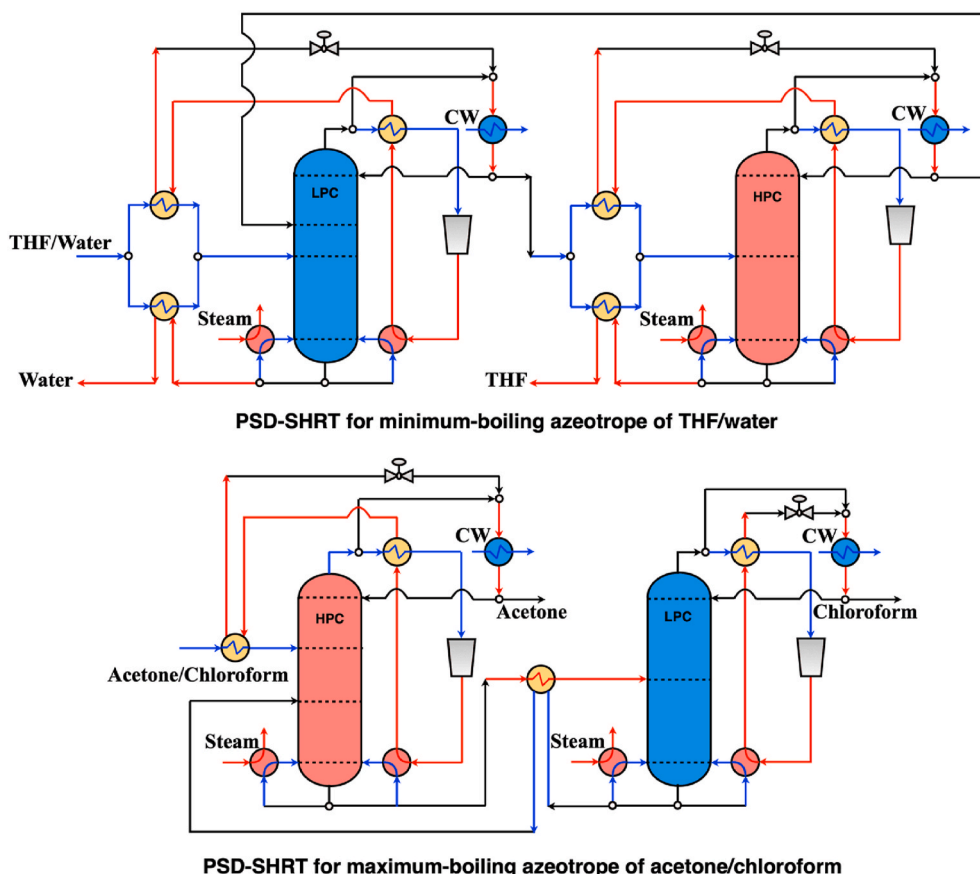


Fig. 25. PSD-SHRT configurations for minimum- and maximum-boiling azeotropes.

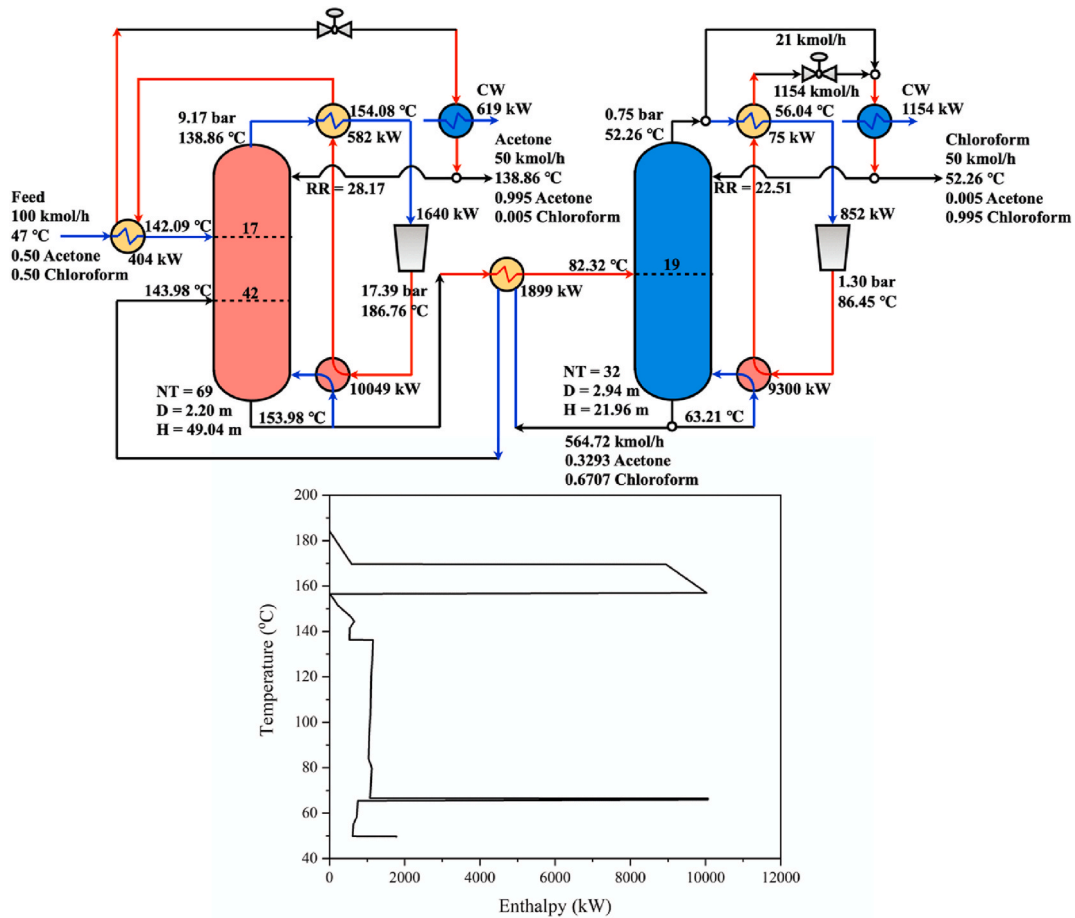


Fig. 26. A PSD-SHRT process for separating maximum-boiling acetone/chloroform azeotrope and its GCC.

Table 7

Summary of studies on process intensification and electrification of PSD.

System	Intensification technique	Electrification technique	Main remarks	Reference
Minimum-boiling ethyl acetate/ethanol	FP/precooling and SSC	SHRT	Compared to benchmark PSD-SSC, the proposed process reduces 72.62 % energy consumption, 89.84 % CO ₂ emissions, and 24.92 % TAC.	[184]
Maximum-boiling ethylenediamine/water	FP	SHRT (MVR and BF)	Compared to benchmark process with partially heat integration, the proposed process achieves the reductions of 59.01 % in energy consumption, 86.60 % in CO ₂ emissions, and 12.78 % in TAC.	[185]
Maximum-boiling methanol/diethylamine	FP	SHRT	Compared to the conventional process, the proposed process can reduce 33.93 % TAC and 89.12 % carbon footprints.	[186]
Minimum-boiling ethyl acetate/ethanol	FP and SSC	SHRT	Compared to benchmark of PSD-SSC, the proposed process reduces 18.81 % energy consumption and 27.97 % CO ₂ emissions.	[187]
Minimum-boiling isopropanol/water	MED	MVR	The electrified PSD reduces 51.30 % TAC in comparison of the conventional one.	[188]
Maximum-boiling ethylenediamine/water	MED	MVR	The electrified PSD has the lower values of Eco-indicator 99 compared to other processes.	[189]
Minimum-boiling i-butanol/isobutyl acetate	FP	MVR	Compared with the conventional PSD, the TAC, energy consumption, and CO ₂ emission of the electrified process are decreased by 69.8 %, 83.99 %, and 79.58 %, respectively.	[190]

immiscibility, HAD overcomes the presence of other azeotropes or tangent pinches in the mixture that would otherwise hinder the desired separation. A typical two-column system is used with one liquid phase from the decanter fed to one column and the other liquid phase fed to the second column. High-purity products are produced from the bottom of the two columns [191]. When the concentration of the crude feed is significantly different from the azeotrope composition, a preconcentration distillation column (PDC) can be incorporated to move the feed composition closer to the azeotropic composition, decreasing the required amount of entrainer flow rate and the associated energy

consumption [192].

Chen et al. [193] proposed multiple HAD processes incorporating MVR and SHRT for the dehydration of tert-butanol using cyclohexane as the light entrainer. Fig. 27 demonstrates the transition from thermal system to an electrified one. The authors discovered that HAD-SHRT could yield significant savings, reducing the TAC by 38.5 %, CO₂ emissions by 93.3 %, and energy consumption by 80.9 % compared to the conventional HAD. Similarly, Fan et al. [194] proposed a systematic approach to determine the optimal combination of SHRT and HAD. The feasibility of the systematic method was examined using two systems:

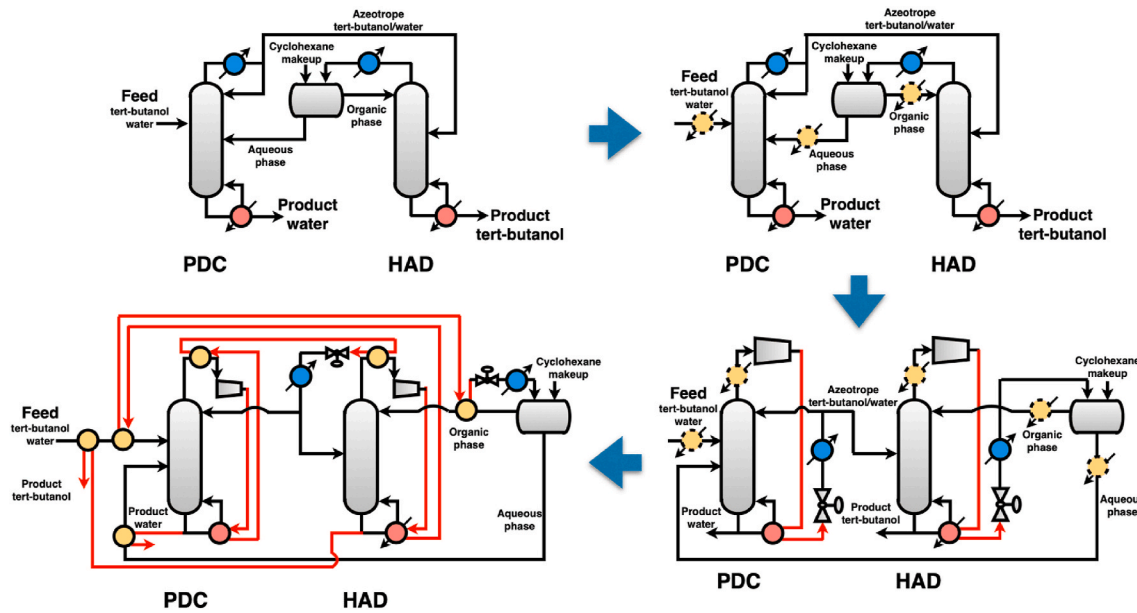


Fig. 27. A transition shift from thermal HAD to electrified HAD.

pyridine/water with toluene and 1,4-dioxane/water with triethylamine. When the maximum heat provided by the compressed stream is equal to or greater than the hot utility requirement of the reboiler, the overhead vapor is directly compressed to provide heat for the bottom stream. Otherwise, adding preheating or auxiliary reboilers are favorable options in terms of economic and energy-saving performance.

It is worth noting that combining electrification with PI options such as A-DWC could achieve better performance. For more detailed information and a comprehensive review of these methods, Table 8 provides further insights into the intensification and electrification techniques and their applications in HAD systems.

4.2.3. Extractive distillation

ED is a separation technique that enables the separation of non-ideal mixtures, including minimum- or maximum-boiling azeotropes as well as components with close-boiling points. In an ED process, a third

component known as a solvent or heavy entrainer is introduced near the top of the extractive distillation column (EDC). Note that the solvents can be either pure solvent, mixed solvent, ionic liquid [205] or deep eutectic solvent [206]. The solvent carries one of the components out the bottom of the EDC. A second column, called solvent recovery column (SRC), is employed to regenerate the solvent, which is then recycled back to the EDC. High-purity products are obtained from the top of both the EDC and the SRC. Gerbaud et al. [207] provided a comprehensive review of ED, covering aspects such as design, operation, optimization, and control.

The solvents typically have higher boiling points, making it challenging to implement heat pumps in most cases. However, if the boiling point of the solvent is not significantly higher than the components to be separated, it is possible to radically electrify the ED process using MVR or BF techniques. In this regard, You et al. [208] investigated an ED process of minimum-boiling acetone/methanol with water as the

Table 8

Summary of studies on process intensification and electrification of HAD.

System	Intensification technique	Electrification technique	Main remarks	Reference
Ethanol/water (benzene as entrainer)	FP	SHRT	Reduce 12.3 % energy required compared to the benchmark	[195]
Tert-butanol/water (cyclohexane as entrainer)	DWC	MVR	Reduce 32.22 % TAC compared to the benchmark	[196]
Isopropyl alcohol/water (cyclohexane as entrainer)	DWC	MVR	Reduce TAC and CO ₂ emissions compared to the benchmark of A-DWC	[197]
Acetonitrile/ethyl acetate/n-hexane (no entrainer)	FP	MVR	Compared with conventional HAD process, the proposed process achieves the reductions of 52.17 %, 68.86 %, 65.87 %, and 65.46 % on TAC, energy consumption, gas emissions and exergy destruction, respectively.	[198]
Tert-butanol/water (cyclohexane as entrainer)	DWC	MVR	Compared to the existing A-DWC, the electrified process reduces TAC and CO ₂ emissions by 32.91 % and 86.43 %, respectively.	[199]
(1) isopropyl alcohol/water (cyclohexane as entrainer); (2) pyridine/water (toluene as entrainer)	DWC	MVR	The proposed electrified process has higher capital investment but a considerably lower operating cost leads to a reasonable payback time, compared with the benchmark process.	[200]
Cyclohexane/tert-butanol/water (no additional entrainer)	FP	MVR	The proposed electrified HAD-PSD process exhibits decreases of 41.98 %, 55.32 %, 52.30 %, and 55.26 % for TAC, total energy consumption, CO ₂ emissions, and exergy destruction compared to conventional HAD-PSD.	[201]
Acetone/butanol/ethanol/water	DWC	MVR	The proposed electrified process allows 60 % energy saving compared to a conventional separation sequence.	[202]
Ethylenediamine/water (N-propyl acetate as entrainer)	DWC	MVR	Compared to the conventional HAD, heat pump assisted A-DWC allows 42.93 % energy and 24.36 % TAC savings with a payback period of 8 years.	[203]
Production of furfural from water, methanol, and acetic acid	DWC and FP	MVR	The proposed sequence can reduce TAC and carbon footprint by 10.1 % and 11.6 % respectively compared to the conventional sequence.	[204]

solvent. The authors examined the performance of MED, MVR, and BF, as depicted in Fig. 28. They proposed new configurations of partial MVR and partial BF heat pumps, leveraging the small temperature difference between the bottom of the EDC and the top of the SRC to enhance the overall efficiency.

Zhu et al. [209] have developed several electrified E-DWC processes in wide-boiling systems. The distinguishing feature of these designs is the incorporation of an IR, which enables the effective separation of wide-boiling systems. Fig. 29 illustrates one of the E-DWC designs with an IR and MVR. These innovative designs aim to enhance energy efficiency, reduce carbon emissions, and promote the integration of renewable energy sources in the ED process, thereby contributing to the broader goal of decarbonization.

Similar to the HAD, a PDC can be added for the sake of reducing the energy cost and TAC. For separating minimum-boiling azeotropes, the top product of the PDC is identical to the products obtained from either EDC or SRC. Consequently, the PDC can be merged with either the EDC or the SRC to intensify the process [210,211]. Considering the use of E-DWC, Kiss and Ignat [212] proposed an innovative single step distillation setup for bioethanol dehydration that integrates the functionality of PDC, EDC, and SRC. Later, by considering the above design concepts, Zhang et al. [213] proposed a systematic process synthesis method of designing E-DWC for separating binary minimum-boiling azeotropes. Based on this work, Cui et al. [214] proposed an improved systematic methodology for the synthesis of electrified ED processes. The methodology considers various PI measures, including modifying the PDC into a stripping column, integrating the PDC with the EDC or the SRC,

employing TCD and SSC configurations, adding MVR to drive an IR, and incorporating E-DWC structures. Fig. 30 illustrates the process synthesis method. Research results showed that electrified distillation could save considerable amounts of CO₂ emissions as well as TAC.

A summary of studies on process intensification and electrification of ED is provided in Table 9. The table offers a comprehensive view of research conducted in this field, showcasing the diverse approaches and techniques investigated by different authors. Additionally, it should be emphasized that ED can also be employed for the separation of ternary or even quaternary azeotropic systems [215–218]. Once the optimal foundational ED processes are achieved, similar electrification measures can be implemented.

4.3. Electrified reactive distillation

RD combines reaction and distillation in a single apparatus, benefiting from a suitable operating window in terms of temperature and pressure. This integration overcomes equilibrium limitations, resulting in improved conversion and selectivity [229]. This section examines two approaches in electrified RD configurations: heat pump-assisted RD and microwave-assisted RD.

Regarding heat pump-assisted RD, a study by Jana and Mane [230] evaluated the multiple feed RD column with IRs and MVR schemes, as shown in Fig. 31. The heat pump-assisted column outperformed its conventional counterpart in the case of a wide boiling mixture, achieving an impressive energy saving of 46.2 % and a payback period of 2.74 years for an ethylene glycol system. The authors further

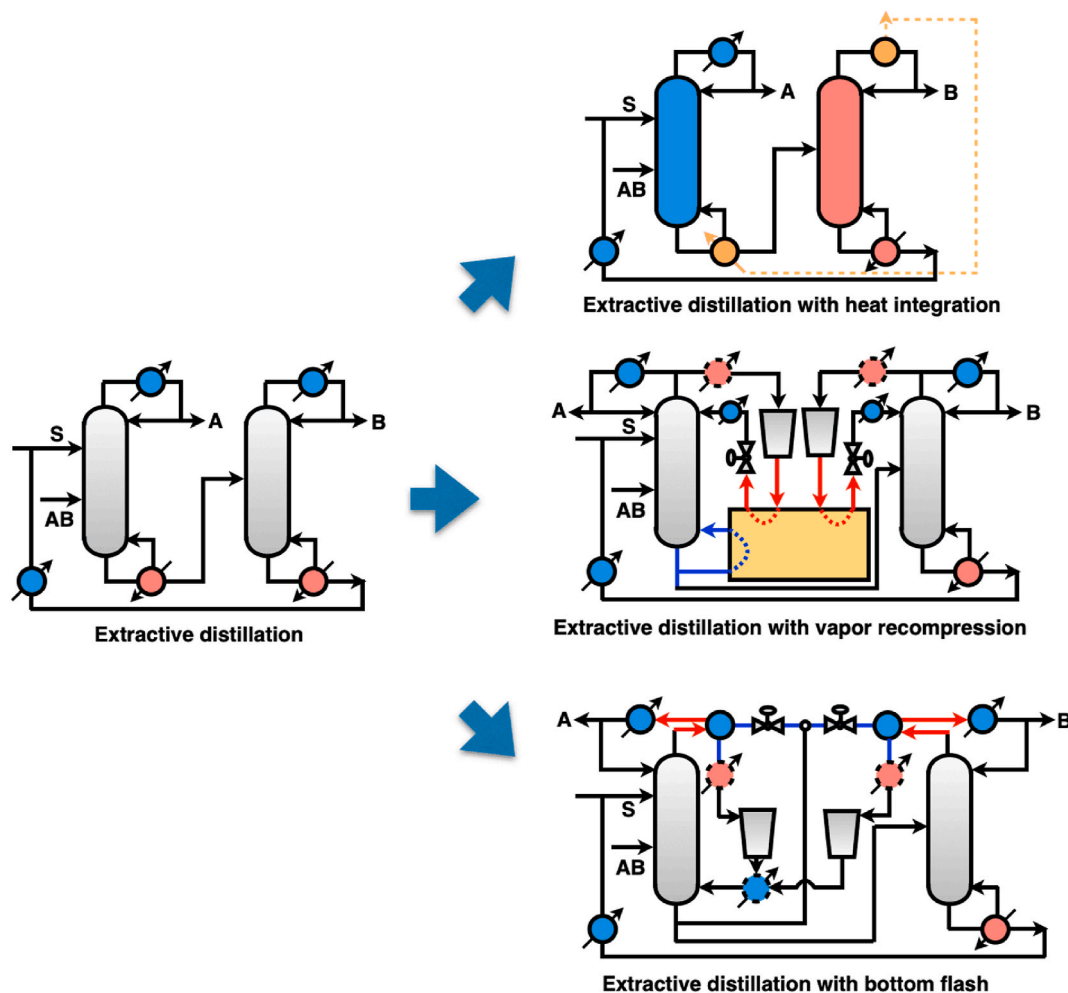


Fig. 28. ED processes with heat integration, vapor recompression, and bottom flash.

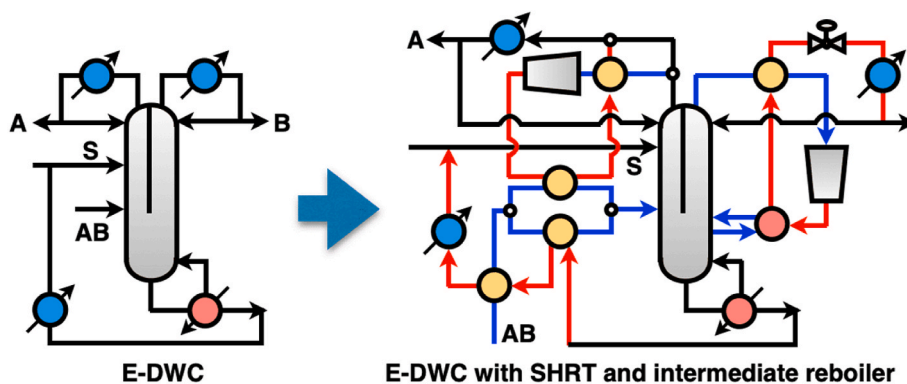


Fig. 29. SHRT assisted extraction distillation processes with IR.

suggested utilizing compressed overheated vapor as a heating medium in the IR and steam in the bottom reboiler.

In a similar vein, Kumar et al. [231] investigated various heat pump arrangements with IRs within the MVR framework. They simulated an industrial RD column producing ethyl *tert*-butyl ether (ETBE) to demonstrate these proposed schemes for separating mixtures with significantly different boiling points. The multistage vapor recompression column, shown in Fig. 32, addressed practical concerns and achieved substantial energy savings (50.6 %) with a reasonably low payback period (3.23 years).

RD can be combined with DWC to intensify the process before implementing electrification. Electrical-driven R-DWC commonly incorporates suitable heat pumps. Table 10 presents several beneficial RD processes with intensification and electrification.

In addition to heat pumps, alternative electric energy forms, such as microwave energy, can expand the operating window of RD [232,233]. While the TRL of microwave heaters is relatively low compared to heat pumps, microwave irradiation offers the advantage of influencing the thermal separation of molecules and accelerating chemical reactions, which cannot be achieved with heat pumps. Research suggests that microwave irradiation affects the separation of mixtures, leading to a more efficient distillation process. Studies indicate that microwaves enhance the concentration of low-boiling components in the vapor phase [234] and even impact the position of an azeotrope in terms of temperature and composition [235]. Furthermore, applying a microwave field in the reactive section of an RD column can induce local heating, such as superheating the liquid phase in homogeneously catalyzed RD or selectively heating solid catalyst particles (hot spot) in heterogeneously catalyzed RD [33]. Higher temperatures resulting from microwave heating can significantly increase reaction rates, leading to improved conversion. For example, Li et al. [236] reported on microwave-assisted RD of catalytic homogeneous esterification of phthalic anhydride with 2-ethylhexanol to produce diethyl phthalate. The authors found that microwaves altered the relative volatility of the system, improving overall performance. However, despite the promising potential of microwave-assisted RD, Werth et al. [33] conducted a systematic investigation and case study on microwave-assisted RD in homogeneously catalyzed transesterification of dimethyl carbonate with ethanol. The results showed no evident enhancement in separation and reaction performance.

5. Control of electrified distillation processes

Most studies discussing the transition of thermal distillation to electrified distillation primarily concentrate on steady-state design, as reviewed in previous sections. As for control of electrified distillation processes, there are mainly two significant challenges: (1) the implementation of electrification measures typically complicates the process dynamics [246]; (2) the introduction of renewables makes the control

contend with the natural intermittency and fluctuations properties.

For the former challenge, adding heat pump typically complicate process design by increasing interactions. Consequently, this may diminish the control degree of freedom, accelerate dynamics and introduce more pathways for disturbance propagation. For instance, Patraşcu et al. [247] investigated the controllability of a heat pump-assisted E-DWC. They discovered instability at the designated operating point due to uneven heat distribution, necessitating the introduction of additional reboilers to enhance control performance. Despite attempts to increase control degrees of freedom, the complex and highly integrated nature of the process rendered the measures insufficient in effectively mitigating significant disturbances.

For the latter challenge, process control must deal with the intermittency and fluctuations associated with renewable energy sources. One cost-effective solution involves adequate energy storage. Alternatively, these uncertainties can be factored into integrated scheduling, design, and control processes. Predictive analytics and machine learning algorithms can play pivotal roles in this integrated concept. These research topics are closely related to energy management systems, which is out of the scope of this review article.

So far, most of the existing literature regarding the control of electrified distillation mainly focuses on the isolated distillation systems. This implies an assumption that the associated utility systems are capable of supplying energy to the distillation systems continuously, steadily and with quick responsiveness. Given this context, the objective here is to discuss and review the fundamental distillation control structures instead of considering plantwide control of multi-scale systems.

5.1. Control structure

In the context of chemical processes, control structures refer to the arrangement and configuration of control systems used to regulate and optimize process operations. The main objective of distillation control is typically to ensure column stability and maintain the product purity within the desired range while overcoming disturbances [248]. To achieve desired production targets and maintain safety, it is necessary to develop appropriate control structures that keep process variables such as temperature, pressure, flow rate, composition, and level within specified ranges [249,250]. Chemical processes employ various control strategies to regulate and optimize their operations. Some common control strategies include feedback control, feedforward control, cascade control, ratio control, override control, and model predictive control (MPC) [251–253]. Among these strategies, the basic PID (proportional-integral-derivative) feedback controller is the most widely used.

In the design of a feedback control structure, it is essential to establish multiple control loops that pair a manipulated variable (MV) and a controlled variable (CV). It is important to note that if an

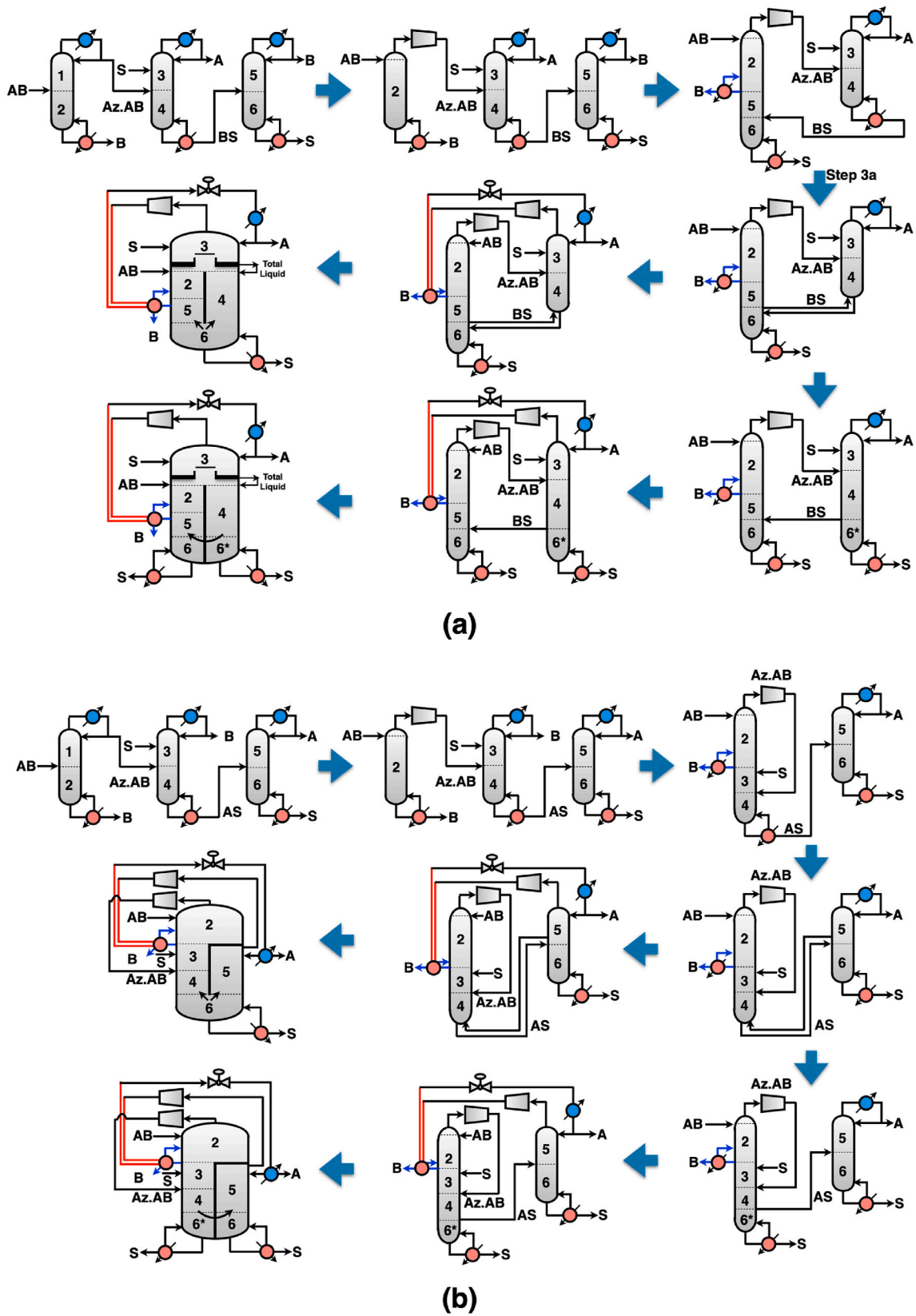


Fig. 30. An improved systematic process synthesis method for ED with PDC: (a) combining PDC with SRC and (b) combining PDC with EDC.

unsuitable feedback controller is employed, the process has the potential to become closed-loop unstable. Therefore, ensuring stability is of vital concern in feedback control systems. This emphasizes the need to design robust control structures based on PID controllers. Furthermore, more

advanced techniques such as MPC are also commonly utilized in these applications. Though their implementation requires more effort, advanced control techniques provide better control because they account for the strong interactions between process variables that arise

Table 9
Summary of studies on process intensification and electrification of ED.

System	Intensification technique	Electrification technique	Main remarks	Reference
Acetone/methanol (water as entrainer)	FP	MVR	Compared to the original ED process, the improved process achieves 52.46 % improvement in thermodynamic efficiency and 35.15 % energy saving.	[219]
Ethanol/water (ethylene glycol as entrainer)	DWC	MVR	Compared to the classic sequence, the MVR-assisted E-DWC save energy consumption and TAC by 40 % and 24 %, respectively. The specific energy requirements drop from 2.07 kWh/kg (classic sequence) to only 1.24 kWh/kg ethanol (MVR-assisted E-DWC).	[220]
Ethyl acetate/isopropanol/water (ethylene glycol as entrainer)	FP	MVR	Compared to the basic process, the electrified ED performs well in both economy and environment. This work also showed that the pervaporation-distillation hybrid process showed poor economic performance due to huge equipment costs.	[221]
Ethanol/ethyl propionate (isobutyl acetate as entrainer)	FP	MVR	Compared to the ED-TC, the electrified ED reduces TAC and CO ₂ emission by 21.09 % and 48.32 %, respectively.	[222]
Acetone/n-heptane (benzene as entrainer)	FP	MVR	The comparison with the indirect ED sequence shows that direct ED-MVR can cause an 83.38 % in steam consumption. While the indirect ED-MVR can save TAC and CO ₂ emissions by 8.24 % and 26.87 %, respectively.	[223]
Ethyl acetate/isopropanol/water (30 % dimethyl sulfoxide + 70 % ethylene glycol as entrainer)	FP or TC	MVR	Compared to conventional ED with mixed solvent, the TAC and CO ₂ emission of the electrified ED are reduced by 34.782 % and 37.156 %, respectively.	[224]
Tetrahydrofuran/isopropanol/water (dimethyl sulfoxide as entrainer)	MED and FP	MVR	Compared to the direct ED, the electrified ED with double heat pump reduces energy consumption and TAC by 64.97 % and 34.26 %, respectively.	[225]
Cyclohexane/sec-butyl alcohol/water (ethylene glycol as entrainer)	TC	MVR	The proposed electrified ED combining TC and MVR exhibits better thermo-economic and environmental performances.	[226]
Ethanol/water (ethylene glycol as entrainer)	DWC	MVR	The electrified E-DWC can save cooling, heating, and total required energies by 19.24 %, 38.61 %, and 18.77 %, respectively, compared to conventional ED.	[227]
n-Hexane/1,2-dichloroethane (N-methyl-2-pyrrolidone as entrainer)	FP	BF and/or MVR	The results show that the thermodynamic efficiency increases from 7.63 % for benchmark ED, to 13.76 % for BF-assisted ED, and 13.16 % for BF-MVR-assisted ED, while CO ₂ emissions can be reduced by approximately 40 % for electrified ED processes.	[228]

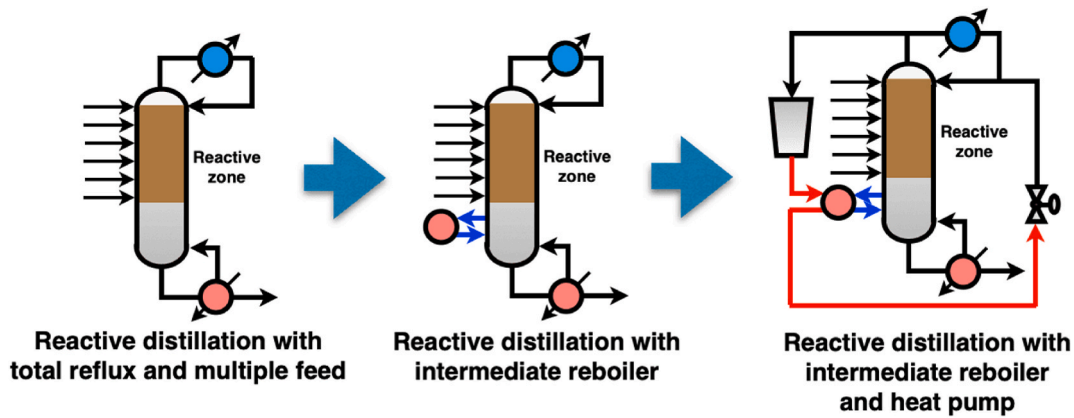


Fig. 31. SHRT assisted extraction distillation processes with IR.

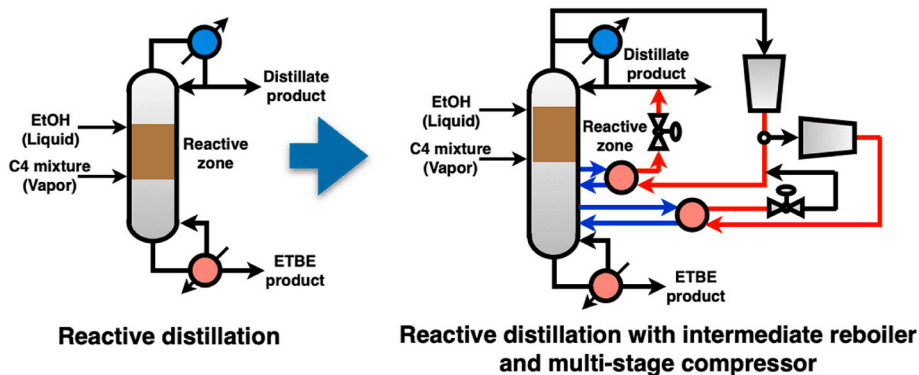


Fig. 32. Reactive distillation processes with IR and multistage compressor.

Table 10
Summary of studies on process intensification and electrification of RD.

System	Intensification technique	Electrification technique	Main remarks	Reference
Transesterification of methyl acetate and n-butanol to yield n-butyl acetate	DWC	MVR	Reduce TAC and CO ₂ emissions compared to the benchmark of A-DWC	[197]
Esterification of methanol and acetic acid to produce methyl acetate	DWC	SHRT	Compared with R-DWC, the R-DWC-SHRT reduces energy consumption by 58.1 % and TAC by 17.8 %.	[237]
Transesterification of methyl acetate and isopropanol to yield isopropyl acetate and methanol	DWC and FP	MVR	Compared to the corresponding R-DWC, the proposed R-DWC with MVR and FP saves 49.86 % energy consumption and 13.76 % TAC.	[238]
Esterification of acetic acid and isopropanol to synthesize isopropyl acetate	DWC	MVR	Compared to conventional RD, the TAC of RD-MVR and R-DWC are reduced by 13.46 % and 21.31 %, CO ₂ emissions are reduced by 13.25 % and 20.17 %, respectively.	[239]
Direct hydration of cyclohexene to cyclohexanol	Side stripper	MVR	Compared to conventional organic-phase-refluxed RD, the proposed heat pump-assisted electrified RD saves energy by 58 %, reduces CO ₂ emissions by 62 %, and reduces TAC by 24 %.	[240]
Synthesis of ethyl propionate	/	MVR	Compared to the conventional RD process, the electrified RD reduces CO ₂ emissions by 59.39 % and TAC by 17.09 %.	[241]
Methyl lactate hydrolysis	PCS	MVR	Compared to the conventional RD, the proposed electrified RD with PCS and MVR save energy by 64.9 %, and reduces TAC by 33.8 %.	[242]
Synthesis of n-propyl propionate	DWC	MVR	Compared to the conventional two-column RD system, the electrified RD saves 57.06 % of total utility consumption, 31.31 % of TAC, and 61.52 % of CO ₂ emissions.	[243]
(1) Esterification of mixed acid with methanol; (2) Reaction of glycerol and hydrochloric acid	DWC	MVR	Simulation results demonstrated that the R-DWC with MVR can substantially reduce utility consumption of R-DWC.	[244]
Two consecutive transesterifications of dimethyl carbonate and ethanol	DWC	MVR	Compared to conventional R-DWC, the R-DWC with MVR reduces the energy consumption by 32.1 % and cut the total utility cost by 21.6 %.	[245]

due to intensification and electrification. In MPC, rather than pairing one CV with one MV, multiple MVs are used to control multiple CVs.

Control structures can be classified as either "conventional" or "on-demand" based on the variable that determines the throughput [254]. Fig. 33 shows a comparison of conventional and on-demand control structures for a binary distillation column. In a conventional control structure, the feed stream to the column is determined by the upstream unit, while an on-demand control structure sets the throughput based on the flow rate of one of the product streams. In the majority of columns, the feed stream originates from an upstream unit, resulting in the product streams being influenced by the feed flow rate and composition. Most of the existing literature focuses on these scenarios. However, in certain plants, the flow rate of one of the products is determined by a downstream user. Consequently, the feed stream needs to be

manipulated to maintain material balance. In the following review, on-demand control is used in an ASU for the downstream oxy-combustion.

All the control structures for electrified distillation systems discussed in the following section were designed with the distillation system being the sole focus. In other words, these control structures were developed to meet the control objectives of distillation systems without considering how the column integrates with the larger plant. However, if the entire plant is taken into account, it becomes necessary to have appropriate control structures that can incorporate the column into the overall plantwide environment instead of treating it as an independent unit.

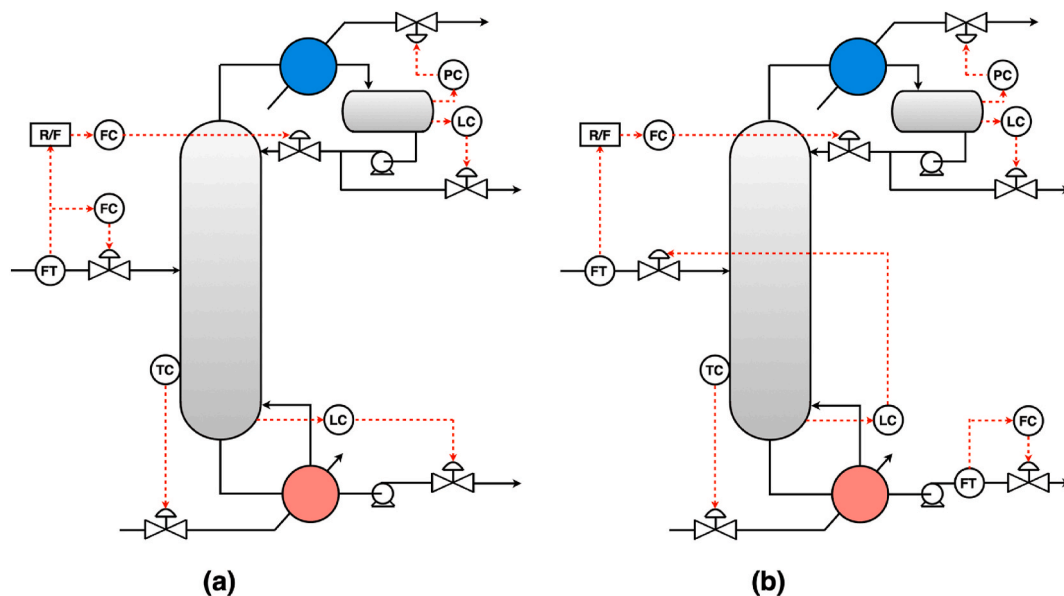


Fig. 33. Control structures for a binary distillation column: (a) basic conventional control structure and (b) on-demand control structure with a flow-controlled bottom stream.

5.2. Electrified zeotropic distillation

This section provides an overview of the control aspects related to the electrified zeotropic distillation, with a particular emphasis on binary separation and ASU. For ternary and quaternary distillation, most of the existing works focused on control of only DWC, using either PID or MPC techniques, without considering the associated electrified techniques [255–257]. For the electrified CDU, there is currently no literature available that specifically discusses its control strategy. This may be attributed to the skepticism about using electrification measures in CDU. Existing research on CDU primarily focuses on conventional designs utilizing either PID or MPC approaches [46,258].

In regulatory control loops, composition controllers have the capability to maintain product quality at the desired values without any offset. However, in industrial practice, the use of tray temperature controller to achieve indirect composition control is more common in quality control loops. This choice is primarily driven by considerations such as the significant time delay associated with composition analysis, as well as the higher capital and maintenance costs of composition analyzer. As a result, only temperature controllers are employed in the regulator control loops discussed subsequently. For the selection of the best location for controlling temperatures, numerous techniques can be applied such as slope criterion, sensitivity criterion, and singular value decomposition [259].

5.2.1. Binary separation

In the context of electrified binary distillation, two relevant studies are reviewed focusing on PID control strategies. Note that usually only proportional-integral actions will be used in distillation control [46].

Li et al. [260] studied the separation of close-boiling i-butanol/n-butanol by using SHRT technology. Fig. 34a illustrates the control structure employed. The manipulation of the overhead vapor flow rate allows for pressure control at the top of the column, while the bottoms flow rate is used to regulate the base level of the column. In addition to controlling column pressure and base level, the distillate flow rate of i-butanol is employed to control the feed temperature. Furthermore, the reflux rate is manipulated to regulate the temperature of the sensitive tray by adjusting the brake power of the compressor. Another temperature controller is used to modify the ratio of boilup rate to feed flow rate (V/F). In the case of temperature controllers, 1 minute deadtime is typically incorporated, and the tuning of the gain and integral time is based on relay-feedback tests and the Tyreus-Luyben tuning rule, which have been widely used in various controller designs [46]. The dynamic

responses demonstrated that the control strategy with dual temperature control effectively handles 10 % changes in both feed flow rate and composition. This proves that the SHRT system not only provides steady-state economic savings but also exhibits satisfactory controllability enabling normal operation.

Hou et al. [145] conducted a study on the dynamic control of an electrified distillation setup used for separating n-heptane/i-butanol. The particular process incorporates an auxiliary reboiler as an additional control degree of freedom. Fig. 34b depicts the control structure employed. In the inventory control loops, the compressor power is adjusted to control the column operating pressure, the distillate flow rate is modified to regulate the reflux drum level, and the bottoms flow rate is adjusted to control the column base level. In the regulatory control loops, dual-end control strategy is utilized, the heat input in the compressor preheater is adjusted to control the suction temperature of the compressor. The reflux flow rate is adjusted to control the upper sensitive tray, incorporating a feedforward action based on the reflux flow rate to fresh feed flow rate ratio (R/F). The heat input of the auxiliary reboiler is manipulated to control the lower sensitive tray. Herein, a feedforward action is employed using the total reboiler heat duty to fresh feed flow rate ratio (Q_R/F) to attenuate transient peaks in product composition and enhance the process response. Dynamic simulation proves that the control structure can overcome 20 % step changes in throughput and feed composition.

5.2.2. Cryogenic air separation

A multitude of research studies have delved into the control of ASUs for diverse applications. These studies have explored both conventional and on-demand control approaches utilizing control strategies of PID and MPC.

In a study conducted by Luyben [261], the control of an electrified ASU-SHRT was explored for oxy-combustion using PID controllers. Two control structures were examined: the first being a conventional structure (Fig. 35a) where the feed air flow rate is manipulated, and the second being an on-demand structure (Fig. 35b) where the oxygen product stream leaving the ASU is manipulated. In the conventional control structure, the temperature in column C2 could be closely regulated by manipulating the flow rate of the bottom vapor side stream, leading to an immediate effect. While in the on-demand structure, this temperature is controlled by the fresh air flow rate, which has to pass through heat exchangers and column C1 before its impact is felt in column C2. As a result, the load response is significantly slower, and transient errors are larger in the on-demand structure. Despite these

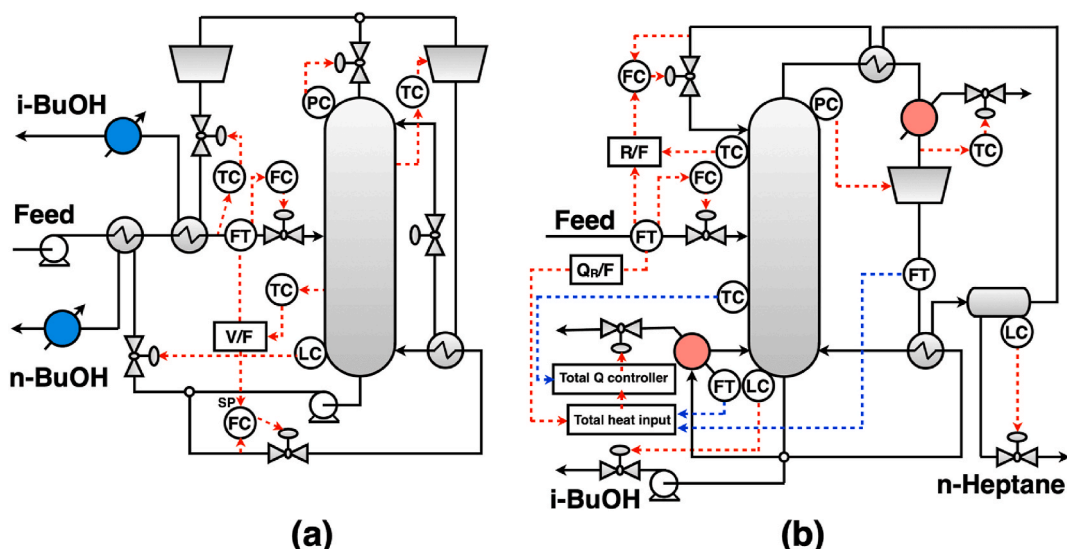


Fig. 34. Control of SHRT assisted-distillation column: (a) i-butanol/n-butanol separation and (b) n-heptane/i-butanol separation.

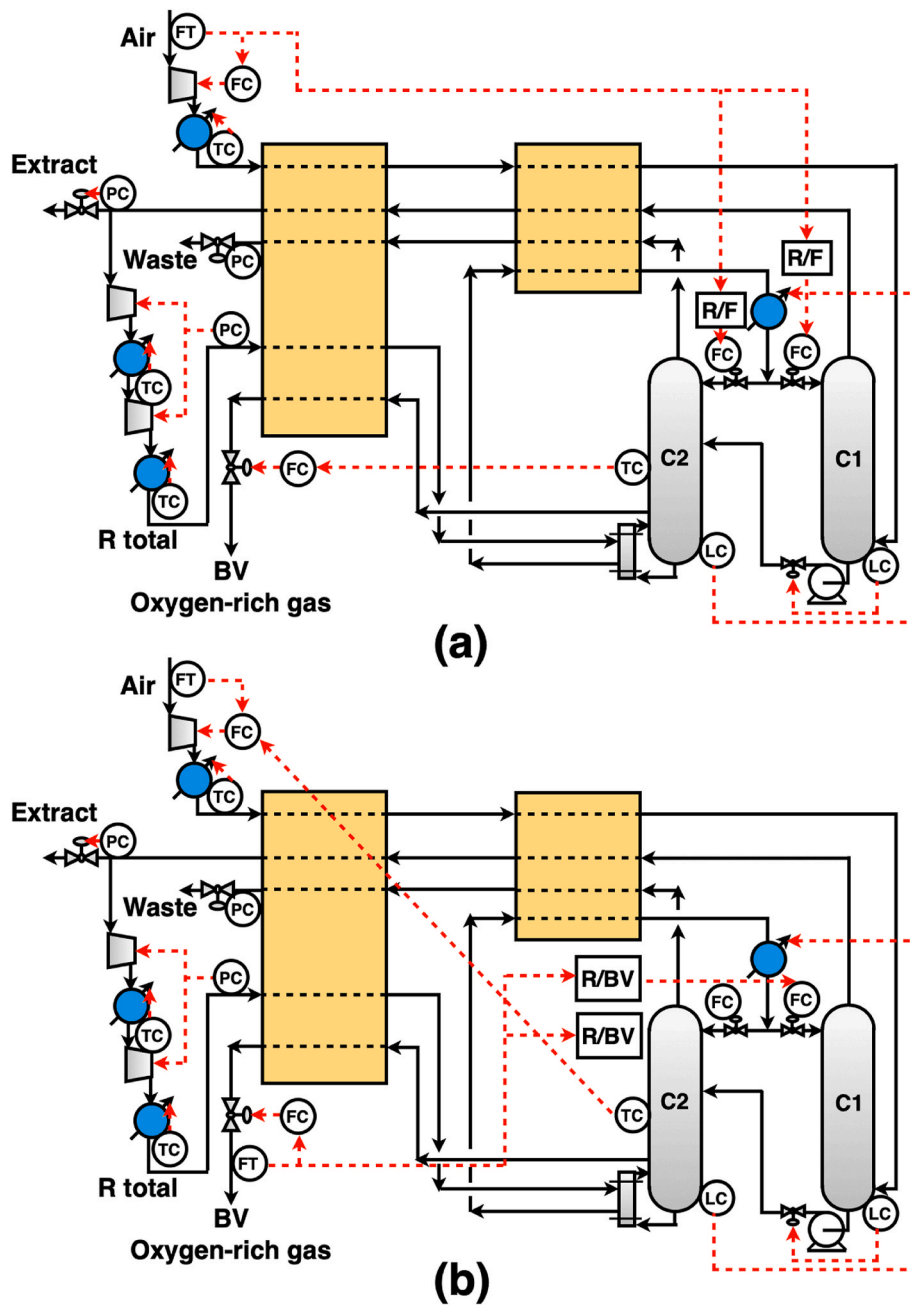


Fig. 35. Control of ASU-SHRT: (a) conventional control structure and (b) on-demand control structure.

differences, when coupled with an oxy-combustion furnace, both control structures exhibited effective handling of furnace load disturbances based on their dynamic responses.

The increasing adoption of renewable electricity has opened up economic opportunities for enhancing the flexible operation of ASU. One effective approach to achieving this flexibility is through the implementation of economic MPC. Economic MPC directly addresses dynamic optimization problems at the controller level, taking into account process models and operational constraints. In a study by Caspari et al. [262], economic MPC is applied to an ASU featuring an integrated liquefier and liquid-assist operation. The authors conducted a closed-loop case study spanning a 2-day time horizon, utilizing historical electricity prices and input disturbances. Comparisons were made against optimal steady-state operation, and economic MPC exhibits similar economic improvements comparable to an idealized quasi-stationary scheduling. Furthermore, the control profiles generated

by economic MPC were qualitatively similar to those obtained from deterministic global optimization of quasi-stationary scheduling. However, the significant advantage of economic MPC was its consistent adherence to product purity constraints, which the deterministic global optimization occasionally failed to meet. This outcome highlights the reliability of economic MPC in satisfying crucial operational constraints. Overall, this demonstrated the effectiveness of economic MPC in facilitating flexible and economically advantageous operation of ASUs under varying electricity prices and input disturbances.

5.3. Electrified azeotropic distillation

This section provides an overview of the control aspects related to electrified azeotropic distillation. The introduction of a recycle stream in the corresponding PSD, HAD, and ED processes adds complexity to their respective control structures compared to zeotropic distillation. For

thermal azeotropic distillations, Luyben and Chien [173] proposed several practical control strategies. Building upon these control schemes, numerous extended control strategies have been adapted and applied to processes operating in the electrical-driven mode.

5.3.1. Pressure-swing distillation

Extensive studies have demonstrated that the dynamics and control of electrified processes are compared favorably to their simple (non) heat-integrated counterparts [263–265]. Fig. 36 shows the control structure employed for separating minimum-boiling THF/water in an electrical-driven mode [265]. Similar to the control approach employed by Li et al. [260] for binary distillation column, the pressures of the HPC and LPC are regulated by manipulating the overhead vapor flow rate. The levels of reflux drum and column sump are controlled by adjusting the respective distillate and bottoms flow rates. In terms of regulatory control loops, single-end temperature control proves sufficient. In comparison to other listed control structures [265], this particular control structure highlights the advantage of the LPC reflux flow rate being influenced solely by the fresh feed flow rate (feedforward R_1/F), which aids in stabilizing the distillate flow rate and its associated MVs. Closed-loop test responses under $\pm 20\%$ throughput and THF composition disturbances demonstrate that this control strategy effectively maintains high purity levels for the THF and water products. Moreover, for the separation of maximum-boiling acetone/chloroform using PSD-SHRT, Yang et al. [264] proposed new control structures to handle throughput and composition disturbances. These control structures incorporate a flow rate controller for the recycle stream to mitigate undesired snowball effects. In addition to these works, relevant studies can be found in Table 11.

5.3.2. Heterogeneous azeotropic distillation

While many authors have studied the steady-state design of electrified HADs, only a few have delved into dynamics and control. Herein, a specific example of tert-butanol dehydration with cyclohexane as the entrainer is reviewed. Building upon the work of Li et al. [196], which highlighted the economic advantages of employing MVR in a complex A-DWC configuration, Luyben [266] further investigated the dynamic controllability of this intricately integrated and interacting electrified process. As shown in Fig. 37, a three-temperature control structure is developed to effectively regulate product quality, even in the presence of significant disturbances in throughput and feed composition. Within the inventory control loops, the base levels are controlled by manipulating bottoms flow rates. The aqueous level in the decanter is regulated through the manipulation of the aqueous flow rate, while the organic phase level in the decanter is controlled via entrainer makeup

manipulation. As the entrainer loss from the process is negligible, the cyclohexane makeup stream essentially remains zero during simulations. The organic level is self-regulatory due to the circulation between the column and the decanter. The decanter pressure is controlled by manipulating the cooling water in the condenser, while the compressor discharge pressure is regulated by a valve downstream of the cooler preceding the decanter. In terms of the key temperature regulatory control loops, the temperature of stage 30 in C2 is controlled by manipulating the flow rate through the compressor/reboiler, while the temperature of stage 3 in C2 is regulated by manipulating the organic reflux flow rate. The bottom temperature in C1 is controlled through manipulation of the reboiler steam. Hence, this control structure effectively manages the control of three temperatures in the A-DWC-MVR. During dynamic response tests, it was observed that the purity of the tert-butanol product could not be maintained due to pressure changes near the bottom of the column. As the throughput increases, the temperature on stage 30 rises due to larger vapor and liquid flow rate. Maintaining the same temperature with a higher pressure results in a higher concentration of lighter components, thereby reducing the purity of the heavier component in the bottoms product. To address this issue, pressure-compensated temperature control is commonly employed. By incorporating pressure compensation in this process, significant disturbances in throughput and feed composition can be effectively managed, ensuring both products remain close to their specified purities. In addition to this work, further relevant studies can be found in Table 11.

5.3.3. Extractive distillation

The control of electrified ED has been extensively studied by many authors, and Table 11 provides some work on this topic. This section reviews a complex electrified ED-TC for acetonitrile dehydration [267]. The configuration involved both main and intermediate reboilers, with acetonitrile separated as an overhead product and water removed as a liquid side stream, while the solvent was recovered from the column base. Fig. 38 illustrates the control structure for ED-TC. In addition to the conventional pressure and level controls, the inventory control loops incorporate a unique approach by utilizing the side stream flow rate to effectively manage the liquid level on the trap out tray (8th stage). Simultaneously, employing a three-temperature control structure enables efficient regulation of the product purity.

5.4. Electrified reactive distillation

Most chemical processes are open-loop stable, meaning they are stable even without the presence of controllers. However, there are exceptions to this rule, and one such example is the exothermic chemical

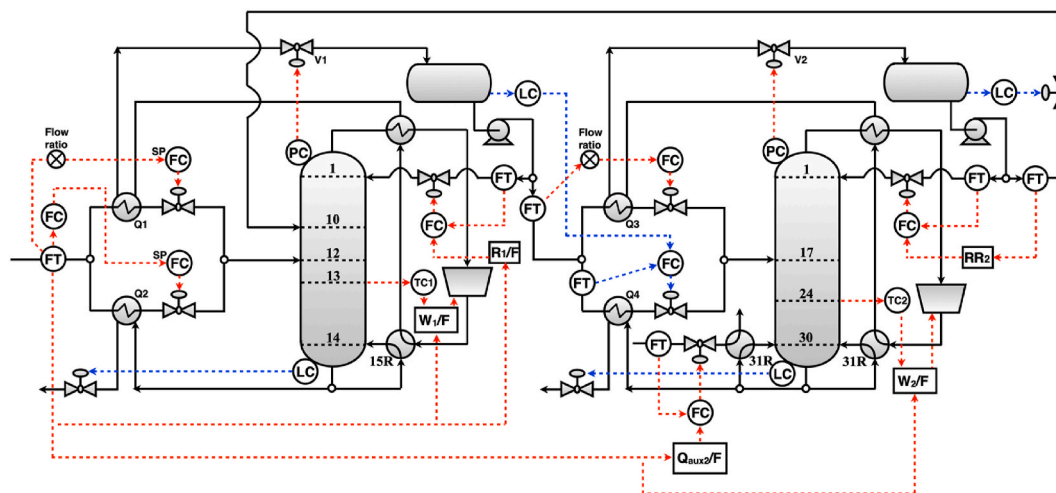


Fig. 36. Control structure for PSD-SHRT of separating minimum-boiling THF/water.

Table 11

Summary of studies on design and control of electrified distillation for separating azeotropes.

System	Separation measure	Intensification technique	Electrification technique	Control strategy	Reference
Minimum-boiling di-isopropyl/isopropyl alcohol	PSD	FP	MVR	PID control	[268]
Minimum-boiling ethyl acetate/ethanol	PSD	PCS	MVR	PID control	[269]
Minimum-boiling ethanol/water (benzene as entrainer)	HAD	FP	SHRT	PID control	[270]
Acetone/butanol/ethanol/water	HAD	DWC	MVR	PID control	[202]
Ethylenediamine/water (N-propyl acetate as entrainer)	HAD	DWC	MVR	PID control	[203]
Minimum-boiling ethanol/water (ethylene glycol as entrainer)	ED	DWC	MVR	PID control	[247]
Minimum-boiling ethanol/water (ethylene glycol as entrainer)	ED	DWC	MVR	PID control	[271]
Minimum-boiling ethanol/water (ethylene glycol as entrainer)	ED	DWC	MVR	PID control	[272]
Minimum-boiling acetone/methanol (water as entrainer)	ED	MED	SHRT	PID control	[273]
Ethyl acetate/isopropanol/water (ethylene glycol as entrainer)	ED	FP	MVR	PID control	[274]
n-Hexane/ethyl acetate (N-methyl-2-pyrrolidone as entrainer)	ED	FP	MVR	PID control	[275]

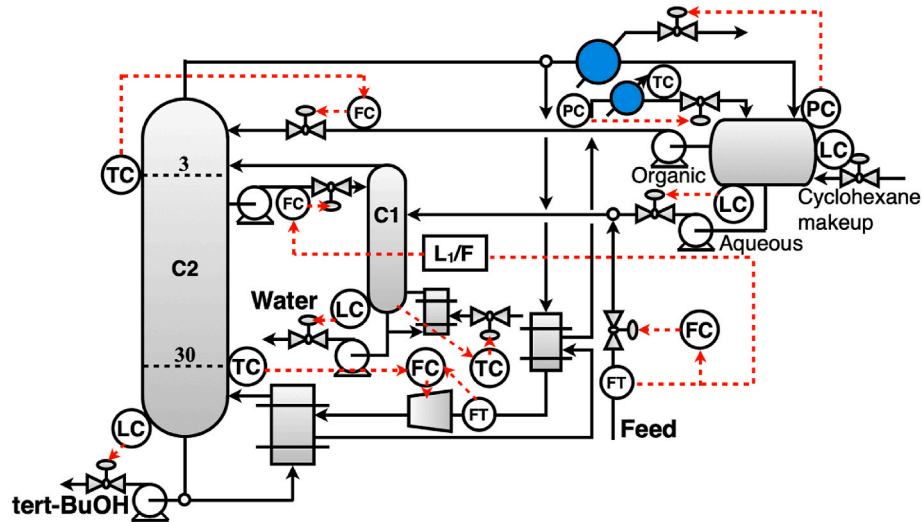


Fig. 37. Control structure for A-DWC-MVR of separating minimum-boiling tert-butanol/water.

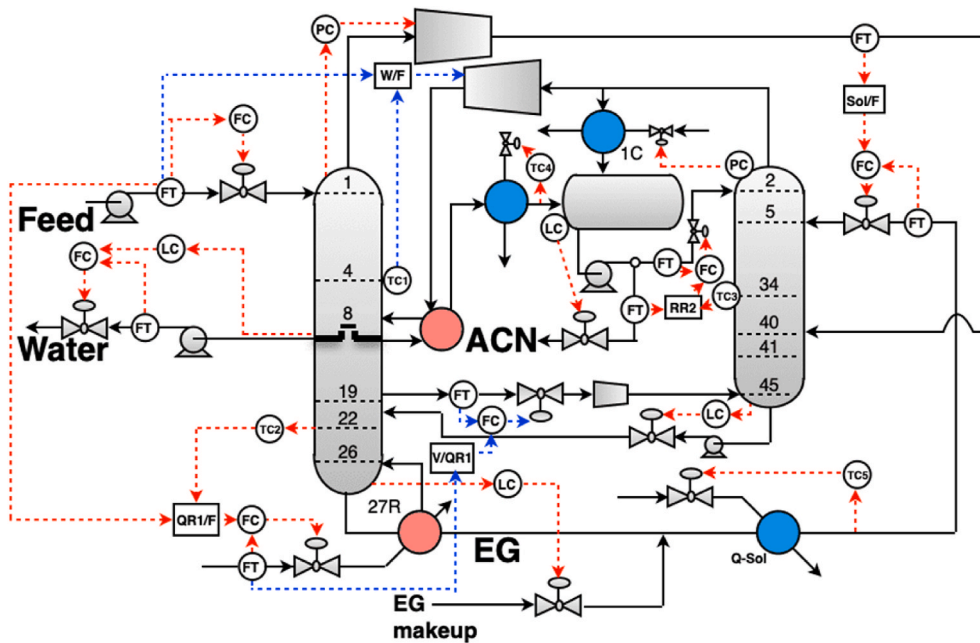


Fig. 38. Control structure for an electrical ED-TC for acetonitrile dehydration.

reactor, which can be open-loop unstable. The control of an RD process is therefore particularly challenging due to the process nonlinearity and the complex interaction between the vapor-liquid equilibrium and chemical reactions. The integration of electrification measures further adds to the complexity. The majority of works regarding the control of RD are studied without any electrification measures [276,277].

In the field of electrified RD, much of the existing work has focused on steady-state design, although there is still a limited number of studies that delve into the control aspects of electrified RD, as shown in Table 12. For instance, Feng et al. [278] developed an effective control structure for a complex electrified MVR-assisted R-DWC to produce n-propyl acetate. The control structure, depicted in Fig. 39, involves several control loops. In the inventory control loops, the feed flow rates of n-propanol and acetic acid are controlled to maintain a stoichiometric ratio. The operating pressure of the RD is controlled by manipulating the vapor flow rate to the condenser (PC1), ensuring the desired compressor inlet pressure. The discharge pressure of the compressor is controlled by manipulating the opening of the pressure-relief valve (PC2), thereby maintaining the specified suction and discharge pressures. The decanter pressure is controlled by manipulating the condenser duty (PC3). The organic phase level in the decanter is controlled by the reflux rate of the organic phase to the top of RD (LC1), while the aqueous phase level is controlled by the draw-out water flow (LC2). The sump level in the product column is controlled by the product flow rate (LC3). The sump level in the RD column is controlled by manipulating the compressor power (LC4), as there is no outflow from the RD column bottom, and the reboiler duty is indirectly supplied by the input work of the compressor. In the regulatory control loops, the proposed control structure utilizes the sensitive tray temperature of the RD column to manipulate the molar flow rate ratio of the n-propanol feed to acetic acid feed (TC1), while the sensitive tray temperature of the product column is used to manipulate its reboiler duty (TC2). Subsequently, the authors found that by fixing the liquid split ratio above the dividing wall, the overall control performance was improved.

6. Real-world implementations and policy implications

This section provides an overview of practical applications of electrified distillation processes and discusses related policy implications of such electrification.

6.1. Real-world implementations

Some case studies regarding the real-world implementations of electrified distillation processes and/or their associated industrial equipment are introduced.

6.1.1. Industrial-scale electrode boiler

This section introduces an advanced industrial-scale electrode boiler manufactured by PARAT, detailed on their website (<https://www.parat.no/en/products/industry/parat-ieh-high-voltage-electrode-boiler/>).

Table 12

Summary of studies on design and control of electrified RD.

System	Intensification technique	Electrification technique	Control strategy	Reference
Synthesis of ethyl propionate	RD	MVR	PID control	[241]
Synthesis of amyl acetate	RD	DPTCD	PID control	[279]
Synthesis of isoamyl acetate	RD	DPTCD	PID control	[280]
Hydrolysis of methyl acetate	RD	DPTCD	PID control	[281]

Fig. 40 shows both a photograph of the e-boiler and a schematic of its steam generation principle. Powered by renewable energy sources, this e-boiler has the potential to significantly cut CO₂ emissions. It can generate steam at pressure ranging from 6 to 85 barg and boasts a capacity of up to 60 MW. Thus, the PARAT e-boiler is capable of powering the majority of the distillation columns examined in this study.

6.1.2. Electrified distillation columns

MVR-assisted distillation columns are among the most prevalent electrified distillation setups in the chemical industry. Fig. 41 shows a photograph of an industrial-scale MVR-assisted distillation unit (more details can be found on the Chart Industries website <https://www.chartindustries.com/Products/Mechanical-Vapor-Recompression#>). However, the provider of this technology, has to date installed over 2500 MVR compressors across more than 70 countries. The versatility of MVR technology is evident in its widespread use across various sectors, including chemicals, food & beverage, pulp & paper, metals, and pharmaceuticals, indicating its significant potential for energy efficiency and carbon footprint reduction.

In addition to the widely-adopted MVR type, our research group has made notable advancements in the field by implementing a practical application of a VC type heat pump. In 2019, we designed and constructed a system on-site for purification of waste refrigerant mixtures, such as R12/R134a and R22/R410a, utilizing a VC-assisted distillation process. The process utilized HFC407C as the working fluid for the heat pump. The system operates on an indirect cascade principle, namely, heat is transferred from the heat pump working fluid to the intermediate working fluid (water), and then transferred to condenser and reboiler of the column. The operating temperature ranges for various components are: 22–33 °C for the column condenser, 40–45 °C for the reboiler, 40–50 °C for the heat pump condenser, and 15–20 °C for the evaporator. The constructed distillation column, depicted in Fig. 42, has a daily capacity of 5 tons and a height of 33 m. Compared to the conventional column, this heat pump-assisted column can achieve energy saving of over 40 %.

6.2. Policy implications

The move towards electrifying distillation processes is in step with global initiatives aimed at diminishing greenhouse gas emissions. This movement prompts significant regulatory and policy considerations, as governments may enforce tougher emissions protocols on sectors heavily dependent on distillation, like petrochemicals and alcohol production [282]. Additionally, legislation could encourage or mandate the adoption of more energy-efficient technologies alongside the integration of renewable energy into industrial operations [283]. When powered by renewables, electrified distillation stands as a benchmark for high energy efficiency and emission reduction. To ease the financial burden of transitioning to these greener processes, mainly due to higher capital costs of electrified equipment and/or heat exchanger networks, governments might provide financial incentives such as tax breaks, grants, or subsidies to facilities that embrace electrified distillation technologies. These measures could help mitigate the upfront costs associated with moving towards electrified alternatives.

Numerous governments have implemented funding or subsidy programs to encourage investment in electrification and heat pump technologies within heavy industries [284]. For instance, Finland has established a subsidy fund aimed at supporting the electrification efforts of its heavy industries. Similarly, the REPowerEU plan has effectively doubled the available budget within the Innovation Fund, allocating a total of EUR 1 billion to foster innovative projects focused on industrial electrification and hydrogen usage. In 2022, Sweden unveiled a comprehensive strategy dedicated to enhancing electrification efforts. This strategy includes measures to increase the capacity of the national grid and to promote the development of the wind energy sector. Table 13 provides examples of the policies at the national level

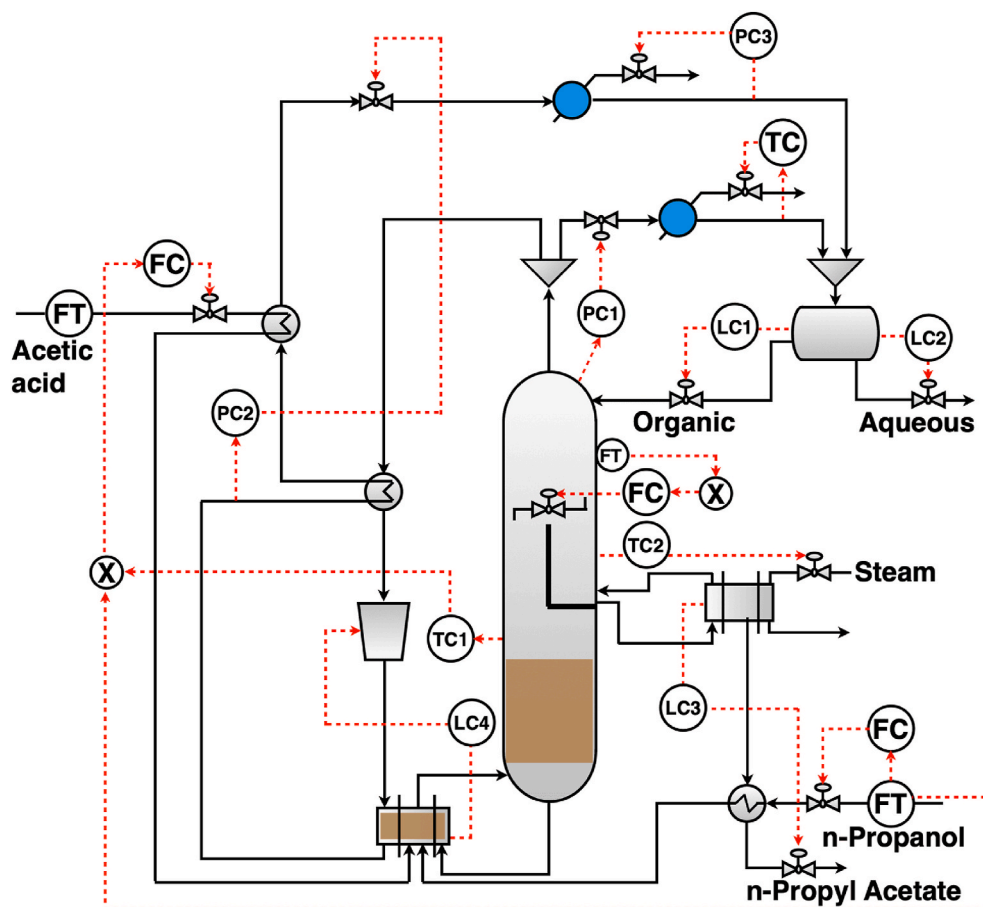


Fig. 39. Control structure for an electrical R-DWC for n-propyl acetate production.

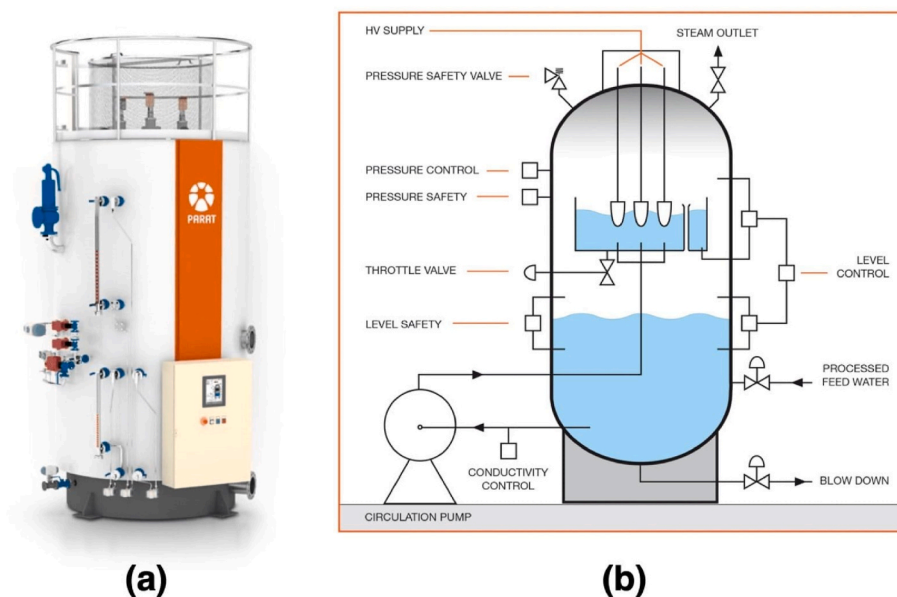


Fig. 40. (a) A photo of an industrial-scale high voltage electrode boiler; (b) Principle diagram of electrode boiler steam generation system.

concerning the electrification of industries. Despite these efforts, current policies do not address the electrification challenge in a holistic manner, especially considering the electrification of process and distillation sectors. To achieve a more comprehensive approach, further policy development is necessary. This development should include plans for

the construction or expansion of electrification infrastructure, such as transmission and distribution grids, the adoption of pricing strategies like time-of-use tariffs, continued research and development in the field of industrial-scale electric storage solutions, and the strategic relocation of industrial operations to areas where renewable electricity is more

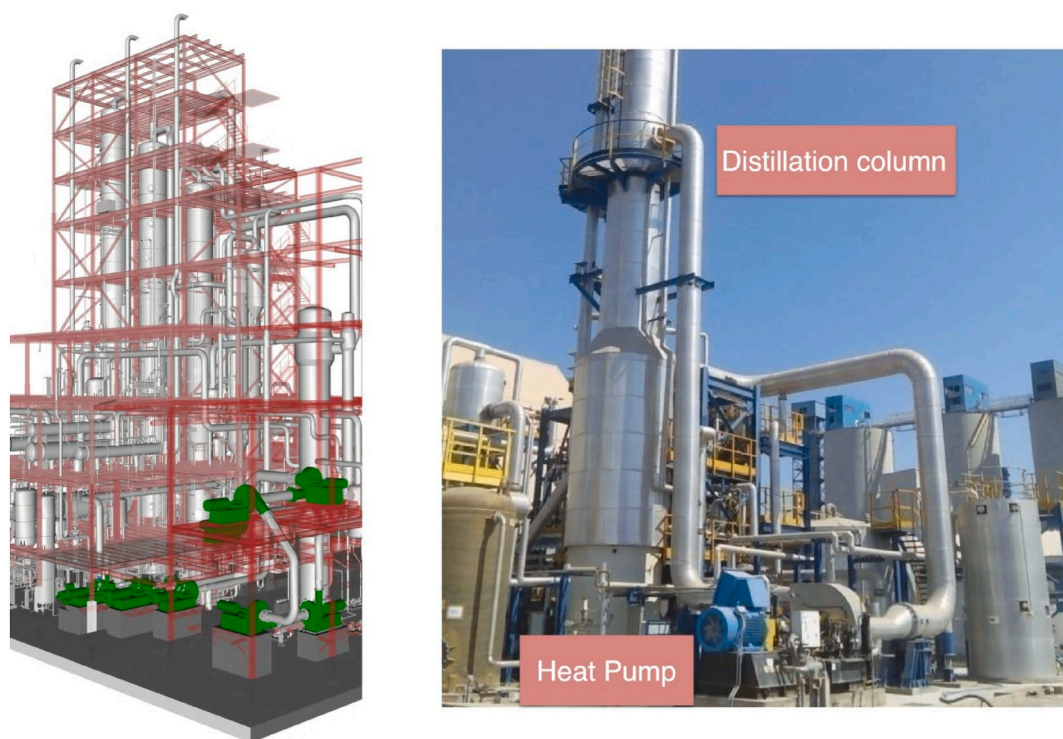


Fig. 41. Photos of industrial-scale MVR-assisted distillation column.

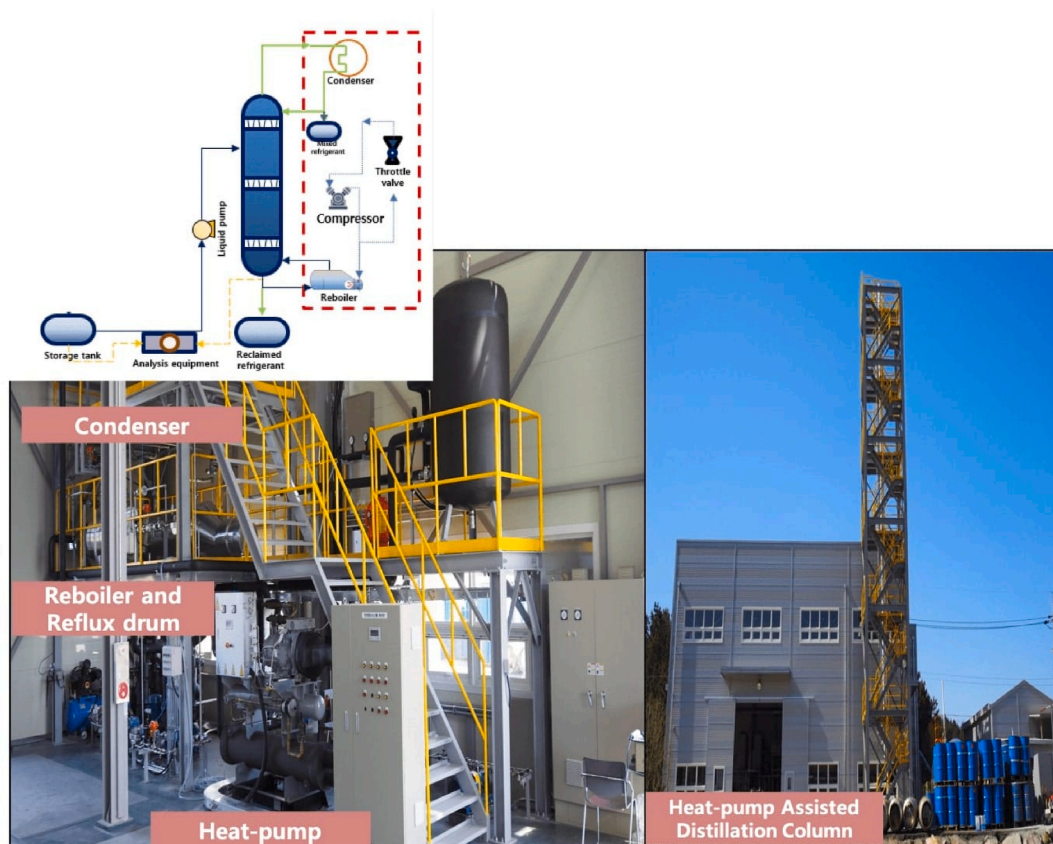


Fig. 42. Photos of the heat pump-assisted distillation column for waste refrigerant purification implemented by our research group in Pohang, Republic of Korea.

Table 13

Examples of the policies at the national level concerning the electrification of industries [285].

Policy	Country	Year	Status
Electrification Strategy	Sweden	2022	Announced
Expansion of subsidies for energy renovation projects	Luxembourg	2022	In force
Green transition investment projects	Finland	2022	In force
Increased budget for fund to support green transition (FSC 2021–2027)	Italy	2022	In force
Promoting energy efficiency and reducing greenhouse gas emissions	Estonia	2021	In force
Sixth Strategic Energy Plan - 2050 Carbon neutral	Japan	2021	In force
Spain 2050 strategy: circular and carbon-neutral economy	Spain	2021	In force
Notice on Matters Concerning the New Energy Feed-in Tariff Policy	China	2021	In force

affordable.

7. Challenges and perspectives

Although many state-of-the-art technologies can be employed for the electrification of distillation processes with the goal of achieving complete decarbonization and improving techno-economic aspects, the utilization of these measures presents challenges in terms of design, optimization, and operation. This section offers valuable insights into the challenges and opportunities that lie ahead in each aspect.

7.1. Development of new electrification/intensification measures

Challenges: The primary electrification approach for distillation currently relies heavily on PtH technologies, particularly heat pumps. Despite their high RTLs, heat pumps are not universally suitable for all distillation tasks. Their efficiency can be compromised by a low COP, especially since distillation often requires high temperatures to separate components with high boiling points. Heat pumps typically operate more efficiently at lower temperatures. Designing heat pumps that can efficiently handle higher temperatures without significant losses in performance or increased costs remains a challenge. Furthermore, current electrification designs that incorporate heat pumps have moving parts and working fluids, potentially requiring more maintenance than passive systems like direct-fired heaters. Ensuring reliability in harsh industrial environments also presents additional challenges.

Perspectives: It is expected that emerging PI measures in distillation could be beneficial for electrification. These could include technologies such as membrane distillation (MD) and cyclic distillation, which should be explored for designing more efficient electrified distillation systems. MD is an emerging technology for fluid separations such as reverse osmosis for water desalination, in which the driving force is the difference in vapor pressure across the hydrophobic membrane, rather than the total pressure [286]. Compared to thermal distillation, MD does not provide significant energy savings but it can offer lower capital expenditure and smaller equipment, along with operation at lower temperatures [287]. The main benefits of MD are: low operating temperatures (which means that low-grade heat such as geothermal and waste heat can be used), high rates of rejection for non-volatile components (e.g. salts, colloids), possibility to work with high solute concentrations in the feed or even with near saturated solutions, and lower hydrostatic pressure than used in pressure driven membrane processes. MD is a promising technology, but it needs further development and optimization to become a mature technology applicable at industrial scale. In addition to using MD solely, it is possible to harvest renewable energy and design hybrid systems that can simultaneously produce freshwater and electricity [288,289]. As MD still requires evaporation, this could be also achieved by electrification, either directly (using electric boilers) or

indirectly (via heat pumps that upgrade low-grade waste heat).

Most of the existing PI techniques employ the conventional continuous counter-current contact of vapor and liquid phases. Cyclic distillation technology is based on an alternative operating mode using separate phase movement which leads to key practical advantages in chemical processes. Cyclic distillation can be rather easily implemented in existing columns by simply changing the internals and the operating mode, thus bringing new life to old distillation columns by significantly increasing the column throughput, reducing the energy requirements and offering better separation performance [290]. Cyclic distillation has many promising prospects, but future research on this topic should tackle key challenges, e.g.: finding new applications that prove the advantages in case of difficult industrial separations (e.g. close-boiling components, high purity products, significantly increased capacity); combining cyclic distillation with other intensified technologies (e.g. cyclic distillation in DWC and/or RD); expanding the usage to azeotropic, extractive, and reactive distillations. Cyclic distillation can also be electrified directly (using electric boilers, which allow turning off/on the heating elements in sync with the vapor/liquid period as required) or indirectly (using renewable heat generated by heat pumps which upgrade low-grade waste heat available in many chemical processes).

7.2. Integrated design and control

Challenges: As demonstrated in Section 5, most existing research on electrified distillation systems has investigated the sequential design and control approach. Typically, this involves first designing and optimizing the steady-state processes, followed by studying their dynamics and control. However, control performance is jointly determined by both the process design and the control system implemented. Therefore, a significant challenge lies in the simultaneous design and control of electrified distillation systems to enhance performance robustness, which is crucial to cope with fluctuations in renewable power supply or operating with dynamic electricity pricing markets.

Perspectives: An integrated concept for design and control of electrified distillation systems holds promise, with aims to identify critical points, achieve synergistic gains, and balance the trade-offs between design and control considerations [291–293]. Some integrated studies use open-loop controllability metrics, such as condition number, as an independent criterion to qualitatively assess how “poor” or “good” the existing design is [294–296]. However, skepticism persists regarding their effectiveness, as they often rely on steady-state or linear dynamic models [297,298]. Consequently, they may only be valid within the vicinity of the nominal operating point, failing to accurately assess controllability when disturbances exceed this range. Nonetheless, they remain valuable in guiding control structure design and highlighting potential input limitations [299]. Alternatively, considering the impact of control decisions on design objectives often necessitates dynamic modeling, increasing implementation challenges, especially in large-scale processes [300]. To address the computational challenges, Sachio et al. [301] introduced an integrated approach leveraging reinforcement learning, although their case studies primarily tackled small-scale problems. In this context, Zhang et al. [302,303] proposed a steady-state integrated model focusing solely on the selection of controlled variables and setpoints, applied to intensified distillation processes. However, to date, there is a dearth of literature exploring integrated methodologies in the context of electrified distillation processes. Consequently, integrated design and control can emerge as a robust and optimal solution for electrified distillation processes in future works.

7.3. Systems design and optimization coupled with renewables

Challenges: It is important to note that incorporating electrification technologies in distillation processes does not automatically lead to a reduction in carbon emissions. Full decarbonization of electrified

processes depends on using electricity sources that are themselves fully decarbonized [304]. Given that electricity generation from the grid is currently associated with carbon emissions, direct utilization of renewable energy in the distillation utility system becomes crucial for achieving full decarbonization. However, unlike traditional distillation processes that operate continuously, designing and optimizing systems that use intermittent renewable power sources, such as solar and wind, presents significant challenges [305]. Additionally, optimization faces difficulties in considering various electrification and PI measures from the outset to minimize costs, which involves accounting for the entire superstructure, from the initial supply of renewable power to its final use in distillation systems.

Perspectives: Optimizing renewable-coupled electrified distillation processes involves considering the impact of power fluctuations on process operations. Design variables, such as technology selection and storage capacity, and operational variables, including scheduling (on/off states) and energy/material flows of each unit, are key decision factors. Incorporating a temporal dimension, optimizing the process for seasonal or annual operations necessitates long-term and high-resolution wind-solar data. The model encompasses a significant number of equations and decision variables, and the optimization of operational variables relies on existing design solutions [306]. Consequently, the design and operational optimization of electrified distillation processes represent a complex two-stage optimization task, posing a significant research problem due to the multitude of equations and decision variables involved. Hence, the development of new optimization strategies, in particular combining with artificial intelligence techniques to lower model complexity and capture system dynamics, is crucial to tackle this challenge and enable the optimal design and operation of electrified distillation processes when coupled with RESs.

7.4. Operation, real-time scheduling, and demand response

Challenges: The primary challenge in implementing distillation electrification lies in the high costs associated with renewable electricity, compounded by the substantial initial investment required for electrification and PtH technologies. These financial barriers are critical as they influence the feasibility and adoption rates of electrified distillation systems in industries that rely heavily on distillation processes, such as chemical manufacturing and petroleum refining. Further complicating the issue is the inherently dynamic nature of the renewable electricity market. The variability in renewable energy production, primarily from sources like solar and wind, leads to fluctuations in electricity prices and availability. This unpredictability can significantly affect the operational costs of electrified distillation systems, making cost management and forecasting more challenging.

Perspectives: Electrified distillation processes, when connected to the grid, can function as electricity storage processes, similar to ASU [168], enabling them to participate in demand response programs. This participation allows them to generate additional profits through electricity arbitrage and a range of reserve services. The control and real-time scheduling of electrified distillation processes play a vital role in achieving these functionalities, as they are crucial for effectively managing the integration of these processes with the grid and optimizing their participation in demand response programs. Although a number of studies have concentrated on production planning and scheduling of ASUs, treating them as energy storage units and accounting for demand and electricity price fluctuations [169,307,308], similar attention should be given to electrified distillation processes for real-time scheduling and optimal plantwide operation. This necessitates further research into the control and dynamics of electrified processes, specifically focusing on understanding and optimizing the intricate interplay between various factors involved in their operation. In order to effectively harness the potential benefits of electrified distillation processes, it is crucial to explore and develop advanced control strategies that can efficiently manage the real-time scheduling, monitor

performance, and adapt to changing conditions within these processes. Additionally, gaining insights into the dynamic behavior of electrified distillation processes will enable the identification and implementation of appropriate control mechanisms, facilitating their seamless integration with the grid and maximizing their participation in demand response programs and electricity arbitrage.

8. Conclusions

Distillation, being the most widely used method for separating and purifying mixtures, poses a significant challenge due to its low thermal efficiency, resulting in substantial energy consumption and carbon emissions. To address this challenge, electrification has emerged as a promising concept, aiming to substitute traditional energy sources with electricity derived from renewable energy resources. In a word, the electrification of distillation processes holds great promise for achieving decarbonization goals and promoting sustainability in the industrial sector.

This review delves into the concept of electrification, elucidates how the integration of RES and electrification technologies can enable a significant reduction in carbon emissions, and provides a comprehensive analysis of case studies that implemented electrification and intensification methods in various distillation tasks. These studies and examples demonstrate the tangible benefits of electrification, ranging from improved energy efficiency and reduced carbon emissions to enhanced process control and operational flexibility.

By providing an in-depth overview and valuable perspectives on the electrification of distillation for decarbonization, this review serves as a valuable resource for industry professionals, policymakers, and researchers seeking to understand the transformative potential of this emerging trend. The comprehensive analysis, supported by empirical evidence and literature examples, establishes a strong foundation for further exploration and innovation in this critical field.

Looking ahead, further research and development are crucial in order to fully realize the benefits of electrified distillation. Future directions should focus on technology development, design optimization, and efficient real-time scheduling of electrified distillation processes. These efforts will enable process industries to capitalize on the advantages of renewable energy integration, enhance process efficiency, and achieve greater sustainability.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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