



# Advances and emerging techniques for energy recovery during absorptive CO<sub>2</sub> capture: A review of process and non-process integration-based strategies

Kelvin O. Yoro<sup>a,\*</sup>, Michael O. Daramola<sup>b</sup>, Patrick T. Sekoai<sup>c</sup>, Edward K. Armah<sup>d</sup>, Uwemedimo N. Wilson<sup>e</sup>

<sup>a</sup> Energy Technologies Area, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA, 94720, United States

<sup>b</sup> Department of Chemical Engineering, Faculty of Engineering, Built Environment and Information Technology, University of Pretoria, Private Bag X20 Hatfield, 0028, Pretoria, South Africa

<sup>c</sup> Department of Biological Sciences, Kadoorie Building, The University of Hong Kong, 999077, Pokfulam, Hong Kong

<sup>d</sup> Department of Chemical Engineering, Durban University of Technology, Steve Biko Campus, 4001, Durban, South Africa

<sup>e</sup> Department of Civil Engineering, Nigerian Defence Academy, P.M.B 2109, Kaduna, Nigeria

## ARTICLE INFO

### Keywords:

Absorptive CO<sub>2</sub> capture  
Amine scrubbing  
Energy recovery  
Flexibility analysis  
Flexible heat exchanger networks  
Process integration

## ABSTRACT

Absorptive CO<sub>2</sub> Capture (ACC) is widely embraced as a mature technology to mitigate CO<sub>2</sub> emission, but it is energy-intensive and expensive to implement on a commercial scale. It is envisaged that energy recovery could be achieved during ACC by synthesizing and integrating a complex network of flexible heat exchangers to transfer as much energy as possible from a set of hot flows to cold flows. This review provides information on the progress made in the development of process and non-process integration-based techniques alongside their benefits for effective energy recovery during ACC. An exposition on the integration of flexible Heat Exchanger Networks (HENs), its synthesis methodologies, and developments for improving energy recovery during ACC is presented. Furthermore, this review highlights the current state of knowledge creation in process integration and ACC, as well as its underpinning principles, challenges, and opportunities to provide a summary and important discussion on current practices in process integration-based strategies for energy recovery. Current opinions on the integration of flexible HENs for energy recovery during ACC are highlighted. The review also presents a proposed roadmap for large-scale energy recovery during ACC, and suggestions on the improvement opportunities for future research and development were provided. Finally, this review revealed that the integration of flexible HENs is a promising technique for energy recovery during ACC. This study will be beneficial to researchers exploring cost-effective methods for designing sustainable energy systems for effective energy recovery.

## 1. Introduction

Global attention is shifting towards the reduction of CO<sub>2</sub> emission and energy penalty minimization [1]. CO<sub>2</sub> capture, utilization, and storage (CCUS) is a reliable technique used in addressing some of the central challenges affecting the world today for example CO<sub>2</sub> emission, global warming, and climate change [2,3]. Absorption, adsorption, membrane separation, cryogenics, and hydrate-based separation techniques are the typical technologies for CO<sub>2</sub> capture, amongst which absorptive CO<sub>2</sub> capture (absorption) is regarded as the most established [4]. While several techniques have been reported for CO<sub>2</sub> capture,

maximization of energy recovery still remains a great challenge [5]. The body of knowledge is rich in state-of-the-art reviews on CO<sub>2</sub> separation technologies [6–9] and process system integration [10–12] that linked selected CO<sub>2</sub> capture techniques and cost reduction in energy-intensive end-of-pipe CO<sub>2</sub> separation. To reduce operational cost and fill the energy demand and supply gap during absorptive CO<sub>2</sub> capture, it is imperative to address its high energy requirement through energy optimization using modern techniques [13].

Absorptive CO<sub>2</sub> Capture (ACC) is a technology that has been in existence since 1930 and was primarily used in food processing and beverage making industries to capture food-grade CO<sub>2</sub> for the preservation of beverage drinks [14]. As such, it can be described as a

\* Corresponding author.

E-mail addresses: [kelvin.yoroo@gmail.com](mailto:kelvin.yoroo@gmail.com), [koyoro@lbl.gov](mailto:koyoro@lbl.gov) (K.O. Yoro).

<https://doi.org/10.1016/j.rser.2021.111241>

Received 6 July 2020; Received in revised form 21 April 2021; Accepted 17 May 2021

Available online 25 May 2021

1364-0321/Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

**List of abbreviations**

ACC	Absorptive CO <sub>2</sub> Capture
CAPEX	Capital expenditure
CCUS	Carbon Capture Utilization and Storage
CHAMEN	Combined heat and mass exchanger network
GAMS	General Algebraic Modeling System
HENs	Heat Exchanger Networks
MEA	Monoethanolamine
MINLP	Mixed Integer Nonlinear Programming
OPEX	Operational expenditure
PCS	Phase change solvents
PZ	Piperazine

commercially-ready technology, but not on the scale required for power plants. Despite being an established technology for CO<sub>2</sub> capture, ACC still faces challenges which includes process inefficiencies, high energy demands and high process costs both in capital expenditure (CAPEX) and operational expenditure (OPEX) [15]. In addition, the integration of CO<sub>2</sub> capture units in power plants results in lower plant efficiency and high energy consumption, leading to a high operational cost [16]. These limitations have hindered the full implementation of ACC technologies on a commercial scale [17]. Although ACC using monoethanolamine (MEA) is a convenient way to capture CO<sub>2</sub> on a commercial scale in coal-fired power plants, researchers have argued that the use of chemicals like MEA to capture CO<sub>2</sub> without sorbent development and process modification could lead to increased energy consumption and reduced plant efficiency from 45% to 35%, as well as other environmental hazards [18–21].

ACC has some advantages which include higher reliability, higher absorption efficiency, and ease of retrofitting in power plants compared to other decarbonization technologies [22,23]. Also, processes in ACC systems carry streams with purity higher than 95% [24], and ACC is independent of human operators [25]. Despite these advantages, ACC is still affected by various process constraints that hinder its commercialization. Notably amongst them is that the ACC technology requires a high heat of absorption, and its energy requirement during sorbent regeneration is also high [26]. This claim has been validated in the reports of Lucquiaud et al. [27], as well as Jackson and Brodal [28] where it was established that for a CCS plant using a current state-of-the-art

absorptive CO<sub>2</sub> capture technology, the energy needed by the capture plant will be about 250–300 kWh of electrical energy per tonne of captured CO<sub>2</sub> (kWh/tCO<sub>2</sub>), while the estimated energy consumption during CO<sub>2</sub> compression is in the range of 80–120 kWh/tCO<sub>2</sub>. To maximize effective energy recovery during ACC, this review explores process integration-based options such as the integration of flexible heat exchanger networks. A schematic illustration of the ACC process showing major energy-consuming units and process streams where heat integration is usually required (in red lines) is presented in Fig. 1. From Fig. 1, the major energy-consuming units in CO<sub>2</sub> absorption processes are heat exchangers, reboilers, and regenerators. The heat exchangers in the ACC process presented in this review have the potential to recover heat from lean hot solvents emanating from the regenerator, and also use the energy to make the rich preheated solvent cold, which significantly reduces energy consumption within the process.

The energy consumed in a typical ACC process that uses monoethanolamine as a sorbent is estimated at 3.8 MJ/kg-CO<sub>2</sub> captured, while the energy requirement of solvent regeneration in a conventional ACC is approximately 3.22 MJ/kg-CO<sub>2</sub> captured [29]. According to Li et al. [30], the minimum reboiler duty during ACC is 3.1 GJ/tCO<sub>2</sub>, which reduces the net power efficiency from 38.9 to 29.8%. Improving efficiency will minimize energy and fuel consumption. Furthermore, optimizing important process specifications in ACC such as solvent temperature, the height of absorber and stripper, flue gas temperature, the reboiler duty could lead to a reduction of about 20% in the thermal energy consumption of the process [31]. The reboiler duty is significantly high at lean loadings because the partial pressure of CO<sub>2</sub> in equilibrium with the liquid phase is low at lean loadings. The heat of desorption accounts for the biggest fraction of the energy requirements in the reboiler, with the stripping steam and sensible heat requirement accounting almost evenly. To lower the heat energy requirement in the reboiler during ACC, it is better to lower the approach temperature in the heat exchanger.

The energy requirement of each unit operation in the process can be determined from Equation (1):

$$Q = m * C_p * \Delta T \quad (1)$$

where Q is the heat energy content, C<sub>p</sub> is the specific heat capacity of the fluid undergoing temperature change, m is the mass flow rate of CO<sub>2</sub>, and ΔT is the difference between the outlet and inlet temperature of the unit streams.

Due to the interdisciplinary nature of process integration and CO<sub>2</sub> capture studies, it is necessary to integrate another discipline like

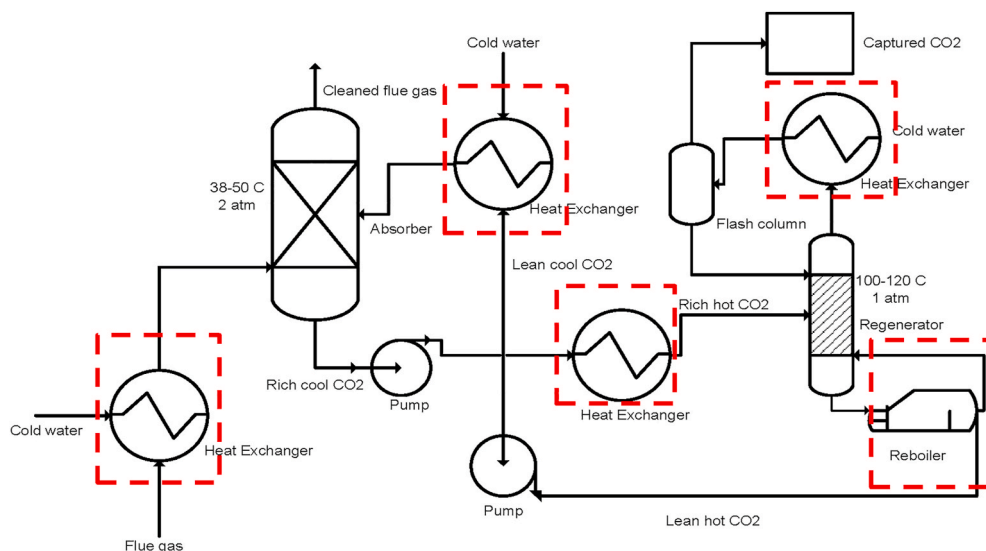


Fig. 1. A typical ACC process showing the major energy-consuming units.

process chemistry into its synthesis. Process integration techniques may be involved at the start of a project (for example a new fossil fuel-fired power plant) or in the upgrading of an existing one (retrofit) to filter interesting possibilities for optimizing its operation for effective energy recovery [32]. During process integration, emphasis is placed on integrating processes in a holistic approach rather than on individual operations [26]. Process integration aims at resource conservation, waste reduction, and the optimization of industrial processes whilst identifying the heat recovery potentials and the optimal integration of energy conversion systems.

The foremost objective of this review is to discuss the importance of integrating flexible Heat Exchanger Networks (HENs) that can transmit heat energy independently of possible periodic fluctuations, to ensure efficient energy utilization during ACC at an industrial scale. Most energy minimization strategies applied in ACC systems in the past are non-process integration-based [33,34]. Although the concept of heat integration is not new to the body of knowledge in this field, its application through flexible HENs for energy minimization during ACC is new and has not been adequately reported in the open literature. The introduction of process integration-based concepts (flexible HENs retrofitting) for effective energy recovery in ACC systems, the development of a schematic framework for superstructure model implementation of flexible HENs for energy recovery during absorptive CO<sub>2</sub> capture, the methodical presentation of a simplified four-step solution approach to synthesize flexible HENs for effective energy recovery during ACC, and the presentation of a new roadmap for large-scale energy recovery in ACC systems, as well as the improvement opportunities for future research and development presented in this review form the major novelty of this study. The major highlight and potential contribution of this review to the field of CO<sub>2</sub> capture are inherently found in the introduction of new process integration-based techniques to tackle the challenge of high energy consumption associated with most CO<sub>2</sub> capture techniques, as well as in the application of process integration concepts for effective energy saving during ACC. A successful application of process integration principles in ACC systems could be instrumental to increasing process efficiency, improving energy recovery, increasing operator effectiveness, reducing maintenance costs, and lowering lifecycle costs.

This review is structured as follows: Section 2 elaborates on the ACC technology which includes a summary of different techniques for energy recovery. Sections 3 and 4 focus on evaluating the approaches for effective energy recovery and the potential of emerging techniques for effective energy recovery during ACC. Then, section 5 introduces the benefits of process integration during ACC, leading to the identification of some emerging process and non-process integration-based techniques for energy recovery. A new perspective for energy recovery during ACC is presented in section 6. Section 7 discusses the progress and limitations of flexible HENs integration in ACC systems, while important factors to consider during the integration of flexible HENs for energy recovery in ACC systems are discussed in section 8. Current opinions on the use of flexible HENs integration approach as an energy recovery strategy during ACC are highlighted in section 10, while a roadmap for large-scale energy recovery during ACC is proposed in section 10. Finally, a conclusion section (11) summarizes the insights from this paper, with recommendations on how future research might tackle the identified shortcomings.

## 2. Absorptive CO<sub>2</sub> capture via amine scrubbing

Amine scrubbing (amine gas treating) is a procedure that involves the use of aqueous solutions of various alkyl-amines to remove certain gases for example hydrogen sulfide (H<sub>2</sub>S) and carbon dioxide (CO<sub>2</sub>) from a mixture of gases [34]. This review focuses on absorptive CO<sub>2</sub> capture via amine scrubbing because, amongst other capture techniques, CO<sub>2</sub> capture by scrubbing flue gas with aqueous amine has been reported as a ready-to-use technology to decrease CO<sub>2</sub> emissions [35]. Though amine

scrubbing is one of the most widely accepted technologies for ACC, there is a large amount of heat lost by the evaporation of water in the reboiler. It is difficult to minimize this wasted energy because the conventional MEA washing process has a trade-off relationship between the cooling load of the condensers and the preheating duty of the heat exchanger.

Amine scrubbing process typically comprises an absorption column, a heat exchanger, a reboiler, and a stripper. The rich stream is always the process stream carrying the flue gas while the lean process stream contains the sorbent (MEA in this case). The CO<sub>2</sub>-rich flue gas goes in from the base of the absorption column, while the cold lean MEA flows from the top of the absorption column. The sorbent selectively absorbs the CO<sub>2</sub> from the flue gas mixture through an exothermic reaction, then flows to the base of the absorption column before going through the heat exchanger for pre-heating. The pre-heated sorbent which contains CO<sub>2</sub> flows via the top of the stripper to get its CO<sub>2</sub> content separated at high desorption temperature. The separated CO<sub>2</sub> is then collected from the top of the stripper, while the hot lean MEA is allowed to drain at the bottom of the stripper. Finally, the hot-lean MEA is cooled by the a cooler. The resultant cold lean MEA from the cooler is then recycled back through the top of the absorption column. A schematic description of the ACC process via amine scrubbing is presented in Fig. 2.

In a conventional ACC process, the reboiler is usually the most energy-intensive unit [36]. To minimize energy consumption in the reboiler, the cooling duty of the condenser should be decreased, or the preheating duty of the heat exchangers be increased with both inlet and outlet feed temperatures fixed. However, it is noteworthy that due to the increase in the vapor pressure of water at high temperatures, cooling duty in the condenser increases when the preheating duties in the heat exchangers are increased. Although setting a maximum preheating duty is a potential strategy to reduce the energy consumption in the reboiler, the cooling duty of the condenser is increased when a maximum preheating duty is set. This means that the energy ejected from the reboiler will be wasted in the condenser without being used. For this reason, it might be difficult to reduce the cooling duty of the condenser by preheating during ACC.

In a similar study, Jung et al. [37] suggested the application of a configured split-flow and phase-separation heat exchanging system to minimize energy consumption during ACC. The authors established that the regenerative energy requirement of the ACC process could be cut down by 2.84 GJ/ton CO<sub>2</sub>, which is 27% better than the conventional ACC process [37]. However, the major disadvantage with their approach is that a high amount of energy is still consumed from the configuration during regeneration and desorption of the CO<sub>2</sub>-containing solvent [24]. Hence, this review suggests the application of a process integration-based concept (flexible HENs integration) to tackle the high energy consumption associated with ACC, especially during stripping and sorbent regeneration. Table 1 presents a summary of recent studies that applied different techniques for energy recovery during ACC via amine scrubbing, as well as the amount of energy saved, while Table 2 compares the competitiveness of CO<sub>2</sub> absorption technology with other CO<sub>2</sub> capture technologies such as membrane, adsorption, cryogenic, etc. To justify why this study focused more on ACC. The basis for comparison in Table 1 is that most of the studies considered focused on ACC. Though non-process integration-based techniques are effective for energy minimization to an extent during ACC, information in Table 1 reveals that non-process integration-based techniques result in higher energy savings.

## 3. Current approaches for effective energy recovery during ACC

Emerging techniques for energy recovery during ACC are categorized under two approaches herein. First, is a process integration-based approach which depends mainly on process modification [82,83], and secondly, a non-process integration-based approach that mainly involves solvent development [84,85]. Although the application of non-process integration strategies for energy minimization during ACC

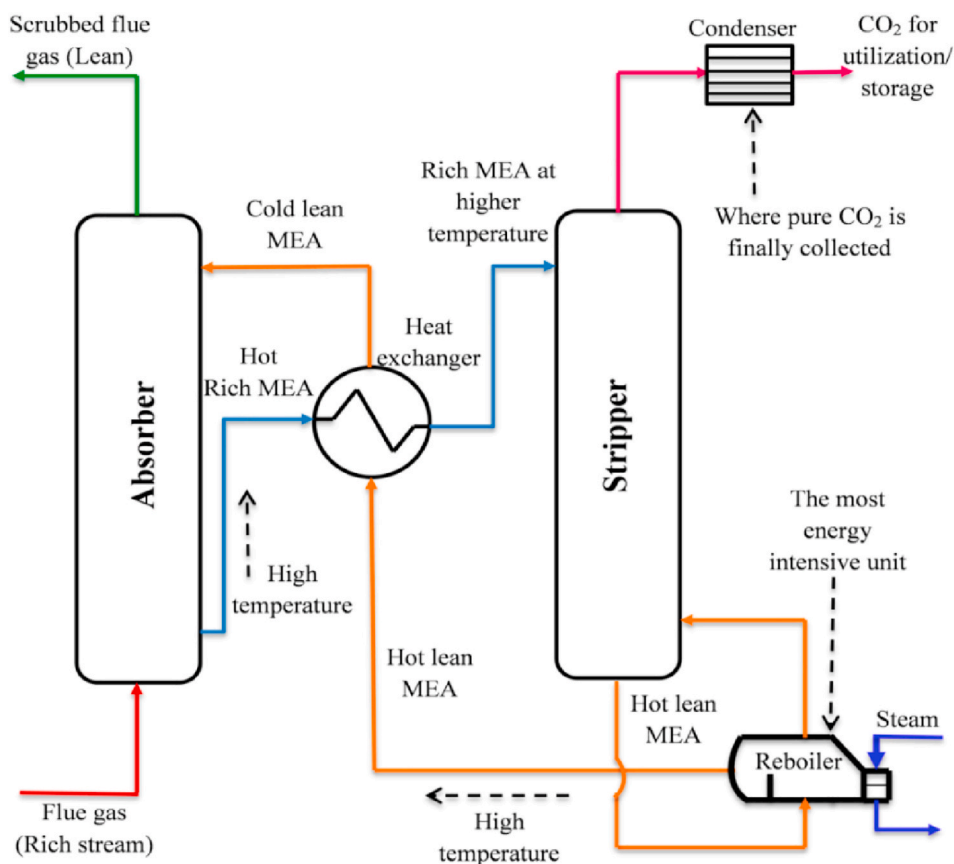


Fig. 2. CO<sub>2</sub> capture via amine scrubbing. Adapted and modified from Rochelle [34].

could result in significant energy saving to some extent, the drop in plant efficiency and increased process cost is usually a major limitation [86]. Several studies on energy minimization in industrial processes have associated high energy consumption with the topological changes in the network of heat exchangers [87,88]. These changes include the addition of new heat exchangers, re-piping, or the re-sequencing of the existing network [89]. A summary of some process and non-process integration techniques that can be used to maximize energy recovery during ACC is presented in Fig. 3.

The goal of the two approaches highlighted in Fig. 3 is to operate at reduced energy costs and make huge profits. As far as could be ascertained, process integration-based approaches have not been adequately harnessed for energy minimization during ACC. Similarly, the integration of flexible HENs for energy recovery during CO<sub>2</sub> capture has not gained much relevance. With the current increase in global energy demands in process industries, as well as its obvious high cost, there is a need to optimize industrial applications to be less energy-intensive and yield profit [90].

The synthesis, integration, and optimization of HENs is envisaged as an effective way to bridge the gap between energy demand and cost in many industrial applications including ACC. However, most HENs that were synthesized and integrated in the past were done under the assumption of a quantified operating condition [91]. This means that, when operating conditions fluctuate, stream temperature and energy efficiency targets can easily fall out of reach. For a process like ACC where process variables randomly fluctuate, there is a need to synthesize and integrate a HEN that can accept changes in operating conditions. Several methods (sequential and simultaneous) have been proposed for HENs integration in the past [92–95]. However, in most of the methodologies proposed, uncertainty has been a major issue. To address this issue, researchers proposed different techniques to synthesize multi-period and flexible HENs [96,97]. Nonetheless, most of the

proposed techniques were based on simultaneous techniques that involve complex mixed-integer non-linear programming (MINLP) which are hard to solve. This review opines that there is a need to also explore sequential techniques to synthesize flexible HENs for effective energy recovery, especially during ACC.

#### 4. The potential of process integration during ACC

Process integration (PI) is a fast-moving area of research and development. PI research began in 1978 with emphases on energy efficiency [98]. Subsequently, more emphasis was placed on developing systematic methods for designing HENs. PI approaches for solving energy problems is not peculiar to a specific industrial application, it can be applied in other aspects of process design, such as water and wastewater minimization [99,100]. The deployment of PI techniques in the field of CO<sub>2</sub> capture could proffer a solution to energy efficiency in CCS systems, and also tackle other challenges affecting the world today in the energy-food-water nexus.

So far, process integration has been applied in some energy-intensive processes like crude distillation [101], CO<sub>2</sub> conversion [102], and cement production [103] because of its significant energy-saving and cost benefits. However, it has not been adequately explored for energy recovery during ACC. Most large industries (for example coal-fired power plants) that use ACC have set up technical procedures to conduct energy assessment studies for their local plants to reduce energy efficiency, available resources, and greenhouse gas emissions [104, 105]. PI through the retrofitting of flexible HENs in existing plants could improve energy recovery during ACC by increasing the heat transfer area of the process. Also, the use of PI-based techniques during the ACC allows the process to use the heat emitted by another unit even if the units do not operate optimally on their own, thereby reducing the overall energy consumption. PI can also be used to evaluate cost and

**Table 1**  
A summary of studies that attempted energy recovery during ACC.

Solvent type	Technique used	Energy-saving	Reference
Monoethanolamine (MEA)	Multivariable optimization	7.1%	[38]
N-methyldiethanolamine	Sorbent modification	5.5%	[39]
Diglycolamine (DGA)	Solvent modification	5.2%	[40]
Diethanolamine (DEA)	Sorbent modification	2.6%	[41]
MEA	Capacitive deionization	10.0%	[42]
NH <sub>3</sub> + MEA	Advanced stripper configurations	27.0%	[43]
NH <sub>3</sub> + AMP	Ammonia blending	7.5%	[44]
PZ + K <sub>2</sub> CO <sub>3</sub>	Use of additives	5.2%	[45]
AMP + EDA	Amine blending	5.5%	[46]
MEA	Upgrading external waste heat	14.0%	[47]
MEA	Lowering purity requirement	20.0%	[48]
MEA	Phase-separation	5.0%	[49]
MEA	Process configuration	15.8%	[50]
AMP + HMDA	Solvent modification	15.0%	[51]
MEA	Superstructure development	17.4%	[52]
MEA	Flow sheet modifications	17.0%	[53]
MEA	Process intensification	28.0%	[54]
MEA	Configurational modifications	35.0%	[55]
MEA	Parameters optimization	9.3%	[56]
MEA	Bifunctional catalyst	23.3%	[57]
EtOH-MEA-H <sub>2</sub> O	Amine blending with alcohol	10.2%	[58]
MEA	Computer Aided Molecular Design	31.4%	[59]
MEA/1-propanol	Energy-saving splitter	39.9%	[60]
MEA + 2-methoxyethanol	Sorbent blending	15.0%	[61]
NH <sub>3</sub>	Capacitive ion separation	35.0%	[62]
MEA	Superstructure optimization	15.0%	[63]
MEA	Multistage process configuration	25.5%	[64]
MEA	Flowsheet modifications	17.4%	[65]
Methanol + MEA	Sorbent blending	12.0%	[66]
MEA + PZ	Process configurations	9.5%	[67]
Amine-functionalized Fe <sub>3</sub> O <sub>4</sub>	Solvent modification	23.2%	[68]
SO <sub>4</sub> <sup>2-</sup> /ZrO <sub>2</sub> /MCM-41	Bifunctional catalyst	28.0%	[69]

energy savings by trading materials and utilities within a process, instead of allowing it to operate independently. Energy integration is an aspect of process integration that can also be used to search for heat source-to-sink matches which could be used to maximize energy recovery during ACC. Other benefits of applying process integration technologies (for example the integration of flexible HENs) during ACC are summarized in Fig. 4. It is worth emphasizing that although the benefits shown in Fig. 4 are not the only benefits of process integration, they represent the three major benefits of flexible HEN integration during ACC. From this standpoint, it is evident that the application of process integration-based concepts (through flexible HENs integration) during ACC presents a wide range of opportunities for effective CO<sub>2</sub> capture with significant energy savings and cost reduction.

## 5. Emerging techniques for energy recovery during ACC

Researchers have suggested different modern techniques to improve energy efficiency and reduce costs during ACC [106–108]. Emerging techniques for energy recovery during ACC have been broadly classified into two groups as earlier highlighted in section 4. These emerging techniques are critically discussed in sections 5.1 and 5.2 of this review alongside their potentials, merits, limitations, and suggestions for further improvement.

**Table 2**  
Competitiveness of ACC with other CO<sub>2</sub> capture technologies.

S/N	Capture technology	Merits	Drawbacks	References
1	Absorption	Most mature technology for CO <sub>2</sub> separation Absorption efficiency is high and greater than 90% Sorbents can be regenerated by heating and depressurization. Easy retrofitting in existing power plants	o High capital and operational expenditure o High energy requirement. o Susceptibility of amines to thermal and oxidative degradation. o A high amount of heat for sorbent regeneration is required. o Equipment corrosion	[70] [71]
2	Adsorption	o High adsorption efficiency is achievable (>85%). o The process is reversible and the adsorbent can be easily recycled. o Slightly lower regeneration energy requirements, and minimized pressure losses o CO <sub>2</sub> purity higher than 95% and recovery higher than 80% can be achieved	o High-temperature adsorbents are required.	[72–74]
3	Membrane separation	o High separation efficiency >80% is achievable. o Can be easily adapted for the separation of other gases	o Low fluxes and fouling. o High energy penalty o Performance is strongly affected by flue gas conditions like low CO <sub>2</sub> concentration and pressure.	[75,76]
5	Cryogenic distillation	o Adapted industrially for CO <sub>2</sub> recovery o Mature technology	o Highly energy intensity estimated to at 600–660 kWh per tonne of CO <sub>2</sub> . o Only viable for very high CO <sub>2</sub> concentration >90% v/v.	[77,78]
6	Hydrate-based separation	o Low energy penalty (6–8%) o Energy consumption could be as low as 0.57 kWh/kg-CO <sub>2</sub> o Most promising long-term CO <sub>2</sub> separation technology identified today	o New technology and more research and development is required	[79–81]

### 5.1. Non-process integration-based techniques

#### 5.1.1. The use of phase-change solvents

Apart from the use of additives with amines which is a popular technique for minimizing energy consumption during ACC, a class of liquid solvents that undergo phase change during the absorption of CO<sub>2</sub> have emerged as a promising alternative to capture CO<sub>2</sub> while reducing the need for regenerative energy; such materials are called phase-change solvents [109,110]. A comprehensive overview of the potentials of phase change solvents during ACC has been adequately captured in the

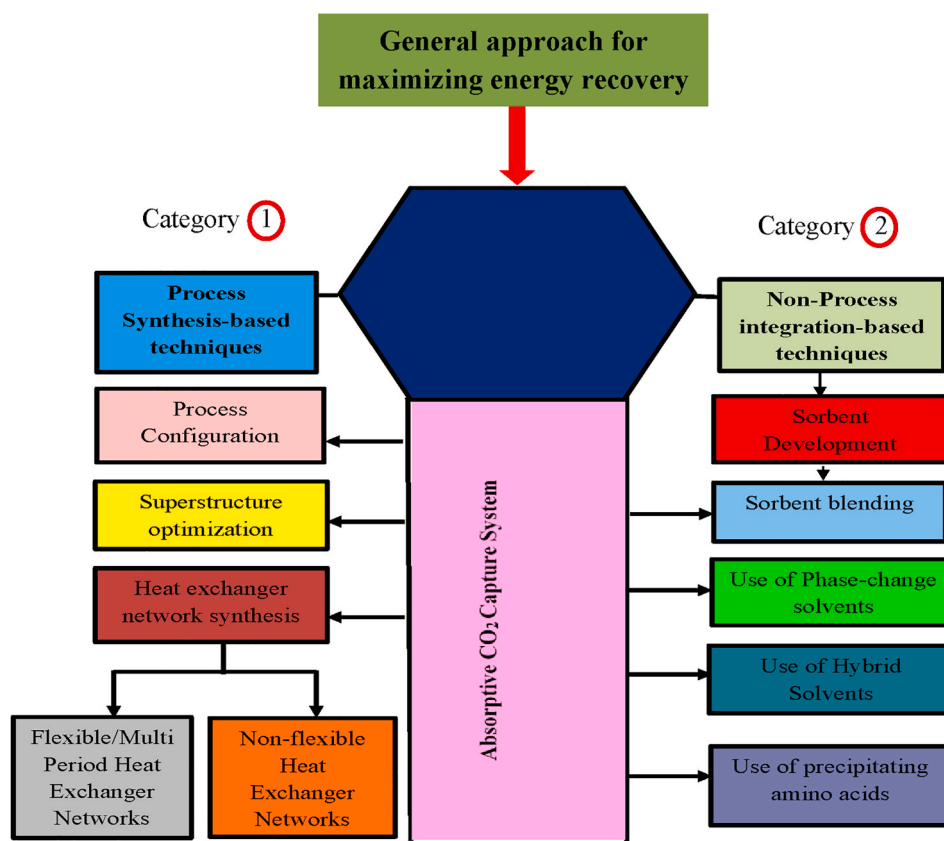


Fig. 3. Current energy recovery techniques during ACC.

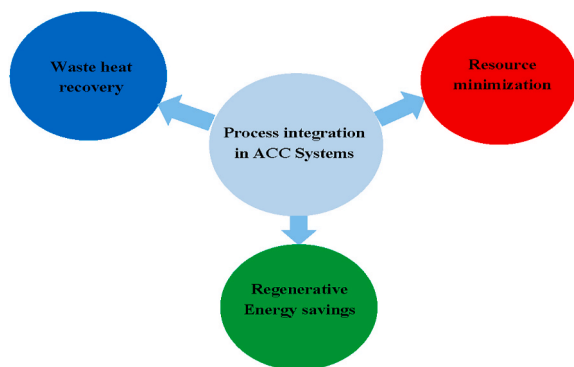


Fig. 4. Prospective benefits of process integration in ACC systems. Modified from Adamu et al. [102].

works of Wang and Li [111], Zhuang et al. [112], Zhang et al. [113] and Papadopoulos et al. [114]. Phase change solvents are used during ACC because certain components of the ACC solvent system can precipitate upon the absorption of CO<sub>2</sub> [115]. This subsequently leads to the formation of a suspension which can be divided into a CO<sub>2</sub>-rich and lean stream. Phase change solvents have several advantages over traditional amines because of their ability to maintain absorption at higher CO<sub>2</sub> and cyclic loads, lower solvent circulation speed, improved kinetics, negligible contact equipment, and low regenerative energy requirement due to their low latent heat demand [116]. However, the major problem with phase change materials is their relatively high cost which impacts negatively on the economic advantage of the ACC process [117].

Generally, it is known that the transition in phase-change solvents (PCS) is usually a change from one of the first two fundamental states of matter (solid and liquid) to the other. But it is worth mentioning in this

review that phase transition also takes place between non-classical states of matter, such as the conformity of crystals, where the material passes from conformity in one crystalline structure to another, which may be at a higher or lower energy state. PCS has been used in different commercial applications where energy minimization was required; for example heating pads [118], power plants [119], waste heat recovery plants [120], and textile production plants [121]. But, the focus of this review is on the application of PCS for effective energy recovery during ACC in coal-fired power plants.

In a typical ACC system that uses phase-change solvents, there is usually an absorption column, heat exchangers, a spray dryer column (stripper), and a compressor as shown in Fig. 5. The sorbent absorbs heat and changes phase when it comes in contact with CO<sub>2</sub>. After the absorbed CO<sub>2</sub> is separated from the PCS, a large amount of heat is given off, and the PCS changes from liquid back to the solid phase. The heat of fusion of the PCS can be used to decrease the heat duty in the stripper during ACC, while the cooling duty can be reduced by melting the sorbent. Several research reports on PCS for energy recovery have surfaced in open literature; for instance, Shavaliyeva et al. [122] reported that the use of phase-change solvents during absorptive CO<sub>2</sub> capture could minimize energy consumption with about 40% energy savings. The major limitations highlighted by the researchers were the non-ideal behaviors of the phase-change materials, as well as their high latent heats.

Though the use of PCS during ACC could lead to significant energy savings, it also incurs increased process cost because phase change solvents are expensive for large-scale ACC. Furthermore, the use of PCS in ACC systems is faced with other limitations such as; low thermal conductivity in their solid phase, difficulty in preventing unsuitable melting and phase separation during sorbent recycling which can lead to a significant loss in latent heat enthalpy, and low volumetric latent heat during stripping [123]. While this review focuses on the integration of flexible HENs to guarantee low cost and significant energy savings in

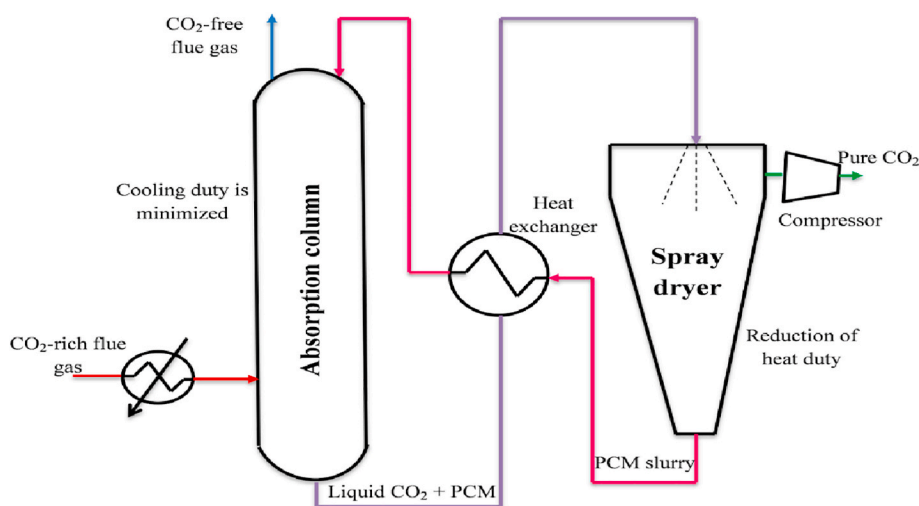


Fig. 5. Absorptive CO<sub>2</sub> capture using phase change solvents. Modified from Zhang et al. [113].

ACC systems, more studies could be conducted in the future to focus on addressing the limitations of phase-change solvents during absorptive CO<sub>2</sub> capture. A few studies that applied the use of PCSs to minimize energy consumption have been summarized in Table 3 with their respective energy savings recorded. From the information provided in Table 3, it could be inferred that the use of PCS to minimize energy consumption during CO<sub>2</sub> capture is well-studied in the literature. As such, there is a need to develop other alternative techniques like flexible HENs integration which has not been adequately reported.

### 5.1.2. Use of hybrid solvents

The quest for more sustainable ways to maximize energy recovery during ACC is still on. Recently, Huang et al. [137] investigated five major classes of hybrid solvents that could aid energy recovery during ACC, while Garrabrant et al. [138] developed a hybrid solvent/solid-state methodology to reduce energy consumption during ACC. Their methodology involved the absorption of CO<sub>2</sub> using aqueous glycine (sarcosine amino acids), which was followed by the crystallization of bicarbonate salts of glyoxal-bis(iminoguanidine). Interestingly, the authors were able to establish that the regenerative energy requirement of their hybrid solvent was 24% lower than the regenerative energy requirement of a benchmark industrial solvent (MEA). In addition, their study also established that regenerative energy

requirements could be 40% lower if sodium glycinate is used. Also, it has been reported in the literature that hybrid solvents show better efficiency compared to the use of aqueous amine solutions during CO<sub>2</sub> capture [139]. However, the major disadvantage of using hybrid amine solvents is sorbent degradation, since the amine solutions must still be heated during regeneration. The adverse effect of solvents (for example sarcosine amino acids) on the environment is another serious concern limiting this technique. There is a need for future research to consider addressing the limitations associated with hybrid solvents and implement its full application during absorptive CO<sub>2</sub> capture because from the literature investigated so far, hybrid solvents (with more reduced limitations) could play a pivotal role during energy recovery in ACC systems.

### 5.1.3. Sorbent blending

Studies have shown that monoethanolamine (MEA) blended with piperazine results in a superior absorption performance and less regeneration energy requirement compared to the current industrial standard involving only monoethanolamine [140,141]. This means that the blending of sorbents (amines with piperazine) could significantly influence effective CO<sub>2</sub> capture with improved energy efficiency. Bougie and Iliuta [142] suggested that blending solvents (for example MEA) with aqueous piperazine solutions during ACC could minimize the high energy requirement of a typical CO<sub>2</sub> absorption process. Although the researchers recorded a slight energy recovery with this approach, blending of sorbents with additives like piperazine has been shown to suffer from limited solvent solubility, especially if solid precipitation occurs simultaneously at high and low CO<sub>2</sub> loadings [143]. Although energy consumption could be minimized to some extent by blending amine (MEA) with piperazine (PZ), the technique will require the use of extra materials (sorbents) which will increase process cost. Also, materials used in designing most of the existing CO<sub>2</sub>-emitting plants will need to be modified to handle the corrosive nature of blended MEA with PZ.

Other studies have also shown that the improvement of MEA-based CO<sub>2</sub> capture units through the use of blended Monoethanolamine–Methyl diethanolamine (MEA–MDEA) with split-flow configurations could potentially make ACC slightly less energy-intensive, but not without an impact on process cost [144,145]. Despite the high cost, it will be better to capture CO<sub>2</sub> at higher efficiencies to achieve greater CO<sub>2</sub> emissions avoidance and energy savings. However, for higher energy recovery targets to be achieved, the gas delivery schemes with steam pressure transferred from the power plants to the CO<sub>2</sub> capture units must be integrated.

Table 3

A summary of studies that used phase change solvents for energy recovery.

Type of PCS	Application	Energy-saving	Reference
1,3-Bis(3-aminopropyl)	CO <sub>2</sub> capture	12.0%	[109]
Potassium salt of sarcosine	CO <sub>2</sub> capture	14.7%	[124]
Ionic liquids	CO <sub>2</sub> capture	11.3%	[125]
N-Methyl-1,3-diaminopropane	CO <sub>2</sub> capture	11.5%	[126]
Amino acid salt	CO <sub>2</sub> capture	13.2%	[127]
Triethylenetetramine	CO <sub>2</sub> capture	19.2%	[115]
Amine–Water Mixtures	CO <sub>2</sub> capture	10.8%	[29]
Paraffin wax	Thermal management	7.3%	[128]
Paraffin RT15	Heat recovery	7.5%	[129]
Amino-functional ionic liquid	CO <sub>2</sub> capture	13.5%	[130]
Potassium proline + water + ethanol	CO <sub>2</sub> capture	15.0%	[131]
Ionic liquids	CO <sub>2</sub> capture	12.0%	[132]
Aminopyridine solvents	CO <sub>2</sub> capture	11.0%	[133]
DEEA/MAPA	CO <sub>2</sub> capture	13.2%	[134]
Potassium proline/ethanol solution	CO <sub>2</sub> capture	14.6%	[135]
PZ/DMF	CO <sub>2</sub> capture	11.0%	[136]

#### 5.1.4. Precipitating amino acids

Amino acid salts show great prospects for application in CO<sub>2</sub> separation processes because of their desirable properties which include high energy efficiency [146], environmentally benign nature [147], lower evaporation [148], and reduced degradation issues [149]. Precipitating amino acids are non-volatile and less noxious compared to conventional amines. Increased stability, resistance to degradation, and lower reboiler duty are additional advantages of precipitating amino acid salts, which could be highly beneficial during ACC. Potassium, lithium, and sodium salts are the common examples of amino acid precipitates that can be formed during ACC. The use of precipitating amino acid salts show significant benefits over conventional amines during ACC because of their increased resistance to oxidative decomposition and insignificant vapor pressure [150]. Furthermore, precipitation in most amino acid salts has the potential to improve sorbent-CO<sub>2</sub> capacity and efficiency of the stripper in a sorption process.

According to literature reports, the use of precipitating amino acids during ACC could lead to reduced energy consumption which could be almost 73% lower than the conventional MEA process that does not use any additive [151,152]. Slurry handling and crystallization control are the major drawbacks linked to the use of precipitating amino acids in ACC systems. According to Goetheer et al. [153], the aforementioned limitations can be addressed via the Decarboxylation (DECAB) process. Taurine, Glycine, Proline, and Lysine are some examples of popular precipitating amino acids that may be further investigated for energy minimization during ACC. Prospectively, precipitating amino acids can increase energy recovery and decrease process cost in gas separation plants. However, more investigations are required to know the long-term effects of the precipitates on the absorption column and general plant operation.

#### 5.1.5. Bifunctional catalysts and the use of additives

The use of bifunctional catalysts for energy recovery is receiving increasing attention from the scientific community due to its exceptional properties which include high catalytic efficiency, pore-geometry, pore-size distribution, distribution of acid sites, hydrogenation/dehydrogenation ability, as well as a large mesoporous surface area [154]. Bifunctional catalysts have been largely used in crude oil reforming [155], hydrocracking of heavy paraffin [156], reductive etherification of cyclohexanones [157], promotion of biomass-derived oxygenates [158], and hydro-isomerization of alkanes [159]. Ni-HZSM-5 [57], MgO-HZSM-5 [43], Al<sub>2</sub>O<sub>3</sub>/HZSM-5 [144], Na-Fe<sub>3</sub>O<sub>4</sub>-HZSM-5 [160], Al<sub>2</sub>O<sub>3</sub>/HZSM-5 [57], and Fe-Promoted SO<sub>4</sub><sup>2-</sup>/ZrO<sub>2</sub>/MCM-41 supported on MCM-41 [69] are popular examples of metal-oxide modified bifunctional catalysts that have attracted tremendous attention in energy recovery studies because of their high energy-saving potential. Furthermore, bifunctional catalysts show high catalytic activity and catalyst stability during the absorption of CO<sub>2</sub> which could be attributed to the good synergistic effect between the two components in the bifunctional catalyst [161]. Typically, research has that the use of bifunctional catalysts with MEA in ACC systems could decrease the regeneration heat duty by about 35%, and increase the desorption factor by 3 times compared to pure amines [162]. Although bifunctional catalysts have found predominant application in the petrochemical industry for energy recovery, it has not been adequately tested in ACC problems. Future studies on CO<sub>2</sub> capture could consider the use of bifunctional catalysts to reduce the regenerative heat duty of the rich amine with less energy consumption.

In addition to the use of bifunctional catalysts, researchers have suggested the introduction of additives into conventional amines to improve desorption and lower regenerative energy [163]. The major benefits that the use of additives could bring to absorptive CO<sub>2</sub> capture include the enhancement of CO<sub>2</sub> absorption kinetics, reduction of the absorber capital costs, and the reduction of solvent regeneration energy demands. However, its main limitation is the formation of precipitate in the absorber. This implies that robust technologies are needed to address

this limitation. Wang et al. [164] studied the effect of using TiO<sub>2</sub> nanoparticles as an additive during an enhanced CO<sub>2</sub> absorption and desorption study. The researchers reported that the introduction of TiO<sub>2</sub> nanoparticles in a monoethanolamine system could save about 42% of energy during desorption. Other additives that may address energy demands during absorptive CO<sub>2</sub> capture include soluble organic weak acids [165] and metal ions [166].

It is evident from the aforementioned studies that the use of bifunctional catalysts and additives show promising energy recovery potentials in ACC systems. Therefore, these materials can play important roles in advancing ACC with minimal energy usage. However, most studies on the use of bifunctional catalysts and additives to enhance energy recovery have been carried out at bench-scale conditions, and this might not be a correct depiction of the process performance at industrial scales due to the complexities of industrial processes. Therefore, more studies could be conducted on a large scale to investigate the effect of bifunctional catalysts and additives on the overall system performance of ACC processes.

### 5.2. Process integration-based techniques in ACC systems

#### 5.2.1. Process configuration

Process configuration is critical for effective energy recovery [167]. To ensure effective energy recovery in ACC systems, new process configurations, including a complete investigation of the operational conditions of the baseline need to be assessed. DECAB Plus is a popular process configuration technique that has found wide industrial applications in recent times. Studies have shown that configuring a process via DECAB plus have the potential to lower energy usage [168,169]. During ACC, energy minimization could include the reduction of solvent regeneration energy, minimization of energy required to liquefy precipitates, and the CO<sub>2</sub> compression energy. For energy recovery tasks, DECAB Plus with lean vapor compression configuration is a reliable technique to reduce the reboiler heat duty by 45% during the regeneration of sorbents, compared to the conventional system without any process configuration [170]. This means that if an improved process configuration is applied during ACC, it could lead to remarkable energy recovery, but results in more process complexity with increased process cost. The limitation identified with process configuration as an energy recovery technique is that process and solvent improvements are not additive, hence process configuration without major improvements may not produce high energy savings beyond a specific limit. Vacuum stripping, double matrix stripping, and multi pressure stripping with or without heat recovery are examples of process configurations that could be used during ACC, while piperazine promoted potassium carbonate (K<sub>2</sub>CO<sub>3</sub>) solvents and promoted tertiary amines are some examples of solvent formulations that may be used for process configuration. There are four different types of changes to structural process configurations (for example combustion gas separation, multiple solvent supply, flow separation, and intermediate absorber cooling), and they have been discussed separately in the literature [171,172].

In the context of this study, structural process modifications could be combined in large processes to achieve maximum energy recovery. Alternatively, energy recovery can still be achieved in ACC systems using a single process modification approach like dividing the flue gas and feed it in two different positions within the absorption column. To ensure that effective energy recovery is achieved beyond any limit and sensible heat losses are minimized in ACC systems, future investigations could consider advanced process configurations with solvents that have very high capacities. Also, more configurations can be explored for advanced solvent formulations and process configurations to improve energy recovery potential during ACC.

#### 5.2.2. Superstructure optimization

A superstructure is supposed to contain all possible alternatives for a potential recovery network, including the optimal solution that is



hidden [173]. Therefore, optimization of superstructures is a potential approach to achieve energy recovery. Although the main objective of optimizing superstructures is to minimize the total cost of a process using mathematical modeling structures, energy recovery can also be achieved in the same way. According to Oh et al. [55], optimization of superstructures via flue gas separation, multiple supplies of solvents, flow separation, and intermediate absorber cooling can be extended to optimize the ACC processes for efficient energy recovery. More specifically, flue gas fractionation has the potential to minimize high regenerative energy requirements and maintain a high CO<sub>2</sub> recovery rate. Also, the superstructure optimization method can be used to identify structural configurations before performing sensitivity analysis on the main operational parameters, considering the solvent rotation rate, poor solvent load, and temperature control around along the absorption column. The main limitation of superstructure optimization is that the mathematical modeling structure results in nonlinear equations that are difficult to solve, especially when using realistic unit usage models [174]. The reformulation of these mathematical modeling framework models and their incorporation into the design of the mathematical programming superstructure can address the aforementioned limitations in future studies.

### 5.2.3. Integration of heat exchanger networks in ACC systems for effective energy recovery

HEN integration was first reported by Masso and Rudd [175]. Since then, the integration of heat exchanger networks has been embraced as a propitious strategy to achieve effective energy minimization in many industrial processes [176,177]. Although the concept of HEN integration is well-known and applied in many areas, it has not been adequately reported in ACC studies. HEN integration in ACC systems could guarantee good use of the energy between hot and cold process flows to reduce consumption of process heating and cooling services [178]. HEN integration could also be used for utility targeting and energy minimization in energy-intensive industrial processes like ACC [179]. Although additional surface area, topology, safety, and working time constraints are the major challenges limiting the application of HENs integration for energy recovery in ACC systems [180], some of these limitations can be tackled by using heat transfer amplifiers at the back of the networks in ACC systems. For effective application of HENs in ACC systems, there is a need to integrate a HEN that is flexible, and capable of addressing the challenge of parametric fluctuations in ACC. To effectively integrate flexible HENs for effective energy recovery in ACC systems, important parameters that should first be considered include CO<sub>2</sub> capture efficiency, coal type, the scheme of flue gas delivery, amine/sorbent type, and supply steam pressure for sorbent regeneration [181]. Future studies should consider addressing these challenges to ensure maximum energy recovery in ACC systems using a flexible HEN integration approach.

## 6. A new perspective for energy recovery during ACC using flexible HENs

Most scientific contributions on HEN synthesis for energy recovery reported in the past assumed nominal fixed operating conditions [182, 183]. But in the real industrial world, problems like ACC are faced with several disturbances within the process, and from the environment. This means that a design that simply refers to a single condition would not meet the full expectations of the process. To address this while ensuring minimized energy consumption using a process integration-based approach, HENs must be designed to be flexible and functional as the process parameters vary [184]. At the same time, the flexible HENs must be cost-effective. The most attractive feature in any flexible HEN integrated for energy recovery during ACC is its ability to be sufficiently flexible within a different range of variations. The early works of Papalexandri and Pistikopoulos [185,186] have provided a good groundwork for flexible HENs, and an up-to-date review detailing

several methods to synthesize flexible HENs has been reported in the work of Kang and Liu [187].

Several attempts have been made in the past to introduce process integration-based energy recovery techniques in the field of CO<sub>2</sub> capture [188]. For example, Escudero et al. [189] proposed a methodology for integrating flexible HENs for energy recovery in oxyfuel CO<sub>2</sub> capture plants using the concept of pinch analysis. However, despite the huge energy savings recorded using this approach, the concept has not been fully implemented for energy minimization in CO<sub>2</sub> capture plants that involve post-combustion capture technologies like ACC. To date, no study has considered integrating flexible HENs for effective energy recovery during ACC while considering heat exchanger loads and costs. This review identifies that the methodologies presented in the works of Chen and Hung [184], Kang and Liu [187], as well as the model of Rooney and Biegler [190], can be slightly modified and used for the integration of flexible HENs with a control strategy that considers the operating stage in ACC systems.

### 6.1. Benefits of integrating flexible HENs in ACC systems

The integration of flexible HENs could lead to energy savings and improved plant efficiency if introduced into ACC systems. Also, due to the flexibility and controllability capabilities of flexible HENs, they can remain operable under varying operating conditions without losing the current temperature targets while maintaining optimum energy integration in ACC systems [191]. Yoro et al. [192] have attempted to integrate a flexible network for energy minimization during CO<sub>2</sub> capture to determine its energy recovery capability. Although their flexible network was not a pure HEN but consisted of both heat and mass exchangers (combined heat and mass exchanger network - CHAMEN), the authors were able to establish that integrating HENs (combined with mass exchanger networks) could minimize about 30% of the regeneration heat requirement during CO<sub>2</sub> absorption. Also, it was observed that if a CHAMEN integration approach is used during ACC, the total annualized cost (TAC) accrued will be about \$199800/yr [193]. But this study envisages that the integration of flexible HENs (without including mass exchangers) for energy recovery during ACC could save more energy with a reduced TAC than when combined with mass exchanger networks. However, to date, this interesting idea has not been given much attention by the scientific community. Therefore, flexible HENs integration as an energy minimization strategy during ACC is new and could be an interesting area to consider in future research.

### 6.2. Synthesis methodologies for flexible HENs in ACC

Several synthesis methods have been proposed for flexible HENs in the past [194,195]. Hybrid methods, pinch analysis and mathematical programming are the major methodologies used for synthesizing and integrating flexible HENs [196]. Pinch-based methodologies adopt the concept and principles of pinch technology to solve HEN synthesis problems using composite curves, grand composite curves, or grid diagrams [197,198]. Some heuristics concepts can also be applied in ACC systems to solve problems of flexible HENs via pinch analysis. According to Shenoy [199], Pinch technology can be used for energy targeting, network design, and flexible HENs integration considering heat transfer enhancements and pressure drop; as such, its application can be extended for energy recovery in ACC systems.

A chart showing some important information that may be required at each stage in the synthesis and integration of flexible HENs for effective energy recovery during ACC is presented in Fig. 6.

## 7. Progress and limitation of flexible HENs integration for ACC systems

Pinch technology and mathematical programming concepts have shown great prospects in synthesizing flexible HENs to tackle energy

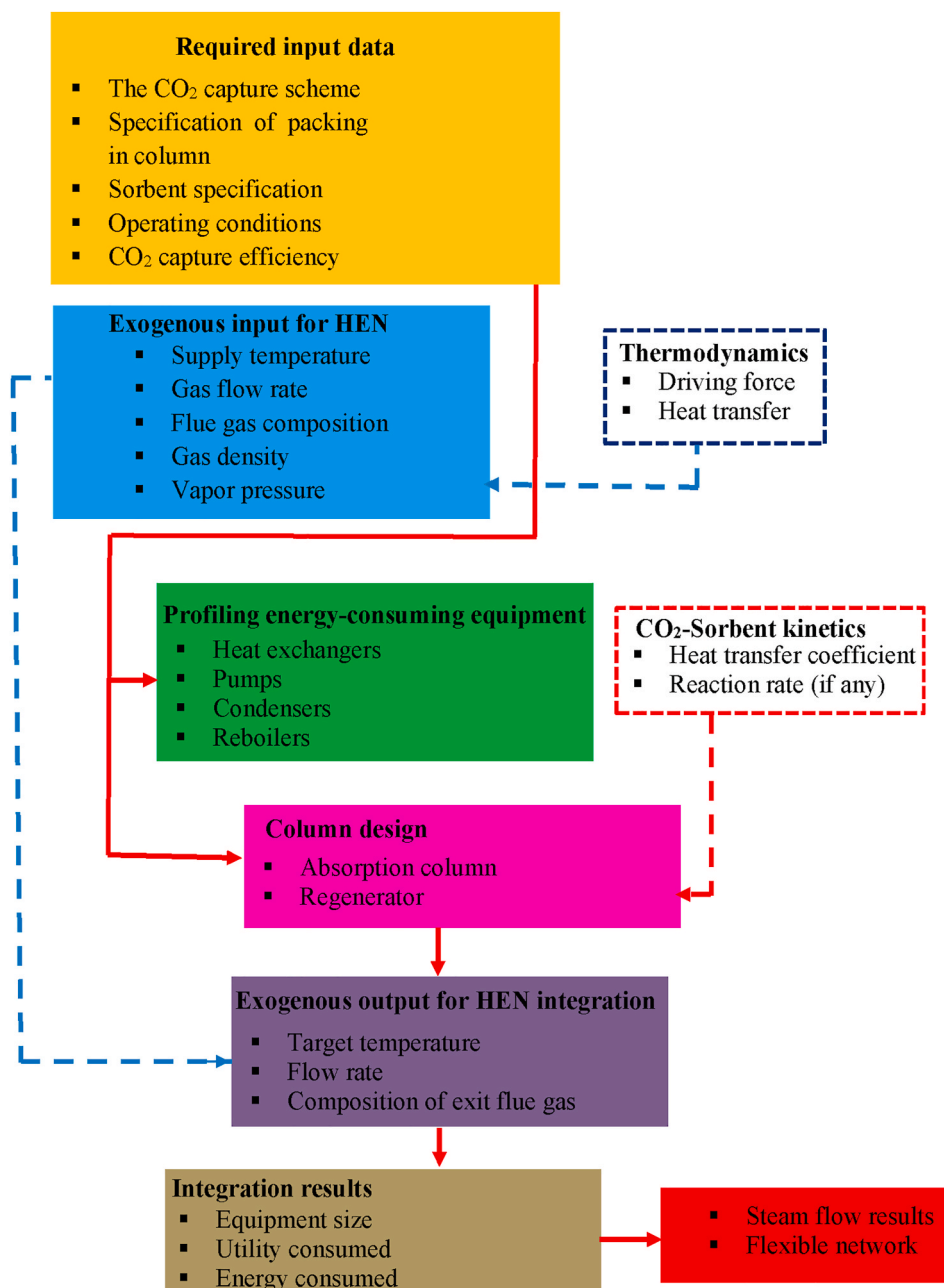


Fig. 6. Important data for flexible HEN synthesis during ACC. Modified from Kang and Liu [187].

consumption challenges in selected energy-intensive processes [200], but the application of these concepts has not been adequately extended to ACC problems in coal-fired power plants. Most research on the synthesis of flexible HENs claimed that all control variables can be adjusted during HEN operation [201], whereas the control and operation strategy in many flexible HENs have been consistently neglected.

Marselle et al. [202] reported a synthesis technique for flexible HENs where flow rates and supply temperatures were varied within the lower and upper limits to accommodate fluctuation in process variables and other disturbances. The researchers used efficient design procedures to achieve robust designs that can manage variations within the condition for maximum energy recovery, with a network design or each condition separately, before manually combining the network settings. Though the synthesis technique proposed by Marselle et al. [202] was useful for flexible HENs for energy recovery in ACC systems, it is worthy to note that no procedure was performed for combining the parameters in their study, and there are still some complications with the approach because

the location of critical operating conditions is usually not obvious in the ACC process. Subsequently, some other groups of researchers attempted to use rigorous methods such as networks with uncertain flows and temperatures to operate flexible HENs on different types of superstructures [203–205]. However, the major limitation observed was that although the proposed methods were thorough, they did not cover some major network structures suitable for ACC.

Fryer [206] proposed a method to synthesize flexible heat exchanger networks using computer simulation and optimization. However, the flexibility study introduced in their work was limited to cases where the networks have no degree of freedom. Furthermore, their general synthesis method did not adequately deal with the systematic derivation of a flexible HENs structure. Hence, this method may not be effective for energy recovery in ACC systems.

Floudas and Grossman [207] used a systematic procedure to synthesize flexible HENs with uncertainty regarding flow velocity and inlet temperature of process streams, while Gadalla et al. [208] proposed a

straightforward method to enhance the process conditions in manufacturing units to decrease the emission of CO<sub>2</sub> and also tackle energy requirements. Although both contributions yielded fair results to an extent, the major limitation observed was that the network flexibility was confined within a certain range. This means that if their approach is used in ACC systems, the synthesized heat exchanger network will be unable to handle variables that fluctuate randomly.

From the progress and limitations recorded so far, this review suggests that the most effective way to address the aforementioned limitations for effective applications in ACC systems is to implement the synthesis and integration of flexible HENs where linear stages of the preliminary network configuration, flexibility analysis, and network development could be easily performed.

## 8. Factors to consider in integrating flexible HENs for energy recovery in ACC systems

The integration of flexible HENs in energy intensive systems like ACC could lead to significant energy savings. However, to effectively integrate flexible HENs in both new and retrofit plants for large industrial processes like ACC, a few factors ought to be addressed. This section discusses some major factors to consider while minimizing energy consumption in ACC using flexible HENs.

### 8.1. Flexibility and sensitivity analysis

The synthesis and integration of flexible HENs depend on flexibility analysis involving a multiple synthesis phase and flexibility analysis phases performed iteratively [209,210]. In the synthesis and integration of flexible HENs for energy recovery in ACC systems, flexibility analysis is usually an optimization-based technique used to identify complex systems relating to uncertainty, for which the flexibility index is a quantifiable pointer. Flexibility analysis is performed to verify the viability of where critical flexibility points and test problems are located for the first time. If the flexibility condition is not met during ACC, several periods could be implemented to bring up-to-date the preliminary design, thereby augmenting the crucial features till an adaptable operation can be assured at all crucial stages. A good flexibility analysis will result in a HEN that accommodates the uncertain parametric fluctuations during ACC. Therefore, it is a critical factor that determines network improvement and the combination of uncertain parameters.

Additionally, sensitivity analysis could be performed in a flexible HEN to examine its response to change in operational parameters in the absorption columns during ACC, because most flexible HENs usually combine reaction and separation systems with their parameter changes to improve operation with minimal energy consumption. This means that to synthesize flexible HENs for effective energy recovery during ACC, the operating conditions of the absorption columns and reactors with other complex interactions between the fluctuations and HEN results must be adequately studied to supply important data for integrating flexible HENs in ACC systems.

### 8.2. Periodic and non-periodic variations

Multiperiod synthesis approaches for flexible HENs generally assume that there are constant changes in operating conditions and parameters over various distinct and finite operational stages, thereby creating reduced critical points for the flexibility of HENs. However, this review opines that during ACC, process constraints in each period also fluctuate randomly. Therefore, this study suggests that multiperiod synthesis methods may be combined with flexibility analysis according to the steps outlined in the work of Tian and Pistikopoulos [211] to address this limitation. During the integration of flexible HENs for energy recovery in ACC systems, multi-period techniques may be used for periodic variation with flexibility analysis, while a bottleneck removal

strategy could be adapted to tackle non-periodic disparities within each period as suggested by Kang and Liu [187].

### 8.3. Uncertainties

The major types of uncertainties associated with flexible HENs designed for energy recovery during ACC can be classified into two categories. These two categories of uncertainties are either dependent or independent on design decisions by the process designer. A classification of uncertainties in flexible HENs for energy recovery during ACC is presented in Fig. 7. Several ways to handle the uncertainties mentioned in Fig. 7 have been discussed in a comprehensive review by Grossmann and co-workers [212,213]. However, despite the tremendous research efforts made by scientists working in this field over the years, this review observed that sufficient attention has not been given to the synthesis and integration of flexible HENs where both exogenous and endogenous uncertainties are included. This is very important in ACC studies; because to synthesize and integrate flexible HENs for effective energy recovery in ACC systems, all uncertainties must be fully considered. On a general note, this review suggests that flexibility and sensitivity analysis, process uncertainties, as well as periodic and non-periodic variations are important factors that must be considered in integrating flexible HENs for effective energy recovery during ACC.

## 9. Opinions on the integration of flexible HENs during ACC

According to Grossman and Sargent [214], critical points for flexibility analysis in flexible HENs are determined by combining the active limits of the constraints based on their heat transfer areas, to solve a non-linear programming problem where the target function is solved within an operating range. Although their assertion is true, this review maintains that in the synthesis and integration of flexible HENs, some simplified approaches could range from model reduction to discretization of uncertain parameters to deal with problems involving many uncertain parameters as obtainable in a typical ACC study. Furthermore, to accelerate the integration of flexible HENs for energy recovery in ACC systems in future research, the following opinions are presented from this review:

- (i) Flexible HENs are designed to have minimized heat exchanger areas and total annualized cost (cost-effective networks) for energy recovery during ACC.

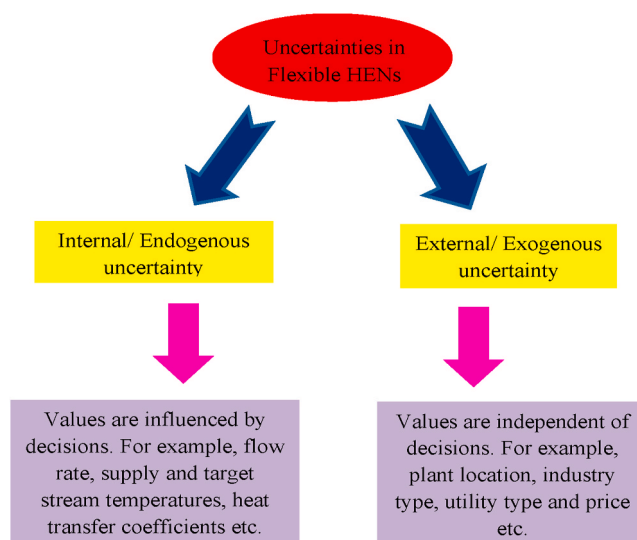


Fig. 7. Possible uncertainties in flexible HENs during ACC. Modified from Grossmann et al. [213].

- (ii) For effective integration during ACC, flexible HENs should not be designed to only meet design goals, but also safety, operability, and controllability objectives.
- (iii) The synthesis and integration of HENs alone is not enough to maximize energy recovery during ACC. An ideal HEN for integration into ACC processes must be feasible and flexible to handle incessant fluctuations in process conditions.

## 10. Proposed roadmap for large-scale energy recovery during ACC

Although the existing and emerging techniques for energy recovery discussed in this review offer evidence that energy recovery is feasible at a bench-scale during ACC, additional commercial-scale implementation is needed to affirm its effectiveness and applicability. Despite the tremendous amount of research that has been reported for energy recovery during ACC, some hurdles still need to be overcome to fully realize the potential of most of the emerging techniques highlighted in this work at an industrial scale. As far as could be ascertained, most of the energy recovery technologies that were reviewed in this paper were conducted under laboratory-scale conditions and have not yet been evaluated on a large scale. Besides, researchers are still investigating the individualistic energy recovery potential of these technologies during ACC to acquire deeper insights into the mechanisms involved during energy recovery, and have not yet examined the synergistic interaction of the technologies on a large scale, which is delaying the industrialization of these emerging technologies. To accelerate the commercialization of the emerging energy recovery techniques reviewed in this paper, stakeholders (for example scientists, industries, and policy-makers) involved in ACC studies should have a specific roadmap that includes the research and design (R&D), industrialization, and application stage as shown in Fig. 8. In this manner, the barriers to energy recovery during ACC can be overcome at an industrial scale.

Finally, research efforts should not stop at upscaling these emerging techniques for energy recovery during ACC (as shown in stage 2, Fig. 8). More efforts should be channeled towards applying them in large industries (stage 3, Fig. 8). Market and cost analysis for these emerging techniques may also be carried out to determine profitability if applied at an industrial level in large industries.

## 11. Conclusions and future prospects

A complimentary range of emerging technological approaches which include hybrid solvents, precipitating amino acids, bifunctional catalysts, and superstructure optimization have been reviewed in this work to enhance CO<sub>2</sub> emissions reduction with significant energy savings. It has been established that energy recovery during ACC involves an assembly of technologies that can tremendously decrease energy consumption. Nonetheless, most of these technologies have been tested only at the research and development phase. Also, the integration of flexible heat exchanger networks was studied and presented as an emerging technique for effective energy recovery during ACC. The following insights were drawn from this review;

- Most of the current technological methods for energy recovery during ACC are still under preliminary stages and are far from industrialization.
- The commercialization of energy recovery techniques during CO<sub>2</sub> capture relies on its scalability. Therefore, it is crucial to develop a technological roadmap that will lead to the scalability of the ACC process considering energy recovery measures.
- Although most of the non-process integration-based techniques for energy recovery in the past were effective to an extent, they contribute to increased process costs during ACC.
- The integration of flexible HENs together with sorbent development represents a promising and emergent technique for maximizing energy recovery during ACC.
- Although the integration of flexible HENs for energy recovery during ACC is not yet as intensive as research on other non-process integration-based techniques, it does not mean that the integration of flexible HENs is not a viable option for energy recovery during ACC; rather, it reveals its lack of maturity compared to other techniques.
- The relatively slow progress observed in adopting the integration of flexible HENs as an energy recovery strategy during ACC can be attributed to its techno-economic risks and uncertainties, which could be addressed through the availability of robust process integration tools.

The following recommendations have been made for future research;

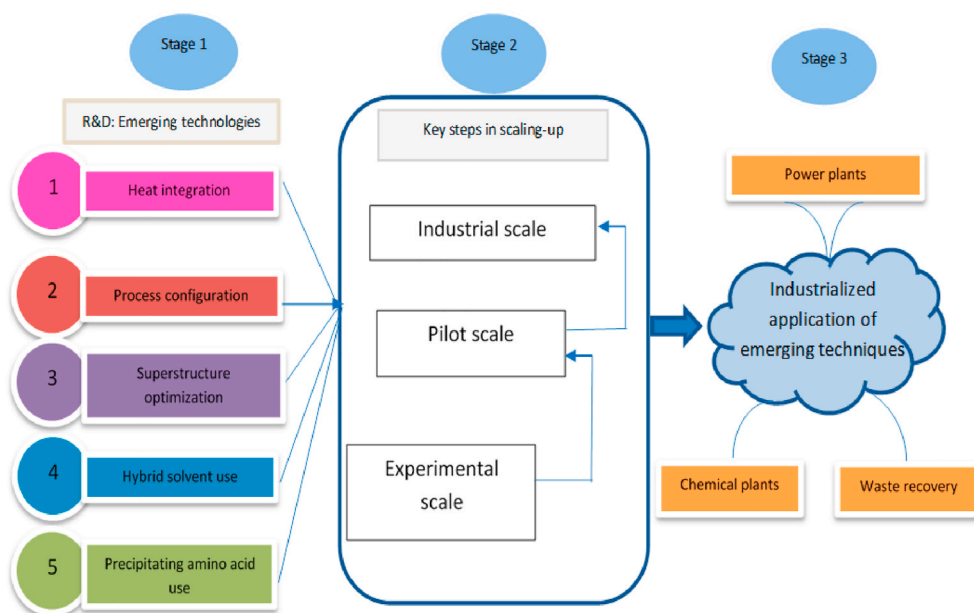


Fig. 8. A proposed roadmap for the commercialization of emerging energy recovery techniques during ACC.

- Since the application of process integration concepts via flexible HENs has not been adequately explored for ACC, integration of flexible HENs for energy recovery during ACC could be extended beyond energy minimization to include waste minimization by considering more detailed designs that combine with mass exchanger networks.
- More studies should focus on developing methodologies for flexible HENs synthesis that identify control constraints as a foundation for the development of heuristics, using block decompositions for retrofit problems instead of the predominantly used mathematical modeling approach.
- Future studies should be tailored towards the economic and cost analysis of flexible HENs to ascertain its profitability if integrated for energy recovery during ACC on an industrial scale.
- Finally, future research should focus on extending process integration-based techniques to maximize energy recovery beyond ACC to other CO<sub>2</sub> capture methods such as adsorption, membrane, and cryogenic separation.

## 12. CRediT author statement

Kelvin O. Yoro: Conceptualization, Methodology, Writing- original draft preparation. Michael O. Daramola: Supervision, Data curation, Writing- Reviewing and Editing. Patrick Sekoai: Visualization, Writing- Reviewing and Editing. Edward K. Armah: Data curation, Writing- Reviewing and Editing. Uwemedimo N. Wilson: Writing- Reviewing and Editing.

## 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.

## Acknowledgments

The idea developed in this review was conceptualized during KOY's doctoral study at the University of Witwatersrand, Johannesburg South Africa. Therefore, KOY appreciates the financial assistance from the National Research Foundation of South Africa [through NRF Grant number 107867], and the University of the Witwatersrand through the postgraduate merit award, [WITS-PMA 1230119].

## References

- [1] Yoro KO, Sekoai PT. The potential of CO<sub>2</sub> capture and storage technology in South Africa's coal-fired thermal power plants. *Environments* 2016;3:24.
- [2] Mac Dowell N, Fennell PS, Shah N, Maitland GC. The role of CO<sub>2</sub> capture and utilization in mitigating climate change. *Nat Clim Change* 2017;7:243–9.
- [3] Yoro KO, Daramola MO. Chapter 1 - CO<sub>2</sub> emission sources, greenhouse gases, and the global warming effect. In: Rahimpour MR, Farsi M, Makarem MA, editors. *Advances in carbon capture*. Woodhead Publishing; 2020. p. 3–28.
- [4] Mondal MK, Balsora HK, Varshney P. Progress and trends in CO<sub>2</sub> capture/separation technologies: a review. *Energy* 2012;46:431–41.
- [5] Yoro KO. Numerical simulation of CO<sub>2</sub> adsorption behaviour of polyaspartamide adsorbent for post-combustion CO<sub>2</sub> capture. Thesis. 2017.
- [6] Aaron D, Tsouris C. Separation of CO<sub>2</sub> from flue gas: a review. *Separ Sci Technol* 2005;40:321–48.
- [7] Baena-Moreno FM, Rodríguez-Galán M, Vega F, Alonso-Fariñas B, et al. Carbon capture and utilization technologies: a literature review and recent advances. *Energy Sources, Part A Recovery, Util Environ Eff* 2019;41:1403–33.
- [8] Li B, Duan Y, Luebke D, Morreale B. Advances in CO<sub>2</sub> capture technology: a patent review. *Appl Energy* 2013;102:1439–47.
- [9] Creamer AE, Gao B. Overview of CO<sub>2</sub> capture technology. In: Creamer AE, Gao B, editors. *Carbon dioxide capture: an effective way to combat global warming*. Cham: Springer International Publishing; 2015. p. 17–24.
- [10] Papadopoulos AI, Zargiannis T, Seferlis P. Computer-aided molecular design of CO<sub>2</sub> capture solvents and mixtures. *Process systems and materials for CO<sub>2</sub> capture*. John Wiley & Sons, Ltd; 2017. p. 173–201.
- [11] Sieniutycz S, Jeżowski J. 12 - heat integration within process integration. In: Sieniutycz S, Jeżowski J, editors. *Energy optimization in process systems and fuel cells*. third ed. Elsevier; 2018. p. 467–75.
- [12] Roh K, Frauzem R, Gani R, Lee JH. Process systems engineering issues and applications towards reducing carbon dioxide emissions through conversion technologies. *Chem Eng Res Des* 2016;116:27–47.
- [13] Dyer CH, Hammond GP, Jones CL, McKenna RC. Enabling technologies for industrial energy demand management. *Energy Pol* 2008;36:4434–43.
- [14] Roger BR. Process for separating acidic gases. 1930, US1783901A.
- [15] Yoro KO, Amosa MK, Sekoai PT, Daramola MO. Modelling and experimental investigation of effects of moisture and operating parameters during the adsorption of CO<sub>2</sub> onto polyaspartamide. *Int. J. Coal Sci. Technol.* 2019;6: 225–34.
- [16] Feng B, Du M, Dennis TJ, Anthony K, et al. Reduction of energy requirement of CO<sub>2</sub> desorption by adding acid into CO<sub>2</sub>-loaded solvent. *Energy Fuels* 2010;24: 213–9.
- [17] Dutcher B, Fan M, Russell AG. Amine-based CO<sub>2</sub> capture technology development from the beginning of 2013—a review. *ACS Appl Mater Interfaces* 2015;7: 2137–48.
- [18] MacDowell N, Florin N, Buchard A, Hallett J, et al. An overview of CO<sub>2</sub> capture technologies. *Energy Environ Sci* 2010;3:1645–69.
- [19] De Guido G, Compagnoni M, Pellegrini LA, Rossetti I. Mature versus emerging technologies for CO<sub>2</sub> capture in power plants: key open issues in post-combustion amine scrubbing and in chemical looping combustion. *Front Chem Sci Eng* 2018; 12:315–25.
- [20] Budinis S, Krevor S, Dowell NM, Brandon N, et al. An assessment of CCS costs, barriers and potential. *Energy Strategy Rev* 2018;22:61–81.
- [21] Nakao S, Yogo K, Goto K, Kai T, et al. Advanced CO<sub>2</sub> capture technologies: absorption, adsorption, and membrane separation methods. Springer; 2019.
- [22] Gomes J, Santos S, Bordado J. Choosing amine-based absorbents for CO<sub>2</sub> capture. *Environ Technol* 2015;36:19–25.
- [23] Ozonoh M, Anikete TC, Oboirien BO, Udeh BC, et al. Prediction of emissions and profits from a biomass, tyre, and coal fired Co-gasification CHP plant using artificial neural network: Nigerian and South African perspectives. *J. Phys. Conf. Ser.* 2019;1378:022021.
- [24] Yoro KO, Singo M, Mulopo JL, Daramola MO. Modelling and experimental study of the CO<sub>2</sub> adsorption behaviour of polyaspartamide as an adsorbent during post-combustion CO<sub>2</sub> capture. *Energy Procedia* 2017;114:1643–64.
- [25] Yoro KO, Amosa MK, Sekoai PT, Mulopo J, et al. Diffusion mechanism and effect of mass transfer limitation during the adsorption of CO<sub>2</sub> by polyaspartamide in a packed-bed unit. *Int. J. Sustain. Eng.* 2020;13:54–67.
- [26] Wang M, Joel AS, Ramshaw C, Eimer D, et al. Process intensification for post-combustion CO<sub>2</sub> capture with chemical absorption: a critical review. *Appl Energy* 2015;158:275–91.
- [27] Lucquiaud M, Liang X, Errey O, Chalmers H, et al. Addressing technology uncertainties in power plants with post-combustion capture. *Energy Procedia* 2013;37:2359–68.
- [28] Jackson S, Brodal E. Optimization of the energy consumption of a carbon capture and sequestration related carbon dioxide compression processes. *Energies* 2019; 12:1603.
- [29] Luis P. Use of monoethanolamine (MEA) for CO<sub>2</sub> capture in a global scenario: consequences and alternatives. *Desalination* 2016;380:93–9.
- [30] Li K, Cousins A, Yu H, Feron P, et al. Systematic study of aqueous monoethanolamine-based CO<sub>2</sub> capture process: model development and process improvement. *Energy Sci. Eng.* 2016;4:23–39.
- [31] Liu L, Wang S, Niu H, Gao S. Process and integration optimization of post-combustion CO<sub>2</sub> capture system in a coal power plant. *Energy Procedia* 2018; 154:86–93.
- [32] Dunn RF, El-Halwagi MM. Process integration technology review: background and applications in the chemical process industry. *J Chem Technol Biotechnol* 2003;78:1011–21.
- [33] Chakma A. CO<sub>2</sub> capture processes — opportunities for improved energy efficiencies. *Energy Convers Manag* 1997;38:S51–6.
- [34] Rochelle GT. Amine scrubbing for CO<sub>2</sub> capture. *Science* 2009;325:1652–4.
- [35] Sartori G, Leder F. Process for removing carbon dioxide containing acidic gases from gaseous mixtures using aqueous amine scrubbing solutions. 1978, US4112052A.
- [36] Sakwattapanong R, Aroonwilas A, Veawab A. Behavior of reboiler heat duty for CO<sub>2</sub> capture plants using regenerable single and blended alkanolamines. *Ind Eng Chem Res* 2005;44:4465–73.
- [37] Jung J, Jeong YS, Lim Y, Lee CS, et al. Advanced CO<sub>2</sub> capture process using MEA scrubbing: configuration of a split flow and phase separation heat exchanger. *Energy Procedia* 2013;37:1778–84.
- [38] Ziafi S, Rochelle GT, Edgar TF. Optimum design and control of amine scrubbing in response to electricity and CO<sub>2</sub> prices. *Energy Procedia* 2011;4:1683–90.
- [39] Chowdhury FA, Yamada H, Higashii T, Goto K, et al. CO<sub>2</sub> capture by tertiary amine absorbents: a performance comparison study. *Ind Eng Chem Res* 2013;52: 8323–31.
- [40] Vega F, Cano M, Camino S, GallegoFernández LM, et al. Solvents for carbon dioxide capture. *Carb Diox Chem. Capt Oil Recov* 2018:142–63. <https://doi.org/10.5772/intechopen.71443>. Available from, <https://www.intechopen.com/books/carbon-dioxide-chemistry-capture-and-oil-recovery/solvents-for-carbon-dioxide-capture>.
- [41] Lang P, Denes F, Hégyely L. Comparison of different amine solvents for the absorption of CO<sub>2</sub>. 2017.
- [42] Jande YaC, Asif M, Shim SM, Kim WS. Energy minimization in monoethanolamine-based CO<sub>2</sub> capture using capacitive deionization. *Int J Energy Res* 2014;38:1531–40.

- [43] Oyenekan BA, Rochelle GT. Energy performance of stripper configurations for CO<sub>2</sub> capture by aqueous amines. *Ind Eng Chem Res* 2006;45:2457–64.
- [44] Asif M, Bak C, Kim W-S. Energy minimization and ammonia abatement for CO<sub>2</sub> capture using a blend of ammonia and 2-amino-2-methyl-1-propanol solution. *Separ Sci Technol* 2015;50:1565–76.
- [45] Chen E. Carbon dioxide absorption into piperazine promoted potassium carbonate using structured packing. Thesis. 2007.
- [46] Kemper J, Ewert G, Grünwald M. Absorption and regeneration performance of novel reactive amine solvents for post-combustion CO<sub>2</sub> capture. *Energy Procedia* 2011;4:232–9.
- [47] Reddick C, Sorin M, Rheault F. Energy savings in CO<sub>2</sub> (carbon dioxide) capture using ejectors for waste heat upgrading. *Energy* 2014;65:200–8.
- [48] Joos L, Huck JM, Speybroeck VV, Smit B. Cutting the cost of carbon capture: a case for carbon capture and utilization. *Faraday Discuss* 2016;192:391–414.
- [49] Farid MM, Khudhair AM, Razack SAK, Al-Hallaj S. A review on phase change energy storage: materials and applications. *Energy Convers Manag* 2004;45:1597–615.
- [50] Muhammad HA, Sultan H, Lee B, Imran M, et al. Energy minimization of carbon capture and storage by means of a novel process configuration. *Energy Convers Manag* 2020;215:112871.
- [51] Singh P, Swaaij WPMV, Wim, Brilman DWF. Energy efficient solvents for CO<sub>2</sub> absorption from flue gas: vapor liquid equilibrium and pilot plant study. *Energy Procedia* 2013;37:2021–46.
- [52] Oh S-Y, Binns M, Cho H, Kim J-K. Energy minimization of MEA-based CO<sub>2</sub> capture process. *Appl Energy* 2016;169:353–62.
- [53] Ahn H, Luberti M, Liu Z, Brandani S. Process configuration studies of the amine capture process for coal-fired power plants. *Int. J. Greenh. Gas Contr* 2013;16:29–40.
- [54] Jin H, Liu P, Li Z. Energy-efficient process intensification for post-combustion CO<sub>2</sub> capture: a modeling approach. *Energy* 2018;158:471–83.
- [55] Oh S-Y, Yun S, Kim J-K. Process integration and design for maximizing energy efficiency of a coal-fired power plant integrated with amine-based CO<sub>2</sub> capture process. *Appl Energy* 2018;216:311–22.
- [56] Zhang G, Yang Y, Xu G, Zhang K, et al. CO<sub>2</sub> capture by chemical absorption in coal-fired power plants: energy-saving mechanism, proposed methods, and performance analysis. *Int. J. Greenh. Gas Contr* 2015;39:449–62.
- [57] Zhang X, Liu H, Liang Z, Idem R, et al. Reducing energy consumption of CO<sub>2</sub> desorption in CO<sub>2</sub>-loaded aqueous amine solution using Al<sub>2</sub>O<sub>3</sub>/HZSM-5 bifunctional catalysts. *Appl Energy* 2018;229:562–76.
- [58] Lai Q, Kong L, Gong W, Russell AG, et al. Low-energy-consumption and environmentally friendly CO<sub>2</sub> capture via blending alcohols into amine solution. *Appl Energy* 2019;254:113696.
- [59] Ahmad MZ, Hashim H, Mustaffa AA, Maarof H, et al. Design of energy efficient reactive solvents for post combustion CO<sub>2</sub> capture using computer aided approach. *J Clean Prod* 2018;176:704–15.
- [60] Wang R, Liu S, Wang L, Li Q, et al. Superior energy-saving splitter in monoethanolamine-based biphasic solvents for CO<sub>2</sub> capture from coal-fired flue gas. *Appl Energy* 2019;242:302–10.
- [61] Guo H, Li C, Shi X, Li H, et al. Nonaqueous amine-based absorbents for energy efficient CO<sub>2</sub> capture. *Appl Energy* 2019;239:725–34.
- [62] Zhang M, Guo Y. Regeneration energy analysis of NH<sub>3</sub>-based CO<sub>2</sub> capture process integrated with a flow-by capacitive ion separation device. *Energy* 2017;125:178–85.
- [63] Oh S-Y, Kim J-K. Operational optimization for part-load performance of amine-based post-combustion CO<sub>2</sub> capture processes. *Energy* 2018;146:57–66.
- [64] Pirklbauer J, Schöny G, Pröll T, Hofbauer H. Impact of stage configurations, lean-rich heat exchange and regeneration agents on the energy demand of a multistage fluidized bed TSA CO<sub>2</sub> capture process. *Int. J. Greenh. Gas Contr* 2018;72:82–91.
- [65] Cousins A, Wardhaugh LT, Feron PHM. Preliminary analysis of process flow sheet modifications for energy efficient CO<sub>2</sub> capture from flue gases using chemical absorption. *Chem Eng Res Des* 2011;89:1237–51.
- [66] Rashidi H, Valeh-e-Sheyda P, Sahraie S. A multiobjective experimental based optimization to the CO<sub>2</sub> capture process using hybrid solvents of MEA-MeOH and MEA-water. *Energy* 2020;190:116430.
- [67] Yu C-H, Chen M-T, Chen H, Tan C-S. Effects of process configurations for combination of rotating packed bed and packed bed on CO<sub>2</sub> capture. *Appl Energy* 2016;175:269–76.
- [68] Hafizi A, Rajabzadeh M, Khalifeh R. Enhanced CO<sub>2</sub> absorption and desorption efficiency using DETA functionalized nanomagnetite/water nano-fluid. *J. Environ. Chem. Eng.* 2020;8:103845.
- [69] Zhang X, Zhu Z, Sun X, Yang J, et al. Reducing energy penalty of CO<sub>2</sub> capture using Fe promoted SO<sub>4</sub><sup>2-</sup>/ZrO<sub>2</sub>/MCM-41 catalyst. *Environ Sci Technol* 2019;53:6094–102.
- [70] Bhowan AS, Freeman BC. Analysis and status of post-combustion carbon dioxide capture technologies. *Environ Sci Technol* 2011;45:8624–32.
- [71] Leung DYC, Caramanna G, Maroto-Valer MM. An overview of current status of carbon dioxide capture and storage technologies. *Renew Sustain Energy Rev* 2014;39:426–43.
- [72] Takamura Y, Narita S, Aoki J, Hironaka S, et al. Evaluation of dual-bed pressure swing adsorption for CO<sub>2</sub> recovery from boiler exhaust gas. *Separ Purif Technol* 2001;24:519–28.
- [73] Clause M, Merel J, Meunier F. Numerical parametric study on CO<sub>2</sub> capture by indirect thermal swing adsorption. *Int. J. Greenh. Gas Contr* 2011;5:1206–13.
- [74] Yoro K, Singo Muofhe M, Daramola MO, Mulopo L. Mathematical modelling of adsorption behavior of sod-ZMOF/chitosan adsorbent during post-combustion CO<sub>2</sub> capture. 2016.
- [75] Brunetti A, Scura F, Barbieri G, Drioli E. Membrane technologies for CO<sub>2</sub> separation. *J Membr Sci* 2010;359:115–25.
- [76] Gielen D. CO<sub>2</sub> removal in the iron and steel industry. *Energy Convers Manag* 2003;44:1027–37.
- [77] Göttlicher G, Pruschek R. Comparison of CO<sub>2</sub> removal systems for fossil-fuelled power plant processes. *Energy Convers Manag* 1997;38:S173–8.
- [78] Song C, Liu Q, Deng S, Li H, et al. Cryogenic-based CO<sub>2</sub> capture technologies: state-of-the-art developments and current challenges. *Renew Sustain Energy Rev* 2019;101:265–78.
- [79] Yang M, Song Y, Jiang L, Zhao Y, et al. Hydrate-based technology for CO<sub>2</sub> capture from fossil fuel power plants. *Appl Energy* 2014;116:26–40.
- [80] Dashti H, Zhehao Yew L, Lou X. Recent advances in gas hydrate-based CO<sub>2</sub> capture. *J Nat Gas Sci Eng* 2015;23:195–207.
- [81] Xu C-G, Li X-S. Research progress of hydrate-based CO<sub>2</sub> separation and capture from gas mixtures. *RSC Adv* 2014;4:18301–16.
- [82] Le Moullec Y, Neveux T, Al Azki A, Chikukwa A, et al. Process modifications for solvent-based post-combustion CO<sub>2</sub> capture. *Int. J. Greenh. Gas Contr* 2014;31:96–112.
- [83] Yoro KO, Isafiade AJ, Daramola MO. Sequential synthesis of mass exchanger networks for CO<sub>2</sub> capture - research portal - converis standard config. *Proc. World Congr. Eng. Comput. Sci.* 2018;II. WCECS 2018 Oct. 23-25 2018 San Franc. USA.
- [84] Hoff KA, Silva EF da, Kim I, Grimsvædt A, et al. Solvent development in post combustion CO<sub>2</sub> capture-Selection criteria and optimization of solvent performance, cost and environmental impact. *Energy Procedia* 2013;37:292–9.
- [85] Yang Q, Puxty G, James S, Bown M, et al. Toward intelligent CO<sub>2</sub> capture solvent design through experimental solvent development and amine synthesis. *Energy Fuels* 2016;30:7503–10.
- [86] Pinto DDD, Knuutila H, Fytianos G, Haugen G, et al. CO<sub>2</sub> post combustion capture with a phase change solvent. Pilot plant campaign. *Int. J. Greenh. Gas Contr* 2014;31:153–64.
- [87] Klemes JJ, Varbanov PS, Pierucci S. Process integration for energy and water saving, increasing efficiency and reducing environmental impact. *Appl Therm Eng* 2010;30:2265–9.
- [88] Bogataj M, Bagajewicz MJ. Synthesis of non-isothermal heat integrated water networks in chemical processes. *Comput Chem Eng* 2008;32:3130–42.
- [89] Liserre M, Sauter T, Hung JY. Future energy systems: integrating renewable energy sources into the smart power grid through industrial electronics. *IEEE Ind. Electron. Mag.* 2010;4:18–37.
- [90] Sekoai PT, Yoro KO. Biofuel development initiatives in sub-saharan Africa: opportunities and challenges. *Climate* 2016;4:33.
- [91] Manousiouthakis V, Martin LL. A minimum area (MA) targeting scheme for single component MEN and HEN synthesis. *Comput Chem Eng* 2004;28:1237–47.
- [92] Zamora JM, Grossmann IE. A global MINLP optimization algorithm for the synthesis of heat exchanger networks with no stream splits. *Comput Chem Eng* 1998;22:367–84.
- [93] Huang KF, Karimi IA. Simultaneous synthesis approaches for cost-effective heat exchanger networks. *Chem Eng Sci* 2013;98:231–45.
- [94] Smith R, Jobson M, Chen L. Recent development in the retrofit of heat exchanger networks. *Appl Therm Eng* 2010;30:2281–9.
- [95] Yoro KO, Isafiade AJ, Daramola MO. multi-period heat exchanger network synthesis with temperature intervals and uncertain disturbances. *Chem. Eng. Trans.* 2019;76:1039–44.
- [96] El-Temtamy SA, Gabr EM. Design of optimum flexible heat exchanger networks for multiperiod process. *Egypt. J. Pet.* 2012;21:109–17.
- [97] Liu L, Bai Y, Zhang L, Gu S, et al. Synthesis of flexible heat exchanger networks considering gradually accumulated deposit and cleaning management. *Ind Eng Chem Res* 2019;58:12124–36.
- [98] Linnhoff B, Flower JR. Synthesis of heat exchanger networks: I. Systematic generation of energy optimal networks. *AIChE J* 1978;24:633–42.
- [99] Zbontar Zver L, Glavič P. Water minimization in process industries: case study in beet sugar plant. *Resour Conserv Recycl* 2005;43:133–45.
- [100] Hansen É, Rodrigues MAS, Aragão ME, de Aquim PM. Water and wastewater minimization in a petrochemical industry through mathematical programming. *J Clean Prod* 2018;172:1814–22.
- [101] Jana AK. Heat integrated distillation operation. *Appl Energy* 2010;87:1477–94.
- [102] Adamu A, Russo-Abegao F, Boodhoo K. Process intensification technologies for CO<sub>2</sub> capture and conversion – a review. *BMC Chem. Eng.* 2020;2:2.
- [103] Ozcan DC, Ahn H, Brandani S. Process integration of a Ca-looping carbon capture process in a cement plant. *Int. J. Greenh. Gas Contr* 2013;19:530–40.
- [104] Napp TA, Gambhir A, Hills TP, Florin N, et al. A review of the technologies, economics and policy instruments for decarbonising energy-intensive manufacturing industries. *Renew Sustain Energy Rev* 2014;30:616–40.
- [105] Chan DY-L, Yang K-H, Hsu C-H, Chien M-H, et al. Current situation of energy conservation in high energy-consuming industries in Taiwan. *Energy Pol* 2007;35:202–9.
- [106] Oyenekan BA, Rochelle GT. Alternative stripper configurations for CO<sub>2</sub> capture by aqueous amines. *AIChE J* 2007;53:3144–54.
- [107] Hasanbeigi A, Price L, Lin E. Emerging energy-efficiency and CO<sub>2</sub> emission-reduction technologies for cement and concrete production: a technical review. *Renew Sustain Energy Rev* 2012;16:6220–38.
- [108] Sanchez-Fernandez E, Heffernan K, van der Ham L, Linders MJG, et al. Precipitating amino acid solvents for CO<sub>2</sub> capture. Opportunities to reduce costs in post combustion capture. *Energy Procedia* 2014;63:727–38.
- [109] Perry RJ, Wood BR, Genovese S, O'Brien MJ, et al. CO<sub>2</sub> capture using phase-changing sorbents. *Energy Fuels* 2012;26:2528–38.

- [110] Mumford KA, Smith KH, Stevens GW. Phase change solvents for CO<sub>2</sub> capture applications. In: Budzianowski WM, editor. Energy efficient solvents for CO<sub>2</sub> capture by gas-liquid absorption: compounds, blends and advanced solvent systems. Cham: Springer International Publishing; 2017. p. 99–116.
- [111] Wang X, Li B. Chapter 1 – phase-change solvents for CO<sub>2</sub> capture. In: Shi F, Morreale B, editors. Novel materials for carbon dioxide mitigation technology. Amsterdam: Elsevier; 2015. p. 3–22.
- [112] Zhuang Q, Clements B, Dai J, Carrigan L. Ten years of research on phase separation absorbents for carbon capture: achievements and next steps. *Int. J. Greenh. Gas Contr* 2016;52:449–60.
- [113] Zhang S, Shen Y, Wang L, Chen J, et al. Phase change solvents for post-combustion CO<sub>2</sub> capture: principle, advances, and challenges. *Appl Energy* 2019; 239:876–97.
- [114] Papadopoulos AI, Tzirakis F, Tsvintzels I, Seferlis P. Phase-change solvents and processes for postcombustion CO<sub>2</sub> capture: a detailed review. *Ind Eng Chem Res* 2019;58:5088–111.
- [115] Zheng S, Tao M, Liu Q, Ning L, et al. Capturing CO<sub>2</sub> into the precipitate of a phase-changing solvent after absorption. *Environ Sci Technol* 2014;48:8905–10.
- [116] Liebenthal U, Pinto DDD, Monteiro JGM-S, Svendsen HF, et al. Overall process analysis and optimisation for CO<sub>2</sub> capture from coal fired power plants based on phase change solvents forming two liquid phases. *Energy Procedia* 2013;37: 1844–54.
- [117] Sharma A, Tyagi VV, Chen CR, Buddhi D. Review on thermal energy storage with phase change materials and applications. *Renew Sustain Energy Rev* 2009;13: 318–45.
- [118] Oró E, de Gracia A, Castell A, Farid MM, et al. Review on phase change materials (PCMs) for cold thermal energy storage applications. *Appl Energy* 2012;99: 513–33.
- [119] Xu B, Li P, Chan C. Application of phase change materials for thermal energy storage in concentrated solar thermal power plants: a review to recent developments. *Appl Energy* 2015;160:286–307.
- [120] Dai Magro F, Savino S, Meneghetti A, Nardin G. Coupling waste heat extraction by phase change materials with superheated steam generation in the steel industry. *Energy* 2017;137:1107–18.
- [121] Mondal S. Phase change materials for smart textiles – an overview. *Appl Therm Eng* 2008;28:1536–50.
- [122] Shavaliyeva G, Papadokonstantakis S, Kazepidis P, Papadopoulos AI, et al. Sustainability analysis of phase-change solvents for post-combustion CO<sub>2</sub> capture. *Chem. Eng. Trans.* 2019;76:1045–50.
- [123] Liang Z, Gao H, Rongwong W, Na Y. Comparative studies of stripper overhead vapor integration-based configurations for post-combustion CO<sub>2</sub> capture. *Int. J. Greenh. Gas Contr* 2015;34:75–84.
- [124] Ma'mun S, Kim I. Selection and characterization of phase-change solvent for carbon dioxide capture: precipitating system. *Energy Procedia* 2013;37:331–9.
- [125] Seo S, Simoni LD, Ma M, DeSilva MA, et al. Phase-change ionic liquids for postcombustion CO<sub>2</sub> capture. *Energy Fuels* 2014;28:5968–77.
- [126] Arshad MW, Fosbol PL, von Solms N, Thomsen K. CO<sub>2</sub> capture with liquid-liquid phase change solvents: a thermodynamic study. *Energy Procedia* 2017;114: 1671–81.
- [127] Wang X, Akhmedov NG, Hopkinson D, Hoffman J, et al. Phase change amino acid salt separates into CO<sub>2</sub>-rich and CO<sub>2</sub>-lean phases upon interacting with CO<sub>2</sub>. *Appl Energy* 2016;161:41–7.
- [128] Pinto A. Development OF paraffin wax as a phase change material for thermal management IN electronic systems. Thesis. 2016.
- [129] Vizitiu R Ștefan, Isopescu DN, Burlacu A, Ciocan V, et al. Energy efficient phase change materials used for an originally designed heat recovery system. *Procedia Manuf* 2019;32:496–503.
- [130] Zhou H, Xu X, Chen X, Yu G. Novel ionic liquids phase change solvents for CO<sub>2</sub> capture. *Int. J. Greenh. Gas Contr* 2020;98:103068.
- [131] Bian Y, Shen S. CO<sub>2</sub> absorption into a phase change absorbent: water-lean potassium proline/ethanol solution. *Chin J Chem Eng* 2018;26:2318–26.
- [132] Eisinger RS, Keller GE. Process for CO<sub>2</sub> capture using ionic liquid that exhibits phase change. *Energy Fuels* 2014;28:7070–8.
- [133] Malhotra D, Page JP, Bowden ME, Karkamkar A, et al. Phase-change aminopyridines as carbon dioxide capture solvents. *Ind Eng Chem Res* 2017;56: 7534–40.
- [134] Ciftja AF, Hartono A, Svendsen HF. Experimental study on phase change solvents in CO<sub>2</sub> capture by NMR spectroscopy. *Chem Eng Sci* 2013;102:378–86.
- [135] Shen S, Bian Y, Zhao Y. Energy-efficient CO<sub>2</sub> capture using potassium proline/ethanol solution as a phase-changing absorbent. *Int. J. Greenh. Gas Contr* 2017; 56:1–11.
- [136] Li Y, Cheng J, Hu L, Liu J, et al. Phase-changing solution PZ/DMF for efficient CO<sub>2</sub> capture and low corrosiveness to carbon steel. *Fuel* 2018;216:418–26.
- [137] Huang K, Chen F-F, Tao D-J, Dai S. Ionic liquid-formulated hybrid solvents for CO<sub>2</sub> capture. *Curr. Opin. Green Sustain. Chem.* 2017;5:67–73.
- [138] Garrabrant KA, Williams NJ, Holguin E, Brethomé FM, et al. Energy-efficient CO<sub>2</sub> capture from flue gas by absorption with amino acids and crystallization with a bis-iminoguanidine. *Ind Eng Chem Res* 2019;58:10510–5.
- [139] Kumar R, Ahmadi MH, Rajak DK, Nazari MA. A study on CO<sub>2</sub> absorption using hybrid solvents in packed columns. *Int J Low-Carbon Technol* 2019;14:561–7.
- [140] Nwaoha C, Saiwan C, Tontiwachwuthikul P, Supap T, et al. Carbon dioxide (CO<sub>2</sub>) capture: absorption-desorption capabilities of 2-amino-2-methyl-1-propanol (AMP), piperazine (PZ) and monoethanolamine (MEA) tri-solvent blends. *J Nat Gas Sci Eng* 2016;33:742–50.
- [141] Artanto Y, Jansen J, Pearson P, Puxty G, et al. Pilot-scale evaluation of AMP/PZ to capture CO<sub>2</sub> from flue gas of an Australian brown coal-fired power station. *Int. J. Greenh. Gas Contr* 2014;20:189–95.
- [142] Bougie F, Iliuta MC. CO<sub>2</sub> absorption in aqueous piperazine solutions: experimental study and modeling. *J Chem Eng Data* 2011;56:1547–54.
- [143] Li L, Voice AK, Li H, Namjoshi O, et al. Amine blends using concentrated piperazine. *Energy Procedia* 2013;37:353–69.
- [144] Idem R, Wilson M, Tontiwachwuthikul P, Chakma A, et al. Pilot plant studies of the CO<sub>2</sub> capture performance of aqueous MEA and mixed MEA/MDEA solvents at the university of Regina CO<sub>2</sub> capture technology development plant and the boundary dam CO<sub>2</sub> capture demonstration plant. *Ind Eng Chem Res* 2006;45: 2414–20.
- [145] Aroonwilas A, Veawab A. Integration of CO<sub>2</sub> capture unit using single- and blended-amines into supercritical coal-fired power plants: implications for emission and energy management. *Int. J. Greenh. Gas Contr* 2007;1:143–50.
- [146] Roger BR. Process for separating acidic gases. 1930, US1783901A.
- [147] Anderson C, Hooper B, Qader A, Harkin T, et al. Recent developments in the UNO MK 3 process—A low cost, environmentally benign precipitating process for CO<sub>2</sub> capture. *Energy Procedia* 2014;63:1773–80.
- [148] Wei C-C, Puxty G, Feron P. Amino acid salts for CO<sub>2</sub> capture at flue gas temperatures. *Chem Eng Sci* 2014;107:218–26.
- [149] Zhang Z, Li Y, Zhang W, Wang J, et al. Effectiveness of amino acid salt solutions in capturing CO<sub>2</sub>: a review. *Renew Sustain Energy Rev* 2018;98:179–88.
- [150] van der Ham LV, Goetheer ELV, Fernandez ES, Abu-Zahra MRM, et al. 5 - precipitating amino acid solutions. In: Feron PHM, editor. Absorption-based post-combustion capture of carbon dioxide. Woodhead Publishing; 2016. p. 103–19.
- [151] Sanchez Fernandez E, Heffernan K, van der Ham LV, Linders MJG, et al. Conceptual design of a novel CO<sub>2</sub> capture process based on precipitating amino acid solvents. *Ind Eng Chem Res* 2013;52:12223–35.
- [152] Feron PHM, ten Asbroek N. New solvents based on amino-acid salts for CO<sub>2</sub> capture from flue gases. In: Rubin ES, Keith DW, Gilbooy CF, Wilson M, et al., editors. Greenhouse gas control technologies 7. Oxford: Elsevier Science Ltd; 2005. p. 1153–8.
- [153] Goetheer ELV, Fernandez ES, Roelands CPM. Method for absorption of acid gases using amino acids. US20120282158A1; 2012.
- [154] Talebi G, Sohrabi M, Royace SJ, Keiski RL, et al. Synthesis and activity measurement of the some bifunctional platinum loaded Beta zeolite catalysts for n-heptane hydroisomerization. *J Ind Eng Chem* 2008;14:614–21.
- [155] Bogdan PL. Reforming process using a selective bifunctional multimetallic catalyst. US6884340B1; 2005.
- [156] Mitsios M, Guillaume D, Galtier P, Schweich D. Single-event microkinetic model for long-chain paraffin hydrocracking and hydroisomerization on an amorphous Pt/SiO<sub>2</sub>-Al<sub>2</sub>O<sub>3</sub> catalyst. *Ind Eng Chem Res* 2009;48:3284–92.
- [157] Verhoeve MJ, Creighton EJ, Peters JA. Reductive etherification of substituted cyclohexanones with secondary alcohols catalysed by zeolite H-MCM-22. *Chem Commun* 1997;1989–90. 0.
- [158] Robinson AM, Hensley JE, Medlin JW. Bifunctional catalysts for upgrading of biomass-derived oxygenates: a review. *ACS Catal* 2016;6:5026–43.
- [159] Zhang Y, Liu D, Men Z, Huang K, et al. Hydroisomerization of n-dodecane over porous Pt-containing bifunctional catalysts: effects of alkene intermediates' journey distances within the zeolite micropores. *Fuel* 2019;236:428–36.
- [160] Wei J, Ge Q, Yao R, Wen Z, et al. Directly converting CO<sub>2</sub> into a gasoline fuel. *Nat Commun* 2017;8:15174.
- [161] Ma J, Sun N, Zhang X, Zhao N, et al. A short review of catalysis for CO<sub>2</sub> conversion. *Catal Today* 2009;148:221–31.
- [162] Zhang X, Huang Y, Yang J, Gao H, et al. Amine-based CO<sub>2</sub> capture aided by acid-basic bifunctional catalyst: advancement of amine regeneration using metal modified MCM-41. *Chem Eng J* 2020;383:123077.
- [163] Shakerian F, Kim K-H, Szulejko JE, Park J-W. A comparative review between amines and ammonia as sorptive media for post-combustion CO<sub>2</sub> capture. *Appl Energy* 2015;148:10–22.
- [164] Wang T, Yu W, Liu F, Fang M, et al. Enhanced CO<sub>2</sub> absorption and desorption by monoethanolamine (MEA)-Based nanoparticle suspensions. *Ind Eng Chem Res* 2016;55:7830–8.
- [165] Liang L, Liu C, Jiang F, Chen Q, et al. Carbon dioxide capture and conversion by an acid-base resistant metal-organic framework. *Nat Commun* 2017;8:1233.
- [166] Lü K, Zhou J, Zhou L, Chen XS, et al. Pre-combustion CO<sub>2</sub> capture by transition metal ions embedded in phthalocyanine sheets. *J Chem Phys* 2012;136:234703.
- [167] Sanchez-Fernandez E, Heffernan K, van der Ham L, Linders MJG, et al. Analysis of process configurations for CO<sub>2</sub> capture by precipitating amino acid solvents. *Ind Eng Chem Res* 2014;53:2348–61.
- [168] Sanchez-Fernandez E, Mercader F de M, Misiak K, van der Ham L, et al. New process concepts for CO<sub>2</sub> capture based on precipitating amino acids. *Energy Procedia* 2013;37:1160–71.
- [169] Feron P. Absorption-based post-combustion capture of carbon dioxide. Woodhead Publishing; 2016.
- [170] Wardhaugh LT, Cousins A. Process implications of CO<sub>2</sub> capture solvent selection. In: Budzianowski WM, editor. Energy efficient solvents for CO<sub>2</sub> capture by gas-liquid absorption: compounds, blends and advanced solvent systems. Cham: Springer International Publishing; 2017. p. 27–67.
- [171] Choi J, Cho H, Yun S, Jang M-G, et al. Process design and optimization of MEA-based CO<sub>2</sub> capture processes for non-power industries. *Energy* 2019;185:971–80.
- [172] Cui C, Li X, Sui H, Sun J. Optimization of coal-based methanol distillation scheme using process superstructure method to maximize energy efficiency. *Energy* 2017; 119:110–20.

- [173] Mencarelli L, Chen Q, Pagot A, Grossmann IE. A review on superstructure optimization approaches in process system engineering. *Comput Chem Eng* 2020; 136:106808.
- [174] Henaio CA, Maravelias CT. Surrogate-based superstructure optimization framework. *AIChE J* 2011;57:1216–32.
- [175] Masso AH, Rudd DF. The synthesis of system designs. II. Heuristic structuring. *AIChE J* 1969;15:10–7.
- [176] Papoulias SA, Grossmann IE. A structural optimization approach in process synthesis—I: utility systems. *Comput Chem Eng* 1983;7:695–706.
- [177] Errico M, Maccioni S, Tola G, Zuddas P. A deterministic algorithm for the synthesis of maximum energy recovery heat exchanger network. *Comput Chem Eng* 2007;31:773–81.
- [178] Angsutorn N, Siemanond K, Chuvaree R. Heat exchanger network synthesis using MINLP stage-wise model with pinch analysis and relaxation. In: Klemes JJ, Varbanov PS, Liew PY, editors. *Computer aided chemical engineering*. Elsevier; 2014. p. 139–44.
- [179] Chaturvedi ND, Manan ZA, Wan Alwi SR. A mathematical model for energy targeting of a batch process with flexible schedule. *J Clean Prod* 2017;167: 1060–7.
- [180] Osman A, Eltayeb M, Rajab F. Utility paths combination in HEN for energy saving and CO2 emission reduction. *Processes* 2019;7:425.
- [181] Foo DCY, Tan RR, Ng DKS. Carbon and footprint-constrained energy planning using cascade analysis technique. *Energy* 2008;33:1480–8.
- [182] Orosz Á, Friedler F. Multiple-solution heat exchanger network synthesis for enabling the best industrial implementation. *Energy* 2020;208:118330.
- [183] Coker AK. Chapter 16 - process integration and heat exchanger networks. In: Coker AK, editor. *Ludwig's applied process design for chemical and petrochemical plants*. fourth ed. Boston: Gulf Professional Publishing; 2015. p. 491–622.
- [184] Chen C-L, Hung P-S. Simultaneous synthesis of flexible heat-exchange networks with uncertain source-stream temperatures and flow rates. *Ind Eng Chem Res* 2004;43:5916–28.
- [185] Papalexandri KP, Pistikopoulos EN. Synthesis and retrofit design of operable heat exchanger networks. 1. Flexibility and structural controllability aspects. 2002.
- [186] Papalexandri KP, Pistikopoulos EN. Synthesis and retrofit design of operable heat exchanger networks. 1. Flexibility and structural controllability aspects. 2002.
- [187] Kang L, Liu Y. Synthesis of flexible heat exchanger networks: a review. *Chin J Chem Eng* 2019;27:1485–97.
- [188] Yang M, Jing W, Zhao J, Ling Z, et al. Promotion of hydrate-based CO2 capture from flue gas by additive mixtures (THF (tetrahydrofuran) + TBAB (tetra-n-butyl ammonium bromide)). *Energy* 2016;106:546–53.
- [189] Escudero AI, Espatolero S, Romeo LM, Lara Y, et al. Minimization of CO2 capture energy penalty in second generation oxy-fuel power plants. *Appl Therm Eng* 2016;103:274–81.
- [190] Rooney WC, Biegler LT. Optimal process design with model parameter uncertainty and process variability. *AIChE J* 2003;49:438–49.
- [191] Yoro KO, Isafiade A, Daramola MO. Synthesis of mass exchanger networks using sequential techniques. In: Ao S-I, Kim HK, Amouzegar MA, editors. *Transactions on engineering technologies*. Singapore: Springer; 2020. p. 173–85.
- [192] Yoro KO, Isafiade AJ, Daramola MO. Synthesis of optimal heat exchanger networks with quantified uncertainties and non-isothermal mixing. *J. Phys. Conf. Ser.* 2019;1378:022018.
- [193] Yoro KO, Chiwaye N, Isafiade AJ, Daramola MO. Energy and material minimization during CO2 capture using a combined heat and mass integration technique. *SINTEF Academic Press*; 2019.
- [194] Toimil D, Gómez A. Review of metaheuristics applied to heat exchanger network design. *Int Trans Oper Res* 2017;24:7–26.
- [195] Ponce-Ortega JM, Serna-González M, Jiménez-Gutiérrez A. Heat exchanger network synthesis including detailed heat exchanger design using genetic algorithms. *Ind Eng Chem Res* 2007;46:8767–80.
- [196] Sreepathi BK, Rangaiah GP. Review of heat exchanger network retrofitting methodologies and their applications. *Ind Eng Chem Res* 2014;53:11205–20.
- [197] Linnhoff B, Polley GT, Sahdev V. General process improvements through pinch technology. *Chem Eng Prog U. S.* 1988;84:6.
- [198] Nordman R, Bernstson T. New pinch technology based hen analysis methodologies for cost-effective retrofitting. *Can J Chem Eng* 2001;79:655–62.
- [199] Shenoy UV. Heat exchanger network synthesis: process optimization by energy and resource analysis. *Gulf Professional Publishing*; 1995.
- [200] Klemes JJ, Varbanov P. Process integration: pinch analysis and mathematical programming - directions for future development. In: Kravanja Z, Bogataj M, editors. *Computer aided chemical engineering*. Elsevier; 2016. p. 2405–6.
- [201] Zhang WVN. Design of flexible heat exchanger network for multi-period operation. *Chem Eng Sci* 2006;61:7730–53.
- [202] Marselle DF, Morari M, Rudd DF. Design of resilient processing plants—II Design and control of energy management systems. *Chem Eng Sci* 1982;37:259–70.
- [203] Calandranis J, Stephanopoulos G. A structural approach to the design of control systems in heat exchanger networks. *Comput Chem Eng* 1988;12:651–69.
- [204] Saboo AK, Morari M, Woodcock DC. Design of resilient processing plants—VIII. A resilience index for heat exchanger networks. *Chem Eng Sci* 1985;40:1553–65.
- [205] Saboo AK, Morari M, Colberg RD. Resilience analysis of heat exchanger networks—II. Stream splits and flowrate variations. *Comput Chem Eng* 1987;11: 457–68.
- [206] Fryer P. Basic concepts in heat exchanger network modelling. In: Melo LF, Bott TR, Bernardo CA, editors. *Fouling science and technology*. Dordrecht: Springer Netherlands; 1988. p. 495–510.
- [207] Floudas CA, Grossmann IE. Automatic generation of multiperiod heat exchanger network configurations. *Comput Chem Eng* 1987;11:123–42.
- [208] Gadalla MA, Olujic Z, Jansens PJ, Jobson M, et al. Reducing CO2 emissions and energy consumption of heat-integrated distillation systems. *Environ Sci Technol* 2005;39:6860–70.
- [209] Kang L, Liu Y. Design of flexible multiperiod heat exchanger networks with debottle necking in subperiods. *Chem Eng Sci* 2018;185:116–26.
- [210] Yoro KO. Integration and synthesis of heat and mass exchanger networks for CO2 capture in power plants. Thesis. 2020.
- [211] Tian Y, Pistikopoulos EN. Synthesis of operable process intensification systems: advances and challenges. *Curr. Opin. Chem. Eng.* 2019;25:101–7.
- [212] Apap RM, Grossmann IE. Models and computational strategies for multistage stochastic programming under endogenous and exogenous uncertainties. *Comput Chem Eng* 2017;103:233–74.
- [213] Grossmann IE, Apap RM, Calfa BA, García-Herreros P, et al. Recent advances in mathematical programming techniques for the optimization of process systems under uncertainty. *Comput Chem Eng* 2016;91:3–14.
- [214] Grossmann IE, Sargent RWH. Optimum design of heat exchanger networks. *Comput Chem Eng* 1978;2:1–7.