Journal of CO2 Utilization 45 (2021) 101432

Contents lists available at ScienceDirect

Journal of CO2 Utilization

journal homepage: www.elsevier.com/locate/jcou

A review of carbon capture and utilisation as a CO_2 abatement opportunity within the EWF nexus

Ikhlas Ghiat [a], Tareq Al-Ansari [a,b,*]

[a] Division of Sustainable Development, College of Science and Engineering, Hamad Bin Khalifa University, Qatar Foundation, Doha, Qatar

[b] Division of Engineering Management and Decision Sciences, College of Science and Engineering, Hamad Bin Khalifa University, Qatar Foundation, Doha, Qatar

ARTICLE INFO

Keywords:
CO_2 sequestration
Resource management
Food
Energy
Water
Nexus

ABSTRACT

Carbon capture and utilisation (CCU) is considered an important CO_2 mitigation strategy to support and compliment carbon capture and storage (CCS) objectives for the abatement and sequestration of CO_2. It represents various pathways that utilise CO_2 as a feedstock in process systems or otherwise for the generation of value-added commodities. The CO_2 used can be captured from different sources including power plants and industrial activities via several existing carbon capture and separation technologies that ensure a pure and safe CO_2 supply. CCU pathways are mainly divided into five wide-ranging categories: CO_2 conversion to chemicals and fuels, mineral carbonation, enhanced oil recovery, biological conversion, and direct CO_2 utilisation. This study reviews the main CCU pathways and highlights their intra-sectoral and inter-sectoral opportunities within the energy water and food (EWF) systems, which is an important resource management concept. It also discusses the global status of CCU operational projects, research and development efforts directed toward CCU deployment, and important decision-making directions when integrating CCU with the EWF nexus. This review highlights that CCU pathways provide several cross-sectoral opportunities within the EWF sectors, by allaying resource competition between sectors and proposing co/tri-integrated solutions for securing EWF resources. Future efforts in this regard should be directed towards studying the EWF nexus within CCU routes in a comprehensive, quantitative, and holistic approach to identify and measure all trade-offs and synergies within EWF sectors, and to optimise CCU supply chains.

1. Introduction and background

Anthropogenic greenhouse gas emissions (GHG) have attained their highest levels throughout history with a multi-decadal warming effect on the climate depicted in higher sea levels, warmed and acidified oceans, lower amounts of ice, and higher surface temperatures, etc. The impacts of climate change have begun to disrupt natural ecosystems and societies, leading to major enforced changes in the management and allocation of natural resources and habitation patterns [1]. The growing vulnerability of the natural and human systems emphasises the need to limit the impact of climate change to avoid extreme and pervasive events such as heat waves, wildfire, floods, droughts and cyclones that threaten the entire ecosystem and hinder the world's social and economic development. Thus, climate change experts advise on stabilising the surface temperature rise below 2 °C relative to pre-industrial levels throughout the 21st century to achieve CO_2-eq emissions of approximately 450 ppm by 2100, which represents the most stringent Representative Concentration Pathway (RCP2.6) set by the IPCC [2,3]. Previous actions adopted to lower GHG emissions are insufficient vis-à-vis the rapid population growth and economic development, anticipating a mean surface temperature increase between 3.7 and 4.8 °C above pre-industrial levels by 2100 [2]. Hence, adequate adaptation and mitigation actions are needed to achieve the 2 °C temperature target and limit global warming. As such, the Paris agreement was adopted in the COP 21 to invigorate the global response to climate change, and drive nations to cooperate and set palpable roadmaps to take action in what is known as the nationally determined contributions (NDCs), which includes areas such as the mitigation of GHG emissions and climate change adaptation [4]. The adaptation and mitigation strategies needed to meet the ambitious global warming goal require reducing GHG emissions by 40 %–70 % by 2050 relative to 2010 levels and achieving neutral to negative emissions by the end of the century.

* Corresponding author at: Division of Sustainable Development, College of Science and Engineering, Hamad Bin Khalifa University, Qatar Foundation, Doha, Qatar.

E-mail address: talansari@hbku.edu.qa (T. Al-Ansari).

https://doi.org/10.1016/j.jcou.2020.101432
Received 17 November 2020; Received in revised form 27 December 2020; Accepted 29 December 2020
Available online 13 January 2021
2212-9820/

Hence, several adaptation and mitigation scenarios have been set to guide through the implementation of these actions and provide climate projections until the end of the 21st century [2].

1.1. Climate change mitigation scenarios

As part of efforts to limit global warming, various CO_2 reduction schemes and technologies have been proposed by governments, industry leaders and scientific institutions. One of which, is the carbon capture and utilisation or storage (CCUS) strategy, which is an essential technology driven mitigation option that converts exhaust CO_2 into stored CO_2 or into value added products [5]. Systems based on CCU complement CCS routes and offer additional benefits. However, it is not an alternative to CCS because of its low sequestered amounts compared to the storage option, and the large amounts of CO_2 needed to be offset to meet climate change targets [6]. For example, the utilisation of CO_2 in the production of two of the most commercial chemicals, methanol and urea, has a sequestration potential of only 0.5 % of the total anthropogenic CO_2 emissions [7]. Moreover, CCU is considered as an imperative mitigation scenario when storage options are limited. For example, in one of the compliant scenarios with the 2 °C temperature target studied by the IEA; the Clean Technology Scenario (CTS) predicts a potential of 250 Mt/year of CO_2 use in the conversion to chemicals and fuels by 2060. Introducing a variant to this scenario by setting a CO_2 storage limit of 10 Gt/year by 2060, the potential of CO_2 sequestration via this CCU pathway is tripled and can reach approximately 878 Mt/year by 2060 [8]. CCU technologies are able to sequester CO_2 for diverse time-scale periods depending on the usage of the final produce. For instance, the enhanced oil recovery (EOR) and mineralisation routes are considered as long term to permanent sequestration options, which are able to store CO_2 for decades, while other CCU routes offer short term sequestration [9]. With the COVID-19 global crisis, progress directed towards the research, development and deployment of CCU projects might be interrupted due to the consequent economic downturn that might halt funding and investments for this technology. Several concerns arise regarding the continuity of CCU project investments; including how resilient government policies are, and how ambitious they are in implementing sustainable recovery plans that will continue to include mitigation projects and respond to the global crisis of climate change. On the contrary, COVID-19 response plans should put mitigation and green energy transition projects at their core and as a unique opportunity to rebuild the economy in a more sustainable manner [10].

1.2. Overview of the EWF nexus

Considering increasing pressures from the rapid population growth and climate change; energy, water and food demand is expected to increase, placing systems under stress, and rendering the allocation of these primordial resources more challenging than ever [11]. By 2050, demand is projected to increase by 60 % for food, by 80 % for energy, and 55 % for water resources. Moreover, the intertwined aspect and competing need of these resources between the different sectors embeds additional constraints in their allocation and management [12]. It has been reported that the agri-food sector accounts for 30 % of the total energy use and 70 % of the global freshwater consumption, while 15 % of the freshwater production is dedicated to the energy sector. Thus, any risks related to one sector impact the security of the others, and any opportunities arising from one sector are mirrored in the others. The consideration and study of these interdependencies between the energy water and food sectors is what is known as the EWF nexus [12]. The EWF nexus was first recognised in 1983 by the United Nations University (UNU) in their Food-Energy Nexus Programme, giving ground for a more profound understanding of the inter-sectoral relationships between the food and energy sectors. The EWF nexus received more attention during two succeeding conferences, the 1984 Brazil conference on "Ecosystems, Food and Energy" and the 1986 "International Symposium on Food Energy Nexus and Ecosystems" held in India, both aiming to highlight the importance of studying interlinkages between the food and energy sectors and the ecosystem [13]. It was not until 2011 during the Bonn conference held in Germany, organised by the German Federal Government and the World Economic Forum (WEF), where the EWF nexus concept was first revealed, prompting the importance of EWF cross-sectoral consideration in achieving energy water and food security [14]. The EWF nexus is an approach that considers the different interlinkages between the energy water and food systems in ascertaining the true consumption of resources and sustainably allocating and managing those resources [15].

1.3. Objective and review outline

The published literature in this field has focused on the evaluation of one or more CCU route(s) with regards to their technical, economic and environmental performance [16–18]. Moreover, published reviews discussed the latest CCU advances and technology deployment, compared the different CCU pathways, inspected the main differences between CCU and CCS, etc (Table 1) [6,19]. However, only few studies have explored the holistic aspect of CCU pathways and were able to explore inter-sectoral linkages for some CCU routes [20,21]. As such, this review aims to respond to this gap by reviewing and addressing two trending topics; CCU and the EWF nexus. It reviews the main CCU routes through a holistic approach and how they are related to various interlinkages within the EWF sectors. The review discusses the different CO_2 sources, briefly reviews the various carbon capture methods and technologies, and provides an overview of all major CCU pathways with a focus on their trans-sectorial symbiosis within the EWF systems. From Table 1 below, it is evident that no review combining CCU and EWF nexus concepts has been published. As such, the objective of this review is to contribute to the development of both fields, and to introduce the foundational basis for which the overall EWF nexus system performance can be enhanced through CCU. The structure of this review is organised such that the first section provides an overview of the different carbon

Table 1
Recent reviews on CCU.

Review paper	Description
Meylan et al. [22]	Discusses integrated CCU pathways from the viewpoint of circular material flow and industrial ecology.
Al-Mamoori et al. [23]	Reviews the techno-economic challenges and opportunities of current carbon capture technologies and provides an overview of the utilisation pathways and their status.
Alper et al. [24]	Provides a comprehensive review on the CO_2 conversion to fuels and chemicals route, and discusses the process' existing, emerging and innovative technologies.
Koytsoumpa et al. [25]	Reviews CO_2 emissions and separation methods from various industries and assesses the potential of CCU pathways focusing on CO_2 conversion to fuels and chemicals.
Norhashyma et al. [26]	Debriefs 3000 patents on CCU technologies including an overview of all major CO_2 utilisation routes and reports their main findings in terms of economic and environmental impacts.
Rafiee et al. [19]	Examines CCU routes from a process angle while considering their main research and development advancements.
Tapia et al. [27]	Reviews planning and decision support tools for CCUS technologies with a focus on process system engineering tools.
Dindi et al. [28]	Discusses the various CCUS applications from fly ash sources, while highlighting their related challenges and opportunities.
Mikulcic et al. [29]	Examines the various CCU pathways and discusses their integration potential with renewable energy systems.
Gulzar et al. [30]	Discusses the various CCU pathways and examines their commercialisation potential while highlighting their main challenges and opportunities.
Wang et al. [31]	Surveys a plethora of CCU routes (laboratory and industrial), highlights their status and discusses their potential.
Zhang et al. [6]	Reviews the most recent advancements in CCU technologies and discusses the main challenges for their large-scale deployment in the future.

fluxes and reservoirs and discusses important aspects of CO_2 source-sink matching. The second section discusses the various carbon separation methods and capture technologies, and the possible CO_2 utilisation pathways. The third section examines the CO_2 utilisation pathways from an EWF nexus perspective, describing their numerous intertwined dependencies within the energy, water and food sectors. The last section suggests certain important decision-making tools and directions for a holistic assessment and a successful deployment of CCU applications in alignment with the EWF nexus concept.

2. Research methods

The work presented in this review studies an assembly of peer-reviewed journal papers and other peer-reviewed sources such as reports, thesis dissertations, book chapters, conference proceedings, within a period from 1990 to 2020. Several recognised databases are used to access these resources such as ScienceDirect, Springer, Wiley Online library, etc. This study reviews the opportunities that carbon capture and utilisation (CCU) offer to the EWF nexus concept, and how CCU as a mitigation technology reinforces existing inter-sectoral links and emanates new interlinkages within the three EWF sectors. Hence, the literature selected in this review revolves around: 1) carbon capture and utilisation pathways; 2) the EWF nexus; and 3) the inherent EWF interlinkages delivered by CCU applications. Table 2 presents the structure of the search undertaken in this literature review which is divided into three main categories. Keywords specific to these aforementioned review objectives are employed in the search within the articles' keywords, title, and/or abstract and include: carbon cycle, carbon capture, carbon utilisation, carbon utilisation challenges, carbon utilisation opportunities, energy water food nexus, EWF interactions, CCU and emissions, EWF decision-making, etc. Proceeding by elimination of unrelated sources in each of the search categories based on the research objectives and the inter-connection within the categories, 95 sources were selected including 39 peer-reviewed research papers, 32 review papers and 24 other documents such as technical reports, conference proceedings, and book sections. Finally, referencing was handled using Mendley software.

Table 2
Search categories, keywords, and database distribution.

Categories	Database classification[a] A B C D E	Total articles[b]	Common keywords used
Carbon sources and sinks	4 1 - 2 3	10	Carbon cycle, CO_2 sources, CO_2 sinks, source-sink matching, CO_2 integration.
CCU pathways	47 1 3 - 9	60	Carbon capture and utilisation, CO_2 utilisation, CCU pathways, CCU as mitigation scenario, CCU challenges and opportunities, CCU and emissions, CCU deployment.
EWF nexus	15 2 1 3 7	28	Energy water food nexus, EWF interaction, energy use, water use, energy water food security, EWF nexus tools, decision-making.

[a] Database classification: A: ScienceDirect; B: Springer Link; C: Wiley Online Library; D: other peer reviewed journals in other databases such as Taylor and Francis, Nature, IOP Science, MDPI, etc; E: other sources like thesis papers, governmental reports, conference proceedings, book sections, etc.
[b] Total sources: 98; Duplicates: 3; Analysed articles: 95.

3. Carbon fluxes and reservoirs

3.1. Natural CO_2 sinks and the carbon cycle

The concentration of carbon dioxide in the atmosphere has witnessed a continuous rise since the industrial era, reaching unprecedented levels of approximately 407.4 ppm in 2018 [32]. This increase is partly due to deforestation and land use changes activities, and mainly driven by anthropogenic emissions related to the use of fossil fuels leading to observable disruptions within the natural carbon cycle depicted in alterations of the natural CO_2 stored in land and ocean reservoirs [33]. For example, as the CO_2 concentration in the atmosphere increases, the CO_2 uptake by oceans declines due to the reduction in the chemical buffer capacity, which reduces the capacity of seawater to absorb CO_2. Moreover, the solubility of CO_2 is reduced due to the rising surface temperature of the waters. Hence, it is important to understand the influence of anthropogenic forced environmental changes on the natural carbon cycle. The carbon cycle is the process of carbon exchanges between the atmosphere, land, and ocean through physiochemical and biological processes. Carbon fluxes within the terrestrial systems involve the CO_2 uptake by plants for photosynthesis, which amounts to one third of the available CO_2 in the atmosphere. However, only a portion of this CO_2 is fixed through the gross primary production (GPP) of carbohydrates by the plants, which is estimated at 120 Pg/year of carbon (about half of the CO_2 uptake), and the remaining is lost back to the atmosphere via respiration. The CO_2 sequestered by terrestrial plants is then emitted back to the atmosphere after decomposition by either heterotrophic bacteria or waste combustion. Moreover, dead organic materials enter the soil where it is respired and are broken down to CO_2 by microbial processes. This CO_2 can be sequestered in soil sinks from decadal to centennial time periods [34]. The carbon cycle also involves CO_2 fluxes between the atmosphere and the ocean. The ocean is considered as a large CO_2 sink, where the amount of CO_2 present in the ocean is 50 times higher than that of the atmosphere. Carbon dissolution into water is mainly due to the high CO_2 solubility in water and chemical reactivity. The coastal carbon cycle involves the transformation of carbon between organic carbon (related to living organisms) and inorganic carbon, and exchanges between riverine, estuaries, continental shelves, etc. Photosynthesis by phytoplankton produces organic carbon, which is then either consumed by zooplankton or becomes waste. The organic carbon waste is then transferred downward from the upper ocean, through which a portion of it sinks to sediments, and the rest is consumed by heterotrophic organisms through respiration. CO_2 fluxes between terrestrial and ocean systems also enter in the carbon cycle. Carbon from lands is also transported via rivers to the ocean sink and is estimated approximately 0.8 Pg/year [34,35].

3.2. CO_2 sources

Carbon dioxide, a major anthropogenic greenhouse gas, originates from numerous sources, either large scale emitting sources related to intensive industrial practices such as power production, steel and cement industries, or medium scale CO_2 releasing sources emanating from commercial and industrial buildings, or small scale sources such as the transportation sector [36]. Fossil-fuel combustion is considered as the largest source of CO_2 emissions, used in various energy applications such as power production, oil refining, and industrial activities. Apart from combustion, other fossil-fuel processes (chemical, physical and biological) also emit CO_2 including production of petrochemicals (e.g. ammonia and ethylene), metals, lime, and biomass fermentation. Moreover, natural gas sweetening is also a process that emits CO_2, whereby CO_2 is separated to enhance the heating value of the gas and to comply with pipeline transport requirements. Large stationary sources, emitting higher than 0.1 $MtCO_2$/year are presented in Table 3. The CO_2 concentration in the flue gas depends on the type of the fuel and the combustion conditions (i.e. amount of excess air). Natural gas-based

Table 3
Profile of global large stationary (> $0.1MtCO_2$/year) sources.

CO_2 sources	CO_2 concentration in flue gas (% by volume)	% of total CO_2 emissions	Average emissions per source ($MtCO_2$/ source)
Fossil-fuels based Power			
Coal boiler	12–15	59.69	3.94
Natural gas boiler	7–10	5.62	1.01
Natural gas turbine	3	5.68	0.77
Petrochemical industry			
Ammonia production	100	0.84	0.58
Ethylene production	12	1.93	1.08
Natural gas sweetening	–	0.37	–
Cement production	20	6.97	0.79
Iron and steel industry			
Integrated steel mills	15	4.71	3.5
Other processes	-	0.12	0.17
Refineries	3−13	5.97	1.25

Adapted from [37]].

combined cycle turbines usually have a low CO_2 content in their flue gas, approximately 3–4 % by volume, as compared to coal-based power plants that emit a flue gas from the boilers with a CO_2 content of 12–15 % by volume. CO_2 emissions from high partial pressure and high concentration sources such as the production of petrochemical and gas processing have a low share in the total CO_2 emissions related to large stationary sources (less than 2%). The carbon dioxide from these sources can be easily separated because of its high concentration and high partial pressure in exhaust streams, whereas it is more stringent and costly to capture CO_2 from low concentration sources [37].

3.3. Direct air capture

Air can be considered as another source of CO_2, with concentrations of approximately 407.4 ppm reported in 2018 and predicted levels expected to reach 600−1550 ppm in 2030 if mitigation actions are not taken [32,38]. Direct air capture (DAC) from the atmosphere is considered as a CO_2 separation technology that can be realised either organically from photosynthesis, through the formation of metal carbonates, or with sorbents [25]. Processes of DAC using sorbents can be achieved either by absorption, which entails the dissolution of CO_2 into the sorbent, or via adsorption, which implicates the binding of CO_2 on the surface of the sorbent. Both processes then treat the sorbent to detach the captured CO_2. The most mature DAC technology uses a strong liquid base such as potassium or sodium hydroxides that reacts with CO_2 and forms a carbonate product. Carbon dioxide can then be separated from the carbonate product via a chemical reaction with calcium hydroxide that generates a precipitate (calcium carbonate). This precipitate then reacts with oxygen at high temperatures (~800 °C) to form CO_2 and calcium oxide. An alternative to strong base sorbents is the use of solid amines for CO_2 adsorption following a two-steps process: the adsorption of CO_2 from the direct air and the separation of CO_2 from the sorbent. The separation of CO_2 from amines is relatively easier than from strong liquid bases as it requires less energy due to the weaker bonds between CO_2 and the solid sorbent [39]. The benefit of the DAC technology is that it can be implemented anywhere because of the fast mixing of CO_2 in the air. However, challenges remain for this technology that are mainly related to the energy requirements for separation. DAC is an energy intensive process, which directly reflects on the higher costs of capture from this application ~27−1000$/$tCO_2$ as compared to carbon capture from large CO_2 exhaust sources ~20−100$/$tCO_2$, and to high purity sources such as ethanol processes with cost estimates for carbon capture of ~6−12$/$tCO_2$. Moreover, energy requirements for this application need to be produced from low-carbon sources, such as, renewable energy systems or recycled high quality energy streams to ensure its sustainability and realise its purpose for CO_2 mitigation [22].

3.4. CO_2 source-sink matching

Matching CO_2 sources with sinks requires the integration of carbon capture and separation technologies, which will enable the supply of pure CO_2 detached from any impurities that might harm the CO_2 utilisation process and hinder the quality of the produced commodity. For example, exhaust gases rich in CO_2 cannot be used directly in some applications, such as food processing or conversion to chemicals because other impurities are present, such as NO_x and SO_x, although it can be used in other sinks, such as oil reservoirs via the enhanced oil recovery (EOR) technique. Carbon dioxide source-sink matching requires extensive studies and analyses to select the appropriate CO_2 sink that will minimise energy use and GHG emissions related to the CO_2 capture and separation from the source and CO_2 transportation between the source and sink. Moreover, other uncertainties that might lead to a mismatch need to considered such as temporal and spatial characteristics (e.g. operating life) of the source and sink, because these components operate independently of one another, and are controlled and operated by separate entities [27]. Several studies explored the integration of CO_2 sources with sinks, and discussed the important aspects that need to be considered for appropriate matching. The first decision acquires the comprehensive assessment of the availability and location of the sources and sinks, the flue gas characteristics, and the sinks' storage capacity. Secondly, the selection of the CO_2 capture technology and method, transportation network, and CO_2 utilisation sink has to be based on the optimal solution that will minimise costs and maximise revenues from the integrative supply chain. Third, the source to sink matching has to examine the net GHG emissions related to this application, including that of capture and displacement of CO_2 in order to minimise emissions. With regard to these interrelated goals, and due to the complexity of integrating the various components of CO_2 source-sink matching, process systems tools (PSE) were adopted to aid in the decision and planning of these systems [27,40–42].

4. Carbon capture and utilisation pathways

Carbon capture and storage (CCS) is considered as an important mitigation route, whereby CO_2 emissions principally from the fossil fuel based power sector are captured and stored long-term in geological formations and deep ocean waters. This method was initially adopted to only eliminate CO_2 emissions from the atmosphere, whilst maintaining the same intensive fossil fuel consumption. Although both CCS and CCU methods share the same initial process of CO_2 capture and the mutual purpose for long or short-term CO_2 sequestration, however, the CCU route provides a different approach towards CO_2 removal and sequestration, whereby CO_2 is converted from existing as a liability for industries and the climate to an asset for CO_2 emitters and users. The CCU option delivers a benefit relative to the CCS pathway with regard to the re-use of a once considered waste to become an alternative resource to fossil fuels. Moreover, CCU provides major economic incentives for business actors, who can diversify their revenue portfolio by benefiting from additional and new industrial practices that utilise the CO_2 or by selling their captured CO_2 to other interested users [43]. Studies comparing CCS to CCU routes suggested that CCS has a larger CO_2 mitigation potential [44]. However, the additional opportunities offered by CCU are worth studying and exploiting. Aldaco et al. [44] validated through a comprehensive LCA analysis that CCU, specifically CO_2 conversion to chemicals (i.e. formic acid) has a better economic performance than CCS, owing that to the additional profits from the conversion of CO_2 to value-added chemicals. To date, 19 carbon capture and utilisation or storage (CCUS) projects are in operation around the globe with a total CO_2 offset of 34 Mt/year. In addition, 4 CCUS projects are under construction, 10 in the advanced development phase, and 18 in the early development phase. Amongst these operational projects 14 are CCU projects (Table 4) [6,45]:

Several climate policies and funding programs have been put in place to develop and promote the deployment of CCU technologies, such as: $110 million federal funding allocated by the US Department of Energy (DOE); $100 million fund accorded by the German government dedicated to research and development projects; €10-billion innovation fund that supports different clean technologies including CCU; 45Q tax credit dedicated for carbon dioxide sequestration via utilisation or storage, etc [46–49]. Aside from the promising potential and the imperative deployment of CCU technology for climate change mitigation, additional benefits stem from this application including [47]:

- Portfolio diversification by the production of additional value-added products used in different industries and applications;
- The generation of supplementary revenues that can feed to the total or partial cost offset of carbon capture and CO_2 transport;
- The reinforcement of circular economy by waste recovery and recycling in the production of profitable products;
- The provision of an alternative solution to the CCS technology in regions with low potential of geological storage.

4.1. Carbon capture technologies and methods

Capturing CO_2 from power and industrial flue gas streams is necessary to lower CO_2 emissions in the atmosphere and comply with emission control through standards and regulations. Carbon from flue gases can be captured via three main technologies: post-combustion, pre-combustion, and oxy-fuel combustion. Post-combustion carbon capture involves the capturing of CO_2 after fuel combustion and is usually separated via chemical absorption or using membranes. The latter capture technology is appropriate for exhaust gases with low CO_2 concentrations (4–14 %v/v), and is capable of producing high purity CO_2 [50]. The pre-combustion captures CO_2 from the flue-gas of the water-gas-shift reaction. Fuel is first gasified, partially oxidised or reformed to produce CO and H_2, which is then fed to a water-gas shift reactor where CO reacts with steam to generate CO_2 and H_2. The CO_2 is then separated and H_2 is combusted to produce energy. The pre-combustion technology is usually used with integrated gasification combined cycle (IGCC) applications. The main advantage of the pre-combustion technique is that it leads to a carbon-free fuel (H_2), which during its combustion does not release sulphur dioxide [51]. Moreover, this practice leads to high CO_2 concentrations in the flue stream, which represents a benefit as it entails the handling of low flue gas volumes for CO_2 capture [50]. The oxy-fuel combustion is similar to the post-combustion technology; the difference is that the fuel is combusted with pure oxygen instead of air, which leads to higher CO_2 concentrations in the flue gas [52]. The main advantage of the oxy-fuel combustion is the absence of NO_x and SO_x components in the flue gas. However, the generation of pure oxygen for this capture technology consumes large amounts of energy, which is reflected in the higher process costs [53].

Several separation methods are available for couplingwith the appropriate carbon source and carbon capture technology, including absorption, adsorption, membrane separation, chemical looping, cryogenic distillation, and hydrate-based separation. The process of absorption involves the chemical absorption of CO_2 by a absorbent solution such as amine-based (e.g. monoethanolamine MEA, miethanolamine DEA) [54]. Several studies investigated the technical performance of chemical absorption as a separation process for various applications such as biomass-based energy systems, and compared the use of different sorbents [55]. Aqueous potassium carbonate (K_2CO_3) is also used as a sorbent in chemical absorption and presents various environmental advantages over amine-based sorbents, including low toxicity, low degradation, and facility of regeneration. Moreover, the addition of some promoters such as diethanolamine (DEA) and piperazine (PZ) demonstrated process improvements by increasing the CO_2 absorption rate by potassium carbonate [56]. Adsorption is another separation method, which appertains to the attachment of CO_2 on the

Table 4
Global status of CCU projects.

Project	Status	Year	Country	Industry	Scale	Capacity (Mtpa)	Utilization route
The CNPC Jilin Oil Field project	Operational	2018	China	Natural gas processsing	Large scale	0.6	EOR
Petra Nova Carbon Capture	Operational	2017	USA	Power generation	Large scale	1.4	EOR
Abu Dhabi CCS	Operational	2016	UAE	Iron and steel production	Large scale	0.8	EOR
Uthmaniyah CO_2-EOR demsontration	Operational	2015	Saudi Arabia	Natural gas processing	Large scale	0.8	EOR
Boundary DAM CCS	Operational	2014	Canada	Power generation	Large scale	1	EOR
Petrobas Santos Basin Pre-salt Oil Field CCS	Operational	2013	Brazil	Natural gas processing	Large scale	3	EOR
Coffeyville Gasification Plant	Operational	2013	USA	Fertiliser production	Large scale	1	EOR
Air Products Steam Methane Reformer	Operational	2013	USA	Hydrogen production for oil refining	Large scale	1	EOR
Lost Cabin Gas Plant	Operational	2013	USA	Natural gas processing	Large scale	0.9	EOR
Century Plant	Operational	2010	USA	Natural gas processing	Large scale	8.4	EOR
Great Plains Synfuels Plant and Weyburn-Midale	Operational	2000	USA	Synthetic natural gas	Large scale	3	EOR
Shute Creek Gas Processing Plant	Operational	1986	USA	Natural gas processing	Large scale	7	EOR
Enid Fertiliser	Operational	1982	USA	Fertiliser production	Large scale	0.7	EOR
Terrel Natural Gas Processing Plant	Operational	1972	USA	Natural gas processing	Large scale	0.4–0.5	EOR

surface (adsorption) of a solid adsorbent or a chemical solution, and then its desorption by either pressure swing adsorption (PSA), temperature swing adsorption (TSA), or electric swing adsorption (ESA) systems [52]. Regarding chemical looping, it is similar to oxy-fuel combustion, although it uses metal oxides (e.g. Fe_2O_3, NiO, Mn_2O_3) as oxygen carriers instead of pure oxygen for the fuel combustion. The process entails fuel oxidisation to CO_2 and water, and the reduction of the metal oxide, which is recycled back after another oxidisation step, where CO_2 is then easily separated by condensation of the water in the output gas [38]. With respect to membrane separation, it uses a semi-permeable barrier in the form of highly selective polymer or ceramic based membranes, which captures CO_2 from the exhaust gas. They are usually coupled with exhaust gases with high CO_2 concentrations and high volume flowrates [50]. As for the cryogenic method, it separates CO_2 using fractional condensation and desublimation at low operating temperatures. The main advantage of the cryogenic method is the high recovery rate and high purity that can be achieved as compared to the other separation means. However, it faces shortcomings related to the risk of condensed water blockage, which increases the separation costs [57]. The hydrate-based separation method involves exposing the flue gas to water, whereby CO_2 is selectively trapped in the lattice of the hydrate, due to the differences in phase equilibrium of CO_2 with the other gases present in the flue gas. The hydrate-based method is appropriate for coupling with the pre-combustion technology, as it can exploit the high-pressure output stream from the water-gas-shift reaction, which is favourable for hydrate formation. Advantages related the hydrate-based method include the use of clean and environment friendly process and materials, energy efficient process, and a high pressure CO_2 output which eliminates the need for further CO_2 compression necessary for transportation and storage [58]. After capture and separation, CO_2 is compressed and transported for utilisation under various pathways as illustrated in Fig. 1. Five main CO_2 utilisation categories are discussed in the next sections: chemical conversion, mineral carbonation, enhanced oil recovery, biological conversion and direct utilisation.

4.2. Conversion to chemicals and fuels

Carbon conversion into chemicals is an important utilisation pathway, representing a large CO_2 sequestration potential of approximately 500 Mt/year [36]. The production of a variety of chemicals through the capture and utilisation of CO_2 is possible such as urea, formic acid, salicylic acid, organic carbonates such as acyclic carbonate, cyclic carbonates like ethylene carbonate, polycarbonates, and fine chemicals such as biotin, etc. Urea is considered as a principal agricultural fertiliser with the largest market size amongst the other chemicals, with an annual production of 150 Mt/year and a CO_2 sequestration rate of approximately 112 Mt/year [23,24]. Urea is also used in other applications including in the production of certain pharmaceuticals, fine and inorganic chemicals, and in polymer synthesis [23]. The production of urea is conducted by the reaction of CO_2 with ammonia at temperatures of approximately 185−195 °C and operating pressures between 180−200 atm. First, ammonium carbamate is produced through the fast and exothermic reaction of CO_2 with ammonia at high temperature and pressure. The ammonium carbamate is then decomposed using the dissipated heat during the previous reaction into urea and water through a secondary slow and endothermic reaction [24].

Carbon dioxide can be converted to produce fuels such as methane, methanol, and syngas [23]. Dry methane reforming and hydrogenation are considered as the main CO_2 to fuel conversion pathway. Dry methane reforming is an endothermic reaction, which consists of utilising CO_2 instead of steam to react with methane and generate synthesis gas. The produced syngas can also be exploited via the Fisher-Tropsch (FT) process to generate a variety of liquid fuels. For example, Al-Yaeeshi et al. [59,60] explored the utilisation of CO_2 into the FT gas to liquid (GTL) conversion process from natural gas reforming. Outcomes of this study demonstrated improvements in the techno-economic and environmental performances of the hydrocarbon synthesis process with the use of CO_2. As for the hydrogenation process, it entails the use of CO_2 instead of CO in the production of methanol. The conventional methanol production process is based on the conversion of syngas, usually generated from natural gas to methanol. Methanol is a liquid petrochemical used as an energy carrier in the transportation sector, and as a feedstock and solvent to produce other chemicals (e.g. acetic acid, formaldehyde, methylamines) and fuel additives [61]. It is especially a valued chemical because it can be produced through a low temperature reaction of CO_2 with hydrogen, and can easily be stored and transported [62]. The CO_2 hydrogenation process consists of two simultaneous

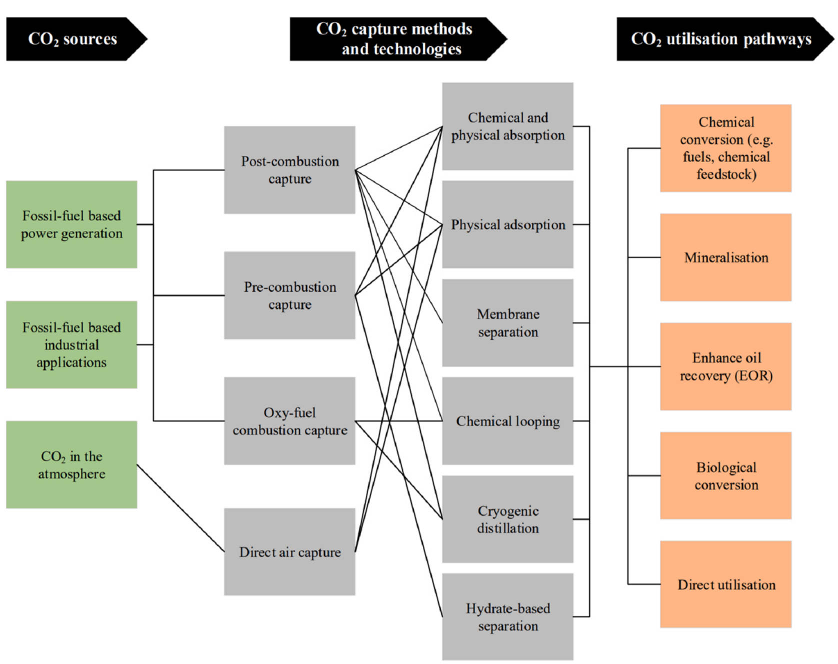

Fig. 1. Carbon capture and utilisation routes.

reactions: methanol formation which is an exothermic reaction, and the reverse water-gas-shift reaction, which is considered as an unfavourable reaction because it also consumes hydrogen and lowers the yield of methanol production (Eqs. (1) and (2)) [24].

Methanol formation reaction:

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O \tag{1}$$

Reverse water-gas-shift reaction:

$$CO_2 + H_2 \leftrightarrow CO + H_2O \tag{2}$$

The hydrogenation of CO_2 was proven to be technically feasible and competes with the conventional process of methanol production from fossil-fuels. In addition, it is a sustainable approach for the generation of additional fuels and chemicals through the utilisation of wasteful CO_2 emitted from different industrial sources [61]. However, the fossil-fuel based hydrogen used in the hydrogenation process of methanol poses additional environmental constraints, whereby additional CO_2 is emitted to the atmosphere from the production of hydrogen. Hence, new techniques and processes for green hydrogen production from renewable energy sources through water electrolysis (i.e. biomass, solar, wind) were proposed and recommended by several studies [23]. For example, AlNouss et al. [63] studied the generation process of value-added fuels and chemicals including methanol from different biomass feedstock, and investigated their techno-economic and environmental performance. Findings of this study demonstrated that methanol production has the best economic performance amongst the other chemicals (i.e. urea, and Fisher-Tropsch liquids).

The conversion of CO_2 to fuels and chemicals pathway delivers broad intra-sectoral benefits within the energy sector, including the elimination of CO_2 emanating from the power and industrial sectors, the additional generation of fuels and chemicals through sustainable processes, and the reduction of fossil-fuel consumption in the generation of fuels and chemicals. In fact, the concept of a methanol economy proposed by Olah et al. [64] demonstrates the advantages of recycling CO_2 within the energy sector as an attractive approach for climate change mitigation. This concept entails the adoption of a carbon cycle through the utilisation of CO_2 for renewable methanol production as a way to complement the natural carbon cycle in efforts to reduce CO_2 emissions in the atmosphere, reduce the reliance on fossil fuels by the energy sector, and produce value-added methanol and its derived chemicals through a carbon-neutral process.

4.3. Mineral carbonation

The mineralisation process consists of the reaction of CO_2 with natural minerals (e.g. serpentine, olivine, wollastonite), solid wastes encompassing metal ions (e.g. fly ash), or metal ions present in wastewaters to form carbonates. Carbonation occurs naturally (natural weathering) when metal oxides such as magnesium and calcium react with atmospheric CO_2 and is characterised by good thermodynamic conditions and reduced consumption of chemicals, however, the reaction process is slow. Hence, CO_2 injection is performed to improve the reaction kinetics. This synthetic extraction process also involves the removal of some impurities such as silicon and iron leading to the generation of pure carbonate products [31]. The reaction of CO_2 with metal oxides found in minerals such as serpentine, olivine and wollastonite is an exothermic reaction, owing to the lower energy state of the carbonates compared to CO_2 (Eqs. (3)–(5)). The carbonation process can be either direct through a single step reaction or indirect following multiple steps. The direct carbonation occurs when the extraction of the mineral coincides with the carbonate formation under high pressures and requires low amounts of energy. However, the indirect carbonation is related to three systematic reactions and enables faster reaction kinetics. The first reaction entails the removal of the metal from the mineral rock via a separating agent such as molten salts. The second reaction involves the hydration of the metal to form metal hydroxides. Finally, the third reaction encompasses the carbonation reaction of CO_2 with metal hydroxides to produce carbonates [7]. An example of the obtained carbonates is calcium carbonate ($CaCO_3$), which can be used in the pharmaceutical industry or as a filling material in construction. Hydrotalcyite is another generated carbonate that finds its use as a catalyst in many reactions such as transesterification of polyesters. The mineralisation process is not only considered as a means to improve the extraction of carbonates, but also to store CO_2 in geological formations. In point of fact, one ton of CO_2 can be sequestered in approximately 1.6–3.7 tons of rock [24].

Serpentine:

$$Mg_3Si_2O_5(OH)_4 + 3CO_2 \rightarrow 3MgCO_3 + 2SiO_2 + 2H_2O;\ \Delta H = +64kJ/molCO_2 \tag{3}$$

Olivine:

$$Mg_2SiO_4 + 2CO_2 \rightarrow 2MgCO_3 + SiO_2;\ \Delta H = +89kJ/molCO_2 \tag{4}$$

Wollastonite:

$$CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2;\ \Delta H = +90kJ/molCO_2 \tag{5}$$

Advantages of mineral carbonation as a CCU route appear in the ease of CO_2 usage with regard to its purity, whereby impurities such as NO_x and SO_x present with CO_2 originating from industrial applications do not have an impact on the carbonation reaction. Hence, the carbon capture process that aims to produce high purity CO_2 is not necessary in this application, which leads to a lower energy consumption. Moreover, the CO_2 fixed by the carbonates can be stored for long periods of time, from decades to centuries, owing that to the stable aspect of the carbonates, and without any leakage concerns [7]. An application of mineral carbonates is in the construction industry using carbonate blocks instead of Portland cement (PC) based concrete blocks because of their negative carbon footprint. Other than natural mineral rocks, residues from steel or cement industries (i.e. rich in calcium and magnesium oxides) can also be used as an alkaline to form carbonates in the presence of CO_2. This is a promising CCU application with a potential capacity for CO_2 sequestration of up to 3.3 $GtCO_2$/year by 2100, which can account for 5–12 % of the total CO_2 emissions by 2100 [18]. Few projects that utilise industrial residues for carbonation are on the commercialisation path or remain under demonstration, such as the Texas SkyMine project (Skyonic corporation) that uses its residues from the Capitol Aggregate cement plant to produce sodium bicarbonate, hydrochloric acid and sodium carbonate in efforts to reduce its CO_2 emissions by 15 % compared to its usual process activities [65].

4.4. Enhanced oil and coal-bed methane recovery

The enhanced oil recovery (EOR) and coal-bed methane recovery (ECBM) techniques are other CCU routes, where CO_2 is injected into oil reservoirs and bituminous coal beds respectively for enhanced oil and gas recovery. The ECBM technique is still not economically feasible and hence is not commercial, contrary to EOR, which has been applied by various businesses in the oil industry for 40 years. Particularly, for the EOR method, CO_2 along with other components (e.g. polymers, nitrogen, surfactants) is directly injected into oil reservoirs to facilitate oil extraction and is applied as a solution for oil reserves that cannot be extracted through the conventional process. Enhanced oil recovery, also called tertiary recovery, is a process where CO_2 is injected in its supercritical form with the ability to easily mix with the oil and reduces its viscosity for an easier displacement. Carbon dioxide is used in this application, as an enabling agent to increase the oil extraction yield, mainly because of its large availability and its relatively low cost. It permits a 30–60 % recovery versus a 20–40 % extraction of the available crude oil in the reservoir reached by the conventional primary and secondary recovery process [7]. This CCU application represents the main market for CO_2 utilisation, since the oil and gas industries exploit large amounts of CO_2 in the EOR process [6]. The improved recovery efficiency plays an important role in increasing the energy security of some countries (i.e. North America) by lowering their oil imports [66]. Moreover, the concept of carbon negative oil has emerged with the application of EOR, whereby the net CO_2 emissions corresponding to the extraction, processing, transportation and utilisation of oil can reach neutral to negative levels. For example, the production of one barrel of oil in the United States utilises 300−600 kg of CO_2 injected during the EOR process, given that the same amount of oil produced releases 100 kg of CO_2 during production and transportation and 400 kg of CO_2 during its combustion [67]. Although the EOR and ECBM applications are able to sequester large amounts of CO_2 per year (30–300 Mtpa), challenges remain for these utilisation routes [26]. They include possible long-term safety and environmental concerns (water leakage, and acidification) that might arise in the future due to the unclear behaviour of CO_2 being stored in these geological mediums. These potential problems emancipate wide social concerns and opposition by the public, which places more restrictions in the deployment of this CCU option [6,22].

4.5. Biological conversion

The highest CO_2 exchange between the atmosphere and land is achieved through photosynthesis, where approximately 440 Gt pa of CO_2 is exchanged [68]. The biological conversion of CO_2 is another CCU pathway with an important potential of CO_2 sequestration. This pathway involves CO_2 absorption and fixation by algae and other terrestrial crops via the photosynthesis process. Microalgae are a type of microscopic algae that grow in water mediums, and are used in various applications, from biofuel production to animal feed. This type of algae can grow in fresh and seawaters, and some can also be grown using wastewaters. Through the process of photosynthesis, microalgae use light to convert CO_2 into organic carbon needed to produce cellular compounds. Microalgae are a beneficial CO_2 mitigation route because of their fast growth rate in the presence of high CO_2 concentrations, which enables higher CO_2 fixation approximately 50 times more than terrestrial grown crops. Microalgae have the potential to produce high lipid content. Up to 90 % of their dry weight was reported for certain types of microalgae grown under specific conditions. Nearly 70 % of the lipids' content of microalgae are made of triglycerides, which can be extracted and converted to biodiesel via the transesterification process [69]. Microalgae can be cultivated either in open or closed growing systems. Cultivation in open systems includes mediums such as lagoons and ponds, while closed systems involve controlled growing conditions in photobioreactors [70]. Several studies explored microalgae cultivation and their intercellular content under varying environmental and growing conditions [71,72]. Others focused on the study of the biofuel production process from microalgae sources, suggesting process improvements and optimisation routes for the profitable generation of microalgae-based fuels [17,69,73]. For example, Wu et al. [17] proposed a simultaneous production system of diesel and ethanol from microalgae and analysed the economic performance of this system by estimating the break-even prices to be 0.49$/kg for diesel and 2.61$/kg for ethanol, which were slightly higher than break-even prices of other biofuel conversion processes fed by animal and other plant sources. The main advantages for microalgae cultivation are as follows [70,74]:

- can be grown in offshore mediums and do not require large cultivation areas;
- can be grown in seawaters and wastewaters;
- can be grown rapidly;
- can offer high lipid content by controlling their growing medium;
- can be converted to a non-toxic, biodegradable, and carbon neutral biofuel; and
- can directly capture and fix CO_2 from the atmosphere.

Moreover, photosynthetic cyanobacteria also have the ability to capture and fix CO_2, and use it to produce its organic content in the presence of light and water via the Calvin cycle. These bacteria offer a great potential of bioethanol production as an alternative to the conventional ethanol extraction from agricultural crops, which are reliant on arable lands and impels land competition concerns with the food system. These bacteria have the possibility to produce approximately 5 L/m^2. year of ethanol, compared to 0.3 L/m^2. year of ethanol from corn and approximately 0.6 L/m^2. year of ethanol from sugar cane sources [70]. Another biological use of CO_2 is the growing of microbial proteins (MPs), which are considered as a competitive alternative to animal and plant based proteins. Carbon dioxide is utilised in this application for the growth of bacteria, and can either be in the form of atmospheric air or pure CO_2 captured from industrial flue gases. However, it should be noted that direct use of atmospheric air can lower the electricity-to-biomass yield (20 %) as compared to pure CO_2 (54 %). Microbial proteins are usually used for animal feed and are equivalent to other protein bases such as soymeal and fishmeal. Moreover, experts are also investigating the potential use of MPs as a protein source for human consumption, considering its safety, and exploring its social acceptance. The main advantage of this utilisation route is its potential reduction in land use and its water savings compared to the cultivation of other plant based proteins (e.g. soybeans) [21].

Carbon dioxide enrichment in agricultural greenhouses is another CO_2 biological conversion pathway, which increases CO_2 concentrations in greenhouse mediums to enhance crop productivity [75,76]. Several studies investigated crop responses subjected to increasing CO_2 levels, which depends on the type of the crop cultivated and the operating parameters of the greenhouse. Generally, CO_2 levels up to 1200 ppm are beneficial for most agricultural crops, with major improvements in yield (up to 30 %) and reduced crop evapotranspiration levels [77,78]. For example, in a study conducted by Sánchez-Guerrero et al. [79], crop water use was reduced by 40 % when CO_2 enrichment was introduced. The lower levels of evapotranspiration can be explained by the decrease in stomata conductance due to CO_2 enrichment, which leads to the shrinking of stomata pores and hence lowers the amount of water lost from the plants to the atmosphere [78]. The higher stomata conductance also leads to a less uptake of pollutants present in the air such as O_3 and SO_2 by the plants [80]. CO_2 enrichment in the agricultural sector is a commercial practice, in which either pure commercial CO_2, CO_2 produced from on-site burners, or CO_2 captured from industrial activities is used. For example, the Netherlands uses approximately 5–6.3 Mt/year of CO_2 for agricultural enrichment, with 500 kt/year of CO_2 originating from industrial flue gases and the rest from on-site CO_2 generators such as boilers [8]. The implementation of burners within the greenhouse has demonstrated to be an efficient and economic approach, although it can introduce NO_x and SO_x pollutants to the greenhouse which affects the health of plants [81].

4.6. Direct utilisation

Direct CO_2 utilisation is applied in many industries and sectors including heating and cooling where CO_2 is used as a refrigerant, carbonation of beverages, and food preservation, etc. Enhanced oil recovery is also considered as a direct utilisation route of CO_2. However, this utilisation pathway is discussed separately due to its high importance and large market size [23]. The utilisation of CO_2 in the food and beverage industry is approximately 11 Mt/year. For instance, the utilisation of CO_2 to generate succinic acid is a promising application, particularly important in the food industry, whereby this acid is used as a pH modifier, an anti-microbial chemical, and a flavouring agent. This chemical is also used in the cleaning sector as detergent and foaming means and in the pharmaceutical industry. Alternatively, the adoption of supercritical CO_2 as a refrigerant is receiving more attention because of its low Global Warming Potential (GWP), low density and high refrigeration capacity (5–22 times higher) compared to other synthetic and natural refrigerants, and the lower size dimensions needed for the system. Several studies determined that CO_2 based heating and cooling systems can reach a higher technical performance (i.e. coefficient of performance COP) as compared to the use of other refrigerants such as hydrofluorocarbons [29]. For example, Yelishala et al. [82] demonstrated that for vapour compression refrigeration systems, an increase of up to 40 % in COP is achieved with a zeotropic refrigerant mixture (combination of hydrocarbons and CO_2) relative to the use of pure hydrocarbons. This articulates additional benefits related to the direct CO_2 utilisation route. Apart from waste recycling, CO_2 sequestration and the generation of new commodities, CO_2 can also improve the efficiency of energy systems particularly heating and cooling systems. Moreover, improvements in systems' efficiency directly reflects on systems' inputs and outputs, implying that higher yields are reached with optimum input usage. Hence, this application has also the potential to lower the utilisation of resources (i.e. water and energy) from heating and cooling systems within the energy sector.

5. The role of CCU in energy, water and food security

The EWF nexus approach highlights the mutual interlinkages between energy water and food resources with the objective of collective security. Energy security describes the availability, accessibility and affordability of reliable energy for all energy-based uses such as cooking, heating, lighting, and communications, etc. Water security relates to the accessibility of safe drinking water and sanitation. Food security represents the "*availability and access to sufficient, safe and nutritious food to meet the dietary needs and food preferences for an active and healthy life*" [83].

The EWF nexus approach was developed and consolidated into analytical assessment tools, conceptual frameworks and collaborative discourses for effective and cohesive decision-making and policy development [84]. This has enabled a deeper understanding of the interactions and dependencies within sectors in terms of resource consumption as illustrated in Fig. 2. Further elements can be incorporated into the EWF nexus such as climate and land-use to account for additional variabilities in the system and be able to mitigate any associated risks [85]. Fig. 2 explicitly exhibits waste as a component to illustrate the additional flow of waste CO_2 that can be realised with CCU applications. The apparent CO_2 stream constitutes only the direct flow offered by CCU applications, in which CO_2 is captured from the energy sector and is either used in the same sector or in the food sector. However, CCU applications also involve other indirect interlinkages with the water sector. The intertwined EWF connections extended by CCU applications are further discussed in this section.

The EWF nexus approach was adopted by several studies with the main aim of quantifying resource interactions and improving nexus systems. Al-Ansari et al. [86] proposed a holistic EWF life cycle assessment (LCA) methodology that assesses the EWF nexus and evaluates the environmental impact of food security scenarios. The tool developed aggregates resources representing each of the EWF subsystems and enables the identification of trade-offs and synergies within these subsystems. This work was later expanded by integrating greenhouse gas control technologies with EWF nexus systems in the form of biomass integrated gasification combined cycle (BIGCC) and carbon capture to establish a negative emission system [87]. With the objective of enhancing food security, Namany et al. [88,89] adopted the EWF nexus approach to investigate different water and energy technologies for the efficient crop cultivation. In addition, a scenario analysis approach was used to assess the virtual water in the agricultural sector in water scarce countries. The EWF nexus approach was also adopted by other process level studies. Similarly, in food system applications, Lahlou et al. [90] investigated a water planning framework to irrigate alfalfa using treated wastewater from different sources through an EWF nexus approach. This study demonstrated that this application is carbon negative and saves a large amount of freshwater resources with a lower energy input. Other studies examined the conversion of non-edible biomass types such as Jatropha in producing energy and food products by adopting an EWF nexus approach to holistically assess the system from cradle to grave [91]. With regard to the multi-dimensional complexity of food systems, further studies were conducted to characterise the connections between the food sector and energy and water resources [92,93]. Al-Thani et al. [94] conducted an optimisation based study to maximise the nutritional value of agricultural produce by optimally allocating energy and water resources; and Haji et al. [95] applied a GIS based method to manage risks and evaluate energy and water consumption for food systems. With the consideration of the multisite aspect of most EWF nexus systems, other studies examined the temporal and spatial integration of EWF sub-systems by proposing optimisation models to manage their supply chains [96,97].

Evidently, there is a significant emphasis on utilising the EWF nexus approach to address energy water and food insecurities, and to better understand the complex interconnections between the EWF systems. In view of this, CCU pathways need to be explored from an EWF nexus perspective to evaluate their true resource consumption, and to identify the trade-offs they may enforce and the potential synergies within the EWF systems. The following section discusses the main EWF intertwined opportunities for CCU pathways presenting an opportunity for EWF system enhancement through the recycling of CO_2. It is divided into energy-water nexus, energy-food nexus, and water-food nexus, and are summarised in Table 5 and Fig. 3.

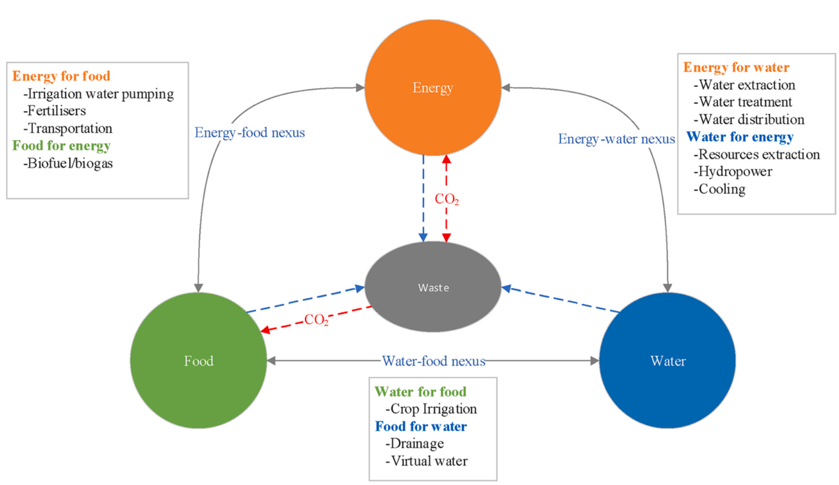

Fig. 2. Resource consumption within the EWF nexus.

Table 5
Summary of CCU opportunities within the EWF nexus.

CCU pathways	Nexus Type	Opportunity
Chemical conversion	**Intra-sectoral symbiosis**	Less fossil-fuel consumption.
	Energy-water nexus	**Lower water consumption** through methanol synthesis via the hydrogenation process.
	Energy-food nexus	-**Reduced energy consumption** using CO_2 in the polyol production process. -The use of Polyol in the **food industry** as a food additive. -**Enhanced food production** using urea as a fertiliser.
Mineral carbonation	**Intra-sectoral symbiosis**	-Valorisation of industrial wastes. -Faster kinetic reactions.
Enhanced oil (EOR) and coal-bed methane recovery (ECBM)	**Intra-sectoral symbiosis**	-**Higher recovery efficiency** of crude oil and coal-bed methane. -**Energy security** by increased fuel extraction.
Biological conversion	**Intra-sectoral symbiosis**	-Better crop yields and faster plant growth. -Lower intake of air pollutants (SO_2 and O_3) for agricultural crops.
	Energy-water nexus	**Lower freshwater consumption** in the energy sector through microalgae cultivation that can use wastewater.
	Energy-food nexus	**Reduced land competition** between the energy and food sectors by bioethanol production from photosynthetic cyanobacteria.
	Water-food nexus	-**Lower crop water use** (evapotranspiration) through CO_2 enrichment in agricultural greenhouses. -**Reduced land competition and reduced water consumption** through the production of microbial proteins with the use of CO_2.
	Energy-water-food nexus	**Reduced land competition and freshwater usage via** microalgae cultivation for biofuel production.
Direct utilisation	**Intra-sectoral symbiosis**	**Higher efficiency** heating and cooling systems with the use of CO_2 as a refrigerant.

5.1. Energy-water nexus and CCU

The energy-water nexus embodies the water needed for energy production (e.g. fossil-fuel extraction and processing, power generation, biomass irrigation, etc.) and the energy required for water extraction (e.g. pumping of groundwater), treatment (e.g. desalination, wastewater treatment) and supply. The production of energy uses about 15 % of the global freshwater withdrawals, of which 11 % is not recycled back and is wasted. Hydropower is a direct illustration of the energy-water nexus, and is a simple example of the dependency of the energy sector on the water sector, where approximately 16 % of the global electricity is hydro-based. As an example of energy demand for water, the United States uses 13 % of their total energy for water services [12]. This cause-effect relation between the energy and water sectors emphasises that with an increased energy demand, the amount of water for energy will increase, and similarly with a higher water demand, the amount of energy for water will rise [15]. It is thus important to explore the intertwined dependencies between the energy and water sectors for CCU applications since they encompass multi-sectoral CO_2 sources and sinks and depend on energy and water resources.

Carbon capture and utilisation technologies englobe several processes into a hybrid supply chain, from the capture and compression of carbon, to its transportation and until its final utilisation. The CO_2 separation process is considered as the most energy and water intensive step for most CCU pathways. Particularly, the process of CO_2 capture consumes large amounts of water, approximately 50–90 % more water consumption relative to conventional industrial processes without integrated carbon capture. The high energy and water consumption translate to higher operating costs, whereby the CO_2 capture process accounts for approximately 80 % of the total expenditures for operating CCU technologies. The amount of water consumed during the carbon capture process varies based on the CO_2 source, the CO_2 separation method and technology, as well as the purity desired for the final captured product. For example, an increase of 45 % of water consumption can be foreseen in fossil-fuel based integrated gasification combined cycles (IGCC) power plants when carbon capture is introduced in the process [20].

The biological conversion route, particularly CO_2 utilisation in microalgae production demonstrates important interlinkages between the energy and water sectors. For its growth, microalgae can use wastewater with the appropriate amount of nutrients (e.g. nitrogen, potassium, and phosphorus) instead of freshwater, and can be exploited as a biomass feedstock for energy generation. This practice eliminates the need to consume additional freshwater resources by the energy sector and provides an inter-sectoral opportunity between the energy and water sectors, whereby wastewater is exploited to produce a biofuel feedstock. Hence, pressures on natural resources (i.e. water and fossil-fuels) are alleviated and synergies (i.e. waste to resource) between the two sectors are availed [22].

The chemical conversion route also manifests some energy-water interlinkages through methanol synthesis. The conventional method for methanol production from fossil-fuels necessities large amounts of freshwater and dissipates a large volume of wastewater. To put things into perspective, for every ton of methanol produced from coal, approximately 20 m^3 of water is needed, in addition to the water required during coal extraction. This represents a main obstacle for fossil-fuel rich and water scarce regions in enlarging their methanol economy. Hence, methanol synthesis through the hydrogenation CCU process can be an important alternative to the fossil-fuel based methanol production, with the potential to achieve carbon-neutrality (Fig. 3) [98].

5.2. Energy-food nexus and CCU

The agricultural sector uses energy in two forms: directly for machinery, transportation, electricity for water pumping; and indirectly for energy dependent inputs such as fertilisers and pesticides. Moreover, energy is also used by the food sector during the distribution, storage, and retail of food commodities. The energy consumption by the food sector accounts for 30 % of the global energy use. This tight connection and dependency of the food sector on energy affects food security, whereby variations and disruptions in the energy sector are reflected on food systems (e.g. oil prices can affect food prices). The energy-food nexus encompasses another dimension; food for energy. The production of bioenergy from agricultural biomass sources is considered as a promising renewable energy source that can mitigate climate change, and as a diversification of the energy portfolio in response to the rising concerns on energy security [12].

The utilisation of CO_2 can also be regarded as a means to enhance resource security in a manner that reduces consumption of primary resources such as fossil fuels. The production of urea, an agricultural fertiliser with CO_2 utilisation from biomass based sources can reduce the energy requirements associated with this generation process and lower its dependency on fossil fuels [63]. Moreover, CO_2 utilisation in the process of polyols production (a chemical used in the food industry as a food additive) can reduce between 13–16 % of fossil fuel consumption relative to the conventional production process. In parallel, the reduction of fossil-fuel use in the polyol production process is directly reflected in its corresponding environmental impact, whereby 3 tons of CO_2 can be offset for every ton of polyol produced when utilising CO_2 instead of fossil fuels. Hence, CO_2 utilisation can be perceived as having a versatile advantage in mitigating climate change by: 1) sequestering the CO_2 that is put into use in the process; and 2) by lowering CO_2

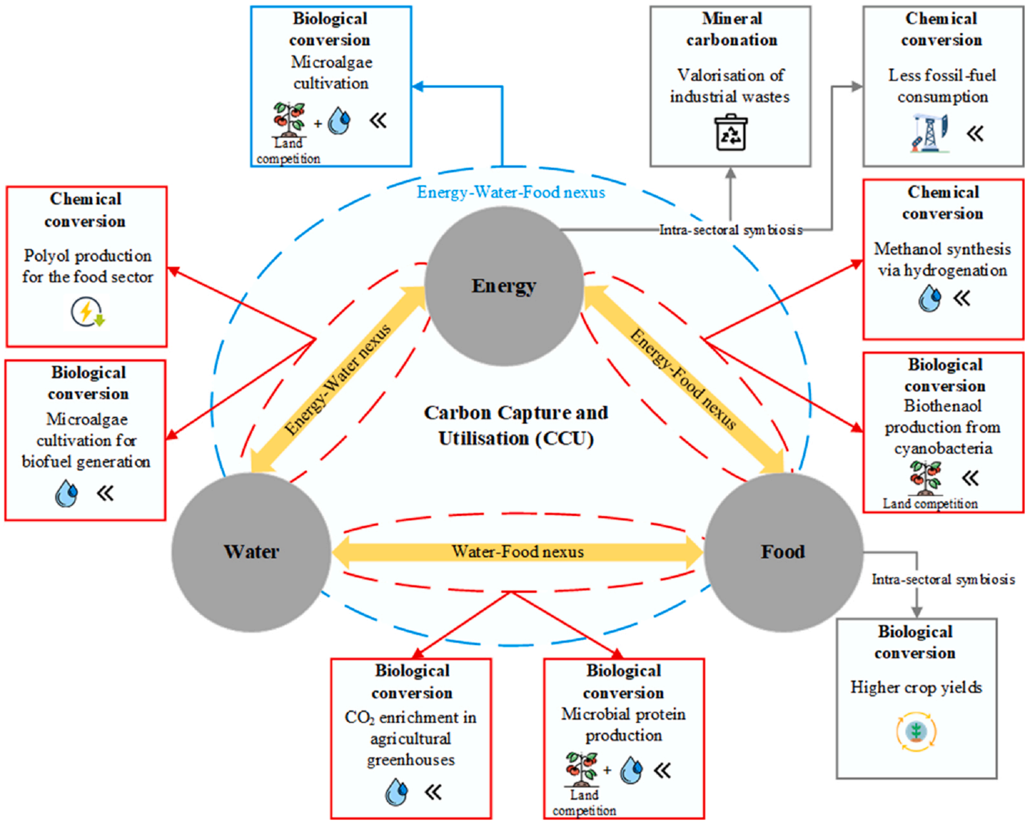

Fig. 3. CCU opportunities within EWF systems.

emissions through reducing the dependency on fossil-fuels [43].

Within the biological conversion route of CO_2, microalgae production displays further opportunities that curtails critical trade-offs between the energy and food sectors when considering crop cultivation for energy generation. The deployment of biomass-based energy systems is considered as a key technology for lowering GHG emissions in the energy sector. However, this poses serious concerns with regard to biomass production, which is contingent on the exploitation of arable lands. As a consequence, biomass production impels competition for land with the food sector and affects the food security [99]. Nonetheless, Microalgae production is not dependent on cultivable lands, and can be performed in offshore mediums, which presents an opportunity for the energy sector to produce sustainably and unchain its pressing ties with the food sector (Fig. 3) [69].

5.3. Water-Food nexus and CCU

Water consumption in the agricultural sector accounts for the largest share of water consumption, approximately 70 %, amongst other applications. With the projected increase in food demand estimated as 60 % by 2050, an increase in irrigation water consumed by the food sector is projected to be approximately 11 % [12]. In addition, animal raising is also a food system activity that requires large amounts of water resources. For example, the water footprint for beef farming is 10 L/kcal of nutritional value as compared to 0.5 L/kcal for cereals [15]. In this regard, specific CCU routes can provide alternative practices that can alleviate certain water-food nexus trade-offs and mitigate some of the future projected challenges that might emerge within the water and food sectors.

Considering the mounting pressures on food security driven by the growing population demand and improved nutritional lifestyles; the development of novel and alternative food sources are essential. Proteins are considered as a key component in the human and animal diet. However, the uneven distribution of land resources makes the availability of this vital macronutrient difficult, thus impacting food security. Moreover, the demand on proteins is escalating, whereby 110 % more protein sources need to be generated by 2050 compared to 2005, implying that more arable lands are required to cultivate more protein-based plants to sustain the population needs. Alternatively, microbial proteins (MPs) can be produced with a reduced dependency on arable lands and a lower environmental impact relative to other protein sources (Fig. 3). The production of MPs via CO_2 utilisation in bioreactors provide an interesting water-food symbiosis. This application has the potential to reduce water use related to the production of proteins, and lower the dependency on land use. According to a study conducted by Sillman et al. [21] of an integrated renewable-based bioreactor for the production of MPs, the water consumption of this later system was assessed as 0.82 L/kg of protein as compared to a water intake of 2.67–6.67 L/kg of protein for soybean cultivation. Moreover, the study explored the land use of this MP system, which was estimated at approximately 0.18−0.26 m^2/kg. year of protein produced in comparison with the 6.4-15.86 m^2/kg. year of land needed for soybean farming. Hence, CO_2 utilisation for the production of MPs provides co-sectoral benefits foreseen in both the food and water sectors, and offers an alternative means to protein cultivation and food availability independent on arable lands which can be implemented in any climate and region [21].

6. Decision-making directions when integrating CCU and the EWF nexus

The interdependent characteristics of EWF sectors require a consideration for the allocation and consumption of natural resources in the production of commodities. Effective waste management can alleviate some of the trade-offs within sectors and provide a certain degree of relief for natural resources. Hence, it is important to comprehensively assess the different pathways for waste utilisation, such as carbon capture and utilisation, and select the appropriate integrative indicators and methods that will enable an evidence informed decision-making. Decision-making is usually adopted from the perspective of one EWF sector, and considers the two other sectors as inputs or users of particular resources within that sector. For instance, from a food perspective, energy and water are considered as inputs. However, a holistic system approach is necessary to develop a comprehensive understanding of the various interlinkages within the EWF sectors, benefit from invaluable synergies, and avoid tensions within sectors; in order to support the evaluation and implementation of optimised strategies for CCU technologies within the nexus [100].

Carbon capture and utilisation networks entail multi-sectoral, multi-stakeholder, and multi-uncertainty dimensions, which make their evaluation and efficient deployment difficult to handle. It is thus necessary to adopt a dynamic decision-making approach that considers the inherent EWF interlinkages to meet the different trans-sectoral objectives, and reduce risks related to EWF resource consumption and CO_2 handling [27,101]. The main decision-making aspects considered in the planning of CCU applications are the maximisation of CO_2 utilisation technology benefits, and the minimisation of the environmental implications of the utilisation route under study. However, when integrating CCU networks within the EWF nexus, decision-making considers a further dimension that aims to maximise mutual benefits of the engaging EWF sectors and their stakeholders, minimising the trade-offs that may arise with non-optimal solutions, and mitigating any negative effects that may impact the EWF interlinkages within the CCU pathway under study [27,102]. By considering the EWF nexus and associated modelling and optimisation tools, multi-scale decision-making and policy development is made possible for CCU applications, whereby competing resources are avoided, and profitable configurations are realised within the EWF sectors. Moreover, the examination and integration of risks related to the economy, environment and society into holistic assessment models for CCU will enable proactive decision-making through which rapid recovery plans are possible in case of crises [102].

Optimisation models associated with CCU applications aim to study the techno-economic performance of one of the sub-systems or aspects of the network, such as studying the technical efficiency of the carbon capture and separation system via energy models, assessing CO_2 logistics and distribution networks, and evaluating source-sink matching pathways. Examining all these aspects at once will engender various complexities in the system and the optimisation model, which require large computing requirements [27]. Dynamic multi-scale approaches can alleviate these issues and capture and mitigate some of the important associated risks in the nexus of CCU applications. The analytical tools offered by the EWF nexus concept can offer multi-sectoral solutions for CCU applications, whereby integrative decision-making and policy development are deployed for the maximisation of synergies and reduction of trade-offs within EWF systems to achieve sustainable outcomes. The life cycle assessment (LCA) method enables through a modularisation approach the evaluation for each of the sub-systems within the CCU network, and aggregates them into an integrative assessment able to provide full environmental performance insights. Computational modelling (e.g. process systems engineering) can be applied to CCU applications, which tests strategies and technologies prior to their implementation through simulation and optimisation models, and can be applied to the process and decision-making levels [84]. Moreover, the mobilisation of other decision-making tools is necessary for CCU applications due to their complex and dynamic nature in the utilisation of resources. Such multi-sectoral and multi-stakeholder configurations require tools such as game theory, which considers the competitive objectives for different stakeholders participating in the CCU network. Agent based modelling can be adopted through which complex networks such as CCU can be modularised into a set of agents each having their specific objective to be optimised [101]. In addition, scenario-based methods are also beneficial in assessing the different and fluctuating variables in the systems, which can be coupled by numerical models such as optimisation [103]. These tools and numerical frameworks can aid decision-makers to maximise benefits from CO_2 capture and utilisation and minimise environmental burdens from industrial activities by carefully assessing CCU applications and selecting the optimal CCU pathway and its associated technologies and network configuration based on the inherent EWF interlinkages.

7. Conclusion

The diverse possibilities for CO_2 sinks and sources and the complex nature of the interlinkages that exist within the EWF sectors compels several uncertainties for CCU applications. Carbon capture and utilisation pathways encompass various system nodes into an integrated arrangement, CO_2 sources, carbon capture and separation methods, and CO_2 sinks, all with intertwined dependencies and impacts on EWF systems and resources. Hence, this review demonstrates its importance by exploring the main CCU pathways and their intrinsic intra-sectoral and inter-sectoral opportunities within EWF systems. In this study, an overview over the major system components of CCUs is conducted, with an emphasis on the utilisation applications, their global status, recent advancements, CO_2 sequestration potential, and their EWF resource consumption. Moreover, important tools and methods are proposed for a dynamic and multi-scale decision-making for the integration of CCU applications with the EWF nexus. Findings from this review demonstrate that CCU pathways can provide substantial opportunities that extend beyond their sector of application and into trans-sectoral synergies within EWF systems. However, more studies need to be conducted to quantitatively explore the trade-offs and synergies within EWF sectors for CCU applications and assess their true impact on EWF resources and GHG emissions and support evidence informed decision-making.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgement

This research is supported by the Qatar National Research Fund proposal (NPRP11S-0107-180216). Open Access funding provided by the Qatar National Library.

References

[1] IPCC, Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007.
[2] IPCC, Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 2014.
[3] K. Calvin, J. Edmonds, B. Bond-lamberty, L. Clarke, S.H. Kim, P. Kyle, S.J. Smith, A. Thomson, M. Wise, 2.6 : limiting climate change to 450 ppm CO2 equivalent in the 21st century, Energy Econ. 31 (2009) S107–S120, https://doi.org/10.1016/j.eneco.2009.06.006.
[4] UNFCCC, What Is the Paris Agreement? (n.d.), 2021, https://unfccc.int/process-and-meetings/the-paris-agreement/what-is-the-paris-agreement.
[5] F. Nocito, A. Dibenedetto, Atmospheric CO2 mitigation technologies: carbon capture utilization and storage, Curr. Opin. Green Sustain. Chem. 21 (2020) 34–43, https://doi.org/10.1016/j.cogsc.2019.10.002.
[6] Z. Zhang, S.-Y. Pan, H. Li, J. Cai, A.G. Olabi, E.J. Anthony, V. Manovic, Recent advances in carbon dioxide utilization, Renew. Sustain. Energy Rev. 125 (2020), 109799, https://doi.org/10.1016/j.rser.2020.109799.
[7] R.M. Cuéllar-Franca, A. Azapagic, Carbon capture, storage and utilisation technologies: a critical analysis and comparison of their life cycle environmental impacts, J. CO2 Util. 9 (2015) 82–102, https://doi.org/10.1016/j.jcou.2014.12.001.
[8] IEA, Putting CO2 to Use, IEA, 2019 iea.org.
[9] M. Pérez-Fortes, J.C. Schöneberger, A. Boulamanti, E. Tzimas, Methanol synthesis using captured CO2 as raw material: techno-economic and environmental assessment, Appl. Energy 161 (2016) 718–732, https://doi.org/10.1016/j.apenergy.2015.07.067.
[10] IEA, The Covid-19 Crisis and Clean Energy Progress, Paris, France, 2020.
[11] UNESCO, Managing Water Under Uncertainty and Risk, Paris, 2012.
[12] IRENA, Renewable Energy in the Water, Energy, and Food Nexus, 2015.

[13] D. Silk, I. Sachs, Food and Energy: Strategies for Sustainable Development, United Nations University Press, 1990.

[14] R. Martin-Nagle, E. Howard, A. Wiltse, D. Duncan, The water, energy and food security nexus - solutions for the green economy. conference synopsis. Federal Ministry for the Environment Nature Conservation and Nuclear Safety, 2012, p. 28.

[15] M. Mannan, T. Al-Ansari, H.R. Mackey, S.G. Al-Ghamdi, Quantifying the energy, water and food nexus: a review of the latest developments based on life-cycle assessment, J. Clean. Prod. 193 (2018) 300–314, https://doi.org/10.1016/j.jclepro.2018.05.050.

[16] P. Batlle-Vilanova, L. Rovira-Alsina, S. Puig, M.D. Balaguer, P. Icaran, V. M. Monsalvo, F. Rogalla, J. Colprim, Biogas upgrading, CO2 valorisation and economic revaluation of bioelectrochemical systems through anodic chlorine production in the framework of wastewater treatment plants, Sci. Total Environ. 690 (2019) 352–360, https://doi.org/10.1016/j.scitotenv.2019.06.361.

[17] W. Wu, K.-H. Lin, J.-S. Chang, Economic and life-cycle greenhouse gas optimization of microalgae-to-biofuels chains, Bioresour. Technol. 267 (2018) 550–559, https://doi.org/10.1016/j.biortech.2018.07.083.

[18] A. Di Maria, R. Snellings, L. Alaerts, M. Quaghebeur, K. Van Acker, Environmental assessment of CO2 mineralisation for sustainable construction materials, Int. J. Greenh. Gas Control. 93 (2020), 102882, https://doi.org/10.1016/j.ijggc.2019.102882.

[19] A. Rafiee, K. Rajab Khalilpour, D. Milani, M. Panahi, Trends in CO2 conversion and utilization: a review from process systems perspective, J. Environ. Chem. Eng. 6 (2018) 5771–5794, https://doi.org/10.1016/j.jece.2018.08.065.

[20] Q. Li, Y.-N. Wei, Z.-A. Chen, Water-CCUS nexus: challenges and opportunities of China's coal chemical industry, Clean Technol. Environ. Policy 18 (2016) 775–786, https://doi.org/10.1007/s10098-015-1049-z.

[21] J. Sillman, L. Nygren, H. Kahiluoto, V. Ruuskanen, A. Tamminen, C. Bajamundi, M. Nappa, M. Wuokko, T. Lindh, P. Vainikka, J.-P. Pitkänen, J. Ahola, Bacterial protein for food and feed generated via renewable energy and direct air capture of CO2: Can it reduce land and water use? Glob. Food Sec. 22 (2019) 25–32, https://doi.org/10.1016/j.gfs.2019.09.007.

[22] F.D. Meylan, V. Moreau, S. Erkman, CO2 utilization in the perspective of industrial ecology, an overview, J. CO2 Util. 12 (2015) 101–108, https://doi.org/10.1016/j.jcou.2015.05.003.

[23] A. Al-Mamoori, A. Krishnamurthy, A.A. Rownaghi, F. Rezaei, Carbon capture and utilization update, Energy Technol. 5 (2017) 834–849, https://doi.org/10.1002/ente.201600747.

[24] E. Alper, O. Yuksel Orhan, CO2 utilization: developments in conversion processes, Petroleum 3 (2017) 109–126, https://doi.org/10.1016/j.petlm.2016.11.003.

[25] E.I. Koytsoumpa, C. Bergins, E. Kakaras, The CO2 economy: review of CO2 capture and reuse technologies, J. Supercrit. Fluids 132 (2018) 3–16, https://doi.org/10.1016/j.supflu.2017.07.029.

[26] R.S. Norhasyima, T.M.I. Mahlia, Advances in CO_2 utilization technology: a patent landscape review, J. CO2 Util. 26 (2018) 323–335, https://doi.org/10.1016/j.jcou.2018.05.022.

[27] J.F.D. Tapia, J.-Y. Lee, R.E.H. Ooi, D.C.Y. Foo, R.R. Tan, A review of optimization and decision-making models for the planning of CO2 capture, utilizationandstorage(CCUS)systems, Sustain. Prod. Consum. 13 (2018) 1–15, https://doi.org/10.1016/j.spc.2017.10.001.

[28] A. Dindi, D.V. Quang, L.F. Vega, E. Nashef, M.R.M. Abu-Zahra, Applications of fly ash for CO2 capture, utilization, and storage, J. CO2 Util. 29 (2019) 82–102, https://doi.org/10.1016/j.jcou.2018.11.011.

[29] H. Mikulčić, I. Ridjan Skov, D.F. Dominković, S.R. Wan Alwi, Z.A. Manan, R. Tan, N. Duić, S.N. Hidayah Mohamad, X. Wang, Flexible Carbon Capture and Utilization technologies in future energy systems and the utilization pathways of captured CO2, Renew. Sustain. Energy Rev. 114 (2019), 109338, https://doi.org/10.1016/j.rser.2019.109338.

[30] A. Gulzar, A. Gulzar, M.B. Ansari, F. He, S. Gai, P. Yang, Carbon dioxide utilization: a paradigm shift with CO2 economy, Chem. Eng. J. Adv. (2020), 100013, https://doi.org/10.1016/j.ceja.2020.100013.

[31] H. Wang, Y. Liu, A. Laaksonen, A. Krook-Riekkola, Z. Yang, X. Lu, X. Ji, Carbon recycling – an immense resource and key to a smart climate engineering: a survey of technologies, cost and impurity impact, Renew. Sustain. Energy Rev. 131 (2020), 110010, https://doi.org/10.1016/j.rser.2020.110010.

[32] IEA, Global Energy and CO2 Status Report: the Latest Trends and Emissions in 2018, 2019 iea.org.

[33] C. Le Quéré, R.M. Andrew, P. Friedlingstein, S. Sitch, J. Pongratz, A.C. Manning, J.I. Korsbakken, G.P. Peters, J.G. Canadell, R.B. Jackson, T.A. Boden, P.P. Tans, O.D. Andrews, V.K. Arora, D.C.E. Bakker, L. Barbero, M. Becker, R.A. Betts, L. Bopp, F. Chevallier, L.P. Chini, P. Ciais, C.E. Cosca, J. Cross, K. Currie, T. Gasser, I. Harris, J. Hauck, V. Haverd, R.A. Houghton, C.W. Hunt, G. Hurtt, T. Ilyina, A.K. Jain, E. Kato, M. Kautz, R.F. Keeling, K. Klein Goldewijk, A. Körtzinger, P. Landschützer, N. Lefèvre, A. Lenton, S. Lienert, I. Lima, D. Lombardozzi, N. Metzl, F. Millero, P.M.S. Monteiro, D.R. Munro, J.E.M. S. Nabel, S. Nakaoka, Y. Nojiri, X.A. Padin, A. Peregon, B. Pfeil, D. Pierrot, B. Poulter, G. Rehder, J. Reimer, C. Rödenbeck, J. Schwinger, R. Séférian, I. Skjelvan, B.D. Stocker, H. Tian, B. Tilbrook, F.N. Tubiello, I.T. van der Laan-Luijkx, G.R. van der Werf, S. van Heuven, N. Viovy, N. Vuichard, A.P. Walker, A. J. Watson, A.J. Wiltshire, S. Zaehle, D. Zhu, Global carbon budget 2017, Earth Syst. Sci. Data 10 (2018) 405–448, https://doi.org/10.5194/essd-10-405-2018.

[34] IPCC, The carbon cycle and atmospheric carbon dioxide. Climate Change 2001: the Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change, 2002.

[35] J.E. Bauer, W.-J. Cai, P.A. Raymond, T.S. Bianchi, C.S. Hopkinson, P.A. G. Regnier, The changing carbon cycle of the coastal ocean, Nature 504 (2013) 61–70, https://doi.org/10.1038/nature12857.

[36] R. Chauvy, N. Meunier, D. Thomas, G. De Weireld, Selecting emerging CO2 utilization products for short-to mid-term deployment, Appl. Energy 236 (2019) 662–680, https://doi.org/10.1016/j.apenergy.2018.11.096.

[37] IPCC, Sources of CO2. IPCC Special Report on Carbon Dioxide Capture and Storage, 2005.

[38] D.Y.C. Leung, G. Caramanna, M.M. Maroto-Valer, An overview of current status of carbon dioxide capture and storage technologies, Renew. Sustain. Energy Rev. 39 (2014) 426–443, https://doi.org/10.1016/j.rser.2014.07.093.

[39] A. Gambhir, M. Tavoni, Direct air carbon capture and sequestration: how it works and how it could contribute to climate-change mitigation, One Earth. 1 (2019) 405–409, https://doi.org/10.1016/j.oneear.2019.11.006.

[40] Y. Huang, S. Rebennack, Q.P. Zheng, Techno-economic analysis and optimization models for carbon capture and storage: a survey, Energy Syst. 4 (2013) 315–353, https://doi.org/10.1007/s12667-013-0086-0.

[41] D.C.Y. Foo, R.R. Tan, A review on process integration techniques for carbon emissions and environmental footprint problems, Process Saf. Environ. Prot. 103 (2016) 291–307, https://doi.org/10.1016/j.psep.2015.11.007.

[42] J. Patricio, A. Angelis-Dimakis, A. Castillo-Castillo, Y. Kalmykova, L. Rosado, Method to identify opportunities for CCU at regional level—Matching sources and receivers, J. CO2 Util. 22 (2017) 330–345, https://doi.org/10.1016/j.jcou.2017.10.009.

[43] T. Bruhn, H. Naims, B. Olfe-Kräutlein, Separating the debate on CO2 utilisation from carbon capture and storage, Environ. Sci. Policy 60 (2016) 38–43, https://doi.org/10.1016/j.envsci.2016.03.001.

[44] R. Aldaco, I. Butnar, M. Margallo, J. Laso, M. Rumayor, A. Dominguez-Ramos, A. Irabien, P.E. Dodds, Bringing value to the chemical industry from capture, storage and use of CO2: a dynamic LCA of formic acid production, Sci. Total Environ. 663 (2019) 738–753, https://doi.org/10.1016/j.scitotenv.2019.01.395.

[45] Global CCS Institute, The Global Status of CCS: 2019, Australia, 2019, https://doi.org/10.1007/springerreference_15392.

[46] US Department of Energy, U.S. Department of Energy Announces $110M for Carbon Capture, Utilization, and Storage, 2019.

[47] W. Schakel, C. Fernández-Dacosta, M. van der Spek, A. Ramírez, New indicator for comparing the energy performance of CO2 utilization concepts, J. CO2 Util. 22 (2017) 278–288, https://doi.org/10.1016/j.jcou.2017.10.001.

[48] European Commission, Innovation Fund, Eur. Comm. (n.d.). ec.europa.eu.

[49] Global CCS Institute, The US Section 45Q Tax Credit for Carbon Oxide Sequestration: An Update, 2020.

[50] A. Raza, R. Gholami, R. Rezaee, V. Rasouli, M. Rabiei, Significant aspects of carbon capture and storage – a review, Petroleum 5 (2019) 335–340, https://doi.org/10.1016/j.petlm.2018.12.007.

[51] M. Aghaie, N. Rezaei, S. Zendehboudi, A systematic review on CO 2 capture with ionic liquids: current status and future prospects, Renew. Sustain. Energy Rev. 96 (2018) 502–525, https://doi.org/10.1016/j.rser.2018.07.004.

[52] A.A. Olajire, CO2 capture and separation technologies for end-of-pipe applications - A review, Energy 35 (2010) 2610–2628, https://doi.org/10.1016/j.energy.2010.02.030.

[53] M.N. Anwar, A. Fayyaz, N.F. Sohail, M.F. Khokhar, M. Baqar, W.D. Khan, K. Rasool, M. Rehan, A.S. Nizami, CO2 capture and storage: a way forward for sustainable environment, J. Environ. Manage. 226 (2018) 131–144, https://doi.org/10.1016/j.jenvman.2018.08.009.

[54] R. Ben-Mansour, M.A. Habib, O.E. Bamidele, M. Basha, N.A.A. Qasem, A. Peedikakkal, T. Laoui, M. Ali, Carbon capture by physical adsorption: materials, experimental investigations and numerical modeling and simulations - A review, Appl. Energy 161 (2016) 225–255, https://doi.org/10.1016/j.apenergy.2015.10.011.

[55] I. Ghiat, A. AlNouss, G. McKay, T. Al-Ansari, Modelling and simulation of a biomass-based integrated gasification combined cycle with carbon capture: comparison between monoethanolamine and potassium carbonate, IOP Conf. Ser. Earth Environ. Sci. 463 (2020), https://doi.org/10.1088/1755-1315/463/1/012019.

[56] I. Ghiat, A. AlNouss, G. McKay, T. Al-Ansari, Biomass-based integrated gasification combined cycle with post-combustion CO2 recovery by potassium carbonate: techno-economic and environmental analysis, Comput. Chem. Eng. (2020), https://doi.org/10.1016/j.compchemeng.2020.106758.

[57] C. Song, Q. Liu, S. Deng, H. Li, Y. Kitamura, Cryogenic-based CO2 capture technologies: state-of-the-art developments and current challenges, Renew. Sustain. Energy Rev. 101 (2019) 265–278, https://doi.org/10.1016/j.rser.2018.11.018.

[58] P. Babu, P. Linga, R. Kumar, P. Englezos, A review of the hydrate based gas separation (HBGS) process forcarbon dioxide pre-combustion capture, Energy 85 (2015) 261–279, https://doi.org/10.1016/j.energy.2015.03.103.

[59] A.A. Al-Yaeeshi, R. Govindan, T. Al-Ansari, Techno-economic-based dynamic network design for optimum large-scale carbon dioxide utilisation in process industries, J. Clean. Prod. 275 (2020), 122974, https://doi.org/10.1016/j.jclepro.2020.122974.

[60] A.A. Al-Yaeeshi, A. AlNouss, G. McKay, T. Al-Ansari, A simulation study on the effect of CO2 injection on the performance of the GTL process, Comput. Chem. Eng. 136 (2020), 106768, https://doi.org/10.1016/j.compchemeng.2020.106768.

[61] S.G. Jadhav, P.D. Vaidya, B.M. Bhanage, J.B. Joshi, Catalytic carbon dioxide hydrogenation to methanol: a review of recent studies, Chem. Eng. Res. Des. 92 (2014) 2557–2567, https://doi.org/10.1016/j.cherd.2014.03.005.

[62] O.Y. Abdelaziz, W.M. Hosny, M.A. Gadalla, F.H. Ashour, I.A. Ashour, C. P. Hulteberg, Novel process technologies for conversion of carbon dioxide from industrial flue gas streams into methanol, J. CO2 Util. 21 (2017) 52–63, https://doi.org/10.1016/j.jcou.2017.06.018.
[63] A. AlNouss, G. McKay, T. Al-Ansari, A techno-economic-environmental study evaluating the potential of oxygen-steam biomass gasification for the generation of value-added products, Energy Convers. Manage. 196 (2019) 664–676, https://doi.org/10.1016/j.enconman.2019.06.019.
[64] G.A. Olah, Towards oil independence through renewable methanol chemistry, Angew. Chemie Int. Ed. 52 (2013) 104–107, https://doi.org/10.1002/anie.201204995.
[65] L. Proaño, A.T. Sarmiento, M. Figueredo, M. Cobo, Techno-economic evaluation of indirect carbonation for CO2 emissions capture in cement industry: a system dynamics approach, J. Clean. Prod. 263 (2020), 121457, https://doi.org/10.1016/j.jclepro.2020.121457.
[66] S. Bachu, CO2 storage in geological media: role, means, status and barriers to deployment, Prog. Energy Combust. Sci. 34 (2008) 254–273, https://doi.org/10.1016/j.pecs.2007.10.001.
[67] IEA, Can CO2-EOR Really Provide Carbon-Negative Oil? IEA, 2019.
[68] A. Majumdar, J. Deutch, Research Opportunities for CO2 Utilization and Negative Emissions at the Gigatonne Scale, Joule, 2018. https://linkinghub.elsevier.com/retrieve/pii/S2542435118301776.
[69] N. Seyed Hosseini, H. Shang, J.A. Scott, Optimization of microalgae-sourced lipids production for biodiesel in a top-lit gas-lift bioreactor using response surface methodology, Energy 146 (2018) 47–56, https://doi.org/10.1016/j.energy.2017.08.085.
[70] S.K. Bhatia, R.K. Bhatia, J.-M. Jeon, G. Kumar, Y.-H. Yang, Carbon dioxide capture and bioenergy production using biological system – a review, Renew. Sustain. Energy Rev. 110 (2019) 143–158, https://doi.org/10.1016/j.rser.2019.04.070.
[71] M. Atta, A. Idris, A. Bukhari, S. Wahidin, Intensity of blue LED light: a potential stimulus for biomass and lipid content in fresh water microalgae Chlorella vulgaris, Bioresour. Technol. 148 (2013) 373–378, https://doi.org/10.1016/j.biortech.2013.08.162.
[72] Y. Wang, B. He, Z. Sun, Y.-F. Chen, Chemically enhanced lipid production from microalgae under low sub-optimal temperature, Algal Res. 16 (2016) 20–27, https://doi.org/10.1016/j.algal.2016.02.022.
[73] Y.I. Mandik, B. Cheirsilp, S. Srinuanpan, W. Maneechote, P. Boonsawang, P. Prasertsan, S. Sirisansaneeyakul, Zero-waste biorefinery of oleaginous microalgae as promising sources of biofuels and biochemicals through direct transesterification and acid hydrolysis, Process Biochem. 95 (2020) 214–222, https://doi.org/10.1016/j.procbio.2020.02.011.
[74] F.A. Rahman, M.M.A. Aziz, R. Saidur, W.A.W.A. Bakar, M.R. Hainin, R. Putrajaya, N.A. Hassan, Pollution to solution: capture and sequestration of carbon dioxide (CO2) and its utilization as a renewable energy source for a sustainable future, Renew. Sustain. Energy Rev. 71 (2017) 112–126, https://doi.org/10.1016/j.rser.2017.01.011.
[75] I. Ghiat, R. Govindan, S. Namany, T. Al-Ansari, network optimization model for a sustainable supply network for greenhouses. Comput. Aided Chem. Eng., 2020, pp. 1885–1890, https://doi.org/10.1016/B978-0-12-823377-1.50315-3.
[76] I. Ghiat, F. Mahmood, R. Govindan, T. Al-ansari, CO2 utilisation in agricultural greenhouses: a novel 'plant to plant' approach driven by bioenergy with carbon capture systems within the energy, water and food nexus, Energy Convers. Manage. 228 (2021), 113668, https://doi.org/10.1016/j.enconman.2020.113668.
[77] B.A. Kimball, S.T. Mitchell, Tomato yields from CO2-enrichment in unventilated and conventionally ventilated greenhouses, J. Am. Soc. Hortic. Sci. 104 (1979) 515–520.
[78] A. Islam, L.R. Ahuja, L.A. Garcia, A.S. Saseendran, Modeling the effect of elevated CO2 and climate change on reference evapotranspiration in the Semi-Arid Central Great Plains, Am. Soc. Agric. Biol. Eng. 55 (2012) 2135–2146.
[79] M.C. Sánchez-Guerrero, P. Lorenzo, E. Medrano, A. Baille, N. Castilla, Effects of EC-based irrigation scheduling and CO2 enrichment on water use efficiency of a greenhouse cucumber crop, Agric. Water Manag. 96 (2008) 429–436, https://doi.org/10.1016/j.agwat.2008.09.001.
[80] L.H. Allen, Plant responses to rising carbon dioxide and potential interactions with air pollutants, J. Environ. Qual. 19 (1990) 15–34, https://doi.org/10.2134/jeq1990.00472425001900010002x.
[81] L.M. Dion, M. Lefsrud, V. Orsat, Review of CO2 recovery methods from the exhaust gas of biomass heating systems for safe enrichment in greenhouses, Biomass Bioenergy 35 (2011) 3422–3432, https://doi.org/10.1016/j.biombioe.2011.06.013.
[82] S.C. Yelishala, K. Kannaiyan, R. Sadr, Z. Wang, Y.A. Levendis, H. Metghalchi, Performance maximization by temperature glide matching in energy exchangers of cooling systems operating with natural Hydrocarbon/CO2 refrigerants, Int. J. Refrig. (2020), https://doi.org/10.1016/j.ijrefrig.2020.08.006.
[83] H. Hoff, in: Understanding the Nexus. Background Paper for the Bonn 2011 Conference: The Water, Energy and Food Security Nexus, Stockholm Environment Institute, Stockholm, 2011.
[84] T.R. Albrecht, A. Crootof, C.A. Scott, The Water-Energy-Food Nexus: a systematic review of methods for nexus assessment, Environ. Res. Lett. 13 (2018), 043002, https://doi.org/10.1088/1748-9326/aaa9c6.
[85] M. Howells, S. Hermann, M. Welsch, M. Bazilian, R. Segerström, T. Alfstad, D. Gielen, H. Rogner, G. Fischer, H. van Velthuizen, D. Wiberg, C. Young, R. A. Roehrl, A. Mueller, P. Steduto, I. Ramma, Integrated analysis of climate change, land-use, energy and water strategies, Nat. Clim. Chang. 3 (2013) 621–626, https://doi.org/10.1038/nclimate1789.
[86] T. Al-Ansari, A. Korre, Z. Nie, N. Shah, Development of a life cycle assessment tool for the assessment of food production systems within the energy, water and food nexus, Sustain. Prod. Consum. 2 (2015) 52–66, https://doi.org/10.1016/j.spc.2015.07.005.
[87] T. Al-Ansari, A. Korre, Z. Nie, N. Shah, Integration of greenhouse gas control technologies within the energy, water and food nexus to enhance the environmental performance of food production systems, J. Clean. Prod. 162 (2017) 1592–1606, https://doi.org/10.1016/j.jclepro.2017.06.097.
[88] S. Namany, R. Govindan, L. Alfagih, G. McKay, T. Al-Ansari, Sustainable food security decision-making: an agent-based modelling approach, J. Clean. Prod. 255 (2020), https://doi.org/10.1016/j.jclepro.2020.120296.
[89] A. Alnouss, S. Namany, G. Mckay, T. Al-ansari, Applying a Sustainability Metric in Energy, Water and Food Nexus Applications: A Biomass Utilization Case Study to Improve Investment Decisions, Elsevier Masson SAS, 2019, https://doi.org/10.1016/B978-0-12-818634-3.50035-7.
[90] F. Lahlou, H.R. Mackey, G. McKay, U. Onwusogh, T. Al-Ansari, Water planning framework for alfalfa fields using treated wastewater fertigation in Qatar: an energy-water-food nexus approach, Comput. Chem. Eng. 141 (2020), 106999, https://doi.org/10.1016/j.compchemeng.2020.106999.
[91] M. Alherbawi, A. Alnouss, G. Mckay, T. Al-ansari, Optimum sustainable utilisation of the whole fruit of Jatropha curcas: an energy, water and food nexus approach, Renew. Sustain. Energy Rev. 137 (2021), 110605, https://doi.org/10.1016/j.rser.2020.110605.
[92] V. De Laurentiis, D. Hunt, C. Rogers, Overcoming food security challenges within an Energy/Water/Food Nexus (EWFN) approach, Sustainability 8 (2016) 95, https://doi.org/10.3390/su8010095.
[93] J. Cottee, A. López-Avilés, K. Behzadian, D. Bradley, D. Butler, C. Downing, R. Farmani, J. Ingram, M. Leach, A. Pike, L. De Propris, L. Purvis, P. Robinson, A. Yang, The local nexus network: exploring the future of localised food systems and associated energy and water supply. Sustain. Des. Manuf. 2016, Springer, 2016, pp. 613–624, https://doi.org/10.1007/978-3-319-32098-4_52.
[94] N.A. Al-Thani, R. Govindan, T. Al-Ansari, Maximising nutritional benefits within the energy, water and food nexus, J. Clean. Prod. 266 (2020), 121877, https://doi.org/10.1016/j.jclepro.2020.121877.
[95] M. Haji, R. Govindan, T. Al-Ansari, Novel approaches for geospatial risk analytics in the energy–water–food nexus using an EWF nexus node, Comput. Chem. Eng. 140 (2020), 106936, https://doi.org/10.1016/j.compchemeng.2020.106936.
[96] Y. Saif, A. Almansoori, I. Bilici, A. Elkamel, Sustainable management and design of the energy-water-food nexus using a mathematical programming approach, Can. J. Chem. Eng. 98 (2020) 2056–2078, https://doi.org/10.1002/cjce.23825.
[97] A. Owen, K. Scott, J. Barrett, Identifying critical supply chains and final products: an input-output approach to exploring the energy-water-food nexus, Appl. Energy 210 (2018) 632–642, https://doi.org/10.1016/j.apenergy.2017.09.069.
[98] C.-J. Yang, R.B. Jackson, China's growing methanol economy and its implications for energy and the environment, Energy Policy 41 (2012) 878–884, https://doi.org/10.1016/j.enpol.2011.11.037.
[99] IPCC, Food security. Climate Change and Land: an IPCC Special Report on Climate Change, Desertification, Land Degradation, Sustainable Land Management, Food Security, and Greenhouse Gas Fluxes in Terrestrial Ecosystems, 2019.
[100] M. Bazilian, H. Rogner, M. Howells, S. Hermann, D. Arent, D. Gielen, P. Steduto, A. Mueller, P. Komor, R.S.J. Tol, K.K. Yumkella, Considering the energy, water and food nexus: towards an integrated modelling approach, Energy Policy 39 (2011) 7896–7906, https://doi.org/10.1016/j.enpol.2011.09.039.
[101] S. Namany, T. Al-Ansari, R. Govindan, Sustainable energy, water and food nexus systems: a focused review of decision-making tools for efficient resource management and governance, J. Clean. Prod. 225 (2019) 610–626, https://doi.org/10.1016/j.jclepro.2019.03.304.
[102] R. Govindan, T. Al-Ansari, Computational decision framework for enhancing resilience of the energy, water and food nexus in risky environments, Renew. Sustain. Energy Rev. 112 (2019) 653–668, https://doi.org/10.1016/j.rser.2019.06.015.
[103] N. Bieber, J.H. Ker, X. Wang, C. Triantafyllidis, K.H. van Dam, R.H.E. M. Koppelaar, N. Shah, Sustainable planning of the energy-water-food nexus using decision making tools, Energy Policy 113 (2018) 584–607, https://doi.org/10.1016/j.enpol.2017.11.037.