# Heat and Mass Transfer in the Food, Energy, and Water Nexus — A Review

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**Abstract**

Engineering innovations – including those in heat and mass transfer – are needed to provide food, water, and power to a growing population (i.e., projected to be 9.8 billion by 2050) with limited resources. The interweaving of these resources is embodied in the food, energy, and water nexus. This review paper focuses on heat and mass transfer applications which involve at least two aspects of the food, energy, and water nexus. Energy and water topics include energy extraction of natural gas hydrates and shale gas; power production (e.g., nuclear and solar); power plant cooling (e.g., wet, dry, and hybrid cooling); water desalination and purification; and building energy/water use, including heating, ventilation, air conditioning, and refrigeration technology. Subsequently, this review considers agricultural thermal fluids applications, such as the food and water nexus (e.g., evapotranspiration and evaporation) and the food, energy, and water nexus (e.g., greenhouses and food storage, including granaries and freezing/drying). As part of this review, over 100 review papers on thermal and fluid topics relevant to the food, energy, and water nexus were tabulated and over 350 research journal articles were discussed. Each section discusses previous research and highlights future opportunities regarding heat and mass transfer research. Several cross-cutting themes emerged from the literature and represent future directions for thermal fluids research: the need for fundamental, thermal fluids knowledge; scaling up from the laboratory to large-scale, integrated systems; increasing economic viability; and increasing efficiency when utilizing resources, especially using waste products.

**Keywords:** thermal fluids, agriculture, sustainability, energy-water, FEW nexus

# 1. Introduction

## 1.1. The global food, energy, and water problem

The food, energy, and water (FEW) nexus embodies the concept that resources are limited and intertwined, as well as incorporating several of the National Academy of Engineering's Grand Challenges for the 21$^{st}$ century (i.e., provide access to clean water and manage the nitrogen cycle [1]). Food production is resource intensive, from the fertilizer stage (e.g., U.S. fertilizer production=0.5% of U.S. energy [2]), to transportation, storage, and consumption (e.g., globally, 1.3 billion tons/year – 33% – of food produced for human consumption is lost or wasted [3]). Additionally, agriculture is responsible for over 2/3 of global water withdrawals [4].

Efficient food, energy, and water production are required to feed a growing population – projected to reach 9.8 billion in 2050 [5] – with limited resources. According to projections by the Food and Agriculture Organization of the United Nations [6], the amount of global arable land is projected to remain nearly constant despite a growing population (i.e., 1,592 million hectares in 2005/7 to a projected 1,661 million hectares in 2050), with declines expected in developed countries to be offset by increases in arable land in developing countries. Limited water resources can have strong local or regional impacts, from the 2017 water crisis in Cape Town, South Africa due to limited rainfall, reduced surface water availability, and increased consumption [7], to the overwithdrawal of the Ogallala Aquifer in the U.S. Central High plains [8, 9], in which aquifer declines of over 45 m were reported due to irrigation [10].

Excellent review papers by D'Odorico et al. [11] and Finley and Seiber [12] analyzed the FEW nexus as a whole. The research objectives of this paper are to identify areas in the FEW nexus where heat and mass transfer play an important role, summarize existing literature, and discuss possible directions and opportunities for future heat and mass transfer research in the FEW nexus. The emphasis of this work is on two or more areas of the nexus (e.g., energy and water;

food and energy; food and water; food, energy, and water), as shown in Figure 1. This paper is very broad in scope; the intention of the broad scope is to provoke new ideas and interest across areas of the FEW nexus.

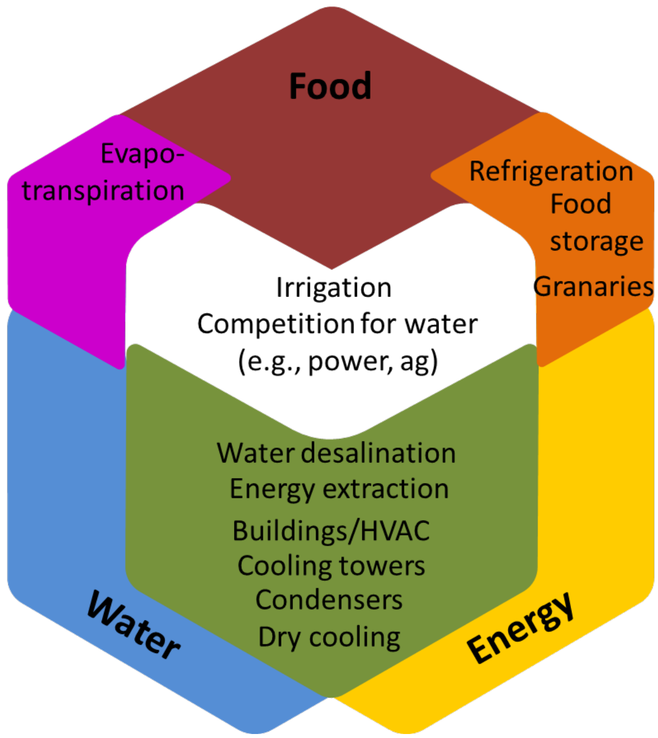


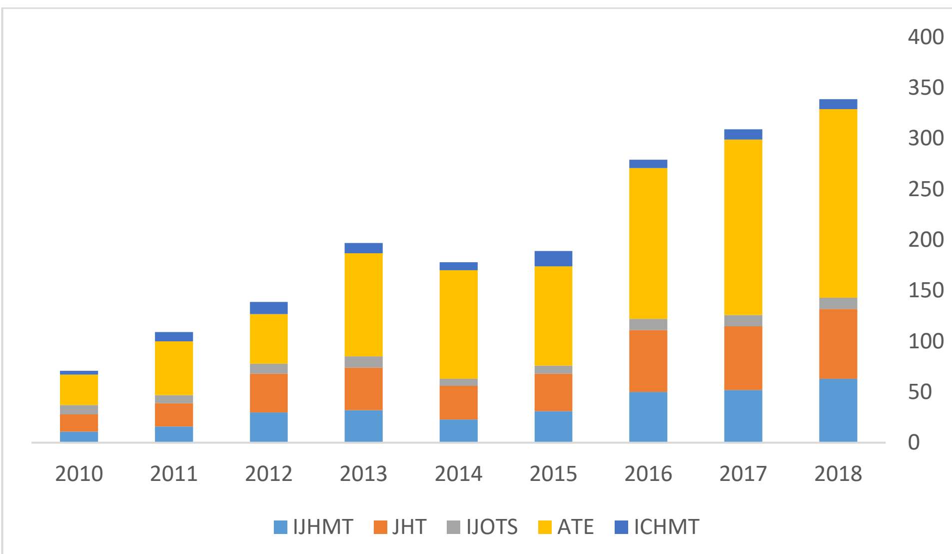

**Figure 1 Examples of heat and mass transfer in the food-water, water-energy, food-energy, and food-energy-water nexuses**

### 1.2. Keyword search in heat and mass transfer journals

Similar to the approach taken by Taylor et al. [13], a keyword/title/abstract search was conducted in Scopus for the years 2010-2018 to show food, energy, and water research trends. Sets of keywords were searched in five heat and mass transfer journals. Keywords included " 'Energy' AND 'Water' " (Figure 2a) as well as " 'Food' OR 'Agriculture' " (Figure 2b). Collectively, Energy-Water papers rose from 71 in 2010 to 339 in 2018, demonstrating the importance of thermal fluids to this area; much of this research pertains to more water-efficient power production, a traditional heat transfer topic. Merging energy and water research (i.e., the energy-water) nexus represents an emerging thermal fluids research area. Searching only "Energy" and the selected five heat transfer journals in 2010-2018 yielded significantly more results [i.e., 1627 (IJHMT), 351 (JHT), 481 (IJOTS), 3599 (ATE), and 307 (ICHMT)]. Searching only “Water” and the five heat transfer journals in 2010-2018 yielded a similarly large number of papers [i.e., 2029 (IJHMT), 328 (JHT), 497 (IJOTS), 2390 (ATE), and 530 (ICHMT)].

Food- or agriculture-related papers published in heat transfer journals averaged approximately 18 papers per year. The largest number of food-related papers appeared in Applied Thermal Engineering, and primarily focused on heat and mass transfer models for food drying and preservation as well as biogas applications. There are many agricultural applications that would benefit from additional heat and mass transfer, and are highlighted in this review; since the FEW nexus is inherently interdisciplinary, relevant heat and mass transfer needs and research are often published in discipline-specific journals outside traditional heat transfer journals.

a)



b)

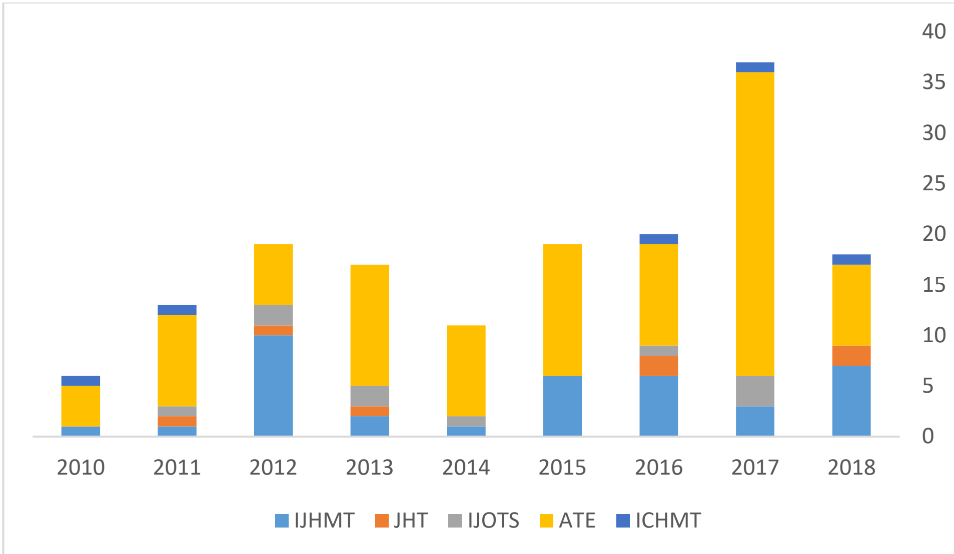



**Figure 2 Results from a keyword/title/abstract search for a) " 'Energy' AND 'Water,' " and b) " 'Food' OR 'Agriculture' " in five heat transfer journals [i.e., International Journal of Heat and Mass Transfer (IJHMT), Journal of Heat Transfer (JHT), International Journal of Thermal Sciences (IJOTS), Applied Thermal Engineering (ATE) and International Communications in Heat and Mass Transfer (ICHMT)]**

### 1.3. Framework of this review paper

This review highlights the state of the art in six broad topics in the FEW nexus, and highlights future heat and mass transfer research opportunities. Due to the critical importance of heat and mass transfer in the energy and water nexus, this review first focuses on energy-water challenges, tracing the flow of energy and water from the natural gas well to end users such as building occupants. Energy and water topics include energy extraction of natural gas hydrates and shale gas (section 2), power production [section 3, e.g., nuclear (section 3.1), solar (section 3.2), and wet, dry, and hybrid cooling (section 3.3)], energy-intensive water desalination and purification (section 4), and buildings and heating, ventilation, air conditioning, and refrigeration (HVAC&R) technology (section 5). Subsequently, this review considers food and agricultural applications, such as the food and water nexus [section 6, evapotranspiration (section 6.1) and evaporation (6.2)], and the food, energy, and water nexus [section 7, greenhouses (7.1), food storage (granaries in section 7.2 and freezing/drying in section 7.3)].

## 1.4. Review papers

The present review provides a broad understanding of heat and mass transfer research and opportunities in the food, energy, and water nexus. Review papers by D'Odorico et al. [11], Finley and Seiber [12] highlight overall food, energy, and water nexus, but do not focus specifically on thermal fluids topics. Other review papers, tabulated in Table 1, provide reviews of specific heat and mass transfer knowledge, systems, and technologies.

**Table 1 Review papers on FEW topics**

| Topics | Review papers |
|---|---|
| **Overview of the food, energy, and water nexus** | |
| General food, energy, and water nexus review papers | D'Odorico et al. [11], Finley and Seiber [12] |
| **Energy and Water: Power production** | |
| Solar power | Overview: Thirugnanasambandam et al. [14]<br>Concentrated solar power: Avila-Marin [15], Fuqiang et al. [16], Ho and Iverson [17], Zhang et al. [18]<br>Solar chimneys: Zhou et al. [19]<br>Photovoltaic and thermal photovoltaic: Lamnnatou and Chemisana [20] |
| Nuclear Reactors | Computer modelling: Habib et al. [21], Li et al. [22]<br>Water-cooled reactors: Rahman et al. [23], Oka et al. [24]<br>Gas-cooled reactors: Ahn et al. [25], No et al. [26]<br>Overview of nuclear reactors: Abu Khader [27], Lenzen [28], Abram and Ion [29] |
| Power plants | Water use: Badr et al. [30], Meldrum et al. [31], Macknick et al. [32]<br>Pre-cooling: Sun et al. [33], He et al. [34], Ibrahim et al. [35], Al-Ibrahim et al. [36]<br>Fins: Mukkamala [37], Bhuiyan and Islam [38] |
| **Energy and Water: Water purification and desalination** | |
| Solar stills | Sharshir et al. [39], Selvaraj and Natarajan [40], Chandrashekara M, and Yadav [41], Kabeel and Agouz [42], Kaushal and Varun [43] |
| Membrane-based desalination | Teow and Mohammad [44], Gao et al. [45], Mahmoud et al. [46], Charcosset [47], Mbarga et al. [48], Al-Amshawee et al. [49], Campione et al. [50] |
| Reverse osmosis | Qasim et al. [51], Li et al. [52], Qasim et al. [53], Jamaly et al. [54], Alghoul et al. [55] |
| Humidification and dehumidification | Srithar and Rajaseenivasan [56], Narayan et al. [57] |
| Metal-organic frameworks | Kadhom and Deng [58] |
| **Energy and Water: Buildings and HVAC&R systems** | |
| Water heating and cooling technology | Water heating: Sadhishkumar and Balusamy [59], Ibrahim et al. [60], Buker and Riffat [61], Shukla et al. [62], Hollands and Lightstone [63], Hepbasli and Kalinci [64]<br>Solar water heating: Jaisankar et al. [65], Shukla et al. [66], Shukla et al. [62]<br>Water chillers: Serag-Eldin [67] |
| Buildings technology | Envelope technology: Wang et al. [68]<br>Indoor environment: Peeters et al. [69], Sarbu and Sebarchievici [70], Xu et al. [71]<br>Passive houses: Wang et al. [72] |

| | |
|---|---|
| | Solar/building integration: Buker et al. [73], Chemisana [74], Ralegaonkar et al. [75] |
| Thermal energy storage technology | Passive application: Akeiber et al. [76], Kuznik et al. [77]<br>Free cooling application: Iten et al. [78], Kamali [79], Osterman et al. [80], Raj and Velraj [81], Thambidurai et al. [82], Waqas and Din [83]<br>Active application: Al-Abidi et al. [84], Du et al. [85], Hasnain [86], Lin et al. [87], Regin et al. [88], Shao et al. [89] |
| HVAC&R technology | Absorption cooling: Ziegler and Riesch [90]<br>Adsorption cooling: Sur and Das [91]<br>Desiccant cooling: Daou et al. [92], Vivekh et al. [93]<br>Evaporative cooling: Costelloe and Finn [94]<br>Magnetic refrigeration: Jeong [95], Mezaal et al. [96], Nielsen et al. [97], Zhen-Xing et al. [98] |
| **Energy and Water: Energy extraction** | |
| Gas hydrates | Energy Development: Chatti et al. [99], Chong et al. [100], Kondori et al. [101], Lee et al. [102], Li et al.[103]<br>Models: Sun et al. [104], Yin et al. [105] |
| Shale oil & gas | Sayed et al. [106], Costa et al. [107]<br>Flow & Transport: Gensterblum et al. [108], Salama et al. [109]<br>Models: Oke et al. [110]<br>Wastewater: Sun et al. [111], Mao et al. [112], Gregory et al. [113]<br>Desalination: Cho et al. [114], Kim et al. [115], Chang et al. [116], Shaffer et al. [117]<br>Desalination Membranes: Adham et al. [118] |
| **Food, Energy, and Water: Sustainable agriculture** | |

| | |
|---|---|
| Sustainable water use | Crop Modelling: Garofalo et al. [119]<br>Irrigation: Yang et al. [120], Aquastat [4], Green et al. [121], Zeng et al. [122], Sharda et al. [123], de Vito et al. [10], Roth et al. [124]<br>Solar/irrigation/water pumping integration: Chandel et al. [125], Kelley et al. [126] |
| Evapotranspiration | Katul et al. [127], D'Odorico et al. [11], Fisher et al. [128], Walter et al. [129], Hanson et al. [130], Chahine et al. [131], Priestley et al. [132], Granger et al. [133], Hragreaves et al. [134], Boulet et al. [135], Peng et al. [136], Diarra et al. [137], Llorens et al. [138], Schlesinger et al. [139] |
| Evaporation from simulated or real soils | Mosthaf et al. [140], Or et al. [141], Bittelli et al. [142] |
| Greenhouses | Lamnnatou and Chemisana [143] |
| Food storage | Drying: Yao [144], Thirugnanasambandam et al. [14]<br>Freezing packaging: Zhao et. Al [145]<br>Freezing (ultrasound): Akdeniz and Akalin [146], Chemat et. Al [147], Zheng and Sun [148] |

## 2. Energy and Water: Energy extraction

The energy extraction landscape is changing due to new technologies and economics. Projections indicate that shale gas will be a significant portion (i.e., 46%) of the U.S. energy supply by 2035 [149], and its extraction represents a confluence of the Energy-Water nexus considering the average well requires over 3 million gallons of water over its lifetime. Although there are many thermal fluid challenges in energy extraction, natural gas hydrates and hydraulic fracturing are the focus of this section due to the need for natural gas and the depletion of more conventional sources [103, 104, 111, 112, 150].

### 2.1. Natural gas hydrates

Gas hydrates are ice-like solids where, at low temperatures and high pressures, water encapsulates gas molecules – mainly methane – in the crystalline lattice [103, 104, 150-152]. Most natural gas hydrates contain methane and can easily be found in permafrost and along the seafloor sediments [99, 103, 104]. Natural gas hydrates exist in porous formations where multiphase flows (i.e., composed of the gas, water, and hydrate) exist [104], thereby preventing flows in pipes and equipment and causing blockages and other problems [99, 153].

However, hydrates may be an untapped resource of unconventional energy and represent an active research area [99, 101, 103, 104, 150-152], yet energy is needed to harvest the gas [104]. To obtain the natural gas, the hydrate must be dissociated; this occurs when the hydrate is no longer at its temperature-pressure equilibrium condition [103, 151]. The hydrate dissociates like ice melting; hydrates near the wellbore dissociate first, creating two different zones – the gas zone (i.e., natural gas and liquid water) and the solid hydrate zone – and the dissociation front then propagates out from the wellbore farther into the reservoir, releasing the gas [103, 104, 151]. Depressurization decreases the pressure below the stable pressure of natural gas hydrates; when the hydrate becomes unstable, it decomposes into separate parts, dissociating the gas [100-104, 151]. Current dissociation methods are depressurization, thermal simulation, and inhibitor injection [102, 150]. A combination of these methods may be more beneficial than using only one [103, 104]; however, when using one, depressurization is currently the most economical method, according to Kondori et al. [101].

Most exploration into gas hydrates has been through modeling [100, 105]. General mass transfer models for dissociation include conservation equations [104, 105, 151, 152]. The dominating factor of dissociation depends on the size of the reservoir: in smaller scales, hydrate dissociation is dominated, in part, by heat transfer to the hydrate, with conduction being more important than convection. In larger scales, such as in the field, fluid flow is a dominating factor of dissociation [103]. In some cases, fluid flow had little effect on the decomposition of the hydrate and intrinsic kinetics and the heat transfer (e.g. the temperature difference between the hydrate equilibrium and the system) were important in the decomposition process [154].

The amount of gas that can be extracted from a hydrate reservoir depends on the properties of the hydrate and reservoir (Equation 1). Initially, in hydrate dissociation, gas production increases quickly, but as time goes on, begins to change slowly,

$$n_{g,t} = V_{g,0} \frac{\left[\frac{p_t}{z_t} RT_t - \frac{p_{t\_diss}}{z_{t\_diss}} RT_{t\_diss}\right]}{1 - \left(\frac{p_t}{z_t} RT_t\right) \left[\frac{M_g + \beta M_w}{\rho_H} - \frac{\beta M_w}{\rho_w}\right]} \qquad (1)$$

where $n_{g,t}$ is the accumulated gas from dissociation at time $t$, in moles, $V_{g,0}$ is the initial volume of the gas phase, $p_{t\_diss}$ and $p_t$ are the pressures at the onset of dissociation and at time $t$, $T_{t\_diss}$ and $T_t$ are the absolute temperatures of the system at the onset of dissociation and at time $t$, $z_{t\_diss}$ and $z_t$ are the compressibility factors, $\beta$ is the real hydration number ("estimated by the correlation of the lined cavity fraction occupied by gas molecules in the hydrate"), $M_g$ and $M_w$ are the molecular weights of the natural gas and water, $\rho_H$ and $\rho_w$ are the densities of the hydrate and the water, and $R$ is the universal gas constant [155]. The natural gas output from the hydrate initially increases due to the increase of the dissociation rate (e.g., due to an increasing temperature difference). However, as extraction progresses, the output of natural gas decreases even though the temperature difference remains high. The dissociation rate decreases due to the reduction of hydrate surface area, resulting in is less hydrate existing to dissociate [151].

## 2.2. Hydraulic fracturing

In 2000, shale oil and gas contributed less than 1% of U.S. gas production; by 2015, it increased to 50% of the U.S. gas production [116] and is a possible bridge from coal (i.e., high carbon emissions) to a lower carbon future [108, 111, 112, 117]. Hydraulic fracturing is used to extract shale gas due to the low permeability of the formation [109]; the permeability of the shale can range from 10 to 1000 nanodarcies [156], with porosities ranging from 2% to 15% [106].

Hydraulic fracturing is used to obtain oil from shale using a sizeable amount of water (Figure 3). By extrapolating information about shale in the United States and applying it to similar shale globally, Rosa et al. [11] determined that between 1.54 and 21.06 $km^3$/year of water are required globally for shale oil and gas extraction. Freyman et al. [157] and Sun et al. [111] noted that a majority of hydraulically fractured wells were developed or are being developed in areas that experience moderate to high levels of water stress (e.g., South Texas and Colorado Shale), before the additional stress of the well. Rosa et al. [11] estimate that of all the shale globally, 31% are in areas of water stress; due to hydraulic fracturing, this could increase to 44%. This creates a competition for water between energy, municipalities, industry, and agriculture [157, 158]: this competition especially comes into play in the 30% of shale areas that are under irrigated agricultural areas [11].

Hydraulic fracturing fluid begins as surface or groundwater [107]; according to Freyman [157], groundwater is typically less regulated than surface waters, leading to many regions using groundwater for hydraulic fracturing and little quantitative information. Water will then be trucked or piped, depending on the distance the water source is from the well. While fracturing fluid is mainly water, during chemical mixing, proppants ("small particles... that flow with the fracturing fluid and hold the fractures open" [113]) and chemical additives (i.e. acid, friction reducers, and salt, among others [113]) are mixed into the water [111, 113, 159]. Once the fluid is mixed it is forced into the shale (i.e., well injection) by surface pumps reaching around 25 MPa to create fractures that reach the gas [159]. Following well creation, the water pumped in and the water generated either flows back out of the well or remains in the well [160] (discussed further in section 2.3.1). When the water returns to the surface it is considered wastewater; disposal and treatment options include storage, deep-well injection, or treatment for surface disposal or can be recycled by treatment for use outside of the hydraulic fracturing industry or treatment for reuse for hydraulic fracturing [111].

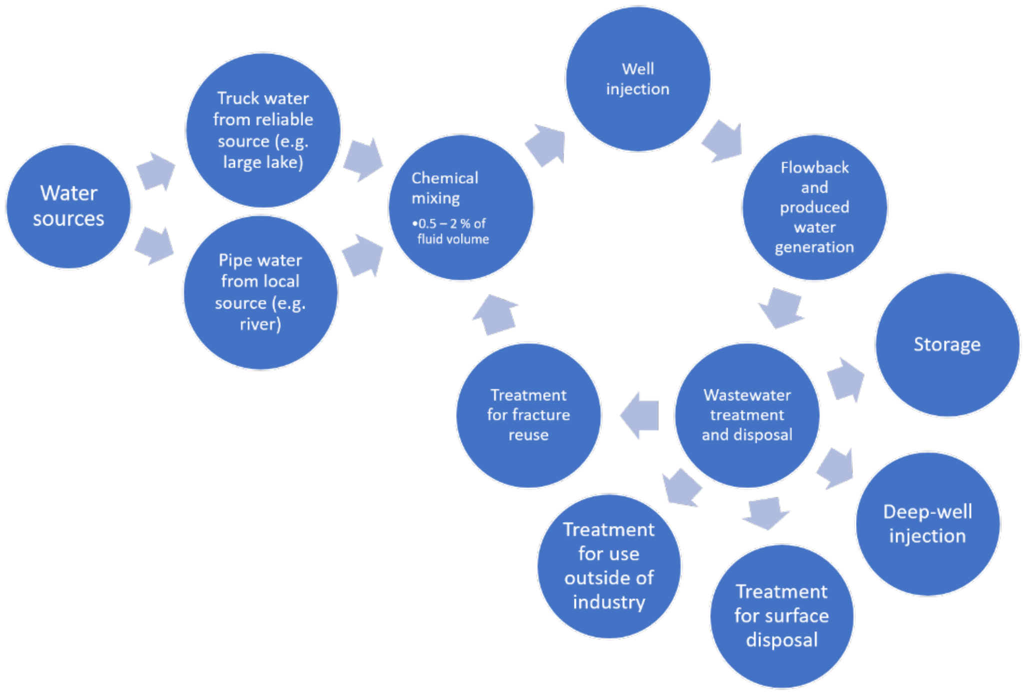



**Figure 3: The life cycle of water used in hydraulic fracturing, based on information from Sun et al. [111], Scanlon et al. [161], Salama [109], and Costa et al. [107]**

### 2.3. Heat and mass transfer in hydraulic fracturing

Modeling hydraulic fracturing is an active research topic. Models for fluid flow in a fractured reservoir include the equivalent continuum, dual porosity, multiple interaction continua method, multiple porosity, and discrete fracture models [108, 109, 156, 160, 162, 163]. Wang and Cheng [163] observed that conventional fluid transport theory does not work for fluid transport in porous shale since the fluid velocity in the shale can be 4-5 orders of magnitude faster and the no-slip boundary condition breaks down. Mass transfer models of the fracturing fluid model multifracture propagation [164]. The width of natural fractures are affected by the pressures, high pressures will increase the leak off velocity, resulting in the decreased width of natural fractures [165].

### 2.3.1. Water use and contaminant transport

Once the water penetrates the shale, it may return to the surface as flowback water [110], remain in fractures [160, 166] or the shale matrix [160], or leave the shale matrix into ground water [111]. However, the amount of flowback from a well can be extremely low (e.g. 10 – 40% of the fluid initially injected [110]), depending on the shale properties [113, 159, 160, 163], and estimating water usage is important but challenging [167]. The mass flow rate of the flowback and produced water is greatest initially after the well has been created; the following first few months experience a rapid decrease in mass flow rate water, then slowly decreases over rest of the lifetime of the well [113, 167]. The flowback water can reach a flow rate of 1000 $m^3$/day before decreasing, the produced water typically has a steady flow rate between 2-8 $m^3$/day [116]. The fluid returning to the surface has a different makeup than that which was pumped into the shale [107]. While the fracturing fluid is flowing in the shale it dissolves and carries minerals from the shale [113]: Contaminants include total suspended solids, metals, organics, and total dissolved solids [110, 113]; of particular interest is how these contaminants diffuse through the fluid [168].

Depending on the salinity and other contaminant concentrations, different options for the flowback and produced water are available upon exiting the well [110, 113, 159, 167, 168]. Methods include deep-well injection [111-113, 116, 157], treatment for surface disposal, treatment for reuse outside of the gas industry, and treatment for fracturing reuse [111, 113, 116, 118]. Deep-well injection is the injection of the wastewater into a deep well to dispose of the waste [112]. Similarly, in water flooding, wastewater is injected to maintain pressure in shale where oil or gas is being extracted [117]. In previous years, deep-well injection was the most common method of wastewater disposal [111, 112]. Wastewater for fracturing reuse requires treatment: different contaminants can degrade the performance of the additives and affect the stability, particularly the salinity [110, 111, 113]. The idea of water reuse for hydraulic fracturing has become attractive for both the reduction of stress on water sources, as well as for the economic benefit to the company; in 2012, 90% of the wastewater in Pennsylvania was reused for fracturing [117].

### 2.3.2. Desalination for energy extraction wastewater treatment

The lack of availability of deep injection wells, concerns about earthquakes, restrictions on water disposal, and other environmental concerns make wastewater reuse attractive to industry [116, 117]. Wastewater can be reused for crop irrigation, livestock water, and indirect potable reuse [111]. For wastewater to be reused, a number of contaminants need to be removed that are not typically removed during traditional desalination [114, 118]. Methods for dealing with wastewater "include basic separation technologies, adsorption, advanced oxidation, low-pressure membrane filtration and desalination technologies" [116]. There is currently not one technology that can treat every contaminant in wastewater [111] (Table 2).

**Table 2 Summary of desalination technologies of interest for wastewater treatment**

| **Desalination Technology** | **When to use it** | **Stage of development** |
|---|---|---|
| Mechanical vapor compression (Thermal) | High salinity, TDS up to 200,000 mg/L [111, 116, 117], low temperatures [111] | Well established [117], high energy requirement [117] |
| Thermal distillation | TDS, dissolved constituents [113] | Well established [113] |
| Crystallization | TDS [113] | Well established [113] |
| Multi-effect distillation | Seawater [116] | Well established [116] |
| Humidification/dehumidification | Separate saline water stream and water vapor [116] | Emerging [116] |
| Electrocoagulation | TSS, microorganisms, metals/metalloids, oil, and organics [111] | Under development [111] |
| **Membrane Technologies** | | |
| **Pressure Membranes** | | |
| Ceramic membranes | High temperatures and variety of chemicals [118], TSS [111] | Emerging [118] |
| **Low-pressure Membranes** | | |
| Microfiltration | Solid/microbial removal [118] | Frequently used [118] |
| Ultrafiltration | Solid/microbial removal [118], organic matter [116] | Frequently used [118] |
| **High-pressure Membranes** | | |

| | | |
|---|---|---|
| Nanofiltration | Multi-valent ions, desalination [118] | Widely used [118] |
| Reverse osmosis | TDS removal, up to 40,000 mg/L [118, 167], salt removal [116, 117] | Widely used [118, 167] |
| **Osmotically Driven Membranes** | | |
| Forward Osmosis | High salinity, TDS [116, 117], salt removal, suspended constituents, dissolved ions [116], salt removal [112] | Emerging [117, 118], needs improvement [111] |
| Pressure-retarded osmosis | "Reconcentrate the diluted draw solution" [116] | A promising technology [116] |
| **Thermally driven Membranes** | | |
| Pervaporation | Saltwater, organic micropollutants [116] | |
| Membrane distillation | High salinity [111, 116-118], salt rejection [116], high TDS [110, 114, 116] | Emerging [117, 118] |
| Membrane crystallization | Extension of membrane distillation, high $Na_2So_4$ [116] | A promising technology [116] |
| **Electrically driven Membranes** | | |
| Electrodialysis | High salinity (partial desal), low-TDS [116] | Still being investigated [116] |
| Membrane capacitive deionization | Organic and inorganic species [116] | |
| Ion-concentration polarization desalination | High salinity, TDS [116] | |
| **Biologically active Membranes** | | |
| Membrane bioreactors | Organic removal [118] | Frequently used [118] |
| Microbial fuel cells | High salinity wastewater for electricity [116] | Currently in use [116] |
| Microbial desalination cells | Salt removal [116] | |

### 2.3.3. Heat transfer in hydraulic fracturing

Heat transfer in hydraulic fracturing is important because temperature can affect the fluids, chemicals, and additives used for hydraulic fracturing [169]. The difference in temperature between the fracturing fluid in the fractures and the reservoir causes heat to move from the reservoir to the fracture [170]. Fracturing fluid viscosities can be temperature dependent [170, 171], and the viscosity of high viscous water-based gels is extremely sensitive to temperature changes [170]. The fluid dynamics can be affected by the viscosity, therefore having an accurate estimate is important in modeling hydraulic fracturing.

Heat transfer through the rock formation occurs through conduction, radially around the wellbore [172]. Sinclair [170] determined that the flow rate per foot of the formation has no effect on the heat transfer in the well when the fluid is being injected at normal fracturing rates. However, Li and Zhu [166] determined that at higher injection rates, the well is cooled faster during injection and heated slower during shut in. Due to the large dependence on conduction for heat transfer, the higher the thermal conductivity of the rock formation, the faster the well warms during shut in. Along with high injection rates, Whitsitt and Dysart [169] noted that the walls of the wellbore are drastically cooled by the injection of the cool fluids; as the fluid flows through the wellbore it heats up, removing negligible heat from the formation. Fracturing fluid injection cools the well and the formation near the well, and when the well is closed, it begins to heat up [172].

Common methods for investigating natural fractures are finite element, discrete element, and boundary layer element models [109, 164, 165]. Models for determining fracture geometry have been developed by Pityuk et al. [173], Guo and Liu [165], and others. Many models assume, because the flow rate in natural fractures is small, the temperature in the fracture is approximately the formation's temperature [165]. However, Biot et al. [171] modeled the temperature profile through the fracture; when the temperature profile was plotted in terms of the constant wellbore temperature, the reservoir temperature, and the dimensionless distance through the fracture, only the thermal conductivity shifted the profile, altering at what distance the fluid obtained the reservoir temperature. Proppant transport properties are greatly affected by heat transfer in the well [174].

### 2.4. Energy extraction: Heat and mass transfer opportunities

Heat and mass transfer research opportunities focus on reducing energy and water consumption for emerging, fossil fuel energy sources. The amount of gas retrieved is low compared to the amount of energy required in natural gas hydrate dissociation [103, 104]; heat and mass transfer research is critical in the effort to lower energy and costs. Dissociation is currently dependent on shifting the hydrate from phase equilibrium through temperature and/or pressure [104], and a better, fundamental understanding of the properties of the hydrates at equilibrium could lead to new ideas phase shifting approaches. This fundamental knowledge on hydrate dissociation could also be useful for flow assurance.

Once equilibrium has been perturbed, heat conduction drives dissociation; this heat originally comes for the sensible heat of the hydrate reservoir and when it is consumed, there is no heat to drive the dissociation [103]. Understanding the thermal properties of the hydrate sediment and conduction through the sediment can lead to research on how to introduce heat to the hydrate reservoir to continue pushing dissociation. Depending on the initial permeability and conductivity of the reservoir, dissociation switches from thermal transfer driven to mass (i.e., fluid flow) transfer driven [103]; it is critical to continue developing fluid flow models [104] that accurately depict real hydrate reservoirs. Research into how the hydrates form and affect fluid flow; sediments gas and water permeability and how it changes during dissociation; dissociation propagation; and the sediment left in the pores from dissociation that can inhibit flows would be extremely beneficial to fluid flow models [102, 103].

Research into the thermal properties and the transport properties of fracturing fluids and wastewater is critical to the fracturing industry and the environment. Many of these fracturing fluids are proprietary [111] and these fluids can deteriorate while in use [165]. With limited knowledge of the fluids, researchers cannot understand the deterioration of the fluids, model the heat transfer occurring in hydraulic fracturing wells, model the fluid flow in the well, or predict the amount of gas a well will produce. Knowledge of the fracturing fluid properties could also help determine the quality of water needed to create fracturing fluid, reducing cost and wastewater. The reuse of wastewater is of particular interest currently – deep well injection is becoming a less attractive option in many areas [113] due to water stress and legislation [111]. Wastewater reuse research lies in the desalination mass transfer research (i.e., effectively removing contaminates to an acceptable level [111, 112]). Desalination mass transfer research will be discussed in Section 4.

## 3. Energy and Water: Power production and cooling

Although power production remains a water-intensive process, average U.S. water withdrawals for power production recently declined, from 15.1 gal/kWh in 2014 to 13.0 gal/kWh in 2017. The reason for this recent decline in water withdrawals was attributed to the changing composition of power generation in the United States; in this time span, production from water-intensive coal plants decreased, and power generated by natural gas combined cycles and non-hydropower renewables such as wind and solar increased [175]. This section discusses the energy-water nexus as it pertains to power production in nuclear reactors and solar power plants, as well as power plant cooling.

### 3.1. Nuclear reactors

Nuclear reactors are typically considered a reliable and green source of energy due to the relatively low cost of fuel, high energy output, and minimal carbon emissions. The two primary engineering drawbacks to using nuclear power are currently that it requires complex engineered safety features and that it consumes large amounts of water (Table 3), which oftentimes cannot be recycled due to the radiation exposure. The most common nuclear power plants (NPPs) are light water reactors (LWRs), which use water as a coolant and moderator in the core, as well as the process fluid by which energy is extracted. LWRs are considered to be Generation II reactors, with relatively low cost and high energy output, but many are coming to the end of their lives and need to be replaced with new designs [176]. Current research is focused on developing reactors to maximize safety and energy output (both electrical and thermal), while minimizing cost and water consumption [177]. These reactor designs, called Generation IV reactors, use varying coolants and core designs to optimize fuel and water use to maximize energy and safety. Generation IV reactors rely on simple designs with passive safety and alternative power cycles, rather than standard steam turbine power cycles.

Several Gen. IV reactor designs (e.g., liquid metal cooled reactors and high temperature gas-cooled reactors) use non-water media as coolants or/and moderators. While these reactor designs do not use water directly as a coolant, they often use water as a secondary coolant, ultimate heat sink, or other process fluid [178]; water use in plants is tabulated in Table 3. Sodium and lead-cooled reactors are designed to have higher energy efficiencies as compared to LWR counterparts. The burn-up (i.e. total energy amount of extracted per fuel weight) is expected to be higher. They are also designed for breeding purposes (i.e. the secondary product of SFRs and LFRs is the breeding more fuel). In other words, liquid-metal cooled breeder reactors have longer term sustainability as compared to LWRs [179]. High temperature reactors (HTRs) are typically divided into high temperature gas-cooled reactors (HTGRs) and molten salt reactors. HTGRs use inert Helium as the coolant, which allows operation at much higher temperatures as compared to light water reactors [180]. Molten salt cooled reactors have higher operating temperatures which make them energetically more favorable and have better passive safety systems [178].

**Table 3 Comparison of reactor designs based on power and coolant**

| Reactor | Electrical Power (MWe) | Thermal Efficiency | Primary Coolant | Working Fluid | Areas of water consumption |
|---|---|---|---|---|---|
| IRIS SMR[181] | 700 | | $H_2O$ | $H_2O$ | All cooling |
| JSFR[182] | 1500 | 42% | Na | $H_2O$ | Through turbine |
| KALIMER-600[183] | 600 | 42% | Na | $H_2O$ | Through turbine |
| PRISM[184] | 311 | | Na | $H_2O$ | Through turbine |
| SSTAR[185] | 19.8 | 44% | Pb | $CO_2$ | Nowhere |

| | | | | | |
|---|---|---|---|---|---|
| HW-MSR[178] | 1000 | 45% | Salt | He | Nowhere/heat sink |
| ELSY [186] | 630 | 42 | Pb | $H_2O$ | Through turbine |

### 3.1.1. Light water reactors (LWRs)

Light water reactors have been used for the past fifty years without significant development due to their high economic efficiency. As many of these LWRs come to the end of their lifetime, there has been some debate on whether LWRs should be further developed. The push for keeping LWRs has primarily been analyzed through the use of small modular reactors, termed SMRs (i.e., <700 MWe) [187]. SMRs might prove to be economically viable for power grids where a medium amount of power is required [188]. Several SMRs designs were created; although their total water consumption is not well documented, it is typically compared to the water consumption for a large LWR. The International Reactor Innovative and Secure (IRIS) pressurized water reactor (PWR), a 335 MWe PWR, uses more water than a large LWR to promote natural circulation, and therefore, passive safety systems [181]. The water usage for LWRs depends on the design, but the average LWR operating with cooling towers uses 1514 L/MWh of water [31].

### 3.1.2. Advanced reactors

Several reactors are currently in development to improve safety, efficiency, and economics compared to typical LWRs. These improvements are achieved mostly through higher operating temperatures as well as improved neutron economy through the use of breeder reactors. Many of these reactors do not use water as a coolant or moderator, but require water for secondary cooling or processing.

**Sodium-cooled fast reactors (SFRs)** use liquid sodium as a coolant. SFRs operate at high temperatures and low pressures, creating higher thermal efficiencies and improved passive safety [179]. There are three primary options for SFRs: loop-type, pool-type, and modular-type [189]. A major loop-type SFR being considered is the Japanese SFR (JSFR), which is a 1500 MWe SFR (Table 3). The sodium is cooled by several steam generators; water acts as a secondary coolant and working fluid [190]. One pool-type SFR currently under consideration is the Korean KALIMER-600 SFR. The 600 MWe reactor SFR utilizes two steam generators to cool liquid sodium, which each have a steam mass flow rate of 663 kg/s [183]. The power reactor innovative small module (PRISM) is a 311 MWe modular SFR. PRISM is a modular pool-type reactor which is passively safe and can use recycled used nuclear fuel from LWRs [184].

**Lead-cooled fast reactors (LFRs)** are a potential alternative to LWRs. Lead is advantageous as a coolant for its high boiling point of 1749º C, but presents challenges due to its high melting point of about 330º C, as the local spots can lead to freezing resulting into unstable scenarios such as uneven cooling [191]. The European lead-cooled system (ELSY) is a 1500 MWt lead-cooled reactor that uses pumps to circulate lead through the core as a coolant. Lead is then cooled by several steam generators, which use water as the system working fluid [186, 192]. Although the ELSY uses lead as a coolant, it consumes water as a secondary coolant. The small, sealed, transportable, autonomous reactor (SSTAR) is a 45 MWt lead cooled reactor, using lead as a primary coolant, and carbon dioxide as a secondary coolant and working fluid [185]. While SSTAR does not produce large amounts of power, it is still more efficient, is passively safe, and uses no water as a process fluid.

**High temperature gas reactors (HTGRs)** power turbines on either a secondary loop with steam turbines or the primary loop with helium turbines. If using a secondary loop, the water consumption is similar for a standard circulating loop coolant reactor, and the efficiency is approximately 38%. If using the primary helium loop, the water consumption would only come from a secondary heat exchanger, if necessary, and the theoretical efficiency would be 48% [193]. The GTHTR300A, a HTGR, was designed to be cooled entirely by dry cooling. The high temperature and high efficiency of the HTGR allow for a dry cooling tower to be viable [194].

**Molten salt reactors (MSRs)** are designed with reactor fuel dissolved into a molten salt, thereby acting as a coolant. Similar to the other Generation IV reactors, MSRs operate at high temperatures, and are safer because they can operate at atmospheric pressure. MSRs also lend themselves to online refueling, a variety of core configurations, and higher neutron economy as a breeder reactor. The primary drawback to MSRs is that the molten salt is chemically reactive and corrosive, thereby making process equipment design more difficult and expensive. Most MSR designs use water as a secondary coolant and working fluid [178]. Reprocessing of fuel allows the continued generation of energy from the fissile material produced as a result of breeding process.

### 3.1.3. Comparison of coolants under comparable operating conditions

Power generation throughout human history has largely relied on the generation of steam, which is then used to rotate a turbine. Helium and carbon dioxide can serve as alternate working fluids. This becomes especially important when comparing reactor technologies because using a non-water coolant as a working fluid can reduce water consumption, while also increasing efficiency due to higher temperatures. In a comparison of steam, helium, and carbon dioxide through a turbine with a constant outlet coolant temperature of 480ºC, turbine efficiencies of 34%, 40%, and 42% were noted for steam, helium, and supercritical carbon dioxide, respectively [195]. Critical heat flux and dryout is an important phenomenon to consider in the safety of nuclear fuel. When dryout conditions are reached or no direct contact of liquid coolant such as water iwith nuclear fuel, the heat transfer from the fuel to the coolant is deteriorated, which drastically increases the fuel temperature causing fuel failure or even meltdown scenarios. With a much higher boiling point for molten salts and liquid metals, the dryout condition is expected to be at much higher temperature than in the case of water.

### 3.1.4. Ultimate heat sink

An ultimate heat sink is important for both normal reactor operation and emergency preparedness under postulated accidental conditions. For most reactors currently in operation, this ultimate heat sink is water from a nearby natural source, which restricts the use of the water resource due to possible contamination. Many newer reactor designs are focused on creating an ultimate heat sink which does not require water, or one where the water is far enough removed from the primary coolant that contamination does not occur. In accident scenarios, these ultimate heat sinks require passive heat removal (i.e., no forced circulation) to the environment through radiative cooling or natural circulation of ambient air in the surroundings. In some scenarios, novel designs have been proposed where water can be used in a closed loop, and the ultimate heat sink can be an external bed of rocks, which restricts the need for water to only recirculation through the core [196]. Under normal operating conditions, using water as an external source would consume approximately 2300 L/MWhr of water, whereas using cooling towers would use approximately 2700 L/MWhr of water [31].

### 3.1.5. Fuel storage and recycling

Once fuel has been spent in a nuclear reactor, it must be stored in a cask until it is safe for transfer to a permanent deep geological storage site. For the initial 3–10 years of storage, most fuel is stored in pools of water, which moderates neutrons and provides cooling. Many Generation IV reactors are designed to recycle spent nuclear fuel and use it again in order to minimize the fuel in storage and maximize energy extracted from the fuel [197]. This water can be classified as either water withdrawn or consumed. Water that is withdrawn is used as a process fluid and most of it is returned back to the reservoir. Water consumed is water loss which is not returned to the reservoir due to evaporation or consumption in chemical reactions. On average, reprocessing nuclear fuel withdraws approximately 2700 L/MWhr and consumes approximately 26 L/MWhr. The water consumption for initial fuel processing for an LWR is approximately 211 L/MWhr [31].

### 3.2. Solar power

Sufficient energy from the sun hits earth within an hour to supply the energy needs for a year [14]. While not all of that solar radiation can be converted to electrical or thermal energy, solar power production can create lower-water-intensity power generation [175]. A brief overview of solar power related to the FEW nexus follows, with an emphasis on energy-water and food-energy issues.

#### 3.2.1. Concentrated solar power plants and solar chimneys

Concentrated solar power plants (CSPs) use mirrors to collect and reflect sunlight onto an absorber. Solar power towers and parabolic dish systems both reflect light from a circular area to a central receiver while linear Fresnel reflectors and parabolic trough collectors reflect light to a long pipe receiver through which a working fluid flows [14, 16-18, 198, 199]. Solar chimneys are a simple thermal power plant which consists of a solar collector, the chimney, and the power conversion unit. Air is heated in the horizontal space between the solar collector and the ground, once heated it begins to rise in the chimney due to buoyance forces and that kinetic energy is then converted to electrical energy in the power conversion unit [19, 200]. Solar chimneys could be designed to simultaneous create energy and benefit agriculture, including the construction of greenhouses within the solar collector as noted by Zhou et al. [19] and drying of agricultural products [201, 202]. There is also interesting in using solar chimneys to harvest atmospheric water by using the buoyancy forces to force air through a cyclone separator [203].

### 3.2.2. Photovoltaic and thermal photovoltaic cells

While a working fluid is not required for the electrical generation, photovoltaic (PV)/thermal photovoltaic (TPV) cells do require cooling. While often cooled by open air, the fluid used to cool PV/TPVs can be used in a hybrid system for application such as domestic water heating [20]. Lamnatou and Chemisana [20] provide a detailed review of PV and TPV systems with an emphasis on environmental concerns. PV and TPV cells can also be used to replace generators used in irrigation or drinking water supply, even without batteries for smaller irrigation or water systems [125, 204].

## 3.3. Power plant cooling

Conventional power plants are significant water users [175]. Three main condenser types are utilized in power production: once through; wet/evaporative; and air-cooled, also termed dry cooling. Once-through cooling (i.e., 43% of US fleet) requires the power plant to be built near a river or lake due to large withdrawal needs (75-150 $m^3$/MWh) [205]; once-through condensers are generally legacy components due to high water consumption and thermal pollution (i.e., increasing river temperatures). Wet cooling towers and cooling ponds (i.e., 42% and 14% of US fleet, respectively) are two methods of wet cooling with lower withdrawal rates compared to once through cooling (e.g., 2-28 $m^3$/MWh), since cooling is achieved by latent heat transfer rather than sensible heat transfer. This leads to much higher consumption (2.3 $m^3$/MWh) compared to once through cooling (0.8 $m^3$/MWh), and is not suited for water scarce regions [205]. In air cooling, sensible heat transfer to the ambient air provides the cooling. Since air has a lower volumetric specific heat (i.e., 1.1 kJ/$m^3$K) than the latent heat of vaporization of water (i.e., 2,252,000 kJ/$m^3$), air-cooled condensers (ACCs) has a lower efficiency than wet cooling and suffers from a hot day penalty (e.g., summer afternoons when high ambient temperatures can cause up to a 20% loss in power production [33]). In order to mitigate some air cooling challenges, hybrid cooling incorporates both wet and dry cooling to minimize water use while increasing plant efficiency of the power plant [206].

The subsequent sections investigate power production and air, hybrid, and wet cooling technologies. The focus of the wet cooling section is on reducing water withdrawals and consumption, the air-cooling section focuses on enhancing its cooling capabilities, and the hybrid cooling section describes the current methods used.

#### 3.3.1. Air-cooling

One major challenge in dry cooling is the effects of ambient air temperature on the heat rejection capabilities of the system. Rising condenser pressures lead to a higher turbine backpressure, thereby reducing power output. Mitigation approaches, such as spray cooling and wetted media, tend to focus on cooling the air from the dry bulb temperature to the wet bulb temperature by evaporating water into the air before the condenser bundles [33-36, 207-213]. Another important parameter is ambient wind velocity, which causes recirculation in the tower, exhaust plume recirculation, and lowers the performance of condenser bundles. Since the effects of wind on air cooling are complex, research investigated the impacts of buildings, condenser geometries, and windbreakers [214-222]. Due to lower efficiencies, air-cooled condensers are typically much larger than their wet-cooled counterparts; therefore, novel heat exchanger designs are needed to increase the performance of the condenser bundles [223-230].

##### 3.3.1.1. Wind effects in air-cooled condensers

Ambient wind velocities negatively impact ACC heat rejection capabilities. Kong et al. [217] compared annularly arranged condensers (AACC) tubing versus vertically aligned A-frame condensers in no wind, slow wind (i.e., 3 m/s), and fast wind (i.e., 15 m/s). Validated simulations showed that the AACC allowed for more even airflow and temperature distribution, resulting in higher mass flow rates and greater heat rejection around the tower for the condenser tubing. In the simulation of high wind, both models showed the presence of vortices inside the tower leading to decreased performance in the condensers around the vortices. Kong et al. [218] compared three different layouts of ACCs: horizontal A-frame (HACC), vertical A-frame (VACC), and combined flat frame (CACC). The CACC contained vertical condenser tubing arranged annularly around the outside of the cooling tower and horizontal condenser tubing on the inside of the tower. Simulations showed that at ambient wind speeds < 9 m/s, the CACC performed the best with an increase in performance of 20-40% depending on the wind speed. However, at wind speeds >9 m/s, the VACC performed the best with an increase in performance of 40-80%.

Zavaragh et al. [221] simulated the impacts of a flat windbreaker inside the cooling tower and an arced shaped windbreaker outside the cooling tower on air recirculation, and concluded that using both windbreakers perpendicular to the flow direction of the ambient wind was the best strategy. Gu et al. [214] used a scale model and wind tunnel and determined wind parallel to the ACC units caused hot plume recirculation from the upstream ACC units in the downwind ACC units. The worst recirculation occurred when the boiler and turbine houses were upwind of the ACC platforms.

### 3.3.2. Pre-cooling

In combined cycles, pre-cooling methods can be utilized to cool inlet air before combustors/turbines [35, 36, 209, 213] and cooling the inlet air for the condensers on a steam cycle. Pre-cooling utilizes the fact that the wet bulb temperature is usually lower than the dry bulb temperature of air. If the wet bulb temperature serves as the cold source for power generation, plant efficiency improves. Spray cooling and wetted media both use evaporation of small droplets/films of water to cool the ambient air.

#### 3.3.2.1. Spray cooling

The review of natural draft cooling towers conducted by Sun et al. [33] determined that spray cooling significantly cooled the air and additional, in depth studies on the spray mechanics would optimize the cooling efficiency. Research focused on the types of nozzle used, number of nozzles, position of nozzles, droplet sizes, droplet distribution, and spray angle. Alkhedhair et al. [207] modeled spray cooling in a duct (i.e., 1m x 1m x 10m) using various droplet sizes (i.e., 20, 35, 50 μm) and air flow rates (i.e, 1, 2, 3 m/s). For a 10-m-long test section, none of the test cases produced complete evaporation. The simulations showed an average decrease in temperature of 8 °C in the saturated region and an average temperature reduction of 5 °C across the entire duct.

#### 3.3.2.2. Wetted media

Wetted media cool air to the wet bulb temperature [34, 210, 211]. He et al. [34] reviewed wetted media types (e.g., cooling pads and fills/packing). Water is retained in cooling pads with concurrent air flow; cooling pads include fiber pads (e.g., wood) and rigid media (e.g., corrugated sheets that forces the water to flow down in thin films while the air is forced to turbulently flow upwards). Both methods are capable of having high cooling efficiencies but there are tradeoffs; fiber pads are cheaper yet rigid media have a lower pressure drop and longer service life. Fills, including splash, film, and trickle, are another type of wetted media. Splash fills intercept the flow of water through the packing and cause droplets to form from the impact, yet require a large amount of space to work effectively increasing the cost of the cooling tower. Film fills allow the water to flow down as a thin liquid film, yet can have large airside pressure drops and are prone to fouling. Trickle fills use small water droplets to flow down the fill surface and wet the fill, yet data are limited. However, current research does suggest that they are more compact than splash fills and have lower pressure drops and less fouling than film fills [34]. He et al. [34] concluded that there is no single, optimal wetted media for air-cooling due to the wide variety of different applications.

### 3.3.3. Alternate air-cooled condenser designs

Through modeling, Bustamante et al. [205] determined that air-cooled condensers can achieve wet cooled condenser efficiencies if air flow rates increase by 68%, convective resistances decrease by 66%, while only increasing the pressure drop by 24%. Various methods have been investigated to achieve enhanced air-cooling performance. One method is using solar energy to enhance the flow rates of air across condenser bundles called solar enhanced natural draft cooling towers (SENDCT) [224, 225, 227, 229, 230]; another is focusing on increasing the performance of fins [223, 226, 228].

#### 3.3.3.1. Solar enhanced natural draft cooling towers

Solar enhanced natural draft cooling towers are similar in design to solar chimneys (e.g., a large tower in the center of a greenhouse-type field). The heat from incident solar energy is trapped in the base structure and is heats the air, enhancing the natural draft and pulling in more cool air that is passed by the steam tubes at the beginning of the base. Much of the research focuses on using these cooling towers for concentrated solar plants. Through modeling, Guan et al. [225] determined that the SENDCT was able to save 2.47 MW of power loss during high temperature periods of the day (e.g., 28.6 – 36.7 °C); cooling was a more efficient use of this air flow, as a similar solar chimney would generate 113 KW. Ghorbani et al. [224] modeled a hybrid SENDCT and SC. They used the cool inlet flow to cool the steam loop in the power plant and injected the hot flue gas from the plant into the top part of the chimney to further enhance the natural draft. They found that they could increase the output of a dry cooled fossil fuel power plant by 4.49 MW which related to a 0.5% increase in efficiency.

#### 3.3.3.2. Fin designs

Fin geometries are an important part of heat exchanger design, and desirable fins increase heat transfer area while minimizing pressure drop. Current popular fin designs are flat or wavy plates and the different sizes and shapes have been studied extensively [37, 38, 231, 232]. Kong et al. [226] simulated the effects of different geometrical parameters on plate fin-tube bundles, varying fin angle, fin spacing, fin thickness, and tube diameter independently to observe the effects on heat transfer and pressure drop for a constant 289.15 K inlet temperature and variable 0.5–3.5 m/s inlet air speed. Two comparison parameters were used to determine effectiveness of the changes. One is the performance evaluation index (PEI) which compares the performance of the individual surface,

$$PEI = \frac{Nu}{f^{\frac{1}{3}}} \tag{2}$$

where $Nu$ is the Nusselt number and $f$ is the friction factor,

$$f = \frac{2\Delta P}{\rho u_{min}^2}\frac{D_h}{L} \tag{3}$$

where $\Delta P$ is the pressure drop across the bundle, $u_{min}$ is the minimum flow velocity, $D_h$ is the hydraulic diameter, and $L$ is the flow length. The global performance criterion (GPC) evaluates the performance of a bundle for a set volume,

$$GPC = \frac{\dot{Q}}{\Delta P\dot{V}} \tag{4}$$

where $\dot{Q}$ is the total heat transfer rate, and $\dot{V}$ is the volumetric flow rate. The PEI varied little with the fin angle; increasing the spacing between fins was found to increase the heat transfer coefficient while decreasing the pressure drop (e.g., a PEI increase of ~60% from a 2-mm spacing to a 6-mm spacing between fins). The PEI showed that, ideally, plate fin-tube bundles would have large fin spacing and tube diameters as well as thick plates. However, all these changes increase the volume of the condenser bundles, thereby increasing size and cost. For the fin angle, the GPC increased minimally for the tested angle; fin spacing improved GPC for spacings up to 10 mm before decreasing. From this study it was concluded that based on GPC, the optimal design for a six-row plate fin-tube heat exchanger is fin angle of 30°, fin spacing of 10 mm, fin thickness of 0.3mm, and tube diameter of 18 mm for *Re* from 220 to 5500. Lin et al. [231] found that trapezoidal converging-diverging plate-fin channels enhances the convective heat transfer. Adding perforations to allow mixing between channels improved the heat transfer performance (50% increase) even more while reducing the friction factor (20% decrease).

A promising method of enhancing fin design is additive manufacturing, thereby permitting more complex and smaller geometries which can improve heat transfer [223, 233, 234]. Arie et al. [223] noted that although there was an improvement in heat transfer compared to conventional heat exchangers, they did not outperform strip fin heat exchangers. This is likely due to the inaccuracy of the manufacturing process that blocked access to some to the air channels decreasing the available area for heat transfer. Since metal additive manufacturing is still relatively new, it is likely that these challenges will be resolved in the future, and performance will increase.

Mao et al. [228] investigated utilizing metal foams on heat exchanger tubes instead of fins. Metal foams increased heat transfer coefficient compared to fins but also increase the pressure drop across the condenser. For the same number of tubes and volume occupied by the condenser, 2–3 times the amount of heat was rejected compared to conventional finned tubes while having acceptable pressure drops.

#### 3.3.4. Hybrid cooling

Hybrid cooling uses both air and wet cooling towers to cool the cycle's working fluid. Hybrid cooling can maintain cooling performances similar to wet cooling towers while reducing water consumption. Wet cooling towers keep the turbine backpressure down [206, 235, 236]. Wagner and Kutscher [236] determined that 50-50 split between air and wet cooling resulted in a 1.67% performance penalty while water use was reduced by 52%. If the ambient conditions are favorable for air-cooling, it is possible to send the majority of the cooling load to the air-cooling apparatus. When ambient conditions are not favorable for air-cooling, the hybrid system operates as a wet cooling tower [206, 235, 237]. Water loss in cooling towers is primarily due to 1) blowdown water discharged from the wet cooling tower in order to maintain steady cooling conditions and remove pollutants; and 2) drift loss, which is the water that evaporates to lower the cooling fluid temperature.

#### 3.3.5. Wet cooling

##### 3.3.5.1. Blowdown reuse

Blowdown water is typically high in dissolved solids and anti-fouling chemicals [238-240]. In order to reuse the water in cooling tower applications, water must be decontaminated or it will increase fouling in the cooling tower. Farahani et al. [239] used a coagulation-filtration pretreatment to determine if the blowdown water could be made suitable for reverse osmosis (RO) and nanofiltration (NF) water treatment methods. The silt density index was reduced to acceptable levels to prevent major fouling in RO or NF; post treatment by RO or NF, 98% or 88% of total dissolved solids were rejected, respectively.

##### 3.3.5.2. Drift loss reclamation

Drift loss produces plumes that emerge from cooling towers. This very moist air is similar to fog harvesting applications being studied to procure water. Different methods for collecting this water can be used, such as drop impingement on a wire mesh or through enhanced condensation [241-245]. Ghosh et al. [242] used wire meshes in cooling towers of a 500MW plant to intercept water droplets in the air. Mesh angles, shapes, and shade coefficients were varied. Cooling tower meshes could retrieve 1.5 $L/m^2h$ of water. Damak and Varanasi [241] ionized water droplets and induced electro-magnetic fields around the mesh, and significantly increased the amount of water captured. This process used 2 $kWh/m^3$ compared to current reverse-osmosis desalination methods (i.e., ~3-5 $kWh/m^3$ to produce the same amount of water). Huber et al. [244, 245] investigated vibrations to motivate droplets through simulations and experiments, thereby reducing the smaller critical droplet diameter for droplet departure in a moist environment ($T$=30 ºC, 50%RH) from 5 mm for the stationary case to 1 mm for the vibrating case.

### 3.4. Power production and cooling: Heat and mass transfer opportunities

Key challenges for power production are the increasing variability in electrical grid loads and reducing water usage; therefore, there is a need for maneuverability in power generation technologies without affecting system efficiency and safety. In case of thermal power plants, such as gas-cooled systems, operating at lower power levels typically leads to dramatic decreases in performance of gas turbines. In case of nuclear power plants, nuclear reactors cannot change power levels abruptly as per grid demand due to safety reasons. Thermal energy storage (TES) options become an obvious choice in these scenarios to follow grid demand without affecting the power level of energy source.

Integrating TES systems with thermal power plants, including nuclear, has been proposed previously and are dependent upon indirect heat exchange process with reactor coolants or secondary fluids [246, 247]. Molten salts (e.g., nitrates) are most widely accepted TES solutions for high temperature and power plant applications, but their melting point is greater than 200 ºC [248], which makes them economically and technically not feasible for light water nuclear power plants as it will lead to a small margin (e.g., $T$=50 ºC) for sensible heat storage, thus increasing the costs. Other alternatives, such as Therminol, can be explored as liquid TES alternatives to molten salt and can be economically viable [246]. However, due to regulatory or layout requirements the only possible route for thermal storage integration is to directly transfer the energy of steam. Wet or dry steam accumulators have been used since 1920s to meet short term peak demand but the drawback of these systems is their inability to deliver steam at constant pressure for long recovery cycles. The design features to keep discharge pressure constant, such as injecting pressurized liquid lead to mixing resulting into exergetic efficiencies as low as 50 % [249, 250].

These limitations can be overcome by allowing thermal transport in a way to avoid thermal mixing within a storage system and reduce parasitic losses [251, 252]. These processes require detailed understanding of thermal dispersion which is highly dependent upon flow assisted thermal fluctuations in a complex geometry. Even with state of art computational and experimental techniques, the local entropy effects of thermal processes such as phase change heat transfer are difficult to capture which govern the design principles for the integrating TES with the large-scale thermal power generating units.

Several types of gas-cooled reactors have been proposed to use instead of traditional water-cooled reactors, and fundamental heat transfer information is needed for these fluids. In the UK, carbon dioxide has been used as a coolant in Magnox reactors and later Advanced Gas Reactors [253], but still use water as the working fluid so that existing turbine technology from coal plants could be implemented. These plants operated at higher thermal to electrical efficiencies than most water-cooled nuclear power plants. Helium has been proposed as a superior alternative to carbon dioxide due to its improved thermal characteristics; however helium is far more expensive than carbon dioxide. The Gas Turbine Modular Helium Reactor uses Helium as both a coolant and working fluid. This allows for even higher efficiencies due to high operating temperatures and implementation of a Brayton cycle, rather than the Rankine cycle used in other reactors [254]. Although it is well-established that Helium is a better heat transfer coolant, the Helium powered gas turbine technology has not reached maturity for deployment due to high leakage issues. In recent developments, supercritical $CO_2$ cycles are being considered for integration with nuclear reactors. Although Supercritical $CO_2$ technologies have advanced in the last 15 years, heat transfer characteristics (e.g., thermal boundary layer and mixing behavior due) remain poorly understood due to a lack of experimental capabilities.

To reduce the amount of water needed in power plant cooling towers, it is clear that additional, future work needs to be conducted on air-cooling. Major areas of concern in the heat and mass transfer field are the effects of ambient wind, the decrease in efficiency when ambient air temperatures are high (i.e., the hot day penalty), and the high thermal resistance of air compared to water. The effects of ambient wind can be addressed by fundamental convection studies and large-scale simulations on the design of windbreakers [214, 221]. There are several promising options to reduce the hot day penalty. In pre-cooling, research is needed on efficiently cooling the air with minimal water, including uniformity, nozzle position, nozzle type, etc. [207, 212]. Another approach is to cool a phase change material at night in order to cool incoming ambient air during the day, thereby focusing on efficient ways to store the thermal load while minimizing system size and maintaining the normal turbine back pressure [86, 255]. Additively manufactured fins offer significant potential in enhancing air-side heat transfer, which could enable fin geometries that outperform fins produced through conventional manufacturing. However, more research is required at the intersection of additive manufacturing and air-side heat transfer [223, 233, 234]. In addition to reducing air-side thermal resistances [205], creation of durable, engineered surfaces for condensation heat transfer enhancement – including sustained dropwise condensation in condenser tubes– represents an opportunity for further heat transfer research [256-261].

## 4. Energy and Water: Water desalination and purification

Particularly in many arid and semi-arid regions, the demand for water exceeds supply; freshwater comprises of 2.5% of the world's water (i.e., 30% in ground water, 0.3% in lakes and rivers, and 70% in mountain snow and ice forms [262]) and 97.5% of the world's water is seawater [262-264]. Desalination is a possible, albeit energy intensive (e.g., specific energy ~4-4.5 kWh/$m^3$ [265]) solution to create fresh water from seawater [263, 264, 266-269] The Kingdom of Saudi Arabia is the largest water purification country with 18 % of the global output and daily water production of 10 $Mm^3$/day [265]. Although desalination is not a new concept – the Greek philosopher Aristotle mentioned seawater desalination in his writings and British navigator James Cook used the process to produce potable water during his travels [270] – heat and mass transfer research is needed to make it more efficient and cost effective.

### 4.1. Solar stills

Solar stills use solar energy to evaporate water, and then condense pure water for domestic and industrial uses (Table 4). In a conventional single sloped solar still (SSSS), water is evaporated using sunlight and condensed to pure liquid; this design can be modified by changing absorber plate geometry [266]. A double sloped solar still (DSSS) uses two inclined glass cover to enhance heat transfer area compared to a single sloped solar still [271-273]. Geometry has a strong impact on performance; Kabeel et al. [266] studied solar stills in Egypt and determined the daily efficiency, $\eta$,

$$\eta = \frac{\sum \dot{m} h_{fg}}{\sum AG(t)} \tag{5}$$

where $\dot{m}$ is hourly condensate mass production, $h_{fg}$ is latent heat, $G(t)$ is solar irradiation as a function of time, and $A$ is the whole device area. The daily efficiency for stepped and conventional single sloped solar stills was 53% and 33.5% respectively.

Methods which increase radiation (e.g., tracking the sun [271, 274]), improve absorption of solar radiation (e.g., water additives such as dyes [272] or nanoparticles [275], optimized tray geometry [266], painting surfaces white [276]), or increase heat transfer (installation in a windy site or suitable elevation [277]) increase water production. Nijmeh et al. [272] obtained a 20% increase in water production by adding potassium dichromate and violet dye as dissolved salts to increase absorption of solar radiation. Sahota and Tiwari [275] investigated the effects of $Al_2O_3$ nano-particles in a double sloped solar still and observed maximum increases in water production of 12%.

Hybrid systems can increase water output with minimal energy input [263, 273-275, 278]. Abad et al. [263] investigated solar desalination with pulsating heat pipe (PHP) and it yielded 75% more water than the passive system. Ansari et al. [278] examined a passive solar still with heat energy storage materials [i.e., phase change materials (PCM)]. The stored thermal energy in the PCM during daytime was used at night for desalination. A novel SSSS system was combined desalination with a PV/T cell to provide electricity and water [273]. Ghaffour et al. [265] studied the feasibility of renewable energy driven desalination systems.

## Table 4 Solar stills and fresh water yields

| Solar still device | Location | Type of work | Output |
|---|---|---|---|
| Single basin solar still with absorbing materials [272] | Jordan | Experimental and theoretical | • Water yield: 0.32 $kg/m^2h$ with $KMNO_4$ compared to 0.24 $kg/m^2h$ without absorbing material<br>• $KMNO_4$ improved still efficiency by ~26% and water yield by 20% |
| Passive solar still (PSS) with condenser [279] | N/A | Numerical | • Water yield: 0.25 $kg/m^2h$ for PSS and 0.16 $kg/m^2h$ for conventional solar still |
| Passive solar still -SSSS and DSSS[271] | India | Experimental and theoretical | • Water yield: 0.06$Kg/m^2h$ for SSSS and 0.05 $kg/m^2h$ with DSSS |
| Modified stepped solar still (MSSS) [266] | Egypt | Experimental and theoretical | • Water yield: 0.25 $kg/m^2$ h for MSSS compared to 0.15 $kg/m^2$ h for SSSS<br>• MSSS offered cost savings of $0.01/kg of water |
| Conventional solar still (CSS) painted with white color termed Improved solar still (ISS)[276] | Malawi | Experimental and theoretical | • Water yield 0.11 $kg/m^2h$ for ISS compared to 0.09 $kg/m^2h$ for the CSS |
| Hemispherical solar still [280] | India | Experimental and theoretical | • 23.53% increment of efficiency - per unit area cost of 233$ with 0.017$/kg of water<br>• The rate of yield was 0.18 $kg/m^2h$ with cooling the top cover compared to 0.15 $kg/m^2h$ without cooling |
| Active solar still [277] | Morocco | Numerical | • Install in a windy site or higher elevation |
| Solar still with pulsating heat pipe (PHP) [263] | Iran | Experimental and theoretical | • 75% higher yield with 8% increase of the cost per liter of water<br>• Maximum productivity was 0.8 $kg/m^2h$ |
| Passive solar still with phase change material [278] | Morocco | Experimental and theoretical | • Nearly 0.24 $kg/m^2h$ pure water production |
| Single slope solar still (SSSS) with PV/T cell [273] | N/A | Modeling | • Water productivity increases by 67%<br>• Combined efficiency of the system increased by 97%, and<br>• Maximum yield was 0.433 $kg/m^2h$ |
| Tracking system in solar field and MED [274] | Iran | Experimental and theoretical | • On average, 253% more fresh water and yield was maximum 92514.69 kg/h in Summer solstice with Full tracking system |
| Effect of nano-particles ($Al_2O_3$) in DSSS [275] | India | Experimental and theoretical | • 12.2% and 8.4% increase of water yield<br>• Maximum total yield was 0.114 kg/h with 0.12% nano-particles compared to 0.1 kg/h for base fluids |

## 4.2. Membrane desalination (MD) systems

In membrane desalination (MD), hot sea water or saline flows through the hot channel and permeate passes through a porous membrane into the cold channel. Heat transfer occurs in three different regions (i.e., hot channel, membrane, and cold channel) [281-283]. Due to temperature gradient between the channels, hot feed water is vaporized to diffuse through the porous membrane, where it passes and get mixed with the cold, pure water. Prior CFD research focused on optimizing efficiency [284-287]. One of the major challenges with desalination is the costly management of waste (i.e., a concentrated brine solution) that can be both a health hazard and harmful for the ecosystems and marine species. Recently, Kumar et al. [288] reported that brine could be converted into sodium hydroxide which is essential for running the desalination plant; sodium hydroxide changed the acidity of the solution, resulting in less membrane fouling.

The membrane desalination process significantly depends on the properties of the membrane [289-299]; fouling or scaling are substantial mass transfer concerns [283, 287]. Khalifa et al. [23] investigated scaling and degradation of polytetrafluoroethylene (PTFE) membranes and observed fouling after 48 hours. The salt rejection factor, SRF, was determined, where $C_F$ is the feed concentration and $C_P$ is the permeate concentration,

$$SRF = \frac{C_F - C_P}{C_F} 100\%. \tag{6}$$

Maximum SRFs of 98% and 99.9% were obtained for tap and sea waters, respectively. A 70%-95% evaporation efficiency with a gain output ratio (GOR) of 0.8-12 was observed. Khayet et al. [290] studied the performance of porous hydrophobic/hydrophilic composite membranes (>99.7% separation factor), which were superior to commercial membranes due to the low path length between the liquid and vapor interfaces. Less fouling and corrosion were observed in electrospun nanofiber membranes during 50 hours of operation due to its high porosity, low tortuosity, large surface pore size, and high surface superhydrophobicity [291].

Detailed analysis on air gap membrane desalination and direct contact membrane desalination suggested that the air gap dominates the desalination process [281]. Using a micro-porous hydrophobic membrane, reducing air gap thickness from 7 mm to 3 mm induced a 130% increase in permeate flux [292]. Bhadra et al. [295] selected a graphene oxide immobilized membrane (GOIM) membrane due to the presence of a polar functional group, selective sorption of water vapors, micro-nano porous structure and nano-capillarities. The membrane durability was verified through continuous experiments over 90 days, while producing 99.9% pure water. Maximum permeate fluxes of 97 kg/m$^2$h were obtained. Less fouling occurred in an ultrathin, highly fluorinated porous membrane due to its anti-wetting properties [298].

Membrane-based air humidification-dehumidification desalination [296, 297] and hybrid desalination systems [299-301] combine membrane and thermal systems. Li and Zhang [296, 297] modeled membrane-based air humidification-dehumidification using hollow fiber bundles with and without air side turbulence. Increasing Reynolds number and packing fractions enhanced the heat and mass transfer at the expense of pumping power. In a hybrid system, high concentration photovoltaic thermal system's waste heat was reused for membrane desalination system [299], converting 85% of the solar radiation into electricity and potable, high quality water (total dissolved solids < 15 ppm). The combination of MD and reverse osmosis (RO) has been applied to improve the recovery rate of brackish water desalination [301]. Brine recovery can be only applied for RO system, as they degrade the performance of MD process by cooling the feed and reducing the net thermal gradient across the membrane.

### 4.3. Reverse osmosis (RO) systems

Reverse osmosis removes dissolved salts, ions, suspended particles, and some biological substances from impure water by flowing it through a semi-permeable membrane, with the aid of pressure to overcome the osmotic pressure of the fluid. Although half of the world's desalination is RO, membrane fouling and scaling issues [302], cost [303] and understanding the flow fields [304] are current challenges. Vibration-assisted seawater desalination can mitigate some inorganic fouling [305]. Membrane performance is critical for overall system performance; Wang and Karnik [302] studied nanoporous graphene membranes which transported water up to 27,500 $kg/m^2hMPa$ (i.e., 1320× higher than a typical membrane), and confirmed more than 99% salt rejection. Water permeability was an order of magnitude higher in hydrophobic MFI zeolites (i.e., aluminosilicate minerals with a microstructure composed of 3–8 Å pores) than hydrophilic MFI zeolites [306]. Successful rejection of chloride and potassium ions was reported, and salt ions were rejected for 5.5 Å MFI Zeolites pores. Warsinger et al. [307] obtained lower specific energy consumption through constant volume reverse osmosis and batch RO. Energy savings of approximately 37% and 64% were obtained by constant volume reverse osmosis and batch RO desalination, respectively, compared to atmospheric pressure brine discharge and steamwise driving pressure.

### 4.4. Humidification and dehumidification (HDH) systems

Humidification and dehumidification systems for water desalination can be decentralized, operate at moderate costs, and exhibit flexibility in capacity. In basic HDH systems, atmospheric air is used as a medium to convert impure water into freshwater with moderate operating temperature at near ambient system pressures [308]. Although dehumidification varies, an air humidification tower is common [309]. Air flow rates, hot water temperatures, and air relative humidity play vital roles in determining system heat and mass transfer [310-312], and increased feedwater salinity can decrease performance [308]. Increasing air humidity and air temperature enhanced the performance of the an HDH-air conditioning system [267].

Solar energy can be easily integrated with the basic HDH system to increase water production [264, 269, 313-315]. Elattar et al. [314] studied solar hybrid air conditioning and HDH system which yielded fresh water with the addition of an auxiliary heating system and a thermal storage tank. Increasing outdoor humidity improved the COP; a maximum COP of 4.25 was observed. Sharshir et al. [264] combined a solar still with an evacuated solar water heater and HDH yielding 1.54 kg/h. Through feeding warm exit water into the solar still, the productivity increased by 242% and GOR increased by 39% compared to a conventional solar still. The average productivity of the HDH unit was 0.92 kg/h and collector was 0.46 $kg/m^2h$ [315].

### 4.5. Water harvesting and condensate recovery

Engineered surfaces are of interest for water harvesting and condensate recovery [316-319]. At low relative humidity, without the use of electric power, some water harvesting systems use available enthalpies of water-adsorption system, such as water-based zeolites and metal-organic frameworks (MOFs). By weight, 82% of water was captured by MOFs below 30% RH [317]. With the aid of sunlight, 2.8 kg water/kg of MOF were captured at 20% RH [318]. Porous metal-organic frameworks (e.g., MOF-801,[$Zr_6O_4(OH)_4(fumarate)_6$]) were integrated with low grade heat source driven vapor-desorption process for atmospheric condensate collection [319]. The device, operating in an arid climate [e.g., 10%–40% RH and sub-zero dew points (Tempe, Arizona, USA)] yielded 0.25 kg water/kg of MOF with a thermal efficiency (solar input to water conversion) of ~14% [319]. Hence, water-based zeolites and MOFs has tremendous potential to collect condensate in the arid regions.

### 4.6. Desalination systems using low grade and waste heat

Multi-stage systems flash water into steam in multiple pressure stages while multi-effect desalination systems spray salt water on hot tube bundles to evaporate water [320-325]. Although both systems consume significant amounts of thermal energy, they can be operated using low grade heat (e.g., geothermal [324]). Fouling remains a concern. In a multi-effect desalination system, the heat transfer coefficient decreased by 9% with a 40% increase in the fouling factor [320]. Aluminum alloys and carbon steel epoxy-coated shells were implemented to reduce fouling [321]. Less corrosion and scale formation are some benefits of low temperature multi-effect desalination unit which increased fresh water production by 50% with a moderate increase of pumping power [322]. The low temperature multi-effect desalination system was integrated into a coal thermal power unit to recover the waste heat of flue gas and utilized the recirculating seawater of steam turbine condenser [325]. The GOR was enhanced up to 12.79 and coal consumption rate was reduced by 6.05 kg/W.

Using an alternative absorption heat transformer, waste heat from a textile industry produced desalted water (e.g., 0.24 kg/s) [326]. Thermally driven adsorption desalination-cooling systems introduces copper sulfate salt hydrate with water vapor as a new adsorption pair [327]. The capacity of water vapor adsorption onto copper sulfate was found to be around 0.51 $kg_{water}/kg_{copper\ sulfate}$. The output for specific daily water production were about 9 $kg_{water}/kg_{copper\ sulfate}$, 227 W/kg of copper sulfate specific cooling power and 0.57 COP. Solar energy was integrated with vacuum spray dryer for water desalination system under reduced pressure [328], producing 0.625 $kg/m^2h$ of fresh water during the peak sunny hours.

### 4.7. Desalination and water purification: Heat and mass transfer opportunities

Membrane fouling impedes membrane-based desalination [283, 287]; fouling represents a mass transfer process and there are open opportunities for research to reduce membrane fouling and energy consumption. For example, Kumar et al. [288] altered brine to sodium hydroxide to reduce the membrane fouling by changing pH. Heat and mass transfer play a role in fabricating membranes such as a defectless graphene membrane (i.e., highly potential material for the membrane) at a minimal cost. Further study is required to understand the transport mechanisms of water and solutes in respect of fluid dynamics, charge, and adsorption effects as well as sieving phenomenon in these membranes [329]. Electrodialysis has been shown to reduce membrane fouling but these membranes are still susceptible to clogging. Electrodialysis reversal (EDR) where the current is periodically reversed shows promise for preventing clogging and fouling [49, 50]. However, electrodialysis is still species limited and fouling can still occur with high total dissolved solids. This is an exciting opportunity that requires additional research regarding heat and mass transport as well as material science research into membrane materials and species selectivity. Many of the challenges with desalination come from the level of purification needed. New opportunities emerge if the water only requires a decrease in salinity as in the use of waste-water for hydraulic fracking.

Increasing water production using renewable or waste heat sources through heat transfer research would be impactful, particularly in areas which offer strong energy or water constraints. For example, membrane desalination systems could be integrated with the diesel generator's exhaust in areas where generators are used for power production. Waste heat (e.g., thermal power plant, internal combustion engine, industrial processes, etc) could drive desalination processes; exergetic analyses would indicate the efficacy of these approaches. For thermally driven adsorption desalination, other compounds (e.g., zinc sulfate, aluminum sulfate, ferrous sulfate) in addition to copper sulfate [327], could be investigated to increase system efficiency.

## 5. Energy and Water: Buildings and HVAC&R technology

In the U.S., almost 40% of energy use comes from commercial and residential buildings, including heating, ventilation, air-conditioning, and refrigeration (HVAC&R) [330]. While some situations involving buildings (e.g. water chillers and freezing food) impact the food, energy, and water nexus directly, much of the buildings and HVAC&R sectors impact the energy-water nexus through water used by building occupants and water used in the energy (i.e. electricity) generation. Aside from reducing energy usage, there is research interest in reducing the carbon footprint of buildings and carbon emissions of HVAC&R systems, including net zero energy buildings and high efficiency retrofits [331, 332]. The Kigali amendment to the Montreal protocol ordered the phase out of currently used, higher global warming potential (GWP) refrigerants (e.g., potential phase out of R134a and R410A). Heat transfer performance, system efficiency, and safety are critical for lower GWP alternatives, which are often flammable [333]. The following sections will discuss research to improve buildings and HVAC&R systems (Figure 5).

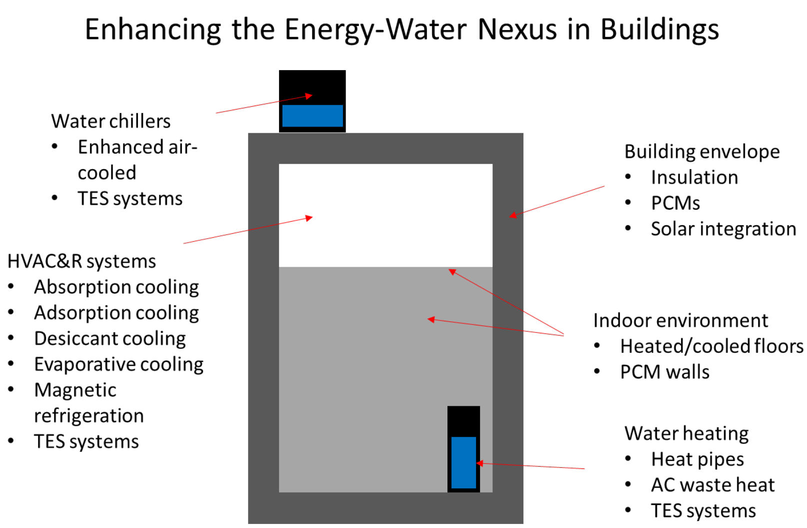



**Figure 4: Impacts of heat and mass transfer on the Energy and Water Nexus in buildings**

## 5.1. Water heating and cooling technology

Water heating and cooling technology directly impacts the energy-water nexus since energy – often in the form of electricity – is required to heat or cool the water. Water heating is the second largest energy user in buildings [334] and refers to domestic hot water that is used for showering, washing hands, and other cleaning uses.

### 5.1.1. Tank and tankless water heating

Standard tank water heaters are heated by electricity or natural gas and can be improved by using a recirculating water heater tank. Brazeau and Edwards [334] studied a recirculating system, which saved some water at the tap because there was less cold-water runout time. However, the system used more energy than a standard system to keep water at a constant temperature. Considering that it takes water to generate electricity – depending on the source – the recirculating system did not save substantial water [334, 335]. Heat pumps have been successfully integrated into water heater tanks [61, 64, 336, 337]. Erickson et al. [337] determined that using a heat pump system used one-third less gas than a standard gas water heater.

Tankless water heaters offer energy savings [334, 338]. Brazeau and Edwards [334] noted that tankless water heaters experienced difficulty heating the water to high temperatures, especially during the winter and even at the minimum required flowrate for the water heater. Therefore, they suggested combining with installation of low or ultra-low flow faucets and shower heads. Grant et al. [338] determined that a tankless water heater had lower water use and a higher energy factor, (i.e. 0.83 compared to 0.55-0.63 for tank water heaters),

$$EF = \frac{\rho_w c_p \left(T_{m,o} - T_{cws}\right)}{Q_{draw} + Q_{sb}} \qquad (7)$$

where *EF* is the energy factor, $T_r$ is the average outlet temperature, $T_c$ is the cold-water supply temperature, $Q_{draw}$ is the energy consumed during the draw portion of the test, and $Q_{sb}$ is the energy consumed during the standby portion of the test [339].

### 5.1.2. Combination heaters

Water heaters can be incorporated into air-conditioning systems to improve overall system efficiency by using waste heat to heat water. While it does not always provide all the energy needed for water heating, it can greatly reduce the required input [339-342]. In a single-family home in

Saudi Arabia, Bahel et al. [341] reported that a combination heater provided 75% of the energy required for heating water for a family of 6. Lee and Jones [339] used the desuperheater from the air-conditioning system to preheat the water in the tank, resulting in an energy factor of 0.77. Der et al. [342] used a tankless water heater coupled with a hydronic air-handling unit for space heating and found that the combination system had higher exergetic efficiencies than traditional space heating methods.

### 5.1.3. Solar water heating

Solar thermal energy can augment or replace other water heater systems and reduce domestic water heating costs by 70%-90% [62], due to the relatively high efficiency of converting sunlight directly to thermal energy (~70%) compared to the lower efficiency of solar to electrical to thermal energy (~17%) [65]. One drawback to using an exclusively solar powered water heating system is that operation of the system is dependent on the Sun's position and weather. In order to mitigate this, solar based systems can be paired with traditional electrical water heaters and/or use a thermal storage system such as a phase change material to heat water when sunlight is not available [66].

## 5.2. Chillers

Water chillers produce domestic water and space cooling, and often represent the highest energy users in buildings [343]; chillers account for 40% of the total air-conditioning energy load [344]. Lee [345], using second law analyses, determined that compressors had the largest opportunity to improve energy efficiency, followed by the condenser and the evaporator, respectively. Ross and Cirtog [346] investigated improving energy efficiency of water chillers by implementing a self-cleaning system to reduce fouling, thereby reducing energy consumption by at least 24.5%.

Similar to power plants, using air-cooling greatly reduces the amount of water used by water chillers, but improved efficiencies are desired [343, 347, 348]. Lee et al. [347, 348] simulated and experimentally tested novel configurations to improve air flow, thus improving heat transfer rates by up to 5.3% [348]. Experimentally, they found that the best cases had 4.5% higher cooling capacity and 7.3% higher coefficient of performance (COP) [347]. Yang et al. [343] examined a hybrid approach (e.g., using a mist pre-cooling system to lower the air temperature entering the chiller). The mist-cooled-air chiller used 15% of the water used by a traditional water chiller while increasing energy consumption by 16.2% and increasing COP by 30%.

## 5.3. Building technology

### 5.3.1. Solar/building integration

Building location, shape, material, orientation, shade, and other factors govern building-solar interactions. Considering these factors when designing a building can reduce heating and cooling costs, produce electricity, and lower electrical lighting demands [73, 75]. Ralegaonkar and Gupta [75] reviewed passive solar architecture methods including window size/location, wall aspect ratio, Sun shade control, and building orientation to allow for climate-appropriate amounts of solar energy to enter a building envelope. The amount of radiative energy entering a building via windows and can be altered by many of the same methods that greenhouses utilize such as near infrared filters, ultraviolet filters and photoselective materials [143, 349]. Photovoltaic (PV) cells and solar concentrators can be used to intercept sunlight and convert it to electrical energy for building use, rather than heating [74, 350].

### 5.3.2. Maintaining the indoor environment

Novel technologies for improving the indoor environment can reduce HVAC&R loads or increase efficiency [70, 71, 351-353]. Ayagaki et al. [351] employed a co-generation system integrated with hot water and floor heating in a building, reducing the total heating load by 8%

compared to a conventional space heating system, while improving thermal comfort. Jiang et al. [352] studied the reduction of heat losses through low temperature cooling and high temperature heating in HVAC systems of buildings. Xu et al. [71] reviewed methods to utilize low-grade heat sources (e.g. geothermal and waste heat) to cool and heat conditioned spaces using active pipe-embedded structures – building features (i.e. floor, ceiling, walls) embedded with pipes allowing cool or hot water to flow through to cool or heat the interior of the building – thereby removing or greatly reducing the need for conventional AC systems. Gao et al. [353] highlighted ground heat exchangers and their integration into buildings. Sarbu and Sebarchievici [70] conducted a review of ground-source heat pumps and found that significant savings for buildings in energy consumption and environmental impacts for hot and cold climates.

One challenge in building design and development is modeling indoor convective heat transfer effects in buildings because they are sensitive to air movements caused by external conditions and natural convection. Correlations are generally used in buildings models to account for convective heat transfer, yet these correlations are sensitive to convective heat transfer coefficient values and the room's set-point temperature [354]. Peeters et al. [69] conducted a review of up-to-date correlations available and determined that the correlations varied in heat transfer coefficient values, reference parameters, and equation formats, thereby leading to over or under sizing of HVAC&R systems and reduced energy efficiency.

### 5.3.3. Envelope technology

Building envelopes are affected by ambient conditions and solar radiation, and these envelopes impact indoor environmental quality and HVAC loads [68, 355, 356]. Wang et al. [68] reviewed active building envelopes focusing on transpired solar collectors. Diaz and Osmond [355] studied the impacts of rainfall on the cooling of buildings. Rain had a slight impact on surface temperatures and heating loads of the interior and exterior of buildings, and accounted for heat loads being overestimated by 10% for the year, resulting in oversized cooling systems.

### 5.3.4. Passive buildings

Passive houses are designed to keep the indoor environment comfortable throughout the year without the use of a conventional HVAC system. Properly designed passive houses can use ten times less heat load through the heating season than conventional buildings [72, 357-364]. Wang et al. [72] reviewed interactions between passive house energy performance and indoor environment quality. Along with a parametric sensitivity study, it demonstrated that passive house standards can simultaneously achieve energy efficiency and indoor environment quality. Badescu and Sicre [360, 361] modeled a passive house in Europe that incorporated a passive solar heating system (i.e., large window), an active solar heating system, and a ground heat exchanger. The model found that the renewable heat sources could cover the heat demand for most of the winter months, except January, which relied on a ground source heat pump.

## 5.4. Thermal energy storage technology

Thermal energy storage (TES) technology shifts energy loads from peak hours to off-peak hours [301] and reduces the temperature variation within a building [365]; it is an active subject for materials and heat transfer research. TES often uses a phase change material to storage thermal energy and release it later for heating, cooling, and power generation [85-88, 366]. PCMs generally have high latent heats of fusion, such as water/brine solutions, salt hydrates, ice slurries, and paraffin waxes. Integrating TES in buildings can reduce the size and cost of AC systems which are currently designed to handle peak loads [84, 89].

Passive applications include integration of PCMs into building elements (i.e. walls [77], ceilings and floors [367], envelopes [76]). Mihai et al. [365] incorporated two layers of PCM into gypsum wallboard in a simulation of a building's exterior walls. One layer incorporated a higher phase transition temperature (25-29°C) and the other layer had a lower phase transition temperature (19-23°C). The cooling load decreased three times and the total cooling energy decreased from 225 kWh/yr to 150 kWh/yr. The peak heating load decreased from 1800 to 1600 W and the total energy for heating decreased from 4141 kWh/yr to 3992 kWh/yr.

During free cooling applications of TES, PCMs pull energy from the building during the day and the stored energy is released at night using the cool ambient air using a fan [78-83, 367]. Alam et al. [367] conducted a case study of a TES system in an 11-story building in Australia. During winter months, the TES system offset the cooling load by 12-37%, but in the summer months, the TES system was not activated because the nightly ambient temperatures did not get below the phase transition temperature of the PCM; therefore the PCM was not able to recharge.

Active application of TES is when the latent heat of PCMs are utilized and PCMs are integrated into HVAC&R systems [367], and is a topic of research interest [301, 368-370]. Aljehani et al. [301] simulated an AC system integrated with a TES system. Compared to a conventional AC system, the TES-integrated system saw a 50% reduction in compressor size, double COP during mid- and off-peak hours, 30% reduction in electricity consumption during the summer months, 45% reduction in electricity bill during summer months, and 30% reduction in $CO_2$ emissions during summer months. Chandrasekaran et al. [368] studied heat transfer characteristics of a water-based PCM with copper oxide nanoparticles in an AC system. Integrating the PCM with the nanoparticles reduced the solidification time by 35%, and integrating the PCM could potentially increase the evaporator temperature (e.g., from -9°C to -2°C), yielding energy savings of 14–21%. Parameshwaran and Kalaiselvam [369] studied an organic ester PCM integrated with silver nanoparticles in a water chiller based AC unit. Daily average energy savings were 7.9% in the summer and 11.8% in the winter compared to an equivalent system without TES. Energy savings were increasing to 17.8% in the winter if an economizer was used.

Researchers also studied slurries as PCMs [371-373]. Dufour et al. [372] created a numerical model using a $CO_2$ hydrate slurry and found that the slurry had higher heat capacity and better heat transfer performance compared to water alone. Wang and Kusumoto [371] studied an ice slurry TES system, which reduced the peak power load by one-third over a convectional cooling system with the same COP. Xie and Yuan [373] studied a thin ring ice thermal storage system; material had the biggest impact, followed by array arrangement, then ring thickness.

## 5.5. HVAC&R technology

### 5.5.1. Absorption cooling

Absorption cycles, in which refrigerant is heated in the evaporator and subsequently vapor is absorbed by the sorbent and pumped to the absorber, can be used in solar applications [374-377]. In the absorber, the refrigerant is vaporized from the sorbent and condensed in the condenser. The refrigerant is passed through the expansion value back into the evaporator to repeat the cycle [376]. Ziegler and Riesch [90] reviewed absorption cycles, which competed successfully with convectional vapor compression cycles. Incorporating improved heat exchanger designs has been shown to improve the performance of these systems [378].

### 5.5.2. Adsorption cooling

Adsorption cooling technology, used in conjunction with low-grade heat (e.g., waste heat, solar energy, and exhaust gases), consists of a bed of adsorbate and adsorbent that are heated during the desorption phase. During the adsorption phase, the bed is cooled back down to the initial temperature. This heating and cooling cycle is repeated, and each cycle leads to a given amount of heat and mass transferred into and out of the adsorption bed. It is also noiseless, noncorrosive, environmentally friendly, uses little to no electricity, and little to no maintenance and operating costs. There are, however, several limitations that have made this technology difficult to implement, including low effective thermal conductivity of the porous adsorption bed and the resistances from the interface between the heat exchanger and the adsorption bed [91, 379-382].

Saha et al. [382] studied a prototype two-stage, non-regenerative adsorption chiller designed to utilize solar or waste heat (i.e., temperature ranging between 40-75°C). The adsorbent was silica gel and the adsorbate was water. With a heat source at 55°C and the water at 30°C, the cooling capacity was 3.2 kW with a COP of 0.36. Grisel et al. [379] studied a tri-generation system incorporating a two-bed, silica gel/water adsorption chiller system utilizing the waste heat from the CHP system. The system was designed for 5 kW of cooling power, but the system could only produce that much during optimal conditions and generally produced 3.6 kW. Using the adsorption system in trigeneration could save 15-20% of primary energy needed for cooling, heating and power demands.

### 5.5.3. Desiccant cooling

There are several advantages of incorporating desiccants into AC systems, including their ability to remove the latent heat load of conditioned spaces, dehumidification, ability to utilize low-grade heat sources, lower pressure drops, and filtration of bacteria, microbials, viruses, and molds [383]. Islam [383] created a simple theoretical model for liquid desiccant dehumidification in AC systems. The simulation was used to study a chiller system incorporated with a liquid desiccant system and the chiller efficiency was improved by 25%.

### 5.5.4. Evaporative cooling

Evaporative cooling chillers are attractive for their low energy use, which utilize ambient dry air as a driving force to produce cooled water between the wet bulb temperature and the dew point temperature of the ambient dry air. There are two types of evaporative cooling technology: direct [384, 385] and indirect [94, 384, 386-388]. El-Dessouky et al. [384] experimentally studied a two-stage evaporative cooling in Kuwait. The first stage was an indirect evaporative cooler; the second stage was a direct evaporative cooler and the efficiency of the combined two-stage system varied between 90-120% which suggests that the dry bulb temperature of the outlet air was lower than the wet bulb temperature of the inlet air. Jradi and Riffat [388] studied a dew-point chiller which cooled the air below the wet-bulb temperature and provided a higher cooling capacity compared to typical evaporative chillers. This type of evaporative chiller was effective at maintaining thermal comfort in buildings, especially in hot climates.

#### 5.5.5. Magnetic refrigeration

Magnetic refrigeration is a novel technology that uses a magnetic solid which heats up in the presence of a magnetic field. Power consumption is reduced by 30-40% compared to conventional vapor compression cycles. It is generally used for super low temperature (<5 K) applications, as discussed in the review paper by Jeong [95], and is being developed for room temperature applications [96-98, 389]. Advantages of magnetic refrigeration include it being environmentally friendly, potential for 20-30% higher thermodynamic efficiency compared to conventional vapor compression systems, silent and vibration free, economical, and few maintenance requirements [96, 390]. Additional research is required to make magnetic refrigeration a viable solution for the future [96, 97].

### 5.6. Buildings and HVAC&R technology: Heat and mass transfer opportunities

Several key heat and mass transfer research opportunities remain to reduce building and HVAC&R impacts on the FEW nexus. For buildings, design aspects should be considered to reduce energy and water use; in chillers, heat must be rejected to air or water. Water-cooled systems have higher efficiencies but also increased water consumption and maintenance costs [391, 392]. Standard "rules of thumb" regarding air- and water-cooled chillers do not consider water use [393]. In the U.S., water prices have risen 41% since 2010 [394], whereas electricity rates have increased by 8.8% [395]. Combined with the rising cost of water, considering water when designing buildings would make designs more water efficient [396, 397].

Designing building shapes to utilize natural ways of cooling and heating (e.g., natural air circulation) could reduce or remove air-conditioning costs [398]. Diaz and Osmond [355] demonstrated that rain can have a noticeable impact on a building's cooling load; intentionally designing for rain cooling could maximum the impact on the cooling load, especially in tropical climates. Incorporating thermal energy storage is another approach to reduce energy and water use, thereby removing peak loads to off-peak times. One of the biggest resistances to implementation is translating the theoretical design of phase change material technology into practice in buildings, as discussed in Alam et al. [367]. Improving the thermal performance of phase change materials and energy storage and integration into building systems remain critical challenges.

Heat transfer research could benefit both new buildings and retrofits. HVAC&R technologies exist that could improve or replace the standard vapor compression cycle, but they have disadvantages that must be overcome. For example, adsorption cooling beds have poor effective thermal conductivities which need to be improved or offset [91]. Magnetic refrigeration is also a promising direction, and future research is required for efficient, room temperature operation [96, 97]. Retrofitting an existing system with novel technology can be more challenging than designing a new system. However, since much of the building stock has already been built, water and energy savings applicable to retrofits hold substantial promise for reducing energy and water use [399, 400].

Due to the transition to lower GWP refrigerants [333], it is important to understand the heat transfer characteristics and system performance (e.g., coefficient of performance and capacity) of new refrigerant blends. Many of the lower GWP refrigerants are mildly flammable (i.e., designated A2L by ASHRAE), so safety guidelines for handling and running equipment with these mildly flammable refrigerants are an important, active research topic [401]. Another area of research for refrigerants is improving their generally low heat transfer characteristics. However, since refrigerants generally have low surface tension, heat transfer enhancement options are challenging. Creating a durable surface that would enhance refrigerant heat transfer through dropwise condensation would be revolutionary [402, 403].

## 6. Heat and mass transfer in Food and Water systems

It is projected that food production will need to increase by 50% by 2030 to meet the demand of a growing population [120]. Seventy percent of global water withdrawals are currently used for agriculture [4], prompting Green et al. [121] to label water as “blue-gold.” There is competition between agriculture and energy for water resources; for example, Zeng et al. [122] estimated that 54% of globally installed hydropower system competed with irrigation. Therefore, it is critical to estimate irrigation rates [119, 123, 404] and ensure sustainable water use [10, 122, 124]. The following sections discuss heat and mass transfer research involving evapotranspiration from crops [i.e., the summation of evaporation from soil and transpiration from plants (itself a mass transfer process [405])] and soils.

### 6.1. Food and Water: Evapotranspiration from crops

Evapotranspiration (ET) completes the water cycle [127, 406] and is a critical component of agricultural management and the food, energy, and water nexus [11, 128]. Evapotranspiration is a combination of evaporation and transpiration, while plant transpire primarily to cool themselves, analogous to humans sweating. Rejecting heat through transpiration is required to bring down the temperature, as high temperature hinders plant growth and flowering [407]; transpiration tends to dominate over evaporation as the plant canopy grows and fully shades the soil [408]. Reductions in evapotranspiration would lead to water savings for crop production. Several important factors (e.g., net solar radiation, wind speed, temperature, relative humidity, soil moisture availability) influence evapotranspiration (eqns. 8 and 9) [129]. Seasonal variability affects evapotranspiration; in the northern parts of the US, transpiration begins in April, reaches maximum in July and starts to decrease in October, whereas in southern parts of the US, evapotranspiration continues throughout winter [130].

Since evaporation is an important component of water cycle and rainfall recycling [131], estimation of ET is necessary to understand and manage the water cycle efficiently. Walter et al. [129] derived equation of crop evapotranspiration ($ET_c$) on the basis of proper crop coefficient ($K_c$). Standardized reference evapotranspiration [($ET_{os}$) or ($ET_{rs}$)] was used to determine crop evapotranspiration (Table 5).

**Table 5 Evapotranspiration and crop coefficient equations, Walter et al. [129]**

| | | |
|---|---|---|
| | $K_{co} = \frac{ET_c}{ET_{os}}$ or $K_{cr} = \frac{ET_c}{ET_{rs}}$ | (**Error! Bookmark not defined.**8) |
| | $ET_{sz} = \dfrac{0.408\,\delta\,(G_{net} - G_{soil}) + \gamma\,\frac{B_{num}}{T + 273}\,u_{2m}\,(p_{sat,1.5-2.5m} - p_{v,act,1.5-2.5m})}{\delta + \gamma\,(1 + B_{denom} u_{2m})}$ | (9) |
| **Symbol** | **Definition** | **Units** |
| $ET_{sz}$ | standardized reference crop evapotranspiration for short (ETos) or tall (ETrs) surfaces | mm d$^{-1}$ or mm h$^{-1}$ |
| $G_{net}$ | calculated net radiation at the crop surface | MJ m$^{-2}$ d$^{-1}$ or MJ m$^{-2}$ h$^{-1}$ |
| $G_{soil}$ | soil heat flux density at the soil surface | MJ m$^{-2}$ d$^{-1}$ or MJ m$^{-2}$ h$^{-1}$ |
| $T$ | mean daily or hourly air temperature at 1.5 to 2.5-m height | °C |
| $u_{2m}$ | mean daily or hourly wind speed at 2-m height | m s$^{-1}$ |
| $p_{sat,1.5-2.5m}$ | saturation vapor pressure at 1.5 to 2.5-m height | kPa |
| $p_{v,act,1.5-2.5m}$ | mean actual vapor pressure at 1.5 to 2.5-m height | kPa |
| $\delta$ | slope of the saturation vapor pressure-temperature curve | m s$^{-1}$ |
| $\gamma$ | psychrometric constant | kPa °C$^{-1}$ |
| $B_{num}$ | numerator constant that changes with reference type and calculation time step | K mm s$^3$ Mg$^{-1}$ d$^{-1}$ or K mm s$^3$ Mg$^{-1}$ h$^{-1}$ |
| $B_{denom}$ | denominator constant that changes with reference type and calculation time step | s m$^{-1}$ |

Eddy covariance, a micrometeorogical mass transfer process, was evaluated to estimate ET [409-415]. Abraha et al. [409] applied the eddy covariance method in seven Midwest U.S. fields to estimate ET of newly established rain-fed cellulosic and biofuel crops. The range of ET varied from 45% to 77% (mean 60%) over 4 years. Marras et al. [413] used direct eddy covariance (DIR) method to estimate daily crop coefficients, which is the ratio of crop evapotranspiration to a standard value (equation 8). Holder et al. [415] used previous eddy covariance models [132-134] to theoretically estimate ET from a high-water-demand plant (i.e., Miscanthus giganteus) and the data were compared with on-site eddy covariance instrumentation.

Evapotranspiration is often partitioned into evaporation and transpiration and calculated using stable water isotopes, including calculation of leaf area index (LAI) and calculating root water uptake [121, 135, 136, 405, 411, 412, 416, 417]. Diarra et al. [137] determined the percentage of transpiration in total evapotranspiration increased from 52% to 74% with increased leaf area indices. In many cases, isotopic biogeochemistry was used to separate evaporation and transpiration [136, 405]. Li et al. [412] applied eddy covariance method to partition ET in 30 experimental sites and observed the ratios are a function of plant type. Mean annual transpiration to evapotranspiration (T:ET) were $0.75 \pm 0.17$, $0.62 \pm 0.16$, and $0.56 \pm 0.15$ for evergreen needleleaf forest ($0.75 \pm 0.17$), croplands, and grasslands, respectively. Leaf area index is a parameter that affects evapotranspiration. Gu et al. [416] partitioned ET of terrestrial biomes into transpiration, canopy interception evaporation, and soil evaporation. The T:ET ratio ranged between 0.29 to 0.72 across different set of biomes, lower than previous studies [138, 139, 418]. Rothfuss et al. [405] partitioned ET from in a fully grown fescue cover (i.e., Festuca arundinacea). The contribution of soil evaporation to total evapotranspiration to decreased from 100% (i.e., bare soil) to 94%, 83%, 70%, and 5% at 16, 28, 36, and 43 days after seeding; with growth of canopy, the percentage contribution of evaporation in total evapotranspiration decreases.

### 6.2. Food and Water: Evaporation from simulated or real soils

Philip and De Vries [419, 420] studied evaporation from partially dry soils in the late 1950s; after partial dryout, evaporation rates were 1.5-5 times that predicted by vapor diffusion equations. This increase in evaporation was attributed to the formation of liquid bridges (i.e., liquid islands) between soil pores; condensation occurred at one interface and evaporation at the other, therefore accelerating evaporation. Jury et al. [421] modified the Philip and De Vries [419, 420] model with increased influence of liquid water on vapor transport.

Evaporation from simulated or real soils begins with a high evaporation rate from the saturated media (i.e., stage-1 evaporation). Once the capillary force is balanced with the gravitational and viscous forces working in the opposite direction, the transition between stage-1 to stage-2 takes place and the evaporation rate decreases significantly. Transition from stage-2 to stage-3 is a slower process as the capillary action takes place against the gravitational force and the evaporation rate decreases [422].

Simulated soil column created with sand [140, 141, 422-428] or glass beads [429, 430] were often used to replicate the properties of soil pores without the added complexity of absorption. Evaporation from hydrophobic soils was 50-65% longer than the evaporation from hydrophilic soils [423-426]. Shokri et al. [424] studied evaporation from hydrophilic sand columns in the presence of hydrophobic layers at 25.9˚C and 22% RH over 30 days; hydrophobic layers restricted evaporation. The largest evaporative mass loss was observed from the 255-mm hydrophilic column (i.e. ~55 g) and the lowest evaporative losses were observed in the 25-mm-deep hydrophobic column on top of hydrophilic sand and 18-mm hydrophilic/7-mm hydrophobic column (i.e. ~15 g) after 30 days. Or et al. [141] and Mosthaf et al. [140] analyzed the transition between stage-1 to stage-2 evaporation on the basis of capillary action and applied Richard's equation to explain the phenomena. Chakraborty et al. [429, 430] evaporated sessile water droplet from a simulated soil pore (i.e., three 2.38-mm glass beads) created with glass (i.e., hydrophilic) and Teflon beads (i.e., hydrophobic) in a controlled atmosphere 45% and 60% RH at 20°C. Evaporation rates were faster from glass pores in part due to varying contact angles and liquid island geometry.

Bittelli et al. [142] studied evaporation from bare soil and modeled the heat coupling mechanism associated with evaporation. Sakai et al. [431] observed evaporation from a sandy column prepared with Hamaoka dune sand. Water vapor entered the sand column, condensed at the bottom, and subsequently liquid water moved upward and was evaporated. The experimental and numerically established model matched with the previous studies. Lu et al. [432] proposed a model to estimate enhanced vapor transport in soil during evaporation. The data indicated that the contribution of latent heat transfer at low temperatures was significant for estimating the enhancing factor. The dependency of latent heat transfer on soil-texture implicated the need to estimate enhancing factors for specific soil rather than using values from previous literatures. Farzi et al. [433] applied different mulch materials to restrict evaporation from soil in semi-arid regions.

### 6.3. Food and Water: Heat and mass transfer opportunities

Evaporation from soil affects irrigation and soil-water availability. Evaporation from soil starts with a higher rate from saturated media (i.e., stage 1) and consequently exhibits slower evaporation rates during partial dryout (stage-2), with the lowest evaporation rates in stage-3 where evaporation is limited by diffusion and condensation/evaporation in liquid bridges [419, 420, 422, 428]. Fundamental modeling of evaporation stages from soils could predict transitions between different evaporation stages to provide information for irrigation. Water use varies by crop and season. For agricultural crops, the primary purpose of evapotranspiration is cooling, which is a heat transfer process itself; often only 1% of water use is needed for plant growth [408], although there are exceptions at key times in the plant cycle (e.g., corn tassling [434]). Evapotranspiration is predominantly used to cool plants and is therefore a fundamentally coupled but not well understood heat and mass transfer problem. Evaporation models could inform irrigation schedules or be combined with plant health sensors. Additional, fundamental heat and mass transfer research could make more water-efficient crops. Transpiration itself is a mass transfer process impacted by leaf coverage, plant type, and ambient conditions; new understanding of the transpiration process, combined with breeding techniques, could create more drought-resistant plants [435].

## 7. Food, Energy, and Water: Food production and storage

Globally, 1.3 billion tons/year (i.e., 33%) of food produced for human consumption is lost or wasted [3]; the majority of losses in industrialized countries are at the consumer stage while in developing countries food losses occur at the early stages of the food chain [436].

### 7.1. Food, Energy, and Water: Greenhouses

Greenhouse farming offers the ability to protect crops against extreme and seasonal weather changes and control other growing conditions, thereby extending the growing seasons and increased crop yield [437]. Depending on the climate, greenhouses may require cooling and/or heating in order to remain at growing conditions [438]. Additionally, not all incident solar radiation is photosynthetically active radiation (PAR) and is therefore unnecessary for plant growth; non-PAR can be filtered out or used for other purposes [349, 438]. Lamnatou and Chemisana [143, 349] documented a variety of greenhouse claddings as well as possible uses for the solar radiation not required for the plants.

#### 7.1.1. Greenhouse filters

Photosynthetically active radiation (i.e., wavelengths between 400 and 750 nm) accounts for approximately half of the energy in solar radiation. By using filters, the total amount of radiative energy entering the greenhouse can be significantly reduced. In summer, this is particularly impactful as reducing non-PAR reduces the amount of energy required to cool the greenhouse [438]. Filtering light can also reduce evapotranspiration, lowering water usage requirements, as well affect plant and fungal growth and pest behavior [143, 349, 438-440].

#### 7.1.1.1. Near-infrared blockers

Near-infrared radiation (NIR) (i.e., wavelengths between 700 nm and 2500 nm) contains the majority of non-PAR solar energy. Hemming et al. [441] evaluated the effectiveness of NIR filtering materials applied to glass and plastic. Their study found that when the filtering material was applied to a glass substrate the transmissivity in the PAR range was good while being reflective in the NIR range. Sonneveld et al. [438] investigated the effects two metallic films which were designed to be PAR transmissive and NIR reflective. Without any other greenhouse design improvements, the films were predicted to halve the heat load of the greenhouse and lower plant transpiration by one third for greenhouse in during summer in northern Europe. Other studies described by Lamnatou and Chemisana [349] also take note of the reduction of greenhouse temperature and plant transpiration. Hemming et al. [442] found that in addition to these benefits, tomato production could be increased by 8-12% through NIR filtering.

#### 7.1.1.2. UV blockers

Unlike NIR, blocking or filtering out ultraviolet radiation (UV), wavelengths ranging from 10 nm to 400 nm, will not significantly heat load a greenhouse's heating load. Instead, blocking UV can affect the growth or behavior of insects, some fungal pathogens, as well as the plants being grown in the greenhouse [349]. Kittas et al. [440] tested two UV absorbing films, 0% and 3 % UV transmittance, as well as a polyethylene film with 5% UV transmittance on the growth of soilless eggplant. Lower UV transmittance was correlated with taller plants and a higher leaf product, increased by 21% and 17%, respectively, compared to the 5% UV case. Fruit size in the UV absent case was also increased. In a similar study, Papaionannou et al. [443] compared the growth of tomatoes grown under surfaces with low UV transmittance (i.e., 0.4%–1.4%) and high UV transmittance (i.e., 20.7%–28.7%). While the total fruit yield, quality, and nutritional values were similar in all cases, the number of fruit which had been damaged by insects were 50%–60% lower compared to the fruit grown in the higher UV environment.

#### 7.1.1.3. Photosensitive claddings

Similar to UV blockers, photoselective claddings (e.g., adjust the wavelength ratio of PAR) affect the growth of plants within the greenhouse without significantly changing the radiative energy entering the greenhouse. Li et al. [444] studied chrysanthemum and bell peppers; at a red/far red ratio of 2.2, there was a 20% and 30% height reduction in the chrysanthemum and bell pepper, respectively, after four weeks. Similarly, Shahak et al. [439] used photoselective shade nettings and found similar results as described for other photoselective films as well as UV blockers.

#### 7.1.1.4. Lenses

Films or filters can be applied to the surface of a lens to allow desired wavelengths to enter the greenhouse while reflecting other wavelengths to a focus for conversion to low or high grade energy. By using lenses to redirect incident radiation, any thermal conversion device needs to only be positioned at the focus of the lens, thereby reducing the size and cost of the system. Due to their lightweight and thin profile, Fresnel lenses are a good option for greenhouses, though parabolic and circular lenses have also been examined [349, 438, 445-447]. While parabolic trough collectors have concentration factors of ~120, the concentration factor is strongly dependent on incidence angle and therefore requires active adjustment of the lens and thermal conversion system

[438]. Circular trough and Fresnel lenses can have concentration factors around 30-40 and are less dependent on incidence angle than parabolic lenses; however, the location of the focus changes and requires active repositioning of the thermal conversion device [74, 438].

#### 7.1.1.5. Fluorescent solar collectors

Fluorescent concentrators utilize a transparent medium of high transmissivity and refractive index intermixed with species that are highly absorbent and emissive. When light enters the fluorescent solar concentrator (FSC), some of it is absorbed and remittent by the species at angles which trap the light within the FSC due to Snell's Law [143]. This trapped light can then be directed toward PV cells for conversion to electrical energy while the remaining light passes through to illuminate the greenhouse. By dyeing FSCs, the same effects described under photoselective claddings can be achieved [448, 449]. Pearson et al. [450] used FSCs to convert UV to light with wavelengths between 400 nm and 480 nm; however, only 16% of the absorbed UV was emitted downwards, into the greenhouse.

## 7.2. Food and Energy: Storing food

### 7.2.1. Overview of granaries

A prominent form of large-scale dry food storage is the granary. Perhaps the most important factor in granaries involving heat and mass transfer is the preservation of food against insects, fungus, and other pests [451-455]. These infestations prefer an environment that is warm, moist, and contains food. Keeping a granary at temperatures of 15ºC and below can prevent insect development [451]. Moist grain (e.g., with ~15% or more moisture content) will respire more quickly than dry grain, a process that can create hot spots [451]. In general, heat and mass transfer has largely been studied in three categories: keeping the storage unit cool and dry [451, 453, 455-460], detecting pests [461], and getting rid of pests once they are found [452, 462-466].

### 7.2.2. Creating cool and dry storage

Air flow can be used for lowering the temperature and moisture content in silos and models were developed to understand heat transfer and air flow in a silo [451, 455-457, 460]; however, increased energy is required to actively motivate air. As grain was subjected to heating and cooling cycles, moisture redistributed within the grain and tended to gather towards the top layers [453]. Increased insulation may be able to effectively reduce storage temperatures passively. Through CFD simulations, Jia and He [459] determined that an identical layer of insulation was considerably more effective on the outer walls of the silo than the inner. A thicker layer of insulation on the inner wall (e.g., a 55 mm expanded polystyrene panel) was less effective than the original layer (e.g., 40 mm) on the outer wall.

### 7.2.3. Detecting and eliminating pests

As grain respires, hot spots are created, and insects gravitate towards these hot spots. In turn, the insects' respiration increases hot spot temperatures, creating a feedback loop [451]. The heat produced by the insects depends on their life stages, ambient air temperature, and moisture content of the grain, resulting in ~2ºC–22ºC temperature increases [467, 468]. Mani et al. [467] simulated *Cryptolestes ferrugineus*, a species of lined flat bark beetle, which requires a minimum temperature of 17ºC to develop and multiply. In wheat grain with a 14.5% moisture content, an initial temperature of 25ºC, and initial infestation of 6,000 adult insects, hot spots did not develop. However, hot spots appeared when the initial temperature was increased to 30ºC, 14.5% moisture content. Initial infestations in this grain were simulated in a 6-m-diameter bin. Uninfested grain reached temperatures as low as 0.5ºC, while introducing 600 adults resulted in temperatures 1ºC above the uninfested bin, 1,300 adults predicted temperatures as high as 39ºC by early winter, and introducing 31,000 adults resulted in a similar hotspot in fall and caused the insects to migrate through the entire bin.

Although important, detecting pests can be challenging. Wu et al. [461] developed an electric nose to detect insects; while the nose did well at low moisture levels of 14%, it was unable to function correctly at moisture levels above 18%. Therefore, more research (e.g., chemical, mechanical, thermal means) focused on destroying pests. Turning the grain disrupted insect-induced hot spots, and more so if it was done repeatedly at intervals, as long as the grain was reduced to a temperature in which the insects no longer thrived (e.g., 12ºC) [469].

Thermal treatments may destroy pests. In order to achieve the best mortality rate with minimum damage to grains, it is desirable to quickly heat grain to 65ºC and then rapidly cool it to 25ºC [465]. Various methods have been considered, such as placing grain in a hot room [463], hot air passing through the grain/dry storage (e.g., alfalfa bales) [458, 463, 464], and radio frequencies [452, 462, 465, 466]. Currently, much of this work has been in understanding the dynamics of and developing a workable simulation model for these methods [452, 463-465]. Experimentally, it has been found that for heated air treatments, increasing relative humidity, temperature, and velocity of inlet air shortens the time needed to reach the desired treatment temperature. For example, increasing inlet air temperature from 76ºC to 78ºC, relative humidity from 14% to 43%, and velocity from 0.12 to 0.15 m/s decreased the time needed to heat an alfalfa bale to 60ºC from an unspecified initial temperature decreased from 226 minutes to 10 minutes [458]. Exposing *Sitotroga cerealella* in white corn to microwaves at powers of 293 W, 390 W, and 475 W for 56, 40, and 37 seconds respectively, and maintaining temperature for 3 minutes before cooling the corn with a fan achieved 100% mortality without significant effects on the corn [466].

### 7.3. Food and Energy: Preserving food

#### 7.3.1. Drying food

Drying is a method of both preserving food and preparing it for consumption. The main concerns when it comes to drying food are energy costs [470-474] and preservation of quality [471-473, 475-477]. Drying food requires energy to evaporate water [474]; in developed countries, it can account for as much as 12-20% of a nation's energy requirements [473]. In order to improve drying methods, research is being done to be able to understand, model, and combine varying processes of drying [470, 471, 473-476, 478-482], and to experiment with various newer forms of drying such as ultrasound and spray drying [144, 472, 477, 483]. At the cellular level, water bound in the food can be strongly bound water, found in the cell wall; loosely bound water, found inside the cell; and free water, found in between cells and in capillaries [482]. During the drying process, the collapsing of cells happens at various times rather than all at once [481].

Perhaps the oldest known method of food drying is solar drying. Weather, insects, animals, and even human intervention can pose challenges [479], yet sunlight can be used in a forced convection greenhouse. Experimentally, a greenhouse produced amla (i.e., Indian gooseberry, dried fruit candy) and reduced the drying time with a calculated payback period of 17 months [478]. A similar greenhouse, used to dry bitter gourds, was fitted with a heat storage medium. The quality of the dried product was superior to open air solar drying, and that the heat storage medium reduced the fluctuation of temperature between the collector and drying chamber, thereby providing more uniform heating [479]. Similarly, infrared is a common method of drying food, but its energy costs are high. Using a solar-heat recovery assisted infrared dryer resulted in a more efficient dryer and higher quality food. At 50ºC, the efficiency of the dryer with and without the heat recovery device averaged at 3g% and 22.6%, respectively [475].

Convection and microwaves are two more forms of drying that are often combined; models have been developed for many foods, including drying of pumpkins [470], drying-roasting of quinoa [480], green peas [474], etc. Some foods (e.g., wheat seeds) are negatively affected by excessive exposure to microwaves [476]. Models have been created to simulate the microwave drying of as well as a combination of microwaves and convection to dry wheat seeds [476]. Kumar et al. [471] suggested intermittent microwaves (e.g., 60 seconds on, 120 seconds off) allowed the temperature to redistribute between pulses and improved the quality of the product (i.e., an apple).

Additional methods of drying are of interest. Ultrasound, typically between 20 and 40 kHz [144], is a fast and energy-efficient method of drying food, though it can negatively affect food composition and nutrients [144, 477]. It is useful in regenerating desiccants such as silica gel which can be used to keep food dry in storage. Microwave-vacuum drying has also been tested on cranberries, yielding 96% faster drying times than convective drying, with increased color retention and antioxidant activity [477]. Electrohydrodynamic drying, which has less impact on food quality than hot air drying, has also been modelled [472]. Another form of drying, most notably used for liquid dairy products, is spray drying, consisting of spraying small (i.e., 50 μm) droplets of the liquid, at a temperature below 100ºC, into a drying chamber at 200ºC before it is cooled in a fluid bed [483].

### 7.3.2. Freezing food

Freezing keeps food safe for consumption for longer periods of time. Common problems in food freezing include the formation of ice crystals due to moisture in the food, which can lower the quality of the food [484, 485], and energy consumption involved in freezing [146, 486, 487]. As of 2019, food refrigeration is accountable for roughly 8% of electricity consumption globally [487]. To address this, fundamental studies are needed to predict the behavior of freezing foods

[485, 488, 489], to improve upon existing methods of freezing foods [145-148, 484, 487, 490, 491], and to explore new approaches [486].

Currently, many freezing methods rely upon the use of cold airflow to freeze food. In a review by Zhao and Sun [145], various forms of packaging were analyzed with the intent of giving a means to compare the effectiveness of different shapes and kinds of packages to protect and cool their contents. Similarly, certain shapes of containers affected the airflow around them and decreased efficiency during the freezing process, such as carton boxes [490]. The combination of air velocity and evaporation temperature of a refrigeration system has also been found to be optimizable; since a slower freezing time lowers energy cost but causes the formation of larger ice crystals which is harmful for food quality, adjusting the evaporation temperature and a constant fan speed to achieve an optimized freezing time is possible [491].

Innovations in the freezing process can reduce energy use. Powell-Palm and Rubinsky [487] examined the food freezing process: instead of a conventional, isobaric process (i.e., atmospheric pressure), an isochoric (i.e., constant volume) system used up to 70% less energy and improved the quality of the frozen product. Static electric fields in freezing reduced the size of water crystals formed by increasing nucleation, thereby reducing the damage caused to the product [484]. Similarly, ultrasound can augment the freezing process. By inducing cavitation in the liquid inherent in the food being frozen, nucleation for ice crystallization increased and caused smaller ice crystals and, therefore, less damage to the food [147, 148]. The use of ultrasound is also observed to speed the nucleation process [146, 147], improve heat transfer rates [146, 148], and therefore speed the process of freezing; however, since it can affect the thermal properties of refrigerants, intermittent – rather than continuous ultrasound usage – is more advantageous [148]. An added benefit to the use of ultrasound is that it helps to prevent the cooling elements from being encrusted in ice, keeping the overall system more efficient [146, 147]. In particular, ultrasound has been researched in the production and preservation of dairy items such as yogurt and ice cream to create smaller ice crystals by decreasing the size of the fat globules in yogurts [146].

### 7.4. Food production and storage: Heat and mass transfer opportunities

Food storage, including freezing and granaries, offer substantial heat transfer opportunities. There is a need for more fundamental models for freezing food [485, 488, 489] and approaches that control crystal size and growth (i.e., quality) while reducing energy usage. Grain moisture content represents an opportunity for heat transfer research due to its impacts on energy consumption, price, and insects. Grain storage is a non-linear function of temperature and moisture content. For example, corn at 16 ºC, 20% wet basis moisture content has a storage life of 25 days; a reduction in moisture to 18% wet basis extends storage life to 50 days. Therefore, grain prices are specified based on moisture content, with reduced prices at higher moisture levels. If field drying cannot be accomplished due to weather or other factors, mechanical drying is employed and, due to large volumes, incurs a significant energy cost [451, 492]. During storage, moisture migration occurs due to convective cooling and leading to moisture gradients in a storage facility (e.g., warm air in the center dries grain, cool air on top may lead to condensation) [492], which can provide moisture for insects and represents an opportunity for CFD in large scale systems and fundamental heat transfer modeling at the granular level. Insect hot spots are also dependent on ambient temperature and moisture content of grain [467, 468].

Indoor agriculture systems also present an opportunity for heat and mass transfer research, including opportunities for materials development and radiation heat transfer. Spectral-dependent materials and radiation heat transfer approaches could reduce non- photosynthetically active radiation, thereby reducing required greenhouse cooling [438]. Heating greenhouses in the winter using power plant and incineration facility waste heat [493]. Understanding the impacts of filtering wavelengths on evapotranspiration, lowering water usage requirements, plant growth and pest behavior are important opportunities [143, 349, 438-440].

There are many considerations for HVAC design for plant and animal enclosures, as highlighted by ASHRAE [494]. Fundamental heat transfer modeling around leaves is an opportunity due to the impacts of moisture on diseases. Recirculation of air in greenhouses is generally favorable; however, high velocities (e.g. > 1 m/s) may inhibit plant growth or harm plants [494]. There are still unresolved, fundamental heat transfer questions related to heat transfer and HVAC design for cannabis grow facilities, which is an emerging area. While lights are on, target temperatures are ~22.2–27.7 ºC (i.e., required for flowering), and ~18.9–21.1 ºC while lights are off; target humidity levels based on the stage of plant growth. The sudden thermal cycling caused by light cycles results in near step changes in HVAC loads and represents heat transfer opportunities [495]. While food and people may require very different indoor environmental conditions there are opportunities to integrate or repurpose technology or systems.

## 8. Heat and Mass Transfer in the FEW Nexus: Opportunities and future directions

Heat and mass transfer play a critical role in many aspects of the food, energy, and water nexus. Several cross-cutting themes emerged from the literature; a few examples are highlighted in this section. In nearly all areas, there was a need for fundamental, thermal fluids knowledge:

- For hydraulic fracturing, fluid properties (e.g., viscosity) are important topics of exploration; fracture fluids cannot deteriorate while in use and understanding how the viscosity changes in the well (i.e., high temperatures and pressures) are essential for predicting fluid flow [165].

- Many novel building technologies have significant potential but have disadvantages that need to be overcome (e.g. the poor effective thermal conductivities of adsorption cooling beds) [91].
- Fundamental, heat transfer improvements for air cooling technology would be beneficial for air-cooled condensers as well as air cooled chillers [205, 347], including leveraging additive manufacturing [223].
- Membrane fouling is a top challenge of desalination [496]; emerging technologies such as capacitive deionization [497] and electrodialysis, particularly when coupled with electrodialysis reversal [49, 50], may be promising alternatives.
- Enhancement of convective cooling in gases for internal and external geometries, of use for combined cycles, nuclear reactors, etc.
- Understanding the spectral impacts of transpiration would yield improved evapotranspiration modelling, thereby evaluating the water use by plants in a more efficient way [498-501].
- Interdisciplinary approaches to understand plant transpiration and reduce agricultural crop water use [11, 128].

Scaling up from the laboratory to large-scale, integrated systems represents significant heat and mass transfer challenges:

- One key challenge is improving process intensification models for the energy industry, which incorporate the role of water. Conventionally, energy and exergy efficiency have been two prime mechanisms for feasibility assessment.
- Quantification of water consumption with a universal metric (e.g., akin to energy efficiency) is a challenging task which needs to be connected to process evaluation tools.

- Scaling methodology – top down or bottom up approaches rely on geometric and dynamic similarities which are built on representing separate or decoupled physical processes. These approaches will need to be revisited for more interacting physical processes.
- Alam et al. [367] implemented active phase change materials in a multi-story building, yet poor implementation of the technology and lack of knowledge by the building maintenance staff resulted in the TES system being ineffective or inactive for a much of the year. Although improved TES systems have strong benefits for buildings and power generation, this case study demonstrates that creating robust, scaled-up systems can be a challenge when environmental conditions are not as favorable as they were in the laboratory.
- Since there are a limited number of Generation IV reactors in commission and water is currently a relatively inexpensive resource for most nuclear power plants, there is little information provided about total water consumption in Generation IV reactors. There is some data on LWR water consumption, but even this is not reliable [31]. Most information on Generation IV reactors has been focused on safety, as these reactor designs have not been implemented and heavily researched in applied settings.
- Combining novel ideas that could lead to better results (i.e. spray cooled solar enhanced natural draft cooling towers) [33].
- Scaling up from laboratory soil samples to field implementation [142, 431-433].

Additional heat and mass transfer research could increase economic viability of new systems:

- Currently, the use of natural gas hydrates as an energy source are unsustainable; the amount of gas retrieved is low, compared to the amount of energy required in hydrate dissociation [103]. There is also a large amount of water produced for the small amount of natural gas. Further research is needed to find ways to sustainably and economically dissociate natural gas hydrates; research into the thermal properties and their effect on the hydrate dissociation could be a good start [103].

- Design of more energy- and water-efficient building systems which can be installed as part of a building retrofit [332].
- Integration of low-cost affordable clean solar energy technologies with other systems (e.g., desalination) [502-505].

Increasing efficiency when utilizing resources, including using waste products, features thermal fluids challenges:

- A research area for hydraulic fracturing is the use of seawater instead of freshwater in fracturing fluid [107, 112]. Fracturing fluid does not have to be of the same quality as water for other use, like irrigation. Using seawater would decrease the freshwater footprint of hydraulic fracturing. Along these lines, there is potential for using wastewater from other places, such as power plants.
- Waste water desalination [506-510].
- Practical uses of the waste heat from power plants (e.g., thermal desalination, HVAC, etc) [325] and integrating desalination and water treatment technologies with renewable energy [48].

## 9. Conclusions

Heat and mass transfer play a pivotal role in the food, energy, and water nexus. This literature review focused on heat and mass transfer applications relevant to two or more branches of the FEW nexus. Broad topics included energy-water (i.e., energy extraction, power production and cooling, water desalination and purification, and buildings/HVAC&R), food-water (i.e., evapotranspiration), and food-energy-water systems (i.e., greenhouses and food storage and preservation). As part of this review, over 100 review papers on heat and mass transfer in the food, energy, and water topics were tabulated in Table 1 and over 350 unique research articles were discussed. Each section focused on the current state of the art and future heat and mass transfer opportunities. Overall, multiple crosscutting themes emerged from literature: the need for fundamental, thermal fluids knowledge; scaling up from the laboratory to large-scale, integrated systems; increasing economic viability of new systems; and increasing efficiency when utilizing resources, including using waste products.

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**Nomenclature**

| | |
|---|---|
| $A$ | Area |
| $B$ | Constant |
| $C$ | Concentration |
| $c_p$ | Specific heat |
| $D$ | Diameter |
| $EF$ | Energy factor |
| $ET$ | Evapotranspiration |
| $f$ | Friction factor |
| $G$ | Solar irradiation |
| $GPC$ | Global performance coefficient |
| $hfg$ | Latent heat of vaporization |
| $K$ | Crop coefficient |
| $L$ | Flow length |
| $m$ | Condensate mass |
| $M$ | Molecular weight |
| $n$ | Number of moles |
| $Nu$ | Nusselt number |
| $P$ | Pressure |
| $\Delta P$ | Pressure drop |
| $PEI$ | Performance evaluation index |

| | |
|---|---|
| $Q$ | Energy |
| $\dot{Q}$ | Heat transfer rate |
| $R$ | Universal gas constant |
| $SRF$ | Salt rejection factor |
| $t$ | Time |
| $u$ | Velocity |
| $V$ | Volume |
| $\dot{V}$ | Volumetric flow rate |
| $z$ | Compressiblity factor |
| $\beta$ | Real hydration number |
| $\delta$ | Slope of the saturated vapor-temperature curve |
| $\varepsilon$ | Evaporation cooling efficiency |
| $\eta$ | Efficiency |
| $\rho$ | Density |

Subscripts

| | |
|---|---|
| *abs* | Absolute |
| *c* | Crop |
| *co* | Crop, using reference for short surface |
| *cr* | Crop, using reference for tall surface |
| *cw* | Cold water supply |
| *db* | Dry bulb |
| *denom* | Denominator |
| *f* | Fluid |
| *F* | Feed |
| *g* | Gas |
| *h* | Hydraulic |
| *H* | Hydrate |
| *i* | Inlet |
| *m* | Mean |
| *min* | Minimum |
| *num* | Numerator |
| *o* | Outlet |
| *os* | Short surface |
| *P* | Permeate |
| *rs* | Tall surface |
| *sat* | Saturation |
| *sb* | Standby |
| *soil* | At the soil's surface |
| *sz* | Standard reference |
| *t* | Time |
| *t_diss* | Onset of dissociation |
| *v,act* | Actual vapor pressure |

| | |
|---|---|
| *w* | Water |
| *wb* | Wet bulb |
| *0* | Initial |
| *1.5-2.5m* | Height of 1.5 to 2.5 m |
| *2m* | Height of 2 m |

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