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Review

Nuclear waste heat use in agriculture: History and opportunities in the United States

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ABSTRACT

Nuclear power plants (NPPs) produce a large amount of waste heat (WH) that has generally been perceived and regulated as an environmental liability. Given the abundance of WH from NPPs and the ubiquity of generally low-grade heat requirements of agricultural operations, from production to post-harvest, there is remarkable potential to harness NPP WH for agricultural uses with mutual economic advantages to NPPs and agricultural sectors. Taking advantage of this WH resource may improve the financial outlook of both the partnered power plants and agricultural businesses by providing an additional revenue stream, decreased heating costs, and a reduced carbon footprint. This review summarizes and interprets the historical discourse and research on agricultural applications of NPP WH in the U.S., and synthesizes technical constraints, unknowns, and opportunities for realizing the benefits of WH derived from the nuclear energy sector for agricultural value chains. Previous applications of WH in the agricultural industry demonstrate that this is a viable option to the benefit of the parties involved under the right conditions, but relatively little has been done to further this technology in the U.S. in recent years or explore novel applications. A revival of interest in this technology may be warranted given the current outlook for NPPs in the U.S. and a general interest in reducing the environmental impact of agriculture.

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1. Introduction

In the cheap generation of electricity the great problem must be how to secure and utilise by-products. With steam-driven stations the chief by-product is an abundant supply of hot water from the condensers, which in this country is looked upon as a nuisance to be got rid of as easily as possible. Would it not be possible to make use of this low-grade heat for agricultural purposes, so supplementing our all too scanty summers? — Turnbull (1916).

In the U.S., low-grade waste heat (WH) accounts for two-thirds of the primary energy supply (Parker and Anders, 2016). Generally in the form of heated water, WH is a low-grade energy by-product of power plant cooling systems and has abundant potential uses (Meekhof et al., 1977; Yarosh et al., 1972). The temperature range of WH varies but is generally 28−47 °C across most industrial sources (Meekhof et al., 1977; Miller, 1970; Papapetrou et al., 2018). Modern Rankine cycle power plants utilize low-grade heat sources but the low thermal efficiency of such systems involves generation of significant amounts of WH (Hung et al., 1997; Yamamoto et al., 2001). Waste heat generated from steam-electric power plants offers agricultural industries multiple opportunities as a potentially low-cost heating source.

Turnbull (1916) provided one of the earliest conceptualizations of utilizing low-grade industrial WH for agricultural applications, a concept that would reappear decades later when the U.S. Environmental Protection Agency (EPA) enacted WH disposal regulations for steam-electric generation plants (Boersma and Rykbost, 1973; Meekhof et al., 1977) including fossil fuel and nuclear power plants (NPPs). Outside the U.S., agricultural systems particularly in Europe are already utilizing energy from combined heat and power plants to meet heat demands (Vermeulen and Lans, 2011; Zwart and Bot, 1997). As interest in thermal power plants expands internationally, other countries are beginning to make strides towards implementing nuclear (Ağbulut, 2019). These new developments may create the foundation for increased use of combined heat and power plants, which can spark an interest in WH use.

Waste heat recovery technology can utilize fossil fuel and non-fossil fuel (e.g., nuclear) WH to meet the thermal energy requirements of climate-controlled agricultural systems. Whereas WH from non-nuclear sources, largely coal-fired plants, has been used in the U.S. since 1916 (Turnbull, 1916), interest in nuclear WH utilization began in the late 1960s and early 1970s (Beall and Samuels, 1971b; Furlong et al., 1973; Olszewski, 1978). Four years after the opening of the world's first commercial NPP in Obninsk, Russia, in 1958 the Shippingport Atomic Power Station in Shippingport, Pennsylvania was the first NPP to open in the U.S. (ASME, 1980a,b; ENSREG, 2018a,b). Rapid growth of the U.S. nuclear power industry occurred during the 1960s and ultimately decreased during the following two decades, despite utility companies viewing production as economical, environmentally clean, and safe (DOE, 1994a,b). Concerns regarding nuclear issues such as safety and waste disposal increased at this time while the demand for electricity decreased (DOE, 1994a,b).

During the 1970s and early 1980s, an energy crisis emerged in the U.S. Among its other impacts, the petroleum shortage of 1973 led to high prices for heating oil in agriculture. As a result, agricultural producers sought alternative energy sources and management practices to lessen the consumption of fossil fuels and to increase the energy efficiency of the agriculture sector (Schnepf, 2004). Higher oil prices affected fuel consumption within the agricultural industry for direct and indirect farm energy uses (Miranowski, 2005). Improving the efficiency of agricultural practices, such as creating new methods for crop irrigation and drying, led to a decline in on-farm energy use (Schnepf, 2004). Simultaneously with the 1973 energy crisis, thermal pollution legislation was implemented during the 1970s. Increasing generation of steam-electric power raised environmental concerns on the impact of WH discharged to surface waters (Meekhof et al., 1977). The large quantities of WH released to surface waters (e.g., lakes, rivers) from power plants in the form of heated water can alter temperature of the receiving surface waters to the point of compromising the health and survival of aquatic organisms and ecosystems (Yarosh et al., 1972). To address this, the EPA produced or amended legislative regulations focusing on the handling and disposal of thermal effluent such as the Federal Water Pollution Control Act of 1972 (Brna, 1979a,b; Meekhof et al., 1977). Concerns over thermal pollution initiated the formation of WH programs within federal organizations such as the Oak Ridge National Laboratory (ORNL) in 1969 (Olszewski, 1978). Thermal effluent guidelines issued by the EPA in 1974 incentivized adoption of then-novel closed cycle cooling systems (i.e. cooling towers) to dissipate WH from steam-electric generating power plants (Brna, 1979a,b).

Drastic changes in the economics of nuclear power since the 1970s have further changed the landscape of WH use from NPPs. While existing power plants have been continuously improved to generate more power and operate more safely, changing market forces such as increased construction costs and deregulated energy markets have made new nuclear plants a risky financial investment. The future of the economics around nuclear power in the U.S. may be more favorable as federal and state governments consider carbon taxes or carbon emission cap and trade programs to discourage carbon-producing energy sources that happen to compete with nuclear power. The economics intrinsic to nuclear plants are expected to continue to improve as existing power plants are uprated, new plant designs reduce construction and operating costs, and the regulation process is streamlined (Joskow, 2006). These market forces are an incentive to find additional revenue streams, such as from WH utilization, and will likely vary across the world (Brook et al., 2014; Brook and Bradshaw, 2015).

Today, WH recovery and re-use offers opportunities to minimize the detrimental environmental impact of reject heat, reduce the handling costs of thermal effluent, and to improve overall energy efficiency (Yarosh et al., 1972). However, the benefits and challenges associated with alternative WH systems requires further research to determine the overall feasibility of implementing such systems. Nuclear WH offers unique opportunities and considerations compared to traditionally employed WH from fossil fuel or more recent sources such as data centers (Pärssinen et al., 2019). Due to the large capacity and constant operation of NPPs, this WH may provide unique opportunities for some applications. While most WH sources generate carbon and are intermittently operational (e.g., Ağbulut, 2019), a benefit of utilizing energy derived from nuclear relative to fossil fuel sources is a continuous source of carbon-free WH. Despite declines in interest and research on nuclear WH in the second half of the 20th century, the advantages of energy security, increased efficiency, and zero-carbon emissions of nuclear energy have spurred renewed interest in and discussions of a nuclear energy revival or renaissance (Ferguson et al., 2010; Janardhanan et al., 2017). Renewed interest in nuclear energy and construction of new NPPs both increase opportunities for co-engineering agricultural re-use of WH from NPPs as well as offering another potential benefit to the portfolio of nuclear energy. This review assesses realized and potential agricultural uses of nuclear WH in the U.S. with a focus on technical considerations, and identifies opportunities, challenges and constraints to its use in agriculture, with an emphasis on non-traditional applications (e.g., greenhouse vegetable crops).

2. Heat usage in NPPs/Agriculture

2.1. Background on NPPs

Nuclear power plants are among the safest and most reliable sources of power, and produce staggering amounts of thermal energy as a by-product. One way of quantifying safety of energy sources is to consider the amount of human lives lost per kilowatt hour of electricity produced. Even when including deaths from uncommonly severe accidents, nuclear power is orders of magnitude less deadly than most other sources of electricity (Brook et al., 2014; Sovacool et al., 2016). The reliability of NPPs is one of the most notable assets of nuclear power generation (Brook et al., 2014). Nuclear power plants constantly generate power at all times of day, at whatever site they are chosen to be built at, and under almost any weather conditions. As a result, high amounts of WH are generated from NPPs. For example, the Braidwood and Byron NPPs (Illinois) can each produce up to 3672 MW of thermal energy (Exelon, 2014a,b). This heat is produced with a relatively small amount of fuel, 3.03×10^{-8} the mass that would be required in a coal-fired plant. The energy density of nuclear fuel has allowed for the development of famously large-scale power plants. These large NPPs can produce electricity on the order of gigawatts, but they are still limited by the inefficiency of the Rankine cycle, rejecting roughly twice the electrical power in the form of WH.

Waste heat from thermal power plants is removed with a condenser and released to the environment. This can take several forms. The large cooling towers which are iconic of NPPs rely on natural evaporation to cool WH water to ambient temperatures, creating clouds as a by-product. As cooling towers can be expensive, in some areas it makes more sense to release WH water directly to surface waters such as a lake or river. This strategy is cost-effective but may require measures to be taken to ensure that the temperature of the surface water body is not altered to the point of inflicting ecological damage. Both methods of heat rejection entail an irrecoverable loss of energy. Concerns regarding fuel prices, power plant efficiency, and thermal pollution have encouraged efforts to find a use for WH to increase the utilization of WH, which also stands to provide a secondary source of revenue.

All thermal power plants reject WH in the process of converting thermal energy to electric power. Whether the source of heat is the combustion of fossil fuels, nuclear fission, concentrated solar rays, or even the geothermal activity of the planet, thermal power plants operate along similar principles. While WH has been explored as an option for increasing the efficiency of different thermal power plants, NPPs offer a unique advantage: they generate more WH than other power plants, and they do so more consistently. Nuclear power plants are the largest WH producers per unit of all power sources due to the combination of their large power rating and largest operational capacity factor (EIA, 2019). This has traditionally been a weakness of NPPs, as it increases the risk of damaging thermal pollution and has even led to costly plant shutdowns during exceptionally warm weather in Europe (Linnerud et al., 2011). If NPPs can utilize WH before it is released to the environment, however, it would be transformed from a weakness to a boon for the industry. Power plants would have an additional, secondary source of revenue, environmental regulations would be easier to satisfy, and a virtually untapped source of energy would be utilized by non-energy industries such as agriculture.

In the U.S. there are 98 nuclear reactors in 60 NPPs distributed across 30 states, producing 20% of total national electricity and over 56% of carbon-free electricity (NEI, 2019a,b). Despite their importance for domestic energy security, it is no secret that NPPs are struggling to remain commercially viable in the U.S. Generating heat and electricity with natural gas is cheaper, and intermittent energy sources have a negative impact on the aging fleet of NPPs, which were designed without the intent to load-follow. To stay relevant, innovation in the use of nuclear power is necessary. In the near future, there are promises of smaller, less expensive and safer reactors that may catalyze a renaissance in the nuclear industry, but the large plants in existence rely on uprating and subsidies to remain viable. Waste heat utilization may offer these plants another lifeline with which to continue depressing carbon emissions of the energy sector until these next-generation reactors can take root (Morgan et al., 2018). Waste heat utilization is not expected to become the primary source of profits to the nuclear energy sector, but its benefits for other industries could further entrench NPPs as an important source of jobs and tax revenue for local and state economies.

Understandably, there is concern about contamination with radioactive by-products from a NPP that must be addressed when discussing using WH, especially in agriculture. Use of the term “waste” in discussions of NPPs can be perceived as ominous, but the WH from producing power via the Rankine cycle is unrelated to the controversial nuclear waste that is a by-product of nuclear fission. The WH stream from the power plant condenser is isolated from the reactor core that would be the source of potential contamination. Additionally, WH is strictly regulated to prevent radioactive contamination of the surrounding area (USNRC, 2015a,b). The only radioactive contaminant that is consistently released from NPPs in measurable quantities is tritium (^3H), an isotope of hydrogen, in water molecules. Tritium loads in WH water are monitored and maintained below regulatory limits that are well below levels that may be considered dangerous. According to the World Health Organization (WHO), receiving 10% of recommended maximum annual radiation dose from drinking water is a reasonable regulatory limit to prevent serious health risks. This means that no more than 1 mSv to an individual should come from drinking water, which corresponds to an activity of approximately7600 Bq/L (CNSC, 2008a,b). The U.S. Nuclear Regulatory Commission (NRC) takes this a step further by assuming more water consumption per person and requiring that 1% of the maximum annual radiation dose be required by regulations, resulting in a regulated activity of 740 Bq/L (CNSC, 2008a,b). To be dangerously irradiated, one would have to drink 75,000 L of tritium-containing drinking water at the NRC regulatory limit according to these conventions. Waste heat utilization efforts do not entail human consumption of this water, so it would take a still greater level of exposure to endanger consumers of food produced from NPP WH-utilizing agriculture. Radionuclides are often automatically considered dangerous by reputation, but tritium is a relatively benign contaminant at the concentrations released by NPP, which are often 10- to 100-fold less than the already conservative regulatory limit. Many regulatory agencies allow considerably more tritium to be released than the U.S. NRC permits. For example, the Canadian Nuclear Safety Commission (CNSC) permits over 9-fold more tritium release in drinking water whereas in Finland over 40-fold more tritium is permitted in drinking water (CNSC, 2008a,b, 2014). Strict controls on tritium contamination and a separation of WH from fission products means that NPP WH may be used without risk of radioactive contamination.

2.2. Heating demands of agricultural systems

The heat needs of U.S. agriculture are currently met through multiple forms of energy such as gasoline, propane, natural gas and electricity (i.e. direct energy consumption). Indirect energy consumption occurs through the manufacturing of fertilizer and pesticide products off-farm (Hitaj and Suttles, 2016). Agricultural industries, particularly the greenhouse sector, rely largely on fossil fuels to meet heating demands, which are determined by climate, product, and management practices. As of 2017, there were 10,849 farms under glass or other protection (e.g., hoop houses) totaling over 112.5 million ft^2 (USDA, 2019). The agricultural sector accounted for less than 2%, or 1714 trillion Btu, of total U.S. primary energy consumption in 2014 (Hitaj and Suttles, 2016).

The feasibility of WH utilization for agricultural applications is dependent on a variety of complex environmental and agronomic factors, though general assessments of technical and economic feasibility are possible. In already established greenhouses, heating is the dominant operational cost (Başak and Sevilgen, 2016; NGMA, 1998a,b). Common commercial heating approaches in greenhouse production includes in-floor, benchtop, and overhead heating. Cooling apparatuses such as evaporative pads also require a heat source for controlling humidity levels within a climate-controlled system. However, commercially available systems that support alternative heat sources, especially nuclear WH, are extremely limited or non-existent.

The heating needs of climate-controlled systems largely depend on climate and crop type. The temperature characteristics of a geographic location (e.g., mean annual temperature, seasonal temperature maximums and minimums) will strongly influence heating needs, which will ultimately determine the choice of crop type and heating application (Chinese et al., 2005). Climates with colder temperatures, in particular nighttime temperatures, require more heat, though this depends on crop-specific heat demands. More spatially extensive and less insulated greenhouse designs are facilitated by cold-tolerant crops (e.g., leafy greens), whereas other crops (e.g., fruiting nightshades such as tomatoes, peppers, and eggplants) require more heat. Crop type merits consideration because it will ultimately determine temperature and lighting requirements, management practices (e.g., hydroponics) and the intended market of the crop.

3. Literature review on agricultural applications of nuclear WH

3.1. Methods

An exhaustive review of WH utilization was conducted by utilizing two search engines, Web of Science and Scopus, and the University of Illinois at Urbana-Champaign (UIUC) library database, during November 2017–April 2018. Additional resources used to collect data included professional websites or programs such as the Nuclear Energy Institute (NEI) and the Department of Energy (DOE). Prospective publications were selected based on keywords of “nuclear waste heat AND agriculture” and “nuclear waste heat utilization OR applications”. Final selection of publications was largely based on repeating themes such as crop types, agricultural systems, and heating mechanisms, and based on whether publications were related to current agricultural systems utilizing traditional or alternative heat sources. After initially collecting over

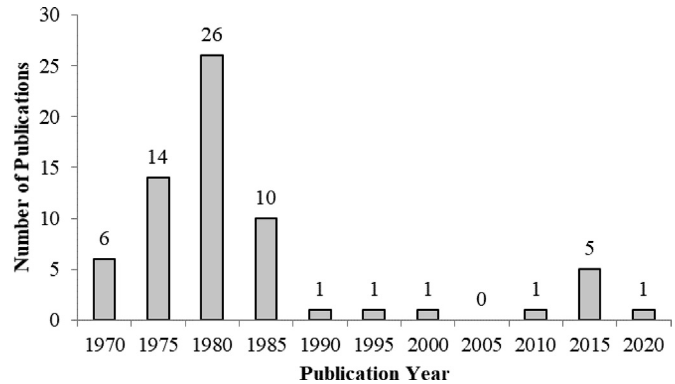

Fig. 1. Research publications on nuclear WH applications in agriculture. Publication year represents literature published within the indicated 5-year interval, based on the literature collected for the WH from digital and non-digital sources (n = 66).

150 publications, a total of 66 digital and non-digital sources were selected as relevant to the agricultural re-use of WH (Fig. 1). Most publications, in particular those found via conference proceedings, were excluded due to a focus on the engineering and modeling aspects of nuclear WH systems for agricultural applications. The selection process was not limited to nuclear WH heat or a timeframe.

Waste heat sources were documented as early as the start of the 20th century and through the 2010s. Relevant publications on nuclear WH re-use was found to be largely in the form of white papers, reports, and a combination of digital and non-digital conference proceedings. Limited access to older, non-digitalized journal publications was a common occurrence. As online journals often did not include issues prior to the 1970s, non-digitized publications were searched for using the UIUC library database.

3.2. Sources and trends in research on agricultural re-use of nuclear WH

The majority of global WH research efforts published in English occurred in the 1970s, with 79% of publications originating in the U.S. and authored largely by Oak Ridge National Laboratory (ORNL) and Tennessee Valley Authority (TVA) (Supplementary Table 1). Various electrical power plants in Japan also conducted WH research through agencies including the Japan Atomic Industrial Forum and the International Electric Research Exchange (IERE) Council (Beall and Yarosh, 1973). The ORNL specifically created a program on the beneficial uses of WH in 1969 in response to the growing concern of thermal pollution (Olszewski, 1978) and often collaborated with the TVA. The EPA and the National Aeronautics and Space Administration (NASA) often sponsored conferences on WH utilization. Similar efforts occurred in this period outside of the U.S. For example, in the mid-1960s, Japan began conducting experiments utilizing thermal effluent for aquaculture (Yang, 1970).

In addition to a handful of federal research agencies driving WH utilization research, two additional themes emerged from the literature. First, integrated agricultural systems that entail two or more conventionally non-proximal systems are commonly proposed (Beall and Samuels, 1971b; Price and Peart, 1973). Proposed systems often consisted of an aquaculture or animal rearing system linked to a climate-controlled greenhouse, where any remaining WH would be fully utilized (Boersma, 1970; Togawa et al., 2014). Second, the pioneer literature on agricultural re-use of nuclear WH emphasizes horticultural applications and a shared set crop species. Whether proposed or grown in a pilot experiment, traditional horticultural crops (e.g., tomatoes, cucumbers, leafy greens) within the WH literature dominate the majority of greenhouse production systems, followed by floriculture (Elsner, 1984; Helgeson et al., 1986). These crop types were likely chosen due to their popularity in commercial operations and overall profitability.

Agricultural applications proposed in the identified WH literature include: greenhouse systems (Manning et al., 1984; Ryther et al., 1977), aquaculture (Coutant, 1970; Pickering, 1970), open-field agriculture with in-ground or irrigation heating ((Boersma, 1970; Rykbost et al., 1975), livestock shelters (Beall and Samuels, 1971a; Miller et al., 1971), algae production (Boersma, 1970; Bond and Russ, 1977) and food processing facilities (Lundberg et al., 1979). Of these, the dominant system was climate-controlled greenhouse production (n = 47 or 71%) followed by aquaculture (n = 22 or 33%). A minority of studies (n = 13 or 20%) entail or propose experimental work with greenhouses to test WH re-use at pilot or commercial scales (Burns et al., 1976; Manning et al., 1984). Successful preliminary experiments for aquaculture systems are scarcer still (Guerra et al., 1976a,b; Suffern and Olszewksi, 1979) likely due to the greater complexity of aquaculture systems relative to greenhouse agriculture (Godfriaux et al., 1979; Suffern and Olszewksi, 1979). Thus, there is a need for experimental work to trial pilot greenhouse and other agricultural operations to determine feasibility of WH re-use.

Publications on WH utilization for agriculture are not necessarily specific to NPPs. In fact, the majority of identified proposed or pilot studies on WH re-use in agriculture evaluate fossil fuel power plants as the heat source. This likely reflects the greater dominance of fossil-fuel plants compared to NPPs. Experimental studies were largely limited to fossil-fuel power plants, whereas the majority of nuclear WH studies were theoretical or modeled and lacked detail on agricultural applications (e.g., economics) and did not consider the use of alternative high-value agricultural products. There were fewer pilot studies or scaled-up operations (i.e. n = 2 or 3%) than there are theoretical or modeled experiments, which were primarily focused on the economic and technical feasibility of using WH systems for agricultural applications. Modeling and testing of engineering and architecture of varying agricultural systems were more prevalent than data on crop yield and production parameters. In particular, synchronizing and optimizing management of agricultural operations reliant on WH with NPP operations were key considerations for realizing this application of WH. The relative absence of successful nuclear WH studies, management and crop data, and consideration for alternative high-value products limits interpretation of past feasibility studies and raises the need for pilot plant-scale research to experimentally determine agronomic and engineering considerations for and challenges to nuclear WH utilization in agricultural systems.

3.3. System-specific challenges

Heating accounts for up to 80% of total costs of greenhouse production (Canakci et al., 2013). Despite the clear advantages of supplementing or substituting greenhouse heating needs with WH, there are several technical obstacles that have historically limited and currently constrain this application. General concerns and/or challenges experienced with greenhouse systems focused primarily on the need for back-up heating systems (Hare et al., 1984; Beall and Yarosh, 1973), infrastructure failure (Ashley et al., 1979), and the difficulty of establishing a uniform temperature (Manning et al., 1984; Shapiro, 1975). Back-up heating systems are ideal in the event of NPP scheduled shut downs for maintenance. Greenhouse growers caould prepare for shut down periods of WH sources by implementing crop rotations with crop species that require or can tolerate cooler temperatures. For example, white button mushrooms require a relatively cool temperature of 14 to 18 °C to initiate fruiting (Maheshwari, 2013). Back-up heating systems within the literature utilized fossil fuel sources in the event a continuous supply of WH could not be provided (Johnson et al., 1982).

Greenhouse architecture can interact with crop type based on heating efficiency and demands, respectively. For example, replacing commonly used single glass panels with double inflated polyethylene film or rigid-twin wall acrylic panels decreased heating energy needs for greenhouse tomato production by 30% (Papadopoulos and Hao, 1997). The range of the heat demands required by common greenhouse crops such as tomatoes and peppers include optimum diurnal temperatures of 18.3–23.9 °C (Jovicich et al., 2004), and temperatures no more than 29.4 °C, above which photosynthetic efficiency rapidly decreases. Relatively uncharacterized, however, are the greenhouse production conditions for tropical crops, many of which are perennial and virtually all of which are field-grown in tropical regions and imported. It is likely that tropical crops would utilize more WH than the aforementioned common greenhouse crops given higher heating requirements of species autochthonous to regions with mean annual temperatures of 21.1–26.7 °C and having the ability to endure high temperature and humidity (>32.2 °C). Retrofitting the WH connection between a greenhouse and existing NPPs is necessary to ensure a safe and efficient delivery of WH to the appropriate heating systems, but can complicate management of crop heat needs. Bond and Russ (1977) considered this design hurdle in addition to acknowledging power plant shutdown periods (Andrews and Pearce, 2011) and expected seasonal variations in WH temperatures (Godfriaux et al., 1979; Ryther et al., 1977).

When using WH in general, there is a concern that a significant amount of heat may be lost en route to its application. To use WH effectively and inexpensively, the application should therefore be situated as close to the WH source as possible. In the case of NPPs in the U.S., agriculture is unrestricted outside the exclusion area boundary, defined by the NRC as a region near the power plant where the reactor licensee has the authority to exclude and remove any people and property. Efficient WH transport is feasible beyond these boundaries, which are typically 1 km from the reactor, but can be as close as 250 m (Burns, 2009). While these exclusion zones are often kept free of activities such as agricultural production, there is precedent for reserving space for WH utilization (Bond, 1977).

4. Assessment of agricultural products for WH systems

4.1. Horticultural food crops

A variety of horticultural products can be produced with WH-supplied production systems, particularly through the use of controlled environment production systems such as greenhouses that enable multiple harvest cycles. Horticultural crops generally hold a higher net return on investment per unit area compared to field crops such as grains, especially when grown in a greenhouse system (Khaliq et al., 2009). Though in the late 1980s there were over three dozen examples of NPP WH use for agriculture (CEC, 1988a,b), and today there exist limited but instructive cases of commercially successful horticultural production systems employing NPP WH, all of which are outside of the U.S. For example, WH from the Grenoble Nuclear Center NPP in France has been used in greenhouse tomato and cucumber production with yields comparable to non-WH greenhouse production systems in the region (Balligand et al., 1978a,b). As a result of buried heating pipes, the ability to maintain soil temperatures at 25 °C year-round was thought to contribute to the productivity of these systems.

The literature on WH use in agriculture mostly consists of traditional horticultural crops (i.e. tomato), but also non-

Table 1
Benefits and potential challenges of various agricultural applications of nuclear waste heat.

Application	Advantages	Challenges
Greenhouse heating	• Controlled environment • Multiple methods of heat transfer: underground pipelines, finned tubes/pipes, and evaporative pads • Wide range of commodities/some with high demands • Integrated agricultural systems • Climacteric crops can have a longer maturation period if sold locally • High security status due to location near NPPs • Humidity is less of an issue at large-scale • Lengthens growing season • Can aid USDA food programs • Can serve as a research facility for local universities and industry	• NPP outages for maintenance/inspection (1–2 months) • Seasonal temp variations of WH • Controlling high humidity • Will likely need a back-up system (fossil-fuel powered) • Potential contamination • Limited usage during summer months • Establishing a representative floor temperature can be difficult • Heating and lighting requirements of certain crops may limit year-round production • Irrigation water source • Consumer perception of risk
Aquaculture	• A solution to overfishing • High demand • Can utilize marginal land • Yield can significantly improve by raising water temperatures slightly • Wide range of fish/marine species • Dietary supplement market	• Pollution (waste, excess feed) • Disease outbreaks • Feed can be expensive • Coastal systems are more cost-effective • Infrastructure is expensive • Most production occurs in open-air raceways
Animal shelter heating	• Swine and poultry production in the Midwest • Can possibly capture CO_2 and sell it • Can increase growth rates • Integrated system approach	• Location is influenced by labor costs and climate • Disease control and waste disposal
Soil heating (open-field agriculture)	• Promotes germination and early crop growth stages • Lengthens growing season	• Small-scale operations only • Placement of WH tube network may interfere with field management
Algal biofuel production	• Sustainable fuel source • Commercial algae production systems mainly serve the dietary supplement market (closed systems) • Certain species of algae can grow low water temperatures (15 °C), but are half as productive than other species	• Sensitivity of species to other species • Systems require lots of space • FDA guidelines • Supplemental CO_2 is needed • Light is the limiting factor
Post-production	• Perception of risk is lower • Potential for industrial parks • Minimize transportation costs	• Seasonal temperature variations of WH and ambient • Potential contamination
Other	• Multiple uses (e.g., wastewater treatment, fertilizer, specialty chemicals, bioplastics)	• Location specific • Perception of risk

conventional or less common greenhouse crops such as spices and herbs (Yu and Nam, 2016), floriculture (Elsner, 1984; Johnson et al., 1982; Manning et al., 1983), berries (Boersma and Rykbost, 1973) and vegetables (CASE, 2009; Horst, 1972). Additional work is required to understand the agronomic and economic feasibility of non-traditional food crops. Specific considerations include feasibility as well as heating and fertilizer requirements of non-traditional crops. For example, many high-value crops are grown in (sub)tropical climates (e.g., spices, fruits) and are generally understudied with respect to field-scale agronomic production (Nature Plants, 2015), much less in controlled conditions such as a greenhouse. Consideration of high-value horticultural products for greenhouse operations is not only essential to maximize profitability, but also to meet demands for local markets that are otherwise met largely by imports into the U.S. (e.g., spices). Waste heat from a standard U.S. NPP could conceivably supply up to 10,000 to 40,000 acres of traditional horticultural greenhouses (CASE, 2009). Thus, even fractional use of NPP WH could significantly contribute to greenhouse production.

The last decade has witnessed increasing demand for regional and local food supplies, in particular for high-value crops well-suited for greenhouse production (Charles, 2015a,b). Concurrently, the recent emergence of peri-urban agriculture initiatives (Lawson, 2016; Van Tuijl et al., 2018) is motivated in part by a reduction of food miles and enhanced regional food security, with an emphasis on horticultural crops (Opitz et al., 2016; Palmer, 2018; Rogus and Dimitri, 2015). Abundant WH from NPPs could be instrumental in supporting year-round production of nutritionally important horticultural crops (e.g., leafy greens and vegetables), in particular for urban regions in temperate climates in which the winter season severely constrains the contribution of local and/or urban agriculture to year-long food security and where controlled environment production systems such as greenhouses play an important role in local food supplies (Goldstein et al., 2016; Sanyé-Mengual et al., 2015).

Compared to other heating sources, the zero-carbon cost of WH from NPPs stands to subsidize or offset high energy costs of scaling up regional food production during winter months (Mohareb et al., 2017). Decreased or avoided carbon footprints afforded by replacing conventional heat sources with WH, as well as lowered food miles from regional production (e.g., greenhouse tomato production in winter months) (Röös and Karlsson, 2013) are likely to enjoy favorable public and consumer perception, especially if climate taxes and/or labels are imposed on foodstuffs (Gren et al., 2019). For example, in the U.S., the energy security benefits of nuclear energy appear to have a positive effect on public opinion that counterbalances negative perceptions of this energy source due to historical accidents (Gupta et al., 2019). More broadly, the re-use of WH from NPPs for food crop production offers an opportunity to realize synergies at the intersection of food and energy in the food-energy-water (FEW) nexus in the densely populated regions near NPPs in the U.S. (Roggema and Yan, 2019) such as the Chicago metropolitan region.

4.2. Non-food agricultural applications

Waste heat systems can be utilized for agricultural products beyond food crops (Table 1). Potential non-food agricultural operations include heating livestock shelters (Beall and Samuels, 1971a; Bond and Russ, 1977; Miller et al., 1971), floriculture, and algal production for biofuel (CASE, 2009). The feasibility of non-food production alternatives has had little to no experimental investigation or evaluation, likely due to the need for retrofitting existing infrastructure. However, these systems are considered to have high profitability potential (CASE, 2009; Yarosh et al., 1972).

Waste heat use in agriculture beyond the production stage has received relatively little attention despite the ubiquity of thermal processes such as sterilization, valorization of waste streams, drying, and fermentation. Though for some of these processes (e.g., steam sterilization), WH from NPPs does not achieve temperatures needed (e.g., >100 °C for steam sterilization), heating costs can be reduced by partial heating. Initial (e.g., Yarosh et al., 1972) to recent (e.g., CASE, 2009) reviews of potential WH applications in agriculture do not mention post-harvest processing of agricultural products (e.g., drying). Pre-production applications could include heat sterilization of soils or soil-free substrates used in nursery and greenhouse production. Processing and/or production of waste-derived products for agricultural fertilizers (Trimmer et al., 2019) can benefit from heat for sterilization and/or expediated drying (e.g., sewage sludge, biosolids) (Apedaile, 2001a,b; Arthurson, 2008; Singh et al., 2011a,b), abating waste stream treatment costs by enabling valorized products for agricultural re-use (Arancon et al., 2013) that may provide feedbacks to agricultural production facilities employing WH. General co-location of NPPs with population centers and thus wastewater treatment plants (Trimmer and Guest, 2018) can mitigate costs of coupling WH and waste streams.

Post-harvest processing of agricultural commodities that could benefit from WH include drying and preservation of grain stocks and quality in storage facilities (Brooker et al., 1992; do Livramento et al., 2017; Ortiz et al., 2016), ensuring dry conditions for seed grain production (Whitehouse et al., 2015, 2017), desiccation of plant tissues (Chauhan et al., 2017; Pane et al., 2016), fermentation in biofuel production (Gabhane et al., 2011; Qureshi et al., 2016a,b; Westman et al., 2017) and fermented food products such as alcoholic beverages (Nikulin et al., 2018; Torija et al., 2003), dairy (Lee and Lucey, 2004a,b), and probiotics (Jayabalan et al., 2014). Co-location of NPPs with wastewater processing, biofuel refineries, and agricultural product processing plants would facilitate coupling WH with these non-production agricultural applications. The interface between NPP and non-NPP systems may necessitate regulatory evaluation and oversite from relevant agencies (e.g. U.S. NRC, EPA, FDA). Novel agricultural considerations include environmental impact programs such as carbon crediting or food miles.

4.3. Unconventional potential applications of NPP WH

High-value and extant agricultural industries that may benefit from WH include greenhouse agriculture and aquaculture. Algae production for biofuels is a substantially smaller agricultural sector with strong but relatively under-evaluated potential to capitalize on WH. High-value agricultural activities that remain largely unassessed for WH use include greenhouse production of tropical crops, hydroponics, and vertical farming. Finally, there has been little consideration of agricultural industries beyond crop production that could make use of WH, such as post-harvest processing.

Previous assessments of WH re-use have largely focused on annual crops traditionally grown in greenhouses (e.g., leafy greens, tomatoes). High-value tropical crops, many of which are perennial, are an overlooked opportunity since they are not commonly produced in greenhouses in temperate regions given generally prohibitive heating costs of tropical crop production. Potential challenges that would require evaluation include cultivars suited for greenhouse-like conditions and the need for tropical crop best-practices (e.g., fertilization). Production of (sub)tropical crops such as citrus in the temperate U.S. has been enabled by geothermal heating (Rubio-Maya et al., 2016a,b; Van Nguyen, 2015). Hydroponic production is also relatively unexplored but stands to benefit from WH. Integration of hydroponics and aquaculture has been proposed to maximize economic returns, though managing differing temperature and non-temperature needs of plant and fish crops (e.g., growth windows, disease) is likely to be challenging (CASE, 2009; Hochman et al., 2018). On the other hand, abundant sources of WH can enable expanding evaluations of coupled horticulture-aquaculture production systems that are generally limited in quantity and scale (Enduta et al., 2011; Goddek et al., 2015). Salient assessment questions concern the design of heated hydroponic systems, and current and possible crop species that would benefit from hydroponic conditions with elevated temperatures.

5. Conclusion

Waste heat from NPPs has potential to be an alternative heating source to fossil fuels in agricultural systems. Though the concept is not new, this review assesses traditional and unique agricultural applications that may benefit from WH as a heat source. The majority of reviewed literature consisted of publications from the late mid-20th century primarily focused on the engineering and modeling aspects of WH systems rather than detailed agricultural data. Despite the literary gaps, detailed information on agricultural-specific challenges were present in the literature and serve to inform next steps toward realizing the potential of WH from NPPs in the 21st century. The opportunities and challenges discussed in this review provides improved insight on the feasibility of nuclear WH for agricultural applications. Future research at or above pilot scale implementation of agricultural production systems that make use of WH is a key next step to realizing NPP WH re-use.

Declaration of competing interest

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

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Appendix A. Supplementary data

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