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Potential Impact of Nuclear Power on Water Resources in the Southeast United States

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Water stress threatens to impact electricity production from thermoelectric plants in the Southeast United States (SE). This is concerning because 97.4% of electricity in the region is produced from thermoelectric sources. These coal, nuclear, and natural gas plants require water for waste heat rejection (WHR), comprising the majority of the SE's water consumption (58.9%). Increasing nuclear power has been proposed as a way to reduce carbon emissions while being an efficient utilization of land resources compared to wind or solar. However, the impact of an increased reliance on water resources should be examined. To do this, it is necessary to characterize the SE's electricity mix, water utilization, and determine how these resources are used. In 2010, nuclear plants produced 22.5% of the electricity in the SE, yet comprised 36.8% of the thermoelectric water withdrawal. Thermoelectric plants withdrew the majority of water in the region (58.9%). Only a fraction of withdrawals are consumed by evaporation, but warmer water is returned to streams, which can have harmful effects on aquatic ecosystems. Nuclear plants have larger water withdrawals per GWh because of their lower thermal efficiencies. As more nuclear plants are added to the region, the thermoelectric water demand will grow. To reduce the amount of water needed for WHR, it is advantageous to build cooling towers in water-stressed areas because of their low water withdrawals and to slowly phase out once-through WHR except in areas where environmental impact is negligible. Technologies that could better utilize water resources such as dry heat rejection, waste heat recovery for desalination, and high-temperature reactors with higher thermal efficiencies, like salt-cooled reactors and super-critical CO₂ systems, should be considered.

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1. Introduction

This paper characterizes the SE's electricity mix and water utilization, determines how these resources are being used, and examines nuclear energy's current and potential future impact on water resources, an increasingly important area of research generally referred to as the water-energy nexus.

Water is used to cool thermoelectric electric plants, grow crops, and supply cities and factories. Similarly, electricity is used to pump water to fields, light homes, and power cities and factories [1]. Because of the interconnectedness of water and electricity, the relationship between these resources and their use is complex. Sustaining the balance between water use and electricity production is of immense importance because the availability and reliability of these resources is what makes modern society possible. This balance is threatened by stress on water resources.

In the SE, nuclear energy makes up approximately a quarter of the net generation of electricity (22.5%), a larger percentage than the national average (19.6%) [2]. This region is unique because most of the reactors planned or under construction are located in this region [3]. Nuclear reactors use more water for waste heat rejection per unit of power than any thermoelectric plant. As such, increased nuclear capacity would mean a higher overall water withdrawal for electricity production in the SE. Nuclear reactors require more water than other power plants because of their lower thermal efficiencies, meaning a lower portion of the thermal output is captured as usable energy. Relatively low steam temperatures affect the thermal efficiency of the system according to the Carnot Efficiency expression:

$$\frac{T_H - T_C}{T_H} * 100\% = \text{Efficiency}$$

Two technologies are primarily used for waste heat rejection in reactors: once-through cooling and recirculating (cooling towers) [4]. Once-through cooling typically pulls water from a reservoir, sea, ocean, or large river because of the high withdrawal needed: 44,000,000 gal/GWh. While the withdrawal is very large, only 269,000 gal/GWh is consumed through evaporation during the waste heat rejection. The rest of the water is returned to the source unpolluted but is a few degrees warmer. As for recirculating cooling, a much lower water intake is needed: 1,100,000 gal/GWh. However, a larger portion of the water is consumed during cooling: 672,000 gal/GWh. Higher capital costs are involved with recirculating cooling because of the construction of cooling towers. Estimates put the cost at constructing a cooling tower to be between \$130-200 million [5], while once-through systems cost significantly less.

Another important factor is the amount of land area needed for electricity production. The number of acres needed for each type of plant's needs varies widely. Hydroelectric dams render approximately 1,000,000 acres unproductive, whereas nuclear plants require approximately 1,750 acres [6] for a 1,000 MWe plant, including the plant itself and the land used for mining and processing (fuel cycle). As a rule, plants using combustion or fission need less land per unit of power. A 150,000-acre wind or a 35,000-acre solar farm would be needed to produce 1,000 MWe (Figure 1).

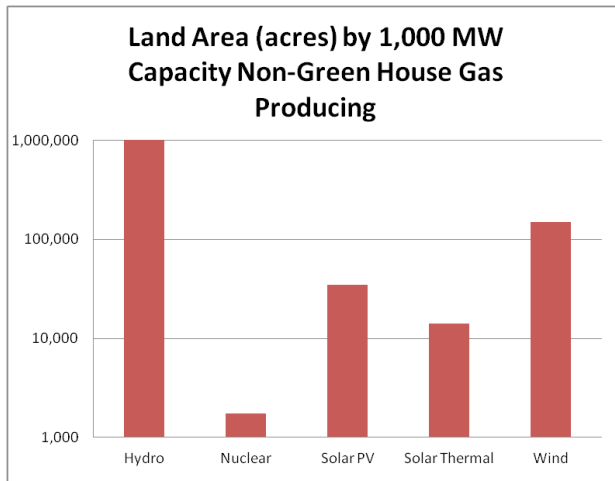


Fig. 1

While renewables may one day meet a substantial portion of electricity demand, for the foreseeable future, nuclear is currently the most promising way to reduce carbon dioxide emissions and provide reliable baseload generation. If nuclear energy is to grow in the SE, it is important to understand how a greater reliance on nuclear energy will affect water and land resources, the cooling technologies plants can use, and where plants can be located. Some issues that should be taken into account are water usage, environmental effects, and the land area on which these new plants will be built.

2. Methods

2.1 Electricity Production

Data for net generation of electricity by region from the eGRID 9th edition Version 1.0 Year 2010 Summary Tables published by the US EPA is the most recent source for which both net generation and water information is available. The net generation for the SE is defined as combined SERC and FRCC totals in the NERC 2010 regions (Figure 2). After 2010, regional boundaries were redrawn. For the purpose of this paper, all SERC and FRCC information comes from the region as defined in 2010.

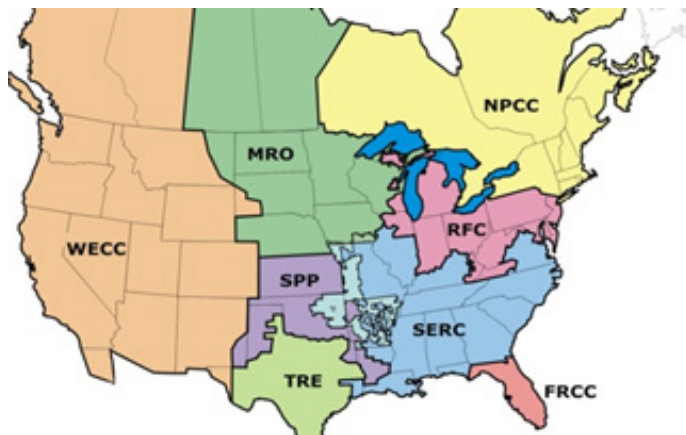


Fig. 2: 2005-2010 NERC Regions

2.2 Electricity Usage

Electricity usage is tabulated as commercial, industrial, and residential sectors. The electricity usage by sector was determined from the Energy Information Agency's (EIA) [7] Retail Sales of Electricity by State, by Sector, by Provider, 1990-2013 tables. From this source, the Total-Electric-Industry-by-state metric for 2010 was used. (The EIA does not collect data for NERC regions and no complete reliable NERC data was available). The electricity usage distribution calculated is only an estimate for the region using states mostly or completely encompassed in the SERC and FRCC regions (Figure 3). These states are AL, AR, FL, GA, KY, LA, MS, MO, NC, SC, TN, and VA.



Fig. 3: Southeast region state boundaries

2.3 Water Origins and Withdrawal

The water information contained within this paper was published by the United States Geological Survey (USGS) in their 2014 report, "Estimated Use of Water in the United States in 2010" [8]. Water withdrawals in gal/day are used as the unit for water use. This must be differentiated from water consumption. For the purpose of this paper, consumption is water lost to evaporation in thermoelectric plants. The data is reported by state. Values calculated are only an estimate for the SE region using states mostly or completely encompassed in the SERC and FRCC regions. These states are AL, AR, FL, GA, KY, LA, MS, MO, NC, SC, TN, and VA.

2.4 Land Usage

Data for land usage by generation source was provided by the Nuclear Regulatory Commission (NRC) [9]. These figures are reported as the acreage needed for 1,000 MWe capacities. For sources which rely on fossil fuels or uranium, the amount of land needed for mining and processing per 1,000 MWe is also included.

2.5 Nuclear Plant Data

Thermal and electrical ratings for currently operating nuclear plants in the SE region were provided by the NRC [10]. The net electricity generation for each plant was provided by utility web pages and documents for the year 2013. Adjustments in the output of each plant were used to estimate the amount of water withdrawn and consumed for each plant in 2010. Water withdrawals and consumption were estimated based on technical information within "A Review of Operational Water Consumption and Withdrawal Factors for Electricity Generating Technologies" (NREL).

3. Discussion

3.1 Characterization of Region

From this study, the characteristics of the SE's electricity mix and water utilization were found to be different from the national average. For example, data from the EIA and reports from SERC and FRCC show the region is much less dependent on renewable energies (hydro, solar, wind, and biomass) and utilizes more coal, natural gas, and nuclear power, as shown in Figures 4 and 5. This means the SE is more reliant on thermoelectric generation (97.4%) compared to the United States average (91.0%). It is interesting to note the margin by which all sectors' electricity demand outpaces that of the national average (Figure 6). With 26.7% of the population, the SE consumed 32.7% of the electricity produced in the United States in 2010. The region uses more electricity per capita than any other place in the United States. This can be accounted for by the region's manufacturing output, agricultural output, and need for electricity (e.g., air conditioners). These factors increase the demand for electricity, and the highest consumption of electricity per capita is found in the residential sector (Figure 7).

Southeast Electricity Mix 2010

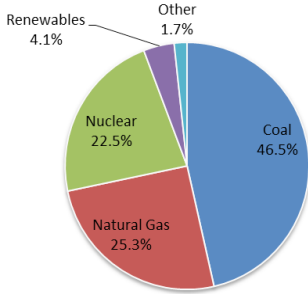


Fig. 4

United States Electricity Mix 2010

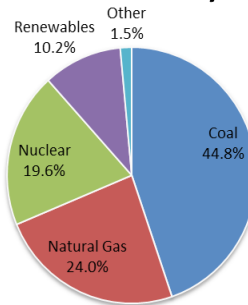


Fig. 5

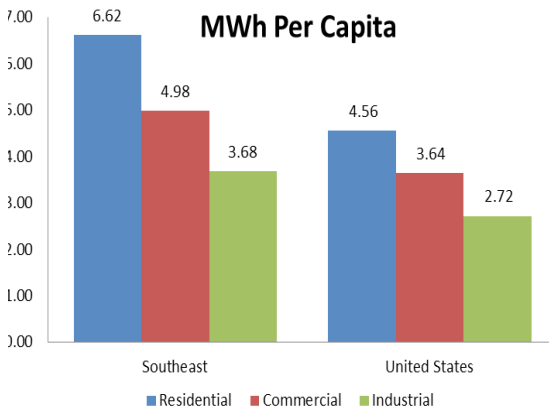


Fig. 6 Rates of electricity usage by region by sector

Southeast Electricity Usage by Sector

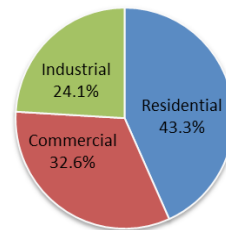


Fig. 7 Southeast Electricity Usage by Sector 20

As for water utilization in the SE, thermoelectric plants comprise the majority of all water withdrawals (Figure 8). This can partially be attributed to the fact that thermoelectric plants also account for a larger fraction of the electricity mix in the region. The sector with the next largest withdrawals is agriculture. While agriculture is a large part of the regional economy, the reason SE withdrawals for agriculture are lower than the national average withdrawals for agriculture is likely that the region can rely on a wetter climate and access to local streams for irrigation. The Midwest and Southwest require much more irrigation because of the arid climate and crop choices [12]. Public supply in the SE is slightly lower per capita than the national average.

Water Use Per Day by Sector gal/capita

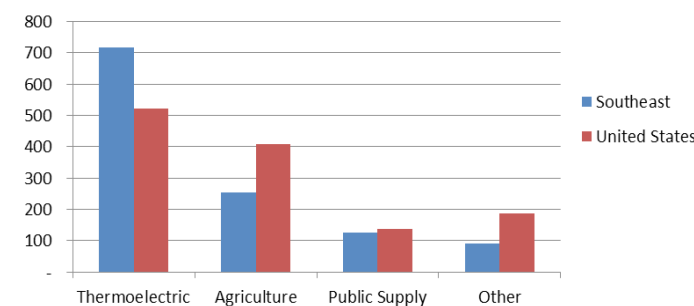


Fig. 8

It is interesting to note the amount of water used each day per capita either directly or indirectly. In the SE, this number is 1,190 gallons per person per day, which is less than the 1,250 gallons per person per day for the national average.

The SE generally avoids water stress due to the abundance of lakes, rivers, dams, and precipitation. The areas that will likely feel the effects of water scarcity most are the population centers, eastern Arkansas, and the Floridian peninsula. The demand for water and electricity in commercial, residential, and industrial sectors can put pressure on water resources. For most of the SE, water stress will be low to moderate according to data by the USGS and predictions from the Natural Resources Defense Council [13], as shown in Figure 9.

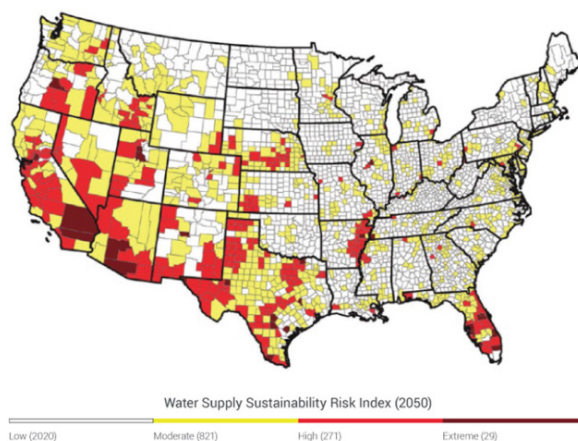


Fig. 9

As shown in this map, Florida and Arkansas are at serious risk of water shortages by the year 2050. These states rely heavily on groundwater to meet demand. It is likely that, by the year 2050, the aquifers and other ground water sources in these areas could be depleted. This could negatively impact agriculture and public water supplies in these areas, as ground water is used heavily in those sectors.

3.1.1 Characterization Summary

1. The electricity mix and water utilization of the SE is characterized by a dependence on thermoelectric plants to meet electricity demand.

2. Coal is the primary source of electricity, followed by natural gas and nuclear. Renewable energies comprise a very small portion of the total electricity generation for the region.

3. The SE has one of the highest rates of electricity use per capita. By sector, residential demand is the highest, followed by the commercial and industrial sectors. The SE uses more electricity per capita than any other region of the United States.

4. Thermoelectric plants withdraw the majority of water for the region due for waste heat rejection. Only a fraction is consumed due to evaporation.

5. Agriculture has the next largest demand for water, followed by the public demand?. Overall water use per capita is slightly lower in the SE than the national average.

6. Water supplies are generally abundant and predicted to be so until at least 2050. However, parts of Florida and Arkansas are expected to have water shortages due to the states' high use of ground water.

7. Population centers are expected to have issues meeting increased water demand

3.2 Nuclear Energy

It is important to understand how water resources in the region will be affected if the electricity mix were to change. One possible and likely scenario for the SE is an increase in the amount of nuclear energy produced.

Currently, nuclear reactors produce about 22.5% of the electricity for the SE. This makes the region the third most reliant on nuclear energy behind the Northeast and the Mid-Atlantic. Interestingly, the SE's nuclear capacity is growing. There are five reactors under construction. By 2020, an additional 5,000 GWe of capacity is planned. In the near term, nuclear and natural gas plants are expected to comprise a larger portion of electricity generation in the SE as coal continues to decline as a result of more stringent emission rules imposed by the Environmental Protection Agency (EPA) and decreased economic competitiveness due to subsidies for renewable energy.

In 2010, Nuclear reactors produced 22.5% of the electricity in the SE yet withdrew a larger fraction of the water going

to thermoelectric plants than might be expected. Overall, 36.8% of the thermoelectric water withdrawal was used for waste heat rejection in nuclear plants. The amount of water needed for WHR is tied to the thermal efficiency of the plant. On average, nuclear plants are able to obtain approximately 33% efficiency, whereas fossil fuel plants range from 32-42% [14]. This translates into a higher water withdrawal for nuclear plants using the same waste heat rejection technology as a comparable fossil fuel plant. For example, a 1,000 MWe nuclear plant with a 33% thermal efficiency needs to reject 2,000 MWth of heat. On the other hand, a 1,000 MWe natural gas plant with 40% efficiency would need to reject only 1,500 MWth of waste heat. Coal and nuclear plants withdraw similar amounts of water.

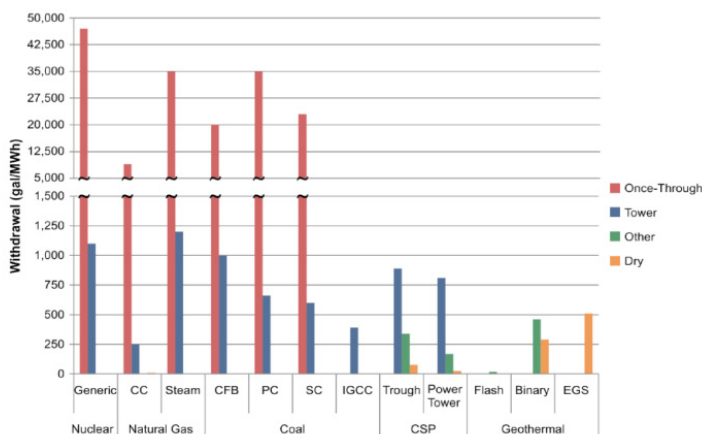


Fig. 10: Withdraws of water for waste heat rejection

For nuclear plants, there are two WHR technologies: once-through cooling and recirculating (cooling towers). In once-through cooling, a large amount of water is withdrawn and passed through the plant to condense the steam from the turbine into liquid water by absorbing its waste heat (none of the water used in WHR comes into contact with radioactivity). Water is then returned to its source at a warmer temperature. Some consumption of the water results from evaporation. A once-through system withdraws on average 44,000,000 gal/GWh (Figure 10) and consumes 269,000 gal/GWh. Only a fraction is lost to evaporation. The other technology used for waste heat rejection is recirculation of water through cooling towers. For this process, 1,100,000 gal/GWh is withdrawn and 672,000 gal/GWh is consumed through evaporation.

Each WHR technology has benefits and drawbacks. Once-through cooling is cheaper to build and maintain but requires such a large amount of water for withdrawals that it can only be built in areas with access to a large body of water. In dry seasons when smaller volumes of water are available for use, plants run the risk of having to shut down because of inadequate water levels or higher water temperatures that are outside allowable operations. There are also environmental concerns over the water returned to the water source. Increased water temperatures can damage local fish populations and lead to toxic algae blooms due to the fact that warmer water holds less dissolved oxygen. Cooling towers on the other hand are associated with significantly higher initial construction costs. This is an economic disincentive to building new plants. However, as a result of the lower withdrawal and higher consumption rate, less heat is returned to the water source. Because of this, the environmental impact on aquatic ecosystems is less than that of once-through cooling. An advantage to cooling towers is that the amount of water available needed to build a new plant is much lower. This increases the number of sites where it is possible to build a new plant.

If the United States is to build more nuclear plants, it would be advantageous to require cooling towers on all new plants located in water stressed areas according to the Water Supply Sustainability Risk Index (2050). As water supplies become stressed, less water could be available for thermoelectric generation. Recirculating systems require less water than once-through systems, meaning that plants with cooling towers can avoid shut downs when water flow rates are low.

Air cooled condensers (ACC) have been suggested as a technology that can reduce the amount of water needed for WHR. ACCs use air to condense steam from thermoelectric plants instead of water [15]. ACCs have been implemented in natural gas and coal plants in order to reduce water withdraws and consumption. This technology comes at the cost of larger facilities, more expensive technology (heat exchangers), and a loss of thermal efficiency by 2-3%. Nevertheless,

this technology is promising because of its reduced reliance on water. Holtech International has developed a Small Modular Reactor (SMR) concept, the SMR-160, which they claim can operate in arid climates using ACCs [16]. Babcox and Wilcox has also suggested their SMR concept, mPower, can utilize ACC to operate in arid climates [17]. However, there are safety and licensing concerns as ACCs could pose increased risks to fuel safety in the event of a meltdown, and no reactor has been licensed to use ACC. It is possible that a hybrid heat rejection system could utilize both water and ACC heat rejection.

New technologies could potentially recover waste heat from reactors to produce desalinated water. There are two primary benefits to this. First, by using waste heat to produce clean water, the profitability of nuclear plants can be increased. Clean water can be sold to communities, reducing the withdrawals for public supply. This could help alleviate water stress. The other benefit is that cooler water is returned to its source. Because more work is being exacted from the water, it is released at a lower temperature. This means that the environmental impact on aquatic ecosystems from building a plant could be significantly reduced. Multi-stage flash distillation (MSF) or multiple effect distillation (MED) could be two technologies that use waste heat in water desalination. All waste heat recovery technologies in consideration operate in conjunction with once-through waste heat rejection.

By 2030, Generation IV reactors could be ready for commercial deployment. New high-temperature designs would increase thermal efficiencies. These designs could come in a variety of outputs. If plants were developed with higher thermal efficiencies, less water would be needed per GWh of operation because of the need to reject less waste heat. One potential reactor that holds much promise for higher thermal efficiencies is the Fluoride salt-cooled High-temperature Reactor (FHR) [18]. From preliminary design concepts, this reactor could potentially reach efficiencies of around 43%. A FHR, compared to a

standard Light Water Reactor (LWR), would reduce water withdrawals and consumption by around 33%. If this technology were to be utilized, the amount of water needed to switch from a fossil fuel base load electricity grid to a nuclear one would be comparable to, if not lower than, current usage. Because of the water conservation benefits of utilizing a FHR to replace current fossil fuel generation, the Department of Energy should increase research into Molten Salt Reactors (MSR).

Another important factor in this discussion is the amount of land area needed for each type of power plant. As cities and suburbs grow larger and the population of the SE expands, it is important to maximize the potential of the land. With regards to electricity generation, this means that plants in the future should be compact and produce large amounts of electricity. As demonstrated in Figure 11, this is an area in which nuclear plants excel.

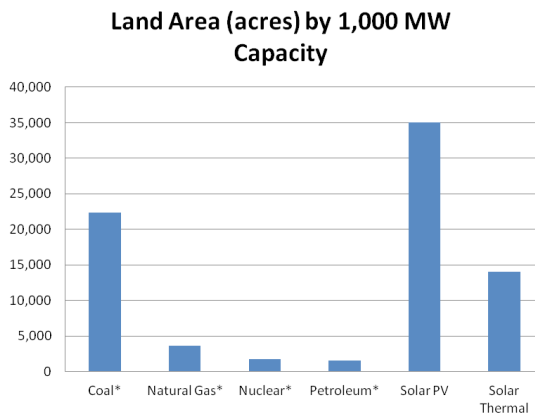


Fig. 11

These estimates take into account the full fuel cycle (mining, processing) where applicable (denoted by an asterisk). Compared to fossil fuels, nuclear energy is the second most energy dense source with respect to land area need. Petroleum comprises only about 1% of US electricity production. Its benefits come from its easy extraction and transportation. Its usage is expected to only decline. Natural gas is only slightly less dense than nuclear electricity generation. However, when only comparing non-greenhouse gas producing generation technologies, nuclear reactors far outpace competitors in land area per MW of capacity. If new sites are to be selected, a tool developed by Oak Ridge National Laboratory (ORNL) called OR-SAGE can aid in this process by scoping out potential water, environmental, geologic, and surrounding population issues [19].

4. Conclusion and Recommendations

If the SE is to add more nuclear power to the region, its effect on water and land resources must be understood. Nuclear reactors require the most water for waste heat rejection (WHR) and the second least land area (behind petroleum) for thermoelectric power plants per GWh. As such, an increase in nuclear power will increase the amount of water needed for electricity production. Water stress could threaten electricity production from thermoelectric plants because water is required for WHR. However, the SE has generally abundant water resources and will avoid most issues regarding water stress. Population centers, eastern Arkansas, and the Floridian peninsula will be at a severe risk of water stress.

With lifespans of 40-60 years, new nuclear reactors in the SE must take into account the possibility of water scarcity in the future. Reducing the amount of water needed per GWh can provide security against water stress. The utilization of cooling towers and the eventual incorporation of hybrid WHR technologies with air cooled condensers can significantly reduce water withdrawals and reduce amount of heat discharged to aquatic ecosystems. Technologies that can recover water for desalination could reduce the temperature of water returned to the environment and provide clean water that can be sold to communities. Furthermore, high-temperature reactor designs can reduce the amount of water needed for waste heat rejection through higher thermal efficiencies. A table of technologies in a 1,000 MWe plant with their relative impact in the areas of water usage, water discharge, and cost is provided on the next page.

Technology	Water Usage	Water Discharge	Cost
Once-through WHR	Highest withdrawal; low consumption	Highest volume and heat discharge; most harmful	Lowest
Recirculating WHR	Moderate withdrawal; high consumption	Moderate volume and heat of discharge	Moderate capital costs for cooling towers
Dry-cooling WHR (ACC)	No withdrawal; no consumption	No discharge	Licensing and high capital costs
Hybrid WHR	Lowest withdrawal; lowest consumption	Lowest volume discharge	R&D, licensing, and high capital costs
Waste heat recovery (desalination)	Variable withdrawals and consumption	Variable volume; lowest heat discharge	R&D, moderate capital costs, production of clean water
Reactors with higher thermal efficiencies	Reduced withdrawal and consumption	Reduced heat discharge	New technology, R&D, licensing, and high capital costs

Tab. 1

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