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Siting Analysis of a Solar-Nuclear-Desalination Integrated Energy System †

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Abstract: Nuclear power is typically deployed as a baseload generator. Increased penetration of variable renewables motivates combining nuclear and renewable technologies into Integrated Energy Systems (IES) to improve dispatchability, component synergies and, through cogeneration, address multiple markets. However, combining multiple energy resources heavily depends on the proper selection of each system's location and design limitations. In this paper, co-siting options for IES that couple nuclear and concentrating solar power (CSP) with thermal desalination are investigated. A comprehensive siting analysis is performed that utilizes global information survey data to determine possible co-siting options for nuclear and solar thermal generation in the United States. Viable co-siting options are distributed across the Southwestern U.S., with the greatest concentration of siting options in the southern Great Plains, although siting with higher solar direct normal irradiance is possible in other states such as Arizona and New Mexico. Brackish water desalination is also attractive across the southwest U.S. due to high water stress, but for brackish water desalination reverse osmosis (an electricity driven process) is most cost- and energy-efficient, which does not require co-siting with the thermal generator. The most attractive state for nuclear and thermal desalination (which is more attractive when using seawater) is Texas, although other areas may become attractive as water stress increases over the coming decades. Co-siting of all CSP and thermal desalination is challenging as attractive CSP sites are not coastal.

Keywords: integrated energy system; siting; technoeconomic analysis; concentrating solar power; desalination; nuclear; GIS data

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1. Introduction

With the growing urgency to combat climate change, there is a heightened push to decrease our dependence on fossil fuels as a means of electricity generation. Currently, conventional fossil fuels remain a majority choice of electricity providers despite producing 40% of the world's carbon emissions [1]. However, recent trends suggest that the global energy supply is shifting towards lower-carbon methods, supporting international climate agreements that endorse the growing deployment of renewable sources. During the 10-year period from 2009–2018, renewable electricity generation increased from 450,000 GWh to 750,000 GWh in the U.S., while renewables capacity rose from 130,000 MW to 240,000 MW [2].

This domestic shift towards renewables is echoed within other nations around the globe. As countries strive towards a net zero emissions target by 2050, global renewable electricity capacity in 2026 is forecasted to rise more than 60% from 2020 levels, with renewables accounting for up to 95% of the increase in total power production [3]. To achieve this objective of augmenting electricity production while reducing the use of fossil fuels, there is a significant emphasis on adopting low-carbon methods of generating electricity. Renewable energy methods such as wind, solar, biomass, geothermal, and hydropower all provide promising and innovative solutions to become alternative global energy providers. However, with the adoption of renewable energy resources comes several challenges with intermittency issues (inherent particularly in wind and solar PV). The disconnect between when energy demand is high and when it is easiest to supply is a key issue in renewable energy production, and it has led to the well-known "duck curve" problem [4] in which midday oversupply of renewables combined with morning and evening demand spikes lead to severe generation ramping requirements for dispatchable generators.

To address these concerns, a potential solution is to utilize Integrated Energy Systems (IES), wherein a renewable generation technology is coupled with a thermal-based energy generator that can provide the system with consistent baseload power, therefore mitigating the impact of the intermittent nature of renewable energy sources. One potential coupling is between nuclear and concentrating solar power (CSP), which has been investigated in the literature [5–8]. The nuclear reactor and CSP are coupled into a shared power-conversion cycle with various coupling architectures being possible. This leverages the benefits of the different system types while minimizing their disadvantages. Nuclear power is most economical when operating at peak capacity as often as possible, which is ideal for fulfilling longer-term energy demands. Meanwhile, solar energy can complement nuclear energy production by flexibly adjusting to the daily fluctuations of electricity usage that alternate in quick bursts, generating additional power to cover deficit loads during peak periods, while reallocating any excess energy to be stored during periods of low demand.

A second possibility is cogeneration, where a plant can produce heat and/or electricity depending on off-taker demand. In this paper, we consider thermal desalination, which is of interest primarily in water-stressed regions where fresh water is scarce. A study of solar-driven desalination suggests that coupling thermal power plants with desalination, notably Multi-Effect Distillation (MED), has garnered noticeable project implementation primarily in the Middle East region due to its geographical conditions of having severe water scarcity and high levels of irradiance [9]. Water scarcity is a current and growing problem in the United States, in particular in the Southwest [10].

CSP-desalination coupling has also been investigated elsewhere, e.g., [11]. Nuclear thermal desalination has been performed in practice [12] and is also the subject of ongoing research [13,14]. The steam Rankine cycle is the most common choice of power-conversion system for such systems, in which case diverting low-temperature heat to the MED trades off against electrical power production. Supercritical CO_2 (sCO_2) can also be a compelling option as the heat-rejection temperature is compatible with the input temperature to MED, so the waste heat of the cycle can be utilized [15,16].

Co-siting these technologies within a single IES has also been postulated in a hybrid design that is comprised of three separate technologies: a nuclear reactor, CSP, and thermal desalination in the form of MED [17]—all of which contain siting limitations that require consideration. A high-level overview of the system concept is illustrated in Figure 1, which includes a nuclear reactor connected to the CSP via an intermediate loop to allow both systems to utilize shared thermal energy storage (TES).

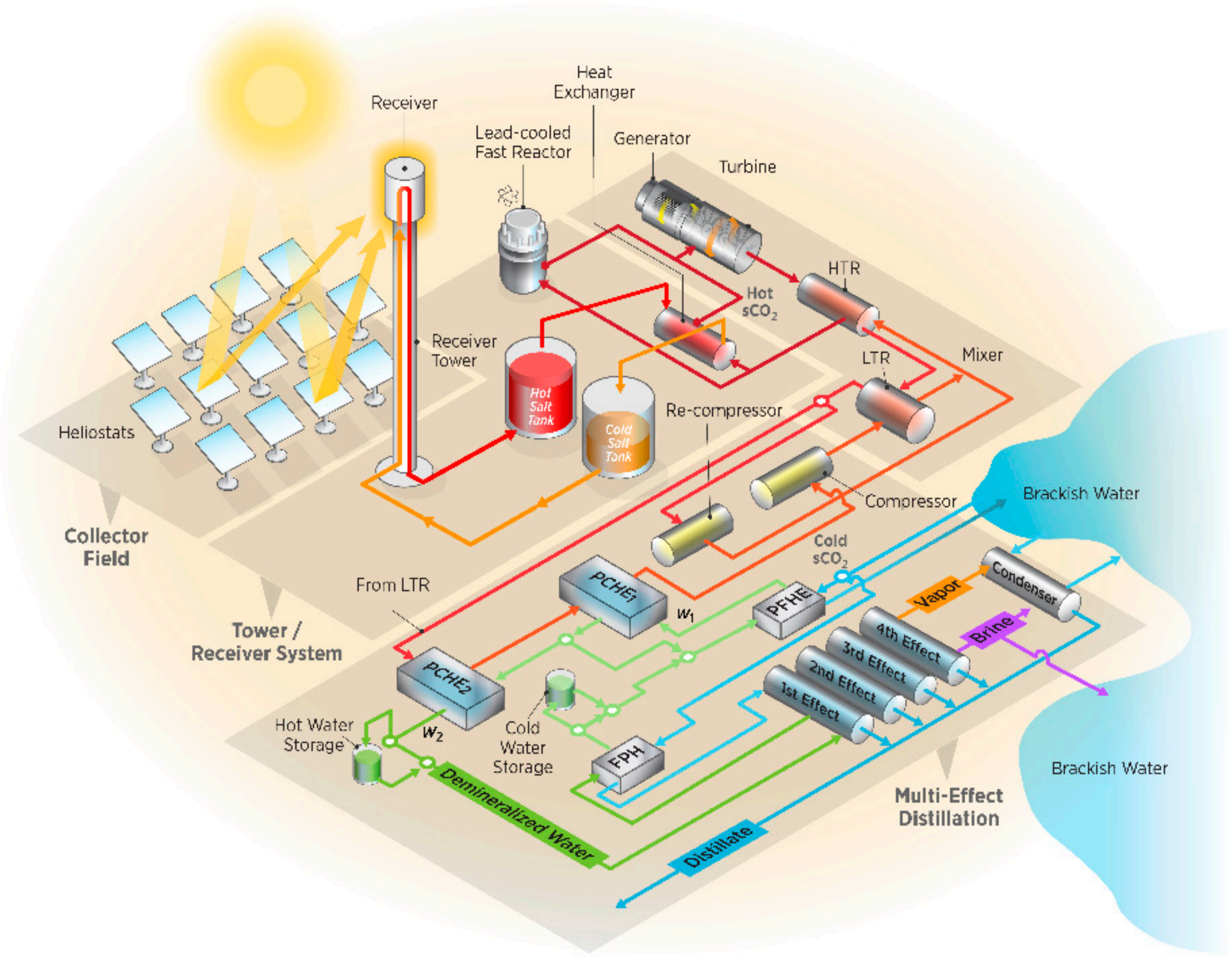


Figure 1. Simplified IES diagram of nuclear LFR into CSP-sCO2-MED system (courtesy NREL).

Other emerging forms of IES—also commonly referred to as hybrid energy systems—are being commissioned around the world, with different combinations of energy systems operating in conjunction. This has led to questions as to what exactly constitutes as an IES [18] with studies investigating optimal siting for varying types of hybrid systems. Other forms of existing hybrid technologies have also been compiled by [19], with most operating systems being implemented in Asian and Middle Eastern countries. However, there is a lack of documentation in siting work for locations that are optimal for IES, particularly for our specific mix of nuclear-CSP-desalination coupling.

Since each system poses unique characteristics and challenges, this paper aims to perform a comprehensive siting analysis and assess locations in the U.S. This is important because the benefits of synergy (i.e., thermal coupling) will likely be incremental. Therefore, the siting must be favorable for the co-sited technologies to make the overall system attractive.

2. Methodology

The overall approach utilized by this study is as follows. First, siting options for nuclear and concentrating solar power are derived from the OR-SAGE tool [20]. This is a large global information survey (GIS) database tool developed by Oak Ridge National Laboratory (ORNL) to support siting evaluations for a range of power plant options. This tool was developed around 2010 and divides the U.S. into 1-hectare regions. Then, various screening factors (discussed further below) are used to rule out sites systematically depending on siting challenges. Previous work performed by ORNL has utilized this tool to identify siting options for nuclear and concentrating solar power [21], and also more recently for advanced reactors [22]—these are adapted here for this study with some updates to the parameters.

In the present work, we first briefly review the siting criteria for nuclear and CSP developed using OR-SAGE. We then perform a brief review of desalination technology and use this to develop criteria for the desalination component of the proposed IES. While we do not have GIS data for the desalination metrics under consideration, we construct such data to low fidelity using publicly available maps produced by the US Geological Survey (USGS). Finally, we synthesize these data to derive siting options for combining two or three of the technologies under consideration. The novelty of the work is (1) in synthesizing solar and nuclear datasets for co-siting studies and (2) the introduction of geodata metrics with relevance to co-siting with desalination, along with screening on this as an additional variable.

2.1. Nuclear and Solar Siting

Siting criteria for nuclear and solar are adapted from [21,22]. These are reproduced in Table 1.

Table 1. OR-SAGE Exclusion Criteria for Nuclear and Solar Plants.

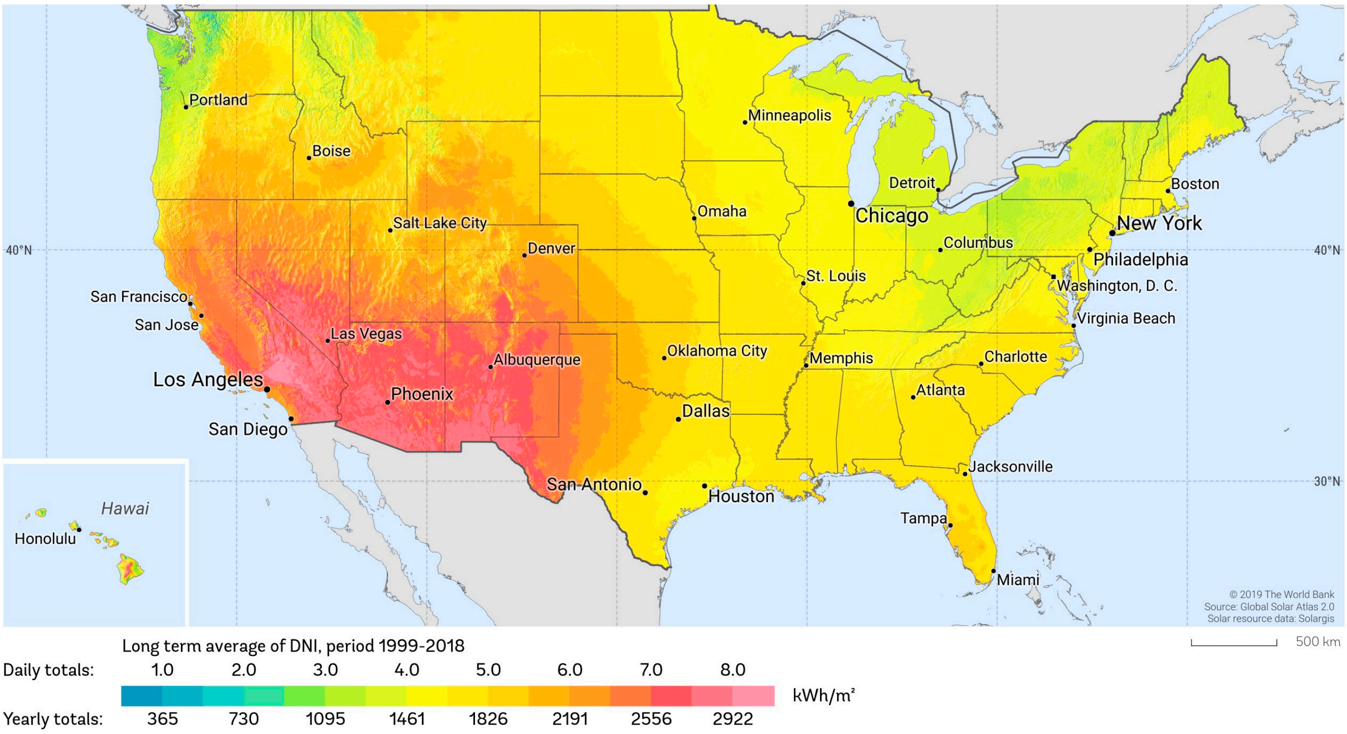
Exclusion Criteria	Typical Large Light Water Reactor	Typical Advanced Reactor	CSP
Population density (people/square mile—ppsm)	>500 ppsm within 20 miles	>500 ppsm within 4 miles	>500 ppsm
Safe Shutdown Earthquake (Ground Acceleration)	> 0.3	>0.3	NA
Wetlands/Open Waters	Avoided	Avoided	Avoided
Protected Lands	Avoided	Avoided	Avoided
Slope	>12% grade	>12% grade	>3% grade
Landslide Hazard (Areas with moderate or high Risk)	Avoided	Avoided	Avoided
100-Year Floodplain	Avoided	Avoided	Avoided
Streamflow (Cooling water makeup)	<8.52 m^3/s	NA *	<0.95 m^3/s (for wet option) *
Proximity to Hazardous Facilities (Airport—5 mi; Oil Refineries—1 mi; and Military Bases—1 mi)	Avoided	Avoided	NA
Proximity to Fault Lines (Depends on length of fault)	Avoided	Avoided	NA
Solar Irradiance	NA	NA	5.0 $kWh/m^2/day$
Plant Footprint	1900 m × 1900 m	450 m × 450 m	450 m × 450 m OR 1500 m × 1500 m **

* It is possible to use air-cooled condensers for new reactors and CSP, although this is more expensive than water cooling. ** Ref. [23] suggests a siting size of 5 km^2 for CSP, larger than that considered here.

It is noted that there are several states in the U.S. that have forms of bans on nuclear energy [24]. Minnesota, the strictest, has had a full moratorium on constructing new plants since 1994 [25]. Similarly, New York passed a law to close the Shoreham Nuclear Plant along with the construction of new plants [26]. California, Maine, Massachusetts, and Oregon have bans on new plant construction until a long-term nuclear waste repository is constructed and would require additional voter approval for new plants [24]. Illinois also has a ban pending a national repository but also allows new construction if it has been "specifically approved by a statute enacted by the general assembly" [24]. New

Jersey requires that its plants' waste disposal conforms to NRC standards and removes danger to the environment and population, which is much more feasible than a national repository [24]. Rhode Island, Hawaii, and Vermont require legislative approval to build nuclear plants but currently have none in operation [24]. Some state regulations around nuclear energy are effectively complete bans on new construction, while others present obstacles that are much easier to overcome. However, the general climate surrounding nuclear construction can change over time.

For CSP siting, one of the most important criteria is a requirement on solar direct normal irradiance (DNI). Figure 2 shows a map of the daily-average DNI levels in the U.S. (image courtesy NREL).



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Source: Global Solar Atlas 2.0
Solar resource data: Solargis

Figure 2. Annual solar DNI across mainland U.S. [27].

An NREL report provides information on potential sites for CSP based on solar capacity, grouped into 12 resource classifications [23]. Low-solar resources constitute classes 1–5, with average DNI levels in geographical areas averaging 5.00–6.25 kWh/m^2-day, while mid-solar resources comprise classes 6–9 with DNIs of 6.25–7.25 kWh/m^2-day. Classes 10–12 include areas that have DNI values above 7.25 kWh/m^2-day. A requirement of at least 5 kWh/m^2/day is used here. Cases with and without access to cooling water are considered.

2.2. Desalination Siting

For siting of desalination facilities, we consider:

- Water supply to the desalination facility. This is either coastal, or inland brackish water.
- Demand for potable water.

When considering co-siting of desalination facilities with nuclear and solar generators, we assume that the nuclear and solar plants use air cooled condensers, i.e., do not require cooling water. This is because availability of cooling water is likely to be negatively correlated with water stress. The Palo Verde nuclear plant is an example of a facility in water stressed area for which water usage is an important consideration. Palo Verde uses treated municipal wastewater from the Phoenix, although the demand for this effluent from other sources is increasing as local water resources become more stretched [28].

Thermal coupling of solar and nuclear with desalination necessitates use of a thermally driven desalination process. The implications of this for use of seawater and brackish water are discussed in the following section.

2.2.1. Desalination Technologies in the Context of Low-Temperature Cogeneration

Desalination technology has become increasingly important in supplementing conventional groundwater extraction as the global demand for freshwater continues to grow rapidly. Desalination provides an alternative method to procuring freshwater, which makes it especially valuable in regions where groundwater is scarce, such as coastal areas and population centers near inland deserts. As reported in Ref. [29], desalination has steadily increased from very little capacity in the 1970s to ~100 million m^3/day as of 2019, especially in high water stress regions with population booms.

Desalination may be performed using an electricity driven process such as Reverse Osmosis (RO), or a thermally driven process such as MED. RO is a water treatment process that removes contaminants and toxic chemicals by forcing the water molecules through a semipermeable membrane and requires input electricity to operate. MED, on the other hand, uses heat to generate evaporated steam from the water, therefore producing clean distillate water. As discussed further below, RO is the most common choice, in particular when using brackish water rather than seawater [30]. However, historically, desalination has generally been powered by fossil fuel energy, and hence, there has been a focus on reducing energy use and therefore cost. As such, it is common to dispose of brines without maximizing the amount of water and salts extracted. Because the IES desalination reviewed in this paper will be powered with low quality or waste heat, using additional energy is not as costly.

Co-siting with MED is more relevant since it is thermally driven, giving the opportunity to be compatible with CSP and nuclear coupling. Restrictions on desalination and brine waste management in the U.S. includes any form of policy framework that invoke specific requirements related to water desalination and brine disposal. Federal and state policies are important [31]. From the federal perspective, the safe handling of brine disposal is regulated according to the National Pollutant Discharge Elimination System [32] and the National Pretreatment Program [33]. Disposal by Underground Injection Control is also regulated [34]. From the state perspective, not all states impose a specific law on water desalination. Several states with potentially more limiting restrictions on water treatment plants are as follows. For example, California places limits on seawater salinity of discharged brine [35]. A potential opportunity to manage brine waste is through Zero Liquid Discharge (ZLD). Brine can be considered a resource that contains potentially recoverable salts and heavy metals, potentially motivating reuse of brine and ZLD systems [36,37]. MED is useful here because it can produce high salinity brines compared to membrane processes, minimizing brine volume. This could also provide scope for lower, higher salinity brine discharge if environmentally preferable. Additionally, many ZLD technologies, such as brine evaporators and crystallizers, require large amounts of thermal power that could be provided by the IES.

Freshwater can be procured from several sources. Understanding the cost of other alternative methods can provide perspective on the competitiveness of generating water through the desalination process. Water-processing costs depend heavily on the type of technology used. Some common freshwater generation technologies aside from desalination include processes that remove solids and unwanted particles from water, such as coagulation and flocculation. Membrane separation is also another common form where water is passed through a passive filter, and typically includes either nanofiltration or microfiltration technology. Disinfection with ozone, chlorine, or ultraviolet (UV) rays are also fairly cheap methods to produce water [38].

Some commonly available water treatment processes are observed to have wide-ranging cost estimates that are heavily dependent on the capacity/production rate and its production method. As the capacity increases to an industrial scale compatible to pre-existing MED plants (>>900 m^3/day), a pricing study by Dore et al. suggests that generating water via the UV/chlorine/ozone disinfection method approaches a horizontal asymptote of ~1.4 USD/m^3 (adjusted for 37.85% inflation, 2008–2023) for all methods [39]. There also exists water treatment processes to remove specific chemical compounds, such as arsenic [40], as shown in Table 2.

Table 2. Cost breakdown of select clean water generation methods [40].

	Cost ($/m^3)			
Technology	**O&M**	**Media Replacement**	**Chemical**	**Electricity**
Adsorptive Media (AM)	6.65	5.93	0.04	0.04
Coagulation/Filtration (CF)	1.06	N/A	0.15	0.19
Ion Exchange (IX)	1.85	N/A	1.47	0.23

The most common freshwater treatment technology, Coagulation/Filtration (CF), has an estimated water-generation cost of ~1.8 $/m^3 (adjusted for 25.22% inflation, 2015–2023). Other alternative technologies such as AM (~12.7 $/m^3) and IX (~3.6 $/m^3) are less common and therefore significantly more expensive. The reported estimates are for a capacity production greater than ~550 m^3/day. Anything less is excluded from the discussion as it is too small for the typical size of an industrial-scale desalination facility currently under review for this paper. It is important to note that the production cost might even go down further as capacity increases.

The cost and energy requirements of various methods of desalination are compared in Table 3. For larger-capacity productions of >100,000 m^3/day, Table 3 shows that the cost of water generation via MED as a stand-alone technology is ~0.98 $/m^3 (adjusted for 27.40% inflation, 2013–2023), while RO averages around ~0.71 $/m^3, both for saltwater treatment [41]. In both cases, cost falls with size of the facility. Ref. [42] reports costs ranges (2013 $/m^3) of 0.2–0.4, 0.5–1.2 and 0.7–1.2 for brackish water RO, seawater RO and MED respectively, giving a similar trend to Ref. [41]. Ref. [42] aims to provide the true treatment cost that excludes administrative and conveyance fees, with the necessary disinfection costs included. Comparing to the cost of other methods above, this indicates that desalination can be a cost-competitive technology for water production, in particular at larger scales. Note that brackish water contains 1000–10,000 mg/L total dissolved solids, while anything greater than 10,000 mg/L is considered highly saline, including seawater [43]. Production capacity for RO and MED varies greatly. From Ref. [44] MED is preferred for larger systems exceeding 5000 m^3/day, while RO are typically less than 100 m^3/day. Nonetheless, larger RO plants have been built in recent years [41].

From Table 3, RO is generally cheaper than MED, which has driven its increased deployment in contemporary preference to thermal desalination systems [45]. At low salinities, i.e., for brackish groundwater, membrane technologies like RO are more energy-efficient [30] and economical than thermal processes like MED. This is because the energy consumption of RO rises with salinity (Table 3), while this is less pronounced with MED. The case for MED is therefore highly challenging with brackish water (i.e., inland). In isolation, cost reduction from utilization of low-temperature cogeneration is unlikely to be a sufficient value proposition based on Table 3, unless the source of water is of high salinity.

However, when performing seawater desalination, costs of MED and RO are similar. From a capital cost and water use perspective, the costs are similar. MED requires 4–7 kWh/m^3 of thermal energy, but also needs ~1.5–2 kWh/m^3 less of electrical energy. If low quality heat is extracted from a steam turbine, this will be anticipated to cause a reduction in electrical output of substantially less than 33% of the heat supplied (as the temperature of supply is ~100 °C and a ~300 °C steam turbine supplies electricity with

~33% efficiency) and therefore we can reasonably expect the energy costs for MED to be similar to or lower than RO.

Table 3. Desalination cost [41] and energy usage [42] as a stand-alone technology.

Process	Water Type	Capacity (m^3/day)	Cost ($/$m^3$)	Thermal Energy (kWh/m^3)	Electrical Energy (kWh/m^3)
MED	Seawater	91,000–320,000	0.52–1.01	4.0–7.0	1.5–2.0
		12,000–55,000	0.95–1.5		
		Less than 100	2.0–8.0		
RO	Seawater	100,000–320,000	0.45–0.66	-	3.0–4.0
		15,000–60,000	0.48–1.62		
		1000–4800	0.70–1.72		
RO	Brackish water	40,000	0.26–0.54	-	0.5–2.5
		20–1200	0.78–1.33		
		<20	0.56–12.99		

Some studies have found a value proposition to using MED with low-temperature cogeneration in preference to RO [46]. This is particularly the case in the Persian Gulf due to its relatively high salinity. For RO, water recovery rates are also worse at high salinities, and membrane fowling also becomes a more prominent issue. However, water discharged from MED is warmer than ambient, which is undesirable from an environmental perspective.

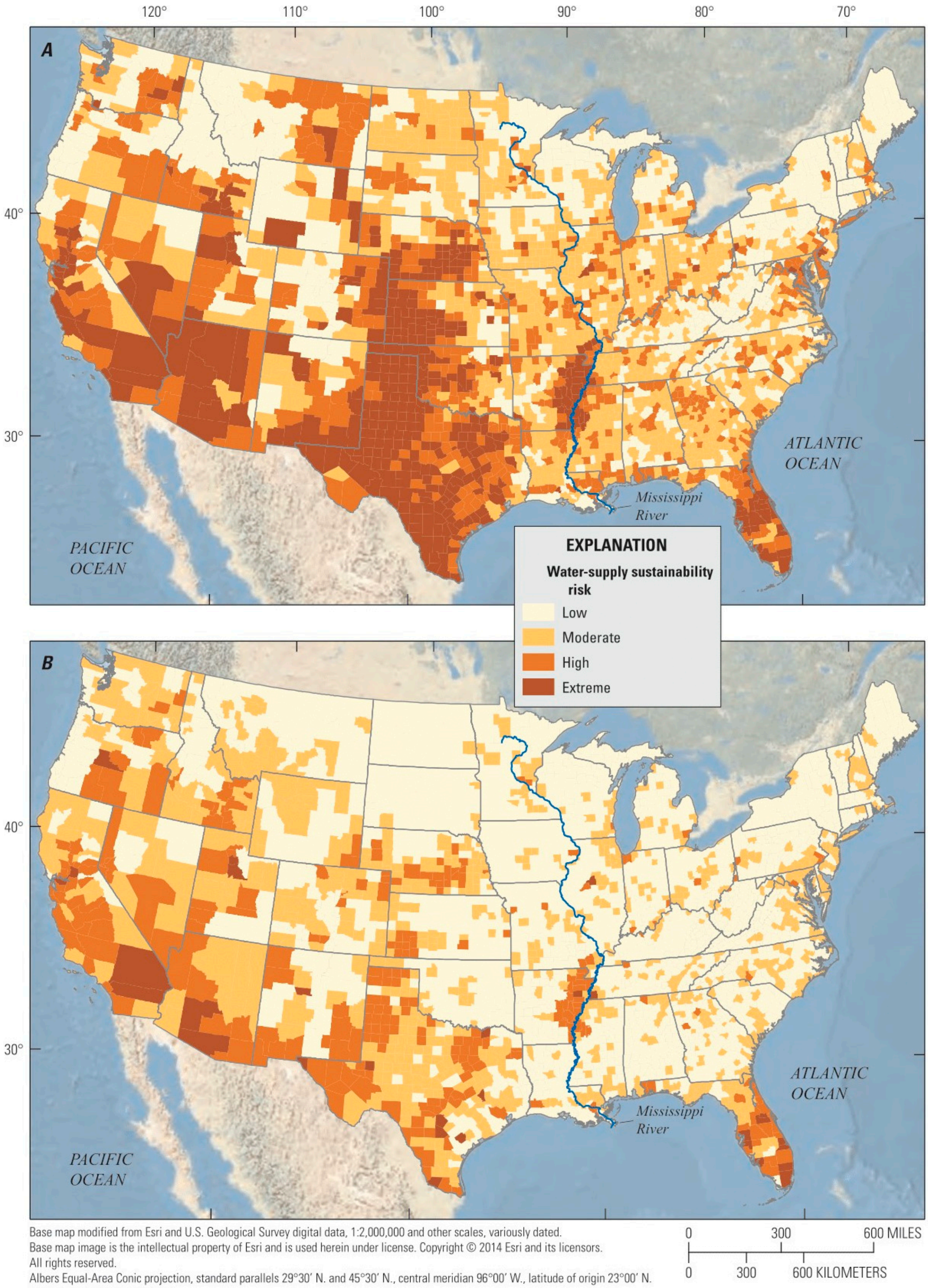
2.2.2. Demand for Fresh Water

The USGS assessed water supply sustainability risk in the United States, considering population growth and power generation. Sensitivity to incorporating the effect of climate change was also included (Figure 3) [47]. Not accounting for climate change effects, the Southwest and Florida are predicted to have the greatest water stress. Accounting for climate change, water stress is generally anticipated to increase. Notably, water stress in the Great Plains is anticipated to increase significantly. In this study, we consider water stress in the 2050 scenario, accounting for the effect of climate change. This is because there is a significant lead time before IES would be built, and they would be anticipated to operate for decades.

2.2.3. Brackish Water Availability

Recognizing from Section 2.2.1 that thermally driven desalination processes are unlikely to be attractive, we nonetheless review the availability of brackish water to perform inland desalination for completeness. For example, it may still prove useful to site new electrical generators near electrically driven desalination processes to reduce transmission costs.

The USGS performed an extensive aggregative of brackish groundwater resources in [47]. Brackish groundwater (define as in the range 1000–10,000 mg/L dissolved solids) was observed in every state except Rhode Island and New Hampshire, with the greatest occurrence in the Great Plains region as shown in Figure 4. These data were then used in a regression analysis to predict the minimum depth to brackish groundwater (Figure 5). Here, we use this minimum depth as an indicator for the practicality of performing brackish groundwater desalination in a given location. It is noted that brackish groundwater is not observed in every location (as shown in Figure 4), so these data are useful for general trends rather than specific sites.



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Albers Equal-Area Conic projection, standard parallels 29°30′ N. and 45°30′ N., central meridian 96°00′ W., latitude of origin 23°00′ N.
North American Datum of 1983

Figure 3. Water-supply sustainability risk index in 2050 with climate change included (**A**) and not included (**B**). Reproduced from [47].

While the depth to brackish groundwater is larger in some of the Southwestern states and this may rule out some locations, it is likely that brackish water is still available in many locations. For example, Idaho National Laboratory performed a case study on the use of brackish groundwater at the Palo Verde nuclear power plant [48] near Phoenix using a local regional aquifer.

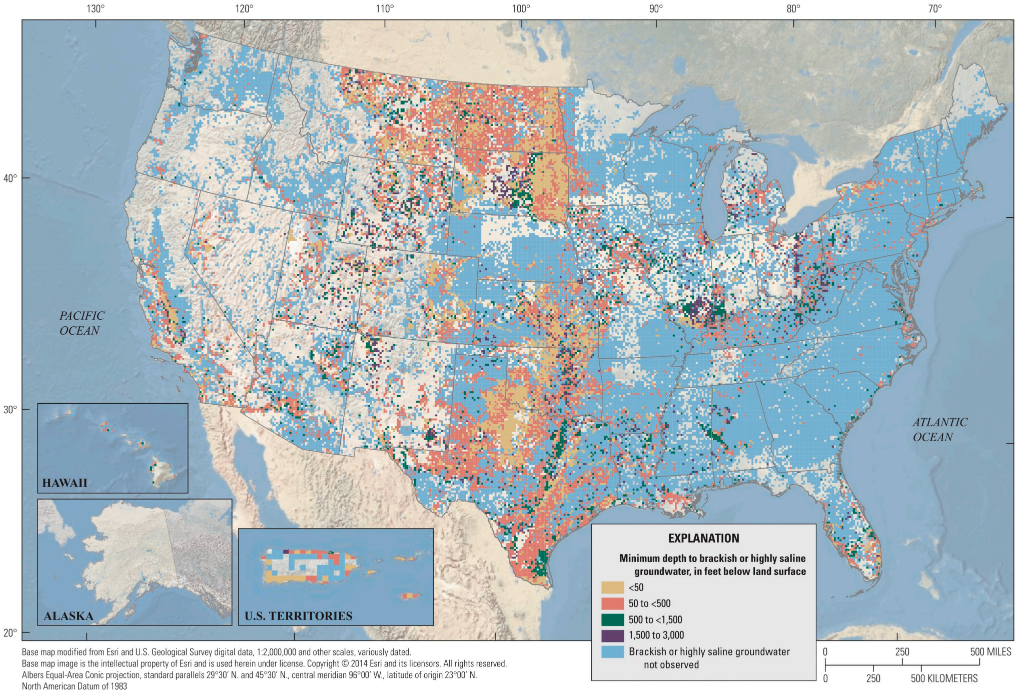

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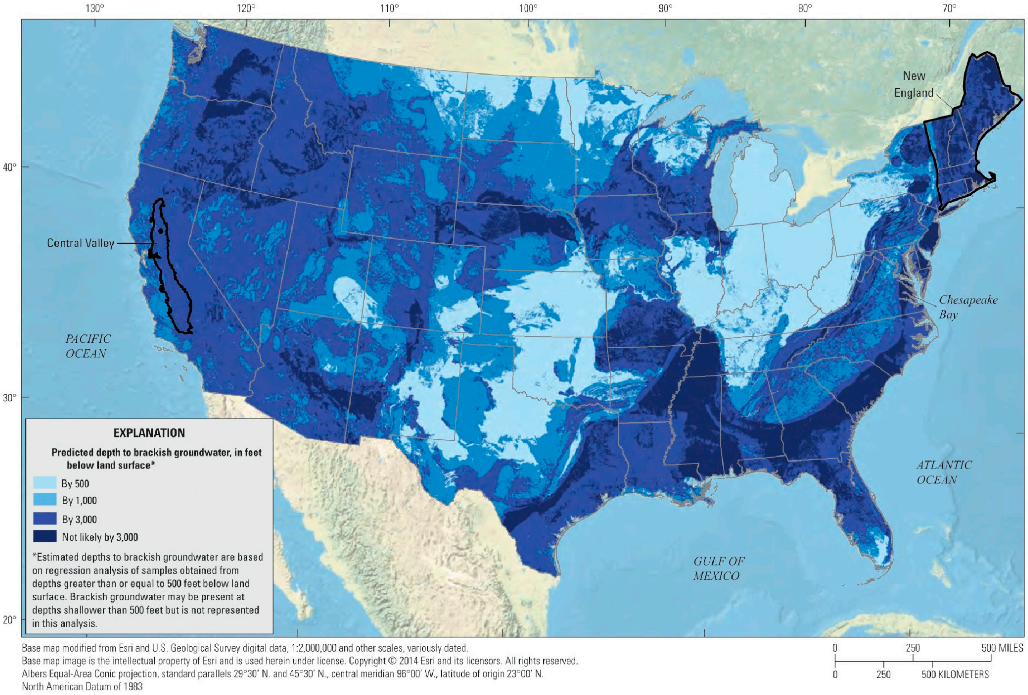
Figure 4. Observed minimum depth to brackish groundwater in the United States. Reproduced from [47].



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North American Datum of 1983

Figure 5. Predicted depth to brackish groundwater for depths between 500 and 3000 feet. Reproduced from [47].

2.2.4. Creation of the Dataset

From the above discussion, we use the following data:

- Water stress in 2050 accounting for climate change as a measure for potable water demand.

- Coastline as a measure for seawater supply.
- Predicted depth to brackish groundwater as a measure for brackish water supply.

The coastline can be observed in the results "by eye". For the other measures, we convert the images shown Figures 3A and 5 into GIS format using the openly available QGIS software version 3.36.0 [49]. This allows these maps to be overlaid with the GIS datasets produced for nuclear and solar. We do not define specific acceptance criteria for water stress or depth to brackish water, but instead overlay the nuclear and/or solar availability and a continuous color map. It is noted that this procedure is not perfect as it relies on the visual image but is sufficient for deriving trends.

3. Results

3.1. Nuclear and CSP Co-Siting

Co-siting options for nuclear and solar are first considered under assumption of an advanced reactor with dry cooling (Figures 6 and 7). There are substantial opportunities for co-siting across the Southwestern U.S. The largest concentration of available sites is in the southern Great Plains region, which combines flat land of low population density with sufficient direct normal irradiance. While sites are more scattered across other states in the Southwest, it is noted that sites in states including Arizona and New Mexico will have higher DNI and, hence, potentially better economic performance. With a larger solar plant, the incidence of available sites is reduced, although the overall trend remains the same.

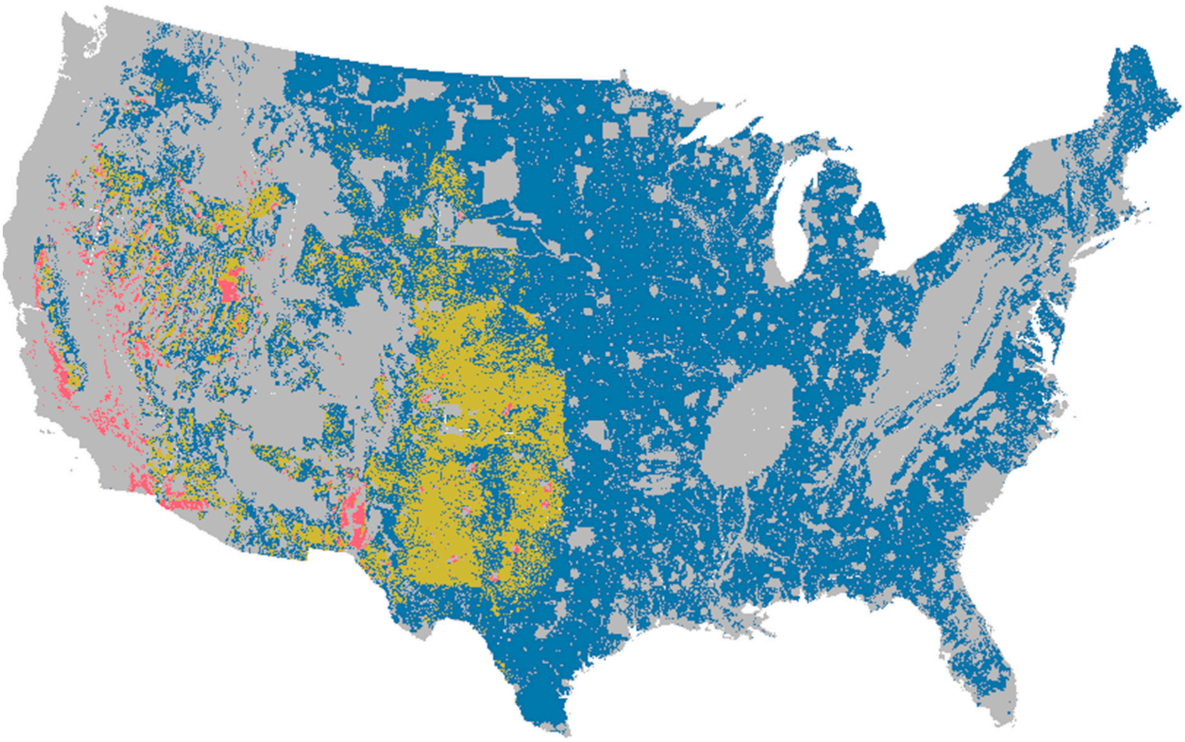

Figure 6. Siting options for nuclear only (blue), solar only (red), and nuclear-solar co-siting (yellow) not requiring water source. Small solar plant considered.

Screening for a LWR, which notably includes a restriction on water availability (Figure 8), reduces the number of available sites, although they remain scattered across the Southwest of the U.S. Here, the water availability is based on the streamflow criterion from Table 1, which is sourced from USGS data as discussed in Ref. [20]. This nonetheless significantly reduces available siting options, especially in the highest DNI areas.

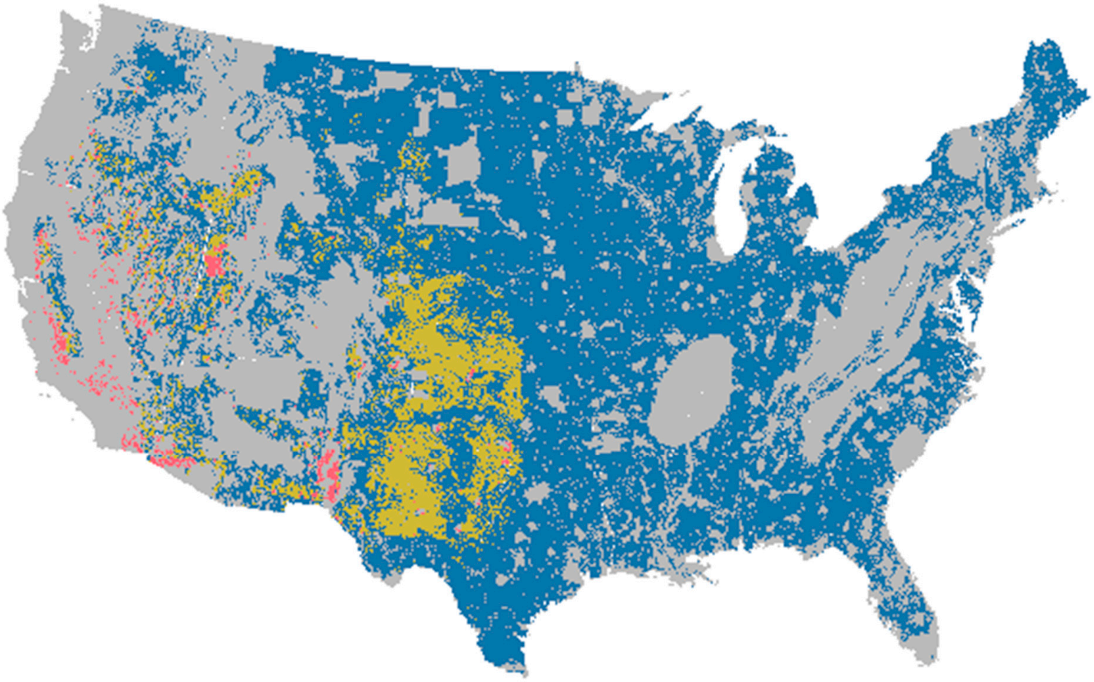

Figure 7. Siting options for nuclear only (blue), solar only (red), and nuclear-solar co-siting (yellow) not requiring water source. Large solar plant considered.

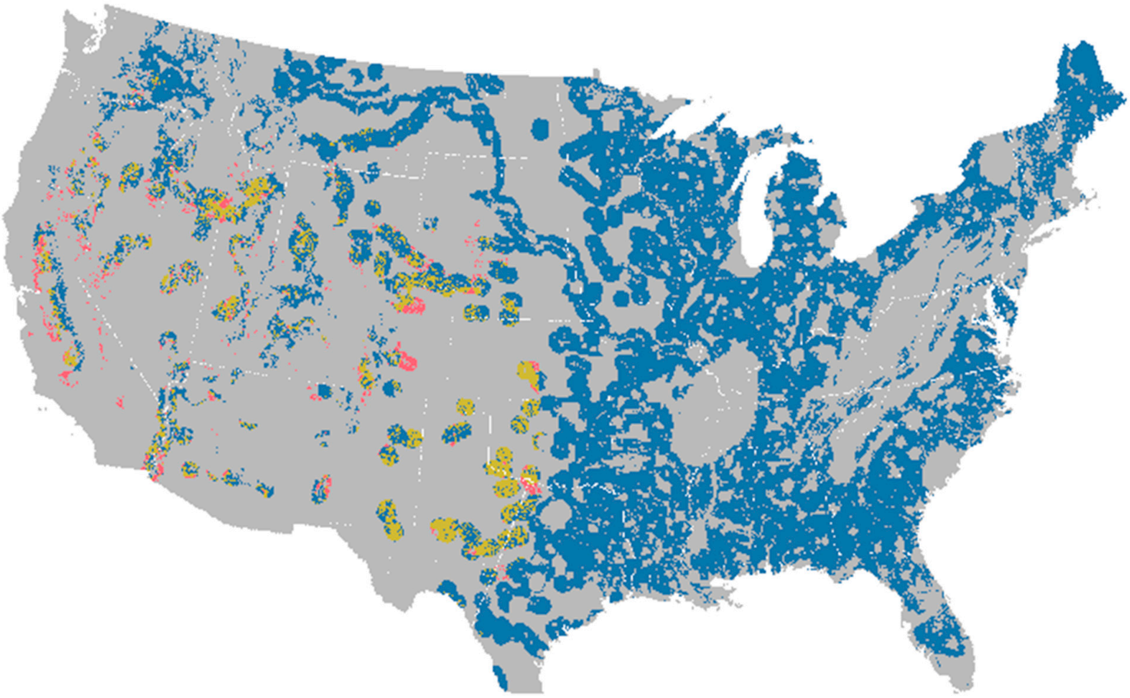

Figure 8. Siting options for nuclear only (blue), solar only (red), and nuclear-solar co-siting (yellow) requiring water source. Small solar plant considered.

While not shown in the maps below, it is noted that construction moratoria on nuclear plants constitute a formidable obstacle to nuclear-CSP siting in California and Oregon in particular (out of the states where co-siting is a potential option).

Another potential challenge with the deployment of large CSP installations is the potential to displace significant areas of arable land. To estimate this, data from the United States Department of Agriculture are used [50], which gives US-wide data on cultivation percentage. Here, we screen on a cultivation percentage of 50% or greater. The dataset is created in the same manner as the brackish water availability and water stress data—i.e., by reading in an image file.

In Figure 9, the nuclear, solar, and co-siting options for a small solar plant and dry cooling are overlaid with cultivation percentage. It is noted that nuclear-only siting is less likely to be affected by this, as nuclear plants are relatively compact, but this is also shown for completeness. Co-siting options are reduced, notably in the central Great Plains. However, a significant number of siting options remain, especially in the Southwest, where cultivation is lower.

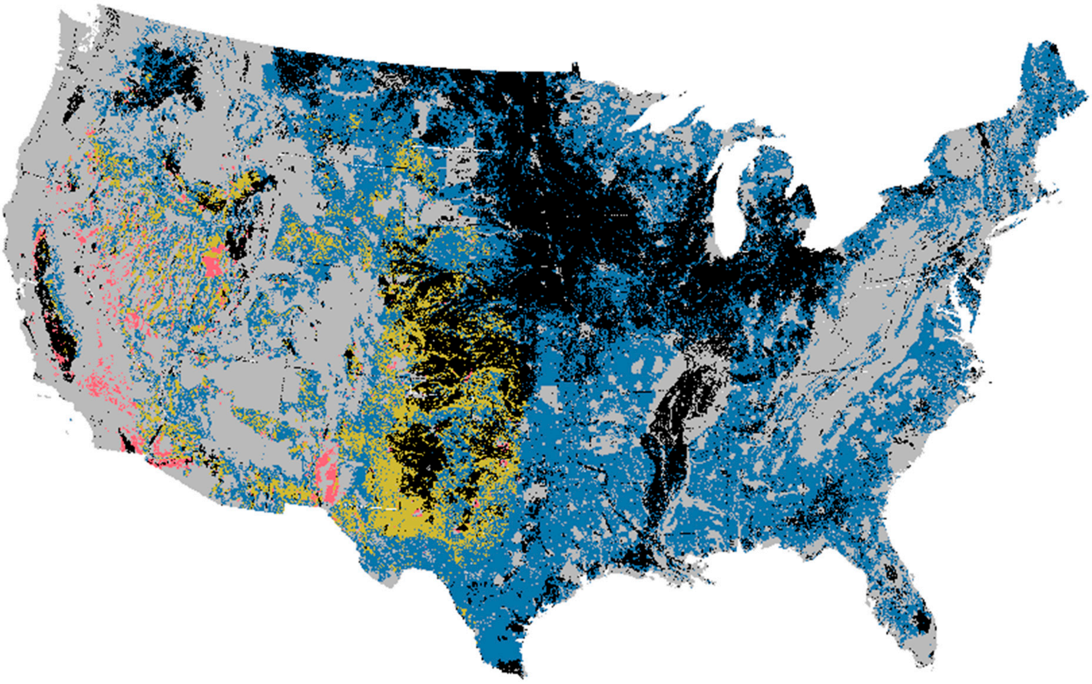

Figure 9. Siting options for nuclear only (blue), solar only (red), and nuclear-solar co-siting (yellow) not requiring water source. Small solar plant considered. Areas which are >50% cultivated are screened out (black). Note: the image processing of the cultivation data also screened out bodies of water, e.g., Salt Lake.

3.2. *Potable Water Demand*

Nuclear siting options are overlaid with water stress in Figure 10. The southern Great Plains combines large areas of available sites with high predicted water stress in 2050. Sites elsewhere in the Southwest are also potential options, also projected to experience acute water stress (even not accounting for climate change). When screening for coastal sites for seawater desalination, the largest concentration of attractive sites is on the Gulf Coast of Texas, which also corresponds to an area of high predicted water stress. There are, however, a few other areas of the Gulf Coast which may present suitable siting options.

It is noted that there are some existing nuclear reactors that are on the coastline in current or predicted higher water stress areas. These include South Texas Project, St Lucie (Florida), Turkey Point (Florida), and Diablo Canyon (California). A recent study assessed the feasibility of using Diablo Canyon as an energy source for desalination using reverse osmosis (which utilizes electricity rather than heat) as modifying the plants steam cycle was discounted as impractical [51]. It is noted that Diablo Canyon currently operates a small (2450 m^3/d) desalination plant for a few on-site uses including drinking water, fire, and dust suppression [51].

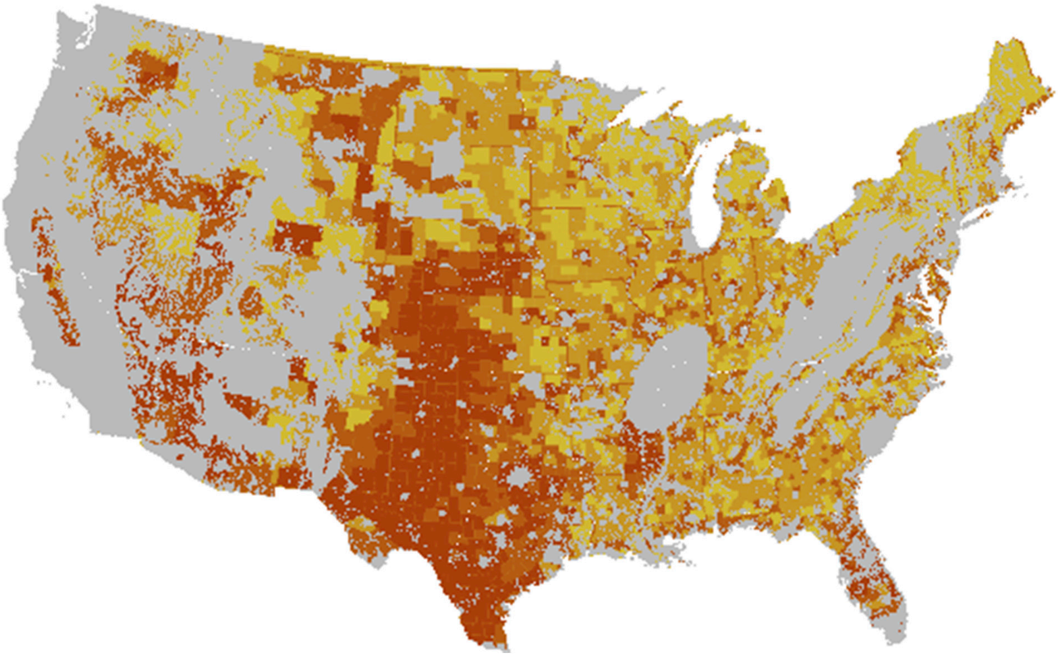

Figure 10. Nuclear siting options shaded according to water stress metric (darker = higher water stress).

Solar siting options with a small solar plant, with water stress overlaid, are shown in Figure 11. This eliminates coastal options. Most suitable solar sites are areas in the Southwestern U.S. that either experience water stress or are projected to do so by 2050.

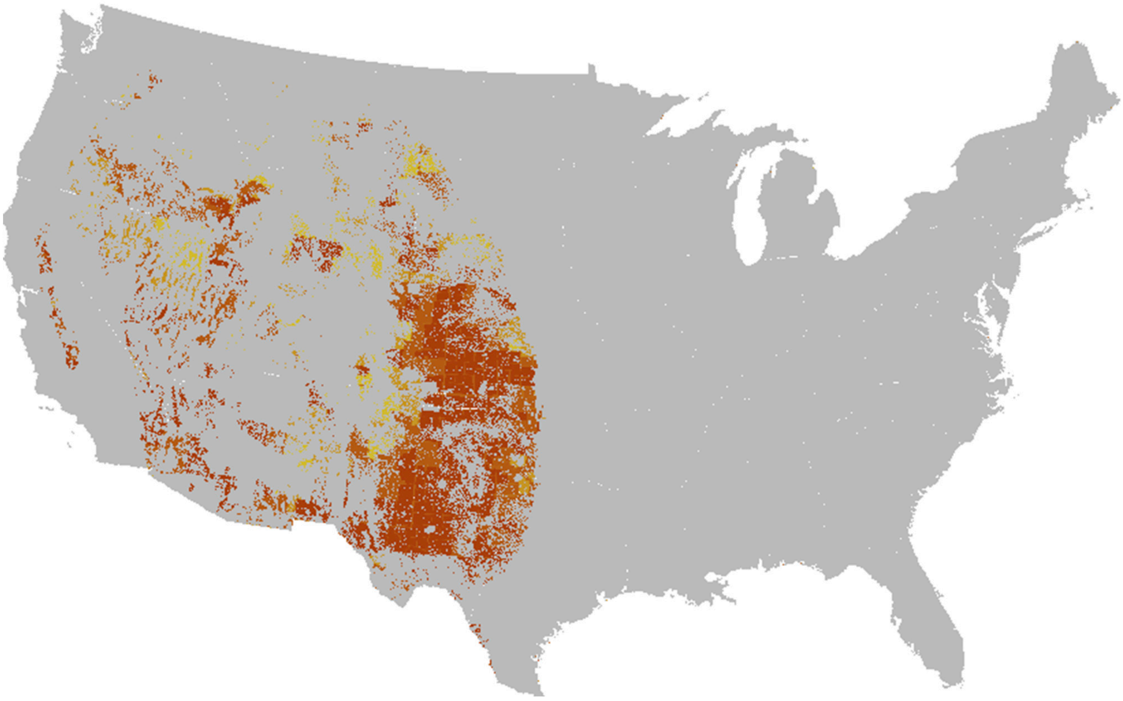

Figure 11. Nuclear + solar siting options shaded according to water stress metric (darker = higher water stress).

3.3. Brackish Water Supply

An overlay of brackish water supply on nuclear and nuclear + solar sites is shown in Figures 12 and 13, respectively. Again, the small solar plant is used. While this cannot give a firm indication of brackish water availability at all sites and there is predicted to be some availability of brackish groundwater across most of the Southwestern U.S., it can give some indications of where might be particularly of interest. Here, the relatively high availability of brackish groundwater in the southern Great Plains is noteworthy and corresponds to the highest concentration of available sites for nuclear-CSP co-siting, as well as being an area of projected water stress in 2050. Nonetheless, it must be reiterated that the most economic option for desalination with brackish groundwater is currently RO, even accounting for the synergy from low-temperature cogeneration.

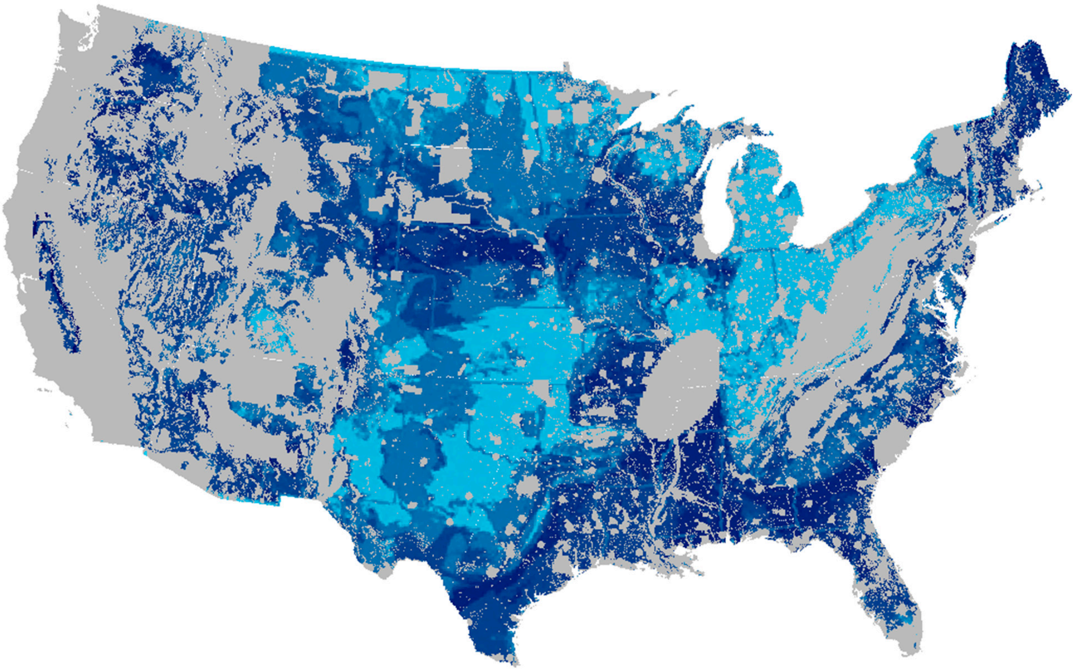

Figure 12. Nuclear siting options, shaded according to depth to brackish groundwater (lighter = closer to surface).

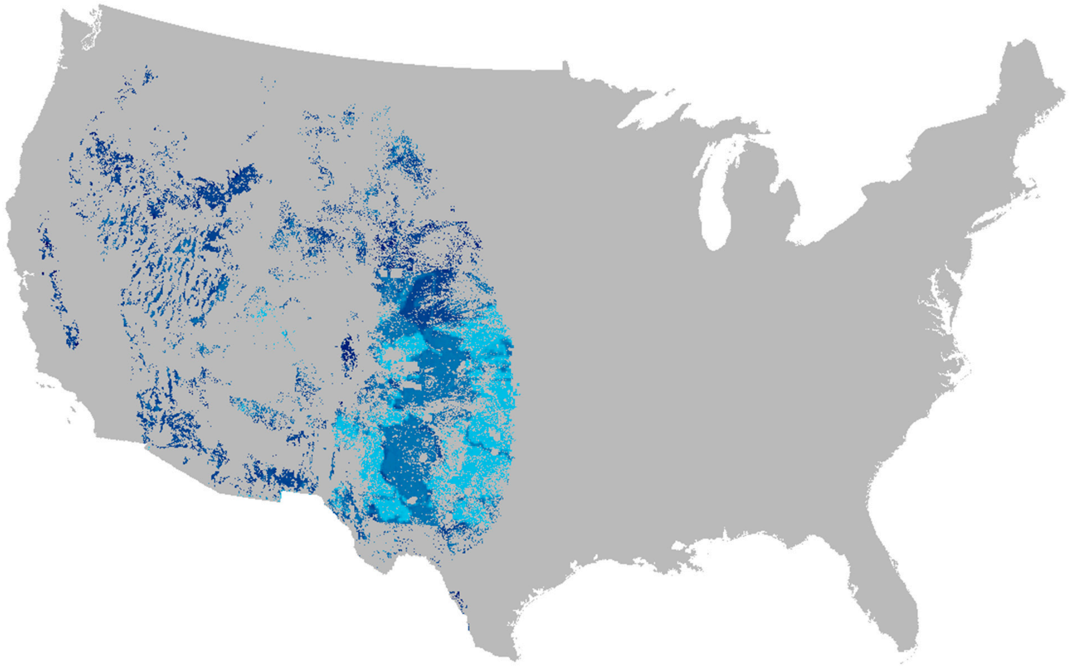

Figure 13. Nuclear + solar siting options (pink), shaded according to depth to brackish groundwater (lighter = closer to surface).

4. Conclusions

In this paper, co-siting options for nuclear, CSP, and desalination have been investigated, with the view to finding suitable regions for deploying IES that use some combination of these technologies.

Co-siting of nuclear and CSP was first considered. With air-cooled condensers, it is generally possible to find suitable sites for co-siting of nuclear and CSP in the Western U.S. The largest concentration of available sites is in the Southern Great Plains. This is largely driven by sparse population, flat land, and sufficiently high DNI to enable CSP siting. There are, nonetheless, other siting options throughout the Southwestern U.S., in many cases with higher DNI and, hence, more attractive for CSP siting, but these are more scattered, e.g., in Arizona and New Mexico. If water cooling is required, the available siting options are much more sparsely distributed, and this may in particular challenge siting in the highest DNI areas.

The potential for co-siting with desalination was also considered. Thermal desalination is unlikely to be economically preferable outside of coastal regions. While electricity-driven desalination could be co-sited with electrical generators, the motivation for doing so is reduced. As the coasts are generally not suitable for CSP, this means that CSP desalination co-siting is unlikely to be preferred in the U.S. Nuclear desalination is, however, possible in coastal regions, and there are siting options along the Gulf Coast. Particularly in Texas, these could be areas where water stress becomes increasingly relevant over the next few decades.

Recognizing that thermal desalination of brackish water may not be attractive, the areas where nuclear and CSP can be co-sited are also generally areas that are experiencing water stress or can be predicted to experience water stress by 2050.

Finally, given some of the challenges associated with finding feasible co-siting options for such systems, it is recommended that co-siting is considered in conjunction with the design of current and future IES to ensure that there are sufficiently attractive deployment options to make the design a practical option.

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