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Review

The need to strategically manage CSP fleet development and water resources: A structured review and way forward

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ABSTRACT

The rapid global growth in the use of renewable energy to reduce GHG emissions and mitigate climate change, through the inclusion of large amounts of PV and wind in existing electricity grids, has highlighted certain challenges. Most critically, their intermittent supply, necessitates flexible dispatchability from other generators in the grid. Currently, few renewable energy technologies offer this dispatchability, with only concentrating solar power (CSP) offering storage. CSP generates electricity from thermal heat, similar to fossil-driven thermal power plants, with the heat-source being inexhaustible concentrated solar irradiance. The thermal process, however, requires cooling, best achieved with a finite resource; water. CSP is ideally suited to areas of high solar irradiation, typically arid and water stressed. The need for water as a source of cooling is often neglected in the planning and development of CSP. This paper identifies water as a constraint to CSP deployment, and explores CSP's potential contribution to generation through the lens of the water-energy nexus. This aids our understanding of how water availability threatens expected CSP production capacity and places natural limits on its sustainable development. For strategic planning of CSP, we therefore propose the inclusion of integrated water resource management in CSP energy infrastructure planning.

Contents

List of acronyms: CSP, Concentrating Solar Power; GIS, Geographic Information Systems; IWRM, Integrated Water Resource Management; PV, Photovoltaic; RET, Renewable Energy Technology.

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1. Introduction

Thermal electricity generation requires water in large quantities; accounting for around 40% of the national annual water withdrawals in the United States (U.S.) in 2006, and 45% in 2010 [1,2]. Globally, water withdrawals for thermal electricity constituted 15% of available fresh water resources in 2010 [3]. Due to improved access to technology by lower- and middle-income groups, and the growth in population, it is estimated that electricity demands will double in regions like China, India and Brazil over the next 40 years, and increase sevenfold in Africa by 2050. This population growth and increased consumption patterns will result in greater demands for both water and electricity [3,4]. This increase in demand for both resources will take place against a backdrop of greater climate uncertainty, with more people living in areas that are under severe water stress [5,6].

There is a gradual global transition away from conventional electricity generation towards Renewable Energy Technologies (RETs). Solar photovoltaic (PV) and onshore wind turbines have seen the greatest increase in adoption, and are expected to reach 48% and wind 35% (82% combined) of new renewable installed capacity by 2022 [7,8]. The costs of these technologies have decreased greatly from their inception in the late 1980's and early 1990's, with the technology-specific costs of PV and onshore wind having decreased by 70% and 50% since 2010, respectively [7,9]. These technologies, however, experience a major limitation due to resource intermittency [10], and the capacity factors of PV (25%) and wind (33%), are much lower than coal or nuclear [11]. Therefore, as the proportion of PV and wind in the power supply mix increases, there is a growing need for storage or more dispatchable supply of electricity in order to meet peaking demands and decreased grid stability [12–14]. Dispatchable renewable energy options include the use of PV and wind with storage in batteries (currently still considered a more expensive solution [15]), power-to-gas,[1] hydro-pumped storage, bioenergy, and CSP with thermal storage [16]. However, to date gas turbines using natural fossil fuel has been the favoured dispatchable power generation option, because of flexibility, low capital costs and short lead times [17,18].

CSP is a renewable energy technology that generates electricity similarly to other fossil-driven thermal power plants. Its source of heat, concentrated solar irradiance, makes it completely independent from fossil fuels. The addition of heat storage to CSP offers dispatchable electricity by enabling power generation at night and times when there is little or no solar irradiation [19–25]. In this study, the term CSP refers only to either parabolic trough or central receiver technologies with varying amounts of storage. Combined with an international push for carbon emissions reduction from the electricity sector, the global demand for dispatchable renewable energy, in the form of CSP, is likely to increase in regions with high solar irradiation, such as Southern Africa, Australia, and the MENA[2] region [7]. As the development of CSP increases in countries with favourable solar resources, "solar parks" will emerge, where CSP and PV plants are grouped together in large quantities to exploit as much high-quality solar resources as possible. Examples of such solar parks can already be found in Morocco and the UAE [26,27]. In South Africa alone, as part of the ministerial determinations on Renewable Energy, a solar park of 5 GW has been planned in the arid Northern Cape Province [28,29].

Similar to all thermal power generation technology, such as conventional fossil fuel power-plants, CSP requires a heat sink and, therefore, some form of cooling technology. The most cost-effective and efficient cooling technology is of the "wet-cooling" group, where water is actively used to cool and condense the steam after it has passed through the last steam turbine [30]. An alternative option that is more costly, but uses 90% less water, is "dry-cooling", which uses ambient air to cool and condense the steam [31]. Its efficiency, therefore, depends on the temperature and humidity of the air [30]. The higher capital cost, combined with its inherently lower efficiency, results in a double cost-penalty for CSP with "dry cooling", compared to "wet cooling". At CSP plants, 90% of water is typically used for cooling, while the rest is predominately used for cleaning of the solar-field and steam-cycle make-up [32]. Alternative water sources like seawater, and the combined generation of desalinated water and renewable electricity, are technically viable options and have received much attention, but typically require even more piping and pumping infrastructure, adding extra cost [33,34]. Combined CSP and desalination are also best-suited in close proximity to coastal areas which unfortunately suffer from lower solar DNI due to higher cloud cover and air-moisture [35]. Many studies have assessed various countries' land potential for CSP based on certain suitability criteria. A summary of the criteria used in literature is given in Table 1.

However, despite the fact that both water and solar resource availability varies spatially and temporally, and the growing evidence of the important linkages between water and energy planning [4,51–65], water resource availability is often poorly considered in CSP planning and deployment [66]. With CSP being a viable solution as a large-scale, fully dispatchable RET, able to counter the intermittency issues associated with higher percentages of PV and wind in countries' energy mixes, its adoption rates are likely to rise. Due to the reliance on high solar irradiation, regions between 15^{O} and 40^{O} North and South of the equator, which are typically arid, will experience the most CSP development [67]. With this in mind, it is foreseeable that this increase in CSP adoption in such arid regions might place further pressure on already stressed water resources, and that constraints on water availability may curtail CSP performance and pose risks to the stranding of CSP assets. This is particularly true if CSP planning does not carefully consider water consumption and water availability at a local level. While there have been many studies on the reduction of CSP technology costs [68–74], cost escalations due to loss of production from reduced water availability poses a tangible risk that can be mitigated through appropriate planning. Therefore, there is a need to assess the potential of CSP in areas of high solar irradiation in light of the constraints imposed by water availability, and strategically manage CSP deployment so that it does not increase water scarcity.

This paper aims to provide an approach to the strategic management and planning of CSP infrastructure through the lens of the water-energy nexus. We assess the constraints of water availability

[1] This is especially an option in European countries where heating is an important energy driver, and where supply from renewables like wind regularly exceed demand [16].

[2] Middle East and North Africa.

Table 1
Suitability criteria for CSP plants from literature.

Criteria	[36]	[37]	[38]	[39]	[40]	[41]	[42]	[43]	[44]	[45]	[46]	[47]	[48]	[49]	[50]
Min DNI (MWh/m2/y)	2	2	1.8	2.2	1.7	1.8	1.8	2.6	1.5	2	1.5	2	1.8	1.8	NA
Max Slope (%)	2.1	1–4	3	2	3	0–3	2	1	1–5	4	2[g]	2.1	3	2.1	2
Excluded areas, buffer(km)*															
Wetlands	NA	0.5	NA	0	0[a]	NA	NA	NA	NA[d]	0	NA	0	NA	0	0
Lakes	NA	0.5	NA	0	0[a]	NA	0	0	NA	0	NA	0	NA	0	0
Rivers	NA	0.5	NA	0.5	0[a]	NA	0.5	0	NA	0	NA	0	NA	0	0
Sandy soil	NA	0.5	NA	10	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Forests	NA	1	NA	0	0	NA	0	NA	NA	NA	NA	NA	NA	0	0
Protected areas	NA	1	NA	0	0[b]	NA	0	0[c]	NA	0[e]	0	0[e]	NA	0	NA
Agriculture	NA	2	NA	0	0[b]	NA	NA	NA	NA	NA	35%[h]	NA	NA	0	0
Roads	NA	2.5	NA	0.05	NA	NA	0.5	NA	NA	NA	NA	NA	NA	NA	NA
Railways	NA	NA	NA	NA	NA	NA	0.5	NA	NA	NA	NA	NA	NA	NA	NA
Mines	NA	NA	NA	3	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Populated areas	NA	0	NA	0	0	NA	0	0	NA	NA	NA	0	NA	6–8	0
High Wind Areas**	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0	NA	NA	NA
Min area (km2)	NA	NA	NA	NA	NA	NA	NA	2	NA	NA	4	NA	NA	NA	NA
Maxi distance to (km)															
Grid	NA	NA	NA	NA	NA	NA	NA	20	20–100	NA[f]	NA	30[i]	40	50[i]	NA[j]
Roads/Rail	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	40	20[i]	NA[j]
Dams	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	9[i]	NA[j]
Rivers	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA[j]

* An area beyond the explicit reach of the unsuitable area, also considered unsuitable, i.e. 0 km means only the area itself, 0.5 km means the area itself with an extended perimeter of 0.5 km around it.
** Areas identified to pose potential risks to CSP structures.
[a] The use of buffers is mentioned but no detail on their extent is given.
[b] The study considered three different scenarios: one excluding, one including protected areas, and one including agricultural areas.
[c] The study used vegetation maps categorized as "critically endangered", "endangered", "vulnerable" and "least threatened", excluding all categories but "least threatened".
[d] The study limited all areas remaining after applying the other suitability criteria to only 1% of the identified area, in order to allow for reduced availability due to other exclusion considerations.
[e] "Environmentally sensitive lands" and Aboriginal Heritage sites are excluded.
[f] While the benefit of closer proximity to transmission infrastructure is discussed, it is not used as a limiting factor.
[g] Slopes up to 7% are considered along with restrictions on the orientation of the slope (North or South), but only <2% is considered explicitly suitable.
[h] Percentage of land cover type considered for CSP development. Similar percentages are applied to other land cover types.
[i] The study used a weighted approach to identify more and less suitable areas according to stakeholder inputs; thus, areas closer to the grid are considered more suitable, an those further are less.
[j] The study modelled the costs associated with building the required infrastructure according to the distance from the infrastructure.

on CSP deployment and propose an approach to the sustainable management and planning of CSP infrastructure. The methodology used in this paper is that of a narrative literature review in order to present a broad perspective of this subject, describe the problem, its context, and opportunities for management [75,76]. The need for improved management and planning of CSP infrastructure in light of the water constraints point to the physical asset management of CSP being integrated with water resource management [77–79].

2. Energy infrastructure management and planning

The physical asset management of CSP involves the integration of CSP generation with the national power generation mix and requires a process of integrated energy infrastructure management. It becomes increasingly challenging to integrate and coordinate energy infrastructure management and planning when the electricity supply market is liberalized or partially deregulated and independent power producers are allowed to enter the regulated market and supply electricity to the national grid [80]. The challenge is to integrate and plan the developments so that supply can be optimised with demand. In South Africa, energy mix expansion is regulated by policy and the future generation mix options are determined by national plans such as the Integrated Resource Plan, Integrated Energy Plan, National Infrastructure Plan and departmental strategic plans [81–84].

Infrastructure asset management is defined in the globally recognised International Infrastructure Management Manual, as "a systematic approach to the procurement, maintenance, operation, rehabilitation and disposal of one or more assets, integrating the utilization of assets and their performance with the business requirements of asset owners or users, with the main focus being the continuous alignment of asset performance to meet service delivery outputs to deliver the desired outcomes" [85]. It considers all phases of infrastructure projects and how they are to be managed in order to continuously ensure optimum performance and cost-effectiveness. When considering the planning phase of electricity infrastructure, there are three categories; strategic, tactical and operative planning [80]. Strategic planning focuses on long-term decisions like investment planning, tactical plans are medium-term ones that focus on, amongst others, project management and budgeting activities, and operational planning looks at short-term tasks like grid stability and plant operation. This paper focusses on strategic infrastructure planning, since the investment-intensive expansion of CSP fleets is under consideration.

Strategic energy infrastructure planning determines the long-term investment timelines for new power plants, and the decommissioning of old ones, in order to maintain a desired power generation and specific mix of technologies in the electricity power supply [85,86]. These studies make use of multi-criteria modelling packages, such as PLEXOS, in order to determine the optimal mix of power generation options-based on their technical and practical capabilities, cost of capital, operation and maintenance costs, and future forecasted electricity demand [87]. However, this type of planning does not provide detailed insight into spatial planning or resource distribution, particularly in the case of RETs [23]. The challenge with RETs is that their operation is highly variable spatially, necessitating more detailed approaches to strategic energy infrastructure planning. Furthermore, these plans do not always carefully consider the water availability for electrical power generation, although a few studies have assessed the amount of water that will be needed to accommodate various power generation mixes with different associated cooling technologies [88–90]. It is argued that this combined total water consumption of energy mixes can be minimized through appropriate technology (power and cooling) selection during the strategic planning phase of energy infrastructure [91].

In the case of South Africa, the Integrated Resource Plan contains the details and schedules for the addition of particular capacities and power generation technologies to the grid, and responds to the White Paper on Energy Policy (1998), and White Paper on Renewable Energy (2003) that highlights the need for affordable renewables in the energy supply mix [92–94]. The Integrated Resource Plan informs the targets of the Renewable Energy Independent Power Producer Procurement Program and results in a competitive bidding process by independent power producers [95,96]. This has resulted in the allocation of 6428 MW of RET capacity between 2010 and 2015 through five rounds of bidding, of which 2372 MW are PV, 3367 MW are Wind and 600 MW are CSP, with the rest being small hydro, landfill gas, biomass and biogas projects [97,98]. The National Energy Regulator of South Africa (NERSA) has also assisted independent power producers to sell electricity through enabling grid access and the partial liberalisation of power supply markets. The Integrated Resource Plan is used by the Department of Energy of South Africa (DoESA) to place targets and timelines for installed capacities of different technologies, thereby serving as the long-term strategic energy mix expansion plan [99].

There are various CSP modelling software packages available and these have been reviewed previously [100]. The particular models that can be used to assess plant output, water consumption and economics include: DELSOL, SAM, SOLENERGY, EXCELERGY, TRNSYS and ColSimCSP, of which the System Advisor Model (SAM) is most notable in academic literature [100,101]. ColSimCSP was recently specifically adapted to simulate CSP operation and water consumption for the international MinWaterCSP project by the European Union [102,103].

3. Integrated water resource management

Integrated Water Resource Management (IWRM) is a process that promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems [104]. It is the response from practitioners and academics within the natural resource management industry to what has since been identified as a lacking approach to rapidly changing natural systems [105]. IWRM acknowledges that water resources within catchments or river basins are complex, and that their interaction with equally (if not more) complex socio-economic and ecological systems add another level of complexity to their interactions [106,107].

In a detailed bibliometric analysis of research trends in the water resource sector, Zare et al. (2017) found that since the 1980s, when there were less than a total of 50 publications per year in the broad field of “Integrated water assessment and modelling”, this has increased to in excess of 1100 per year in the 2010s [108]. Furthermore, the analysis found that the word most prevalent in titles, keyword lists and abstracts was “management”, alluding to the growing realisation of the importance of the concept of active involvement and planning in how human activities interact with water resources. A sharp increase in research focussed on IWRM is seen from 1992 and this is likely due to the publication and formalization of the United Nations (UN) Agenda 21, chapter 18, which emphasises the importance of all UN member states in establishing sound IWRM practices [109], and provides definitions on what constitutes IWRM and guidelines on how to establish such strategies [110]. It suggests that IWRM should be carried out at the catchment or sub-catchment level in the pursuit of the following four cardinal principles:

- IWRM strategies should be dynamic, collaborative, iterative and cross-sectoral with a special focus on identifying and protecting potential freshwater supply sources, and which considers not only environmental and human health wellbeing, but also technological means and socio-economic goals;
- Planning for sustainable and balanced use, and conservation and management of water resources should be based on local community needs within the agenda of national economic development policies;
- IWRM must include the design, implementation and reassessment phases of on-going projects and programmes to ensure they remain both economical and socially relevant through full, indiscriminate public participation;
- The identification and improvement of appropriate institutional, legal and financial instruments that ensure that water policies and their execution positively contribute to sustainable social progress and economic growth.

Following the above principles as well guidelines from other NGOs and development agencies, the Water Environment Research Foundation (U.S.) proposed a framework for Sustainable Water Resource Management [111]. This framework makes the distinction between “integrated” and “sustainable” water resources management, based on the concept that sustainable use of water resources should be a natural outcome of IWRM as much as it is set as a goal. In lieu of this, they developed the process flow-chart, shown in Fig. 1, to guide entities responsible for water resources management and related decisions. The framework consists of parallel proactive- and crisis-components of water resources management, and is adaptable to any water-related management problem. Step 1, the realisation that a water crisis has emerged, is omitted in this representation of the process flow diagram since the steps that need to be taken prior to this, and in response, are of interest. It is important to note that the principles of Steps 2 to 9 of the crisis management process are encapsulated in Steps 10 to 20 of the proactive management process, which highlights the need for strategic planning.

The Sustainable Water Resource Management framework also highlights the need for participation and inclusion in considering the management and allocation of water resources so that water resources management is tailored to local needs. This consultation and inclusivity must be considered at different levels, with consideration of local communities, but within the regional (or national) context and policy perspective [112].

4. Water resource constraints to CSP deployment

In order to explore the constraints posed to CSP deployment, the details regarding water consumption at CSP plants and water resource availability in countries of high solar irradiation need to be examined in some detail.

4.1. Estimating water available for CSP deployment

Estimating water availability for industrial water use, particularly for CSP, needs to consider both the water quantity and quality [113]. Both can be modelled according to complex runoff models

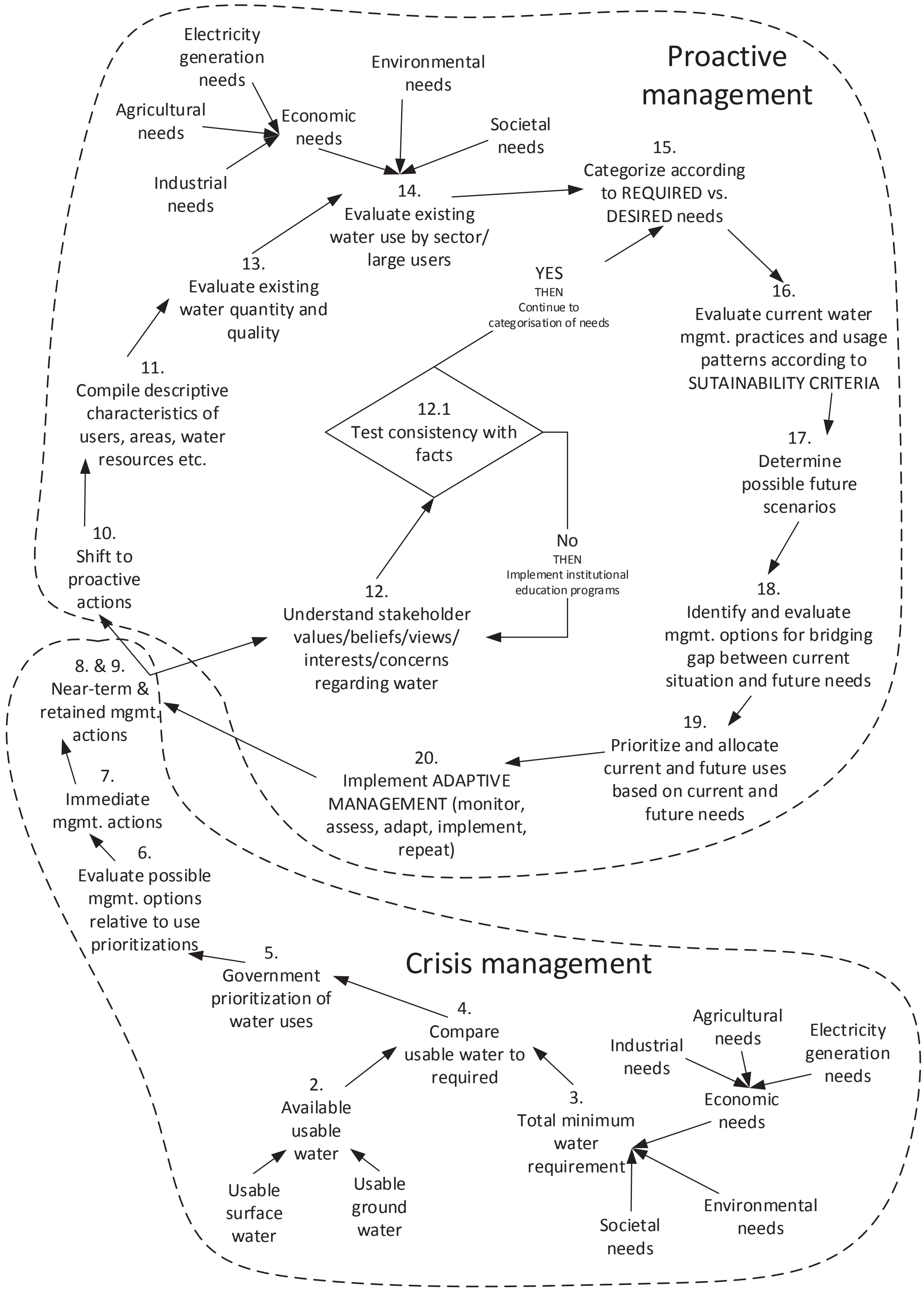

Fig. 1. Sustainable Water Resource Management framework process flow-chart. Recreated from Ref. [111].

that attempt to accurately approximate the hydrological cycle from a sub-catchment to a national and in some instance global scale [114–116]. These intricate computer models consider a range of input variables on water quantity and quality, and approximate water resource availability using clearly defined parameters for surface water and aquifer balances, an overview of typical inputs and outputs is shown in Table 2 [117–119].

These models use existing rainfall and hydrological data to model stream flows and storage capacities, and can also carry out scenarios analysis to understand various system interdependencies; such as ground water salinity and the impact of agricultural and mining activities on local water resource quality [120,121]. These water resource modelling packages typically take the form of system network models [117]. They are comprised of

Table 2
Overview of runoff water model input variables and outputs.

Model inputs	Model outputs
Topography on runoff quantities and directions.	Potential recharge.
The impact of geology on the absorption of water into different ground types and this impact on aquifer recharge rates.	Aquifer recharge.
The quantification of evapotranspiration rates for different plant and crop types.	Surface water baseflow.
The prevalence of crop types in different areas.	Groundwater baseflow.
The withdrawal and consumption rates of various industries and socio-economic activities.	Stream interflow.
Evaporation rates.	Transmission losses.
Rainfall estimates from detailed weather forecasting models.	Groundwater evapotranspiration.
Dam storage capacities and historic levels.	Groundwater outflow and storage.
Silt deposit rates in dams.	Rainfall and runoff.

various modules describing the underlying factors that interact with water resources; such as irrigation modules, mining modules, demand nodes and consumption nodes [119]. These modules need to be developed in adequate detail to assess water availability in support of water allocation decisions and formulation of water policy [120]. In South Africa, the recent water resources appraisal used measured stream-flow data to calibrate the WRSM2000 hydrological model; in order to more accurately estimate the mean annual runoff and hence surface water availability and its level of assurance, given the current and future demands [122,123].

4.2. Estimating water requirements for CSP deployment

In the light of Sustainable Water Resource Management, water requirements take into account social, economic and environmental needs. Minimum water requirements refers to the minimum amount of water required to sustain the most necessary activities under drought conditions; and typically refers to the water required to fulfil basic human-needs and the functioning of critical ecosystems. To estimate the local water availability for CSP deployment, one needs to first ensure available water resources are allocated to the basic human needs reserve and the ecological reserve. Once these needs are met, the water available for CSP deployment can then be considered in the context of various other industrial, domestic and agriculture water demands.

The water withdrawals of CSP plants are similar to that of other thermal power plants, in that the majority of water being used at a plant is for cooling purposes [124,125]. Water withdrawals refer to the gross amount of water abstracted from a source, and encompass water that is used and lost from the point of abstraction (non-return flows) as well as water that is used and then returned to the point of abstraction (return flows). Consumptive use refers to water that is extracted from a source, and used in a process or incorporated into a product such that it is so altered that it cannot be returned to the source [2]. In the case of CSP, most use is consumptive, with little to no water being returned to the source because it is evaporated to the atmosphere either as part of the cooling process or in evaporation ponds. The water use of a CSP plant consists of: Steam cycle cooling cycle (recirculating wet cooling, air-cooled condenser), mirror cleaning, steam cycle (boiler feedwater closed cycle), auxiliary equipment cooling cycle, fire-fighting systems, dust suppression, and potable water for operational personnel.

4.2.1. Steam cycle cooling

By far, the largest portion of water used at a CSP plant is steam cycle cooling (in the case of wet-cooling). This is the major concern when it comes to water use at any thermal power plant since the condensing and cooling of the steam exiting the low-pressure turbine is critical to plant efficiency and operation [32]. There are two major methods used for cooling at CSP plants: recirculating (evaporative) wet-cooling and dry-cooling.[3]

Wet-cooling technology uses water as the cooling fluid, absorbing the latent heat of condensation from the steam exiting the low-pressure turbine. There are two types of wet-cooling technologies: (i) Once-through cooling-water is extracted from a source, used to cool the steam in a condenser and returned to the source to replenish the water abstraction, albeit with water at an elevated temperature [126]. (ii) Recirculating, evaporative cooling-cooling water is circulated between a cooling tower and a condenser; but the warm cooling water is evaporated into the atmosphere. These two wet-cooling technologies are depicted in Fig. 2 [127]. Once-through cooling has never been used for CSP because of the lack of adequate water resources in high DNI areas. Recirculating wet-cooling is, however, very prevalent, with almost 80% of all operational plants using this cooling technology.[4] This is due to the lower capital cost of wet-cooling technology and greater efficiency, compared to dry-cooling [32]. Furthermore, compared to recirculating wet-cooling (hereafter referred to as wet-cooling only), the reduced efficiency of dry-cooling results in a larger solar field required to maintain the power output, at higher capital costs [31].

Wet-cooling is very effective because the heat from the steam is rejected to the air through the evaporation of the cooling water. Therefore, compared to dry-cooling, the wet-cooling process is less affected by variations in ambient air temperature, since the evaporative cooling is dependent on wet bulb temperature, and as a result of this, wet cooling uses almost 10 times more water than dry-cooling [31]. There are two major mechanisms of water loss in wet-cooling. Evaporative cooling of the warm water leaving the condenser in the cooling towers, is the primary heat transfer method and water loss mechanism. This results in the concentration of minerals each time water is lost to the atmosphere. Secondly, dilution is required to prevent the cooling water from becoming saturated with minerals; which will result in scale formation and reduced cooling efficiency. Dilution is achieved by adding fresh cooling “makeup water”, and rejecting the higher concentration cooling water, known as “blowdown”, thereby continuously limiting mineral saturation and its consequences [30].

Dry-cooling uses air for cooling instead of water and requires an air-cooled condenser where the steam passes through a bundle of tubes, and ambient air absorbs the heat. This means that the effective cooling that can be achieved is dependent on the dry-bulb temperature of the air; which is always higher than the wet bulb temperature in dry, arid conditions-where CSP is most prevalent. Further, ambient temperatures are highest on days of high solar irradiation, resulting in the highest efficiency losses on days that are supposed to be the most productive [128]. Dry cooling requires

[3] Based on NREL's global projects database available at https://www.nrel.gov/csp/solarpaces/.

[4] Calculated from NREL's Concentrating Solar Power Projects database at https://www.nrel.gov/csp/solarpaces/, and excluding unreported cooling technologies.

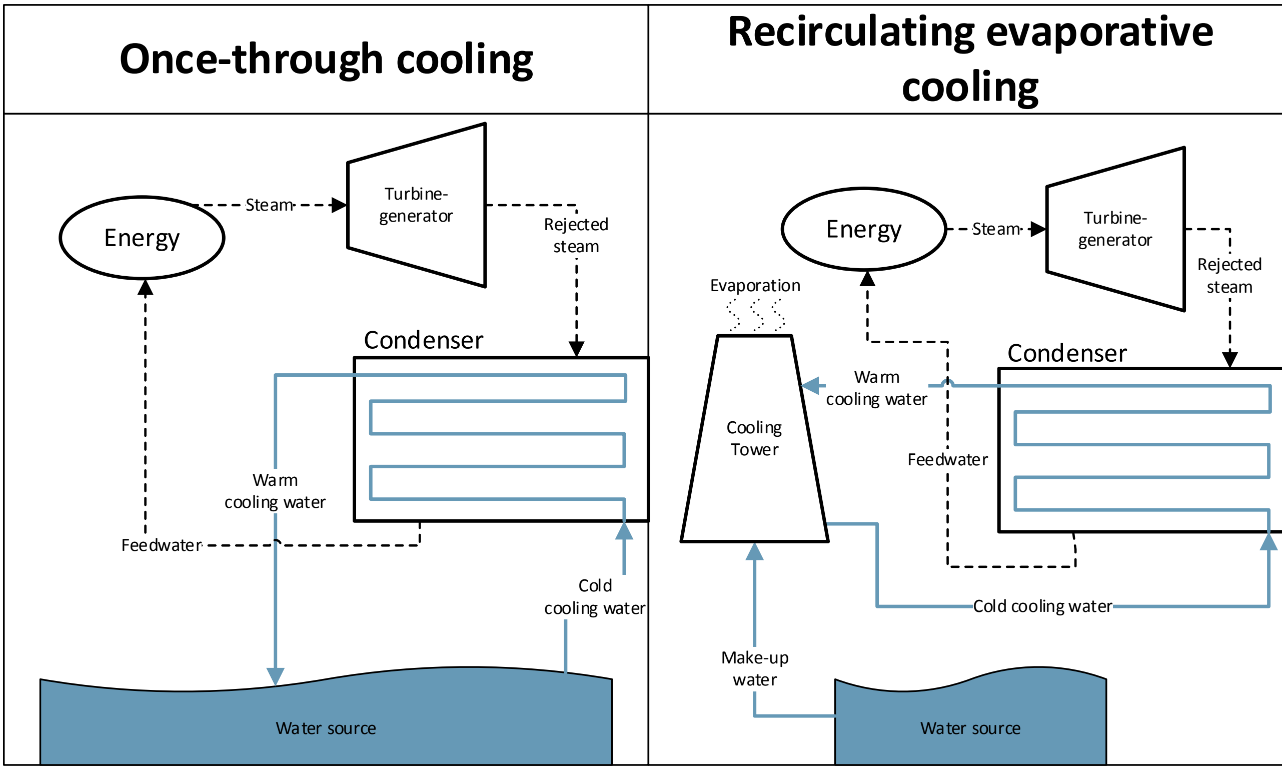

Fig. 2. Schematic comparing once-through and recirculating evaporative cooling. Recreated from Ref. [131].

minimal water only for cleaning of the condenser tube bundles. This cleaning is carried out at fixed intervals to prevent external fouling on the tubes and ensure efficient operation [129]. As discussed, the main drawback of dry-cooling is the reduced CSP power plant efficiency and higher capital costs, and resulting higher cost of electricity. Studies have found that, depending on the location, dry-cooling can result in increased generation costs of between 5.65% and 7.87% for cool and hot climates, respectively [128].

The overall plant water consumption rates of various power technologies have been compared in other studies [130–132] and the specific water use for CSP with wet- or dry-cooling were estimated to be in the following ranges (Fig. 3). Clearly, dry-cooling uses between 91% and 97% less water than wet-cooling, (trough and central receiver technology, respectively).

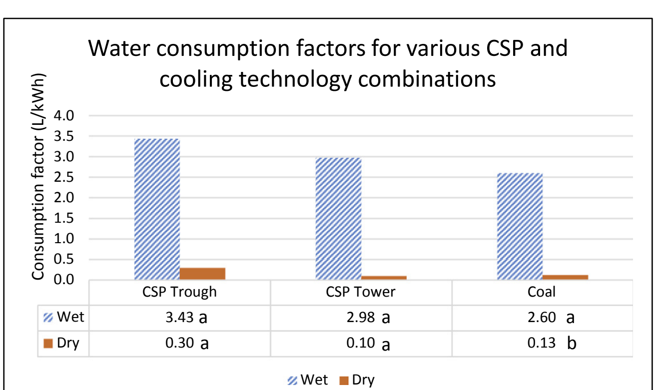

Fig. 3. Comparison of water consumption factors for various CSP and cooling technologies, compared to that of Coal. a – Mean values taken from Ref. [135]. b – Mean value calculated from Ref. [70].

4.2.2. Mirror cleaning

Mirror cleaning is the second most significant predictable consumptive use of water at CSP plants. Mirror cleaning is carried out at predetermined intervals using defined amounts of water per square meter of mirrors. Typically, cleaning water is collected, either by the cleaning trucks or the storm water drainage system that conveys possibly contaminated water to the evaporation ponds. Mirror cleaning at trough plants can be between an effective 75–152 L/MWh [133], but typically only accounts for between 1.4% and 2% of total CSP water consumption [32,134]. In a study to reduce the amount of water required for cleaning, it was found that at SHAMS 1 parabolic trough plant in Abu-Dhabi, cleaning of the 192 loops twice a week, each requiring 1.5 m^3 of demineralized water, and has been reported to amount to between 11 and 31 million litres of water per year [135]. There are opportunities to reduce this water use by between 25% and 50%, through the recovery and recycling of water [135,136].

4.2.3. Steam cycle makeup

Steam cycle makeup water is another consumptive water use at any CSP plant, and is typically between 113 and 228 L/MWh [133]. This accounts for around 3% of total annual water consumption for wet-cooled plants, and between 44% and 53% for dry cooled plants [31]. Generally, it is assumed that total steam cycle makeup remains almost constant irrespective of the cooling system employed, except for a slight increase for dry-cooled plants at start-up. This is based on the premise that ACCs take longer to achieve full vacuum and reach optimal steam cycle chemistry, resulting in more steam cycle and quench water being consumed in the process [31].

4.2.4. Auxiliary equipment cooling and fire-fighting

Equipment cooling water is circulated between a water-cooling unit (typically a bank of air-cooled condensers) and the components that need to be cooled, such as pump lubrication systems and bearings. Fire-fighting equipment is vital to ensure the safe operation of any CSP plant since receiver temperatures are typically between 290 ^{O}C and 390 ^{O}C at trough plants and even higher at central receiver plants-in excess of 500 ^{O}C [32], and synthetic oils are often used as the heat transfer fluid, posing a significant fire-risk [137,138].

4.3. Water resources and high solar irradiation areas

Once the available water resources have been estimated, the constraint of water on CSP deployment in areas of high solar irradiation can be assessed. Obviously, areas of high solar irradiation are most suitable for CSP, but are also the most water-scarce, arid regions globally. Fig. 4 clearly shows the agreement between high solar irradiation (DNI exceeding 2000 kWh/m^2/year or 6 kWh/m^2/day) and high aridity (chess-board cross-hashing), and that these are areas where most CSP projects are located.

The maps in Fig. 5 show the intersection of existing CSP locations with a) arid areas; b) water-stressed areas; c) areas with high seasonal resource variability; and d) areas with high inter-annual resource variability. Map a) clearly shows that CSP plants are mostly located in areas considered semi-arid, arid or hyper-arid, according to the United Nations Environment Programme's (UNEP) aridity index. It is based on the UNEP classification and is a measure of precipitation availability over atmospheric water demand [139]. Map b) shows the intersection between CSP locations and areas with medium to extremely high baseline water stress, showing that CSP-suitable areas already experience lower availability as compared to demands [140]. Map c) and d) shows that these areas are sensitive to variability, both seasonally (monthly) and inter-annually, increasing water-related risks.

Higher temperatures are typically associated with areas of high DNI, and as mentioned before, these warmer atmospheric conditions at CSP plant locations further negatively impact cooling efficiency. Higher atmospheric temperatures are associated with higher cooling-water consumption at wet-cooled plants, and likewise greater efficiency losses in the case at dry-cooled ones [31]. As a result this, CSP with wet cooling typically uses greater amounts of water when compared to other conventional power generation plants with similar wet cooling technology [130]. This mismatch between optimal CSP locations and impact on cooling efficiency further adds to the disparity between water resource availability and CSP's consumptive demands in these areas and highlights the need to take local conditions into consideration in CSP deployment.

4.4. Water-related risks for the power industry

Water constraints are a significant risk for the power industry, as shown by the recent power-plant curtailments in India. CSP operations had to be curtailed at 18 different power plants, because of reduced water availability; with a loss of 14 TWh of power generation in 2016, and curtailment having gradually increased from 6 TWh in 2013 [141]. The Parli Thermal Power Station in Maharashtra, India, had a capacity factor of only 38% due to water availability constraints, and this resulted in a loss of revenue in the order of $1.2 billion in 2016 [141]. The curtailment at the Farakka plant in West Bengal was due to lower than expected rainfall and an inter-boundary water management policy requiring water to be allocated to supply Bangladesh [142]. These incidents highlight the financial risks of poor water resource management in strategic energy infrastructure planning. This risk is even more severe for RETs since their generation relies on the availability of a natural resource (solar irradiation or wind, etc.), and therefore cannot be regained once production has been lost. The above incidents highlights that many developed countries suffer from a lack of integrated water resource management in CSP planning and deployment. In the U.S. between 2000 and 2015, there were 43 separate incidents of power plant curtailment due to water availability and temperature issues [143,144]. Furthermore, the impact of drought conditions on U.S. power plants highlighted that few regulatory bodies have established detailed priority systems for allocating water use to certain water uses during constrained availability [145].

5. Discussion: incorporating water resources management into the strategic planning and deployment of CSP

The suggested approach of this paper is that of combining strategic energy infrastructure planning with integrated water resource management. This integration is essential for the successful deployment of CSP; since the areas of high CSP potential are located in hot and arid areas, where water availability for CSP cooling may be limited and a constraint to CSP reaching its potential for deployment. Strategic planning and policy support is

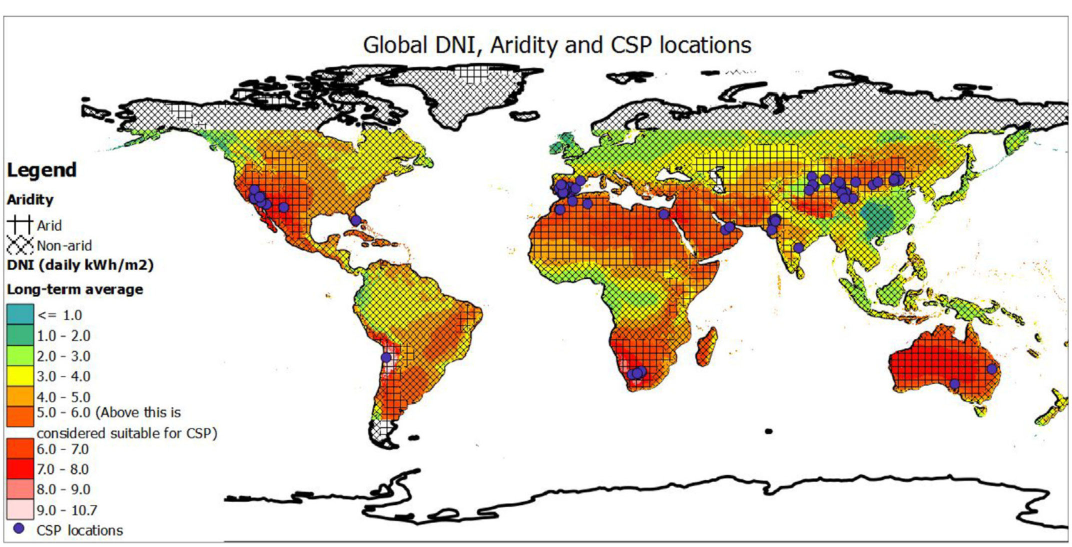

Fig. 4. Global DNI, Aridity and CSP locations.

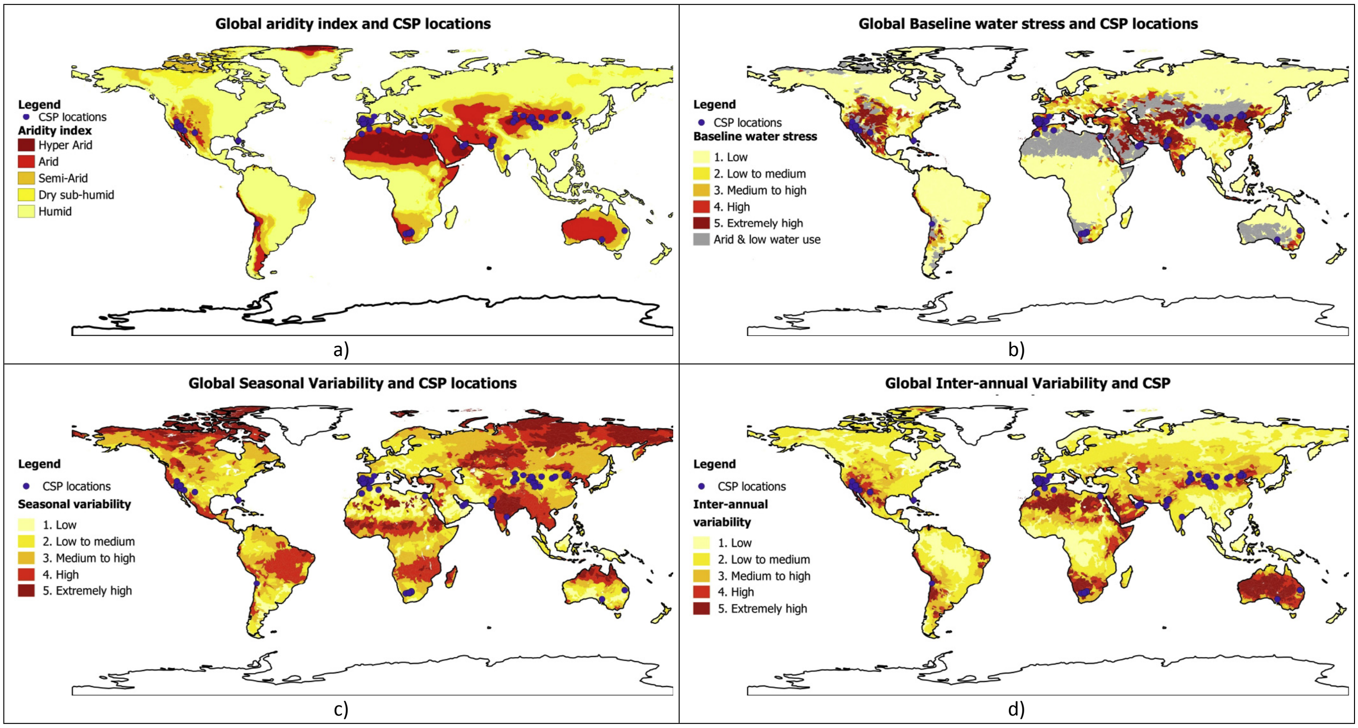

Fig. 5. Maps of planned and existing CSP locations and: a) aridity; b) water stress; c) seasonal resource variability; d) inter-annual resource variability. Maps compiled using aridity data from the UN's Aquastat database (available at http://ref.data.fao.org/map?entryId=221072ae-2090-48a1-be6f-5a88f061431a), water stress data from the World Resources Institute's (WRI) Aqueduct study (available at http://www.wri.org/publication/constructing-decision-relevant-global-water-risk-indicators), Global DNI data from SolrGIS (available at https://solargis.com/maps-and-gis-data/download/world) and NREL's Concentrating Solar Power Projects database (see previous footnotes).

needed to ensure that CSP deployment has minimal impacts on water resources, and that the deployed CSP plants reach their expected performance through the prevention of curtailment due to water availability constraints.

Water is used in different processes within a CSP plant. The water consumption is influenced by the CSP power plant capacity, the cooling technology used, and the solar resource and atmospheric conditions at a particular location. CSP performance at a given locality needs to be modelled in light of seasonal water availability from spatial and temporal variation. The performance of CSP will influence the financial viability or levelised cost of electricity produced. The viability of CSP is also strongly influenced by feed-in tariffs and the market value of dispatachable power. The ability of CSP with storage to produce dispatchable power is an obvious advantage to meet peaking loads, and may receive favourable tariffs to do so. Conversely, the lower night-time tariff may be less favourable due to reduced demand [146]. However, generation during night can reduce CSP water consumption since production during these times will take place under cooler ambient conditions. It is challenging to model CSP deployment potential at a national scale, since various CSP capacities and configurations are possible in each location according to grid expansion requirements, and various possible future feed-in tariff structures. However, the maximum theoretical generation capacity based on the available suitable land and solar resources can be estimated for each quaternary water catchment area and then the water resources availability and assurance of supply in that catchment can be assessed accordingly.

Water resources are spatially and temporally distributed unevenly at a global, continental, regional, national and even subcatchment level. Drought conditions, defined as periods of restricted water availability due to lower than required rainfall, occur at unpredictable multi-year intervals and result in increased competition for water resources among water users [147]. It is therefore important to be able to evaluate a long period of water resource data in order to see the drought occurrence frequency, as well as establish the baseline water availability in each quaternary catchment to assess potential vulnerability to CSP curtailment and increased water stress.

There are various modelling tools available to increase our understanding of how water resources can limit CSP from reaching higher levels of potential deployment. Aside from engineering modelling of CSP plant design and hydrological modelling of water resources, geographic information systems (GIS) are particularly valuable in planning energy infrastructure and managing water resources, specifically in an integrated manner. GIS is widely used in both water resource planning and infrastructure planning as a means to visually depict specific information such as evaporation rates, flood occurrences, electrical grids, and the energy and water demands. This makes GIS an ideal final tool to represent the results from the modelling and data analysis above, and use these visual representations (maps) to not only inform decisions, but also guide policy developments [148].

Once the water consumption and water resource availability are both represented in accurate models, the CSP potential can be assessed, and appropriate design requirements can be specified for further deployment. For example, in South Africa, the driving regulatory authority is the Department of Energy, through its Renewable Energy Independent Power Producer Procurement Program (REI4P). This program stipulates various requirements that need to be met by any prospective RET developer, ranging from specifications on the minimum required local content and social and economic development involvement, to minimum plant ramp-up rates and ability to supply electricity when demand is higher. These national policies directly impact RET plant location, design decisions, operating strategies and costs [149].

Water use needs to be regulated and integrated through policy to ensure that water resources are protected, used, developed, conserved, managed and controlled in such a way as to ensure and promote efficient, sustainable and beneficial water use [150,151]. Coal power plants are highly dependent on water in South Africa, while coal mining also incurs significant impacts to water resources [152]. As a result, guidance notes have been issued to prospective coal independent power producers on water availability for further development in coal-rich areas, recommending various water-use efficiency measures [153]. However, similar recommendations for other RETs such as CSP have not been made. This dependence is also highlighted in the possible impact that loss of water supply from pump stations to these coal power plants could result in loss of generation [154]. Policies can inform and encourage certain power plant configurations to achieve desired water consumption rates and also to promote the use of alternative water sources by power plants [155–157]. Coordinated strategic planning between responsible stakeholders can help ensure that targets set out in joint water-energy policies are achieved [158]. Energy infrastructure management and planning will need to integrate water resource availability with the potential for CSP deployment in high solar irradiation areas. In doing so, several questions should guide and frame CSP developments: To what extent is water resource availability and variability a constraint on CSP deployment? Can this constraint be adequately addressed through technology-specific strategic planning? What alternative sources of water are available in areas with inadequate natural water supply? How can policies be used to promote the use of such alternative sources in order to ensure sustainable management of natural fresh water source? What measures need to be put in place to incentivise responsible use and monitoring of water use at CSP plants?

6. Conclusion

With the increasing deployment of solar PV and wind in the electricity generation mix, more responsive dispatchable, or peaking generation capacity, is needed to respond to the changes in demand. CSP with storage can overcome the supply intermittency experienced by many RETs. However, the spatial potential of CSP based on the solar resource needs to be tempered by taking into consideration local water availability for CSP power plant cooling. Hydrological models can assess the water availability at various locations, and this can be spatially superimposed with the solar irradiation using geospatial tools to determine areas where biophysical constraints water scarcity hinders CSP reaching its full deployment potential. Integrated water resources management and national policies for sustainable development can be used as a process to explore how local water resources should optimally be used (which takes into account a range of water demands), and therefore enables a more realistic assessment of water availability for CSP deployment. It will be critical to establish a standardised approach to assessing this dualistic managerial problem, and apply it in different countries within the context of national planning. There may also be instances where international water relations need to be considered. Therefore, CSP infrastructure management and planning needs to be integrated with water resources management to allow for contextual differences between different countries, regions, and specific locations. The development of a model-based guiding framework and methodology to achieve this will provide the required insight to tailor policy specifically suited for the country or region in question, which is needed to enable the sustainable development of CSP.

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