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Solar Energy Within the Water-Energy-Food Security Nexus: A Systematic Review

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1. Abstract

Since the Water-Energy-Food Security (WEF) nexus was officially established during the Bonn 2011 Conference, nexus research has grown rapidly. As a result, and due to its interdisciplinary nature, an array of academic literature now engages in the WEF nexus, often in seemingly separate disciplines. Solar energy is one of the most popular renewable energy sources; however, its role within the WEF nexus has only recently gained traction. Through a systematic review, this article examines the current state of knowledge regarding solar energy's role within the WEF nexus, how solar energy impacts water, energy, and food (in)security, and its potential synergies and trade-offs within the WEF nexus. Accordingly, all the relevant English-language peer-reviewed publications from 2011 and onwards that focus on solar energy's role within the WEF nexus are reviewed, followed by qualitative conventional content analysis. Four main themes emerge from the review and analysis process: general solar energy deployment, agrivoltaics, aquavoltaics and solar energy greenhouse desalination systems. This article shows that, although the current state of knowledge about solar energy's role within the WEF nexus is sparse, solar energy creates great synergies regarding improving water, energy, and food security and has an overall positive impact within the WEF nexus. However, threats to local water sources remain a challenge since increased access to unregulated solar energy in areas without or with little previous access to energy can create water overuse, often due to extensive irrigation of food crops. On the other hand, agrivoltaics and aquavoltaics create strong synergies, and both offer water-efficient means of producing energy and food. However, aquavoltaics often undermine food production, while agrivoltaics impact on food production varies depending on what crops are grown and their location. Solar energy greenhouse desalination systems offer a way of creating self-sufficient food production but have only been examined on a small-scale level. All main research areas require more research to identify the full scope of solar energy's role within the WEF nexus.

Keywords: *Solar, WEF, Nexus, water security, food security, energy security*

2. Introduction

The demand for energy, water, and food increases rapidly worldwide, while such resources simultaneously experience significant shortfalls and stress (Karan et al., 2018). While these vital resources face increasing insecurity, the need to move towards a decarbonized world is becoming more pressing than ever (Mohammadi et al., 2020). To reach the emission reduction goals under the Paris Agreement, while at the same time making energy, water, and food resources secure, rapid renewable energy expansion is needed (Gielen et al., 2019). Solar energy is one of the most promising renewable energy resources, commonly referred to as the 'king of renewables' due to the potential it has to provide decarbonized and diversified energy to a diverse set of regions (Zhou et al., 2015: Moumin et al., 2020; Adam & Apaydin, 2016). Compared to wind, solar energy resources are more abundant and accessible and can therefore be scaled to a greater extent to meet human needs (Campana et al., 2019; Pringle, Handler & Pearce, 2017). Furthermore, the price for solar energy has been significantly reduced in the past years, while its capacity between 2010-2019 increased by more than ten-fold (Wiser et al., 2016; IRENA, 2019).

While emission-reduction is needed, solar energy can, at the same time, create additional energy, water, and food security while positively impacting people's health. Solar energy can serve as a vital key to ensure energy and subsequent water and food security for cities, municipalities, and off-grid communities due to the different ways it can be deployed (Ravi et al., 2016; Toboso-Chavero et al., 2019; Madriz-Vargas, Bruce & Watt, 2018). Since solar energy can function off-the-grid, through microgrids or standalone system, it has the potential to be deployed in regions which currently lack a secure energy supply and hence reduce energy poverty around the world (Zaman et al., 2021). Increased energy access through solar microgrids can enhance households' access to clean water and subsequent irrigation for crops, which improves their ability to secure a stable food supply through agricultural activities (Guta et al., 2017). Furthermore, energy sources such as fuelwood, agricultural waste, charcoal, and animal dung has severe negative health impacts on people living in developing countries (Herington & Malakar, 2016; Were et al., 2020). Solar energy could serve as a cost-effective measure to reduce emissions while providing an alternative, clean energy source (Schahsavari & Akbari, 2018). Although solar energy is crucial to reach a decarbonized world energy supply and mitigate climate change, and create additional energy security and subsequent benefits, deploying a relatively new technology on a massive scale without accounting for its full scope of impacts can have unintended consequences. Without adequate consideration for the potential trade-offs solar energy might create with other resources, the mechanism to mitigate and adapt to such trade-offs will be impossible to implement (Santos et al., 2019).

The Water-Energy-Food security (WEF) nexus was officially established during the Bonn 2011 Conference: Water Energy and Food Security Nexus-Solutions for the Green Economy. WEF attempts to determine the synergies and trade-offs between management practices and policy decisions concerning water, energy, and food (Simpson and Jewitt, 2019). The WEF nexus explicitly acknowledge water, energy, and food systems as interdependent by evaluating how the resources interact and operate. The main goals of the nexus approach are to minimize trade-offs while maximizing synergies, internalize environmental and social impacts, and improve resource efficiency (Albrecht, Crootof & Scott, 2018). Furthermore, the WEF nexus approach improves cross-sector management regarding water, energy, and food security (Scott et al., 2016), and therefore enhances how these sectors and resources interact and create more coherent and holistic policymaking through an intersectoral sustainability approach. The approach can therefore develop the discourse for more beneficial policy and management solutions while promoting collaboration between different sectors by framing issues and their solutions holistically (Keskinen et al., 2016).

With the rapid expansion of solar energy and its potential to provide energy and subsequent water and food security, a nexus approach to solar energy deployment is needed. However, many nexus studies are water-centric, focusing primarily on hydropower, water-food, or water-energy interactions (Smajl, Ward & Pluschke, 2016). To maximize the synergies and minimize the trade-offs, examining how solar energy impacts the full WEF nexus is therefore crucial. Establishing the impacts of the current usage of solar energy within the WEF nexus can showcase the positive impacts of solar energy while mitigating the potential adverse effects its deployment and usage might have on water and food resources (Closas & Rap, 2017). Therefore, this article aims to answer the following research questions of how solar energy impacts the WEF nexus; *what is the state of knowledge about solar energy's role within the WEF nexus; which implications does solar energy have within the WEF nexus; what synergies and trade-offs within the WEF nexus are identified in the literature when using solar energy?*

3. Methodology

To answer the research questions, this article systematically reviews the current academic literature to provide a clear overview of current published research about solar energy within the WEF nexus, its implications and summarise and highlight the different synergies and trade-offs of solar energy within the WEF nexus. This article only uses studies that explicitly refer to and include solar energy, water, and food (in)security in their research to ensure a thorough and replicable review study.

This review article uses a systematic review methodology to examine the current state of knowledge regarding solar energy's role within the WEF nexus. The Scopus database was searched for the keywords 'water', 'solar', 'energy', 'food', and 'nexus' in the abstract, title, and keywords of the database articles. The search was limited to peer-review journal articles in English, published through 2011 and onwards since this was when the WEF nexus was established. Thereafter, the same process was conducted in the Web of Science (WoB) database to ensure no important information was missed. Most of the articles from Scopus overlapped with the WoB; however, due to the higher number of documents in WoB, relevant additional articles were found. The keywords 'photovoltaic' and 'PV' was used to replace the search term 'solar', and each other to make sure that articles that use different terms for solar energy were included in the research process. The Scopus and WoB databases were searched for with alternative language to make sure further articles covering solar energy's role within the WEF nexus were included that might not use this specific terminology. Keywords such as 'irrigation' and 'agriculture' together with one of the keywords for solar energy used in this research (i.e., 'solar', 'photovoltaic', and 'PV') and the term 'nexus', was searched for and included in the review process, for further details see table 1.

Table 1

The searching terms used and the total number of publications from each database

Databases	Searching string and Searching Terms		No of articles	Date of acquisition
Scopus	Main searching term using title, abstract, and keywords	'water' AND 'solar' AND 'energy' AND 'food', AND 'nexus'	47	21/03/2021
		'water' AND 'PV' AND 'energy' AND 'food', AND 'nexus'	9	21/03/2021

	Secondary searching terms	'water' AND 'photovoltaic' AND 'energy' AND 'food', AND 'nexus'	19	21/03/2021
		'irrigation' AND solar' AND 'energy' AND 'food' AND 'nexus'	9	21/03/2021
		'water' AND 'solar' AND 'energy' AND 'agriculture' AND 'nexus'	26	21/03/2021
		'irrigation' AND 'solar' AND 'energy' AND 'agriculture' AND 'nexus'	8	21/03/2021
		'irrigation' AND 'PV' AND 'energy' AND 'agriculture' AND 'nexus'	3	21/03/2021
		'irrigation' AND 'photovoltaic' AND 'energy' AND 'agriculture' AND 'nexus'	5	21/03/2021
Web of Science	Main searching terms	'water' AND 'solar' AND 'energy' AND 'food', AND 'nexus'	65	24/03/2021
	Secondary searching terms	'water' AND 'PV' AND 'energy' AND 'food', AND 'nexus'	21	24/03/2021
		'water' AND 'photovoltaic' AND 'energy' AND 'food', AND 'nexus'	30	24/03/2021
		'irrigation' AND solar' AND 'energy' AND 'food' AND 'nexus'	15	24/03/2021
		'water' AND 'solar' AND 'energy' AND 'agriculture' AND 'nexus'	47	25/03/2021
		'irrigation' AND 'solar' AND 'energy' AND 'agriculture' AND 'nexus'	19	25/03/2021

	’irrigation’ AND ’PV’ AND ’energy’ AND ’agriculture’ AND ’nexus’	7	25/03/2021
	’irrigation’ AND ’photovoltaic’ AND ’energy’ AND ’agriculture’ AND ’nexus’	7	25/03/2021

As seen in Table 1, the total number of articles equaled 345. However, due to similar key terms and use of both Scopus and Web of Science, there were many duplicate articles. To ensure that articles that can answer the specific research questions are included in the research process, this research paper applies the inclusion and exclusion criteria, as seen in Table 2, where articles that fulfil the inclusion criteria were selected for further analysis and content assessments. Firstly, duplicate articles were excluded. Thereafter, articles were included based on three additional criteria’s; (1) they use the nexus concept regarding natural resource usage; (2) they include all the three resource sectors: water, energy, and food meaningfully (i.e., includes how it is impacted and not only mentions one sector to thereafter focus on the other two), and (3) the energy part of the nexus framework refers to solar energy specifically. To be included in this review paper, articles must fulfil all the inclusion criteria’s seen in table 2. To ensure a coherent review method, articles that did not meet the selection criteria were excluded. For example, some studies mentioned solar energy, photovoltaic, or PV in either the abstract, title and keywords but did not focus on the specific energy source throughout the paper and was thus excluded. Furthermore, examining the full scope of the nexus, i.e., the three different sectors, is the main point of the WEF nexus. Therefore, articles that simply mentioned the nexus but then only referred to two of the sectors throughout the paper was excluded since examining the three sectors is inherently more complex and the purpose of using the WEF nexus approach. Based on these criteria, 16 articles were selected as appropriate for the scope of this review article. This process is shown in Figure 1.

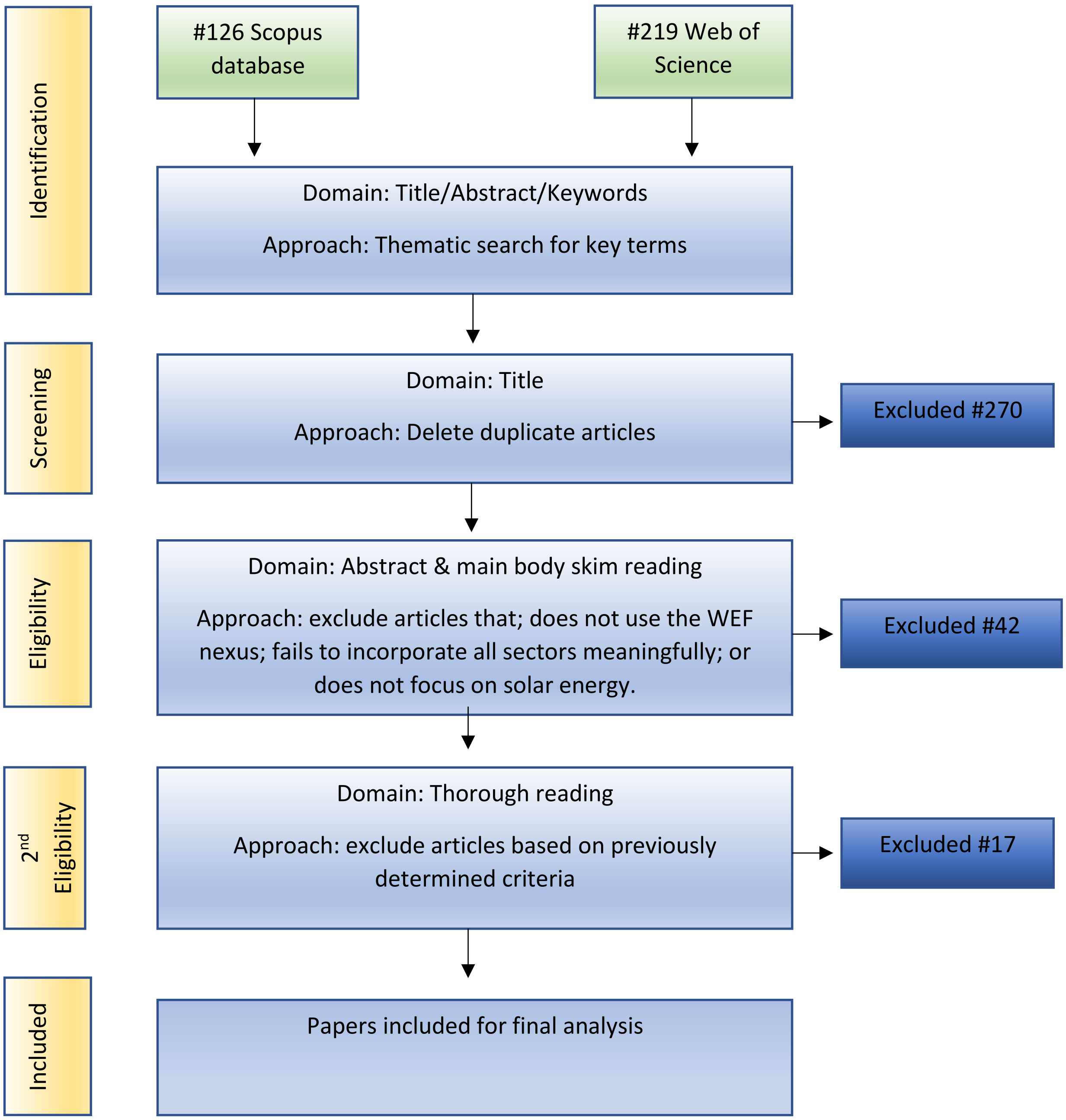
Table 2

Study selection of literature using inclusion and exclusion criteria

Criteria	Decision
Predefined keywords exist in title, keywords, or abstract section of the paper.	Inclusion
The paper is published in a scientific peer-reviewed journal	Inclusion
The paper is written in the English language	Inclusion
Uses the WEF nexus concept	Inclusion
Include all sectors of the nexus concept meaningfully	Inclusion
The energy part of the nexus concept refers to solar energy	Inclusion
Papers published before 2011	Exclusion
Papers that were duplicated due to the different key terms and databases	Exclusion

Figure 1

Process of literature review search and selection



Due to the few articles deemed suitable for further analysis and the wide range of disciplines covered by the included articles, this review paper uses a qualitative conventional content analysis to examine the research findings further. The qualitative content analysis focuses on the context and content portrayed in the text (Hsieh & Shannon, 2005). For the WEF nexus, context-specific research is very important since one solution that works in one place might not function in another (Tyagi, 2020). Furthermore, the qualitative content analysis focus on the meaning of the texts to a larger extent, not only the presence of words. This allows categorising texts that showcase similar meanings from different disciplines and research approaches to be used (Weber, 1990). Since this review article covers literature with case studies and models spanning across the globe, incorporating a wide range of disciplines and research methods, the qualitative content analysis allows the meaning of the other literature to be portrayed with attention to its context-specificity.

Moreover, since solar energy's role within the WEF nexus recently started to emerge, this type of design is appropriate since it does not require existing theory about a phenomenon and instead allows the researcher to derive categories and themes from the data itself. Coding and analysing the data hence occur interchangeably while reading the text, creating categories and themes that appear based on the text reviewed (Hsieh & Shannon, 2005). Following this process, the 16 articles selected for review was read repeatedly to allow the creation, deletion and recreation of categories related to the research question. From this analysis, based on 16 publications, four key features for solar energy's role within the WEF nexus was derived, as discussed in section 4.

4. Solar Energy Through the WEF Nexus

Research focusing on solar energy's role within the WEF nexus did not gain traction until 2015. However, in the past two years, an increasing number of articles has started to emerge. Four key features have been found throughout this articles review process, as seen in this section.

4.1 General Solar-Deployment

The first theme, general solar deployment, covered the highest number of articles in this review. Although the articles are still on the lower end, significant findings were identified for solar energy's role within the WEF nexus. Two broad categorisations of the general solar deployment theme can be identified – articles with one or several case studies and articles that use a model-based approach. As seen in Table 3 and Table 4, both categories show that solar energy has a generally positive impact within the WEF nexus. Strong synergies within the WEF are identified in all four case-study articles when deploying solar energy technologies, as seen in Table 3. The main facet of using solar energy for water, energy, and food security is using solar energy to generate electricity, often in rural areas with non-existent, low, or unreliable electrification rates. Small-rural villages substantially benefit from solar-powered energy since it provides them with cheap energy that does not pollute their local environment (Ibrik, 2020). The easy access and potential for smaller independent micro-grid systems enhance the potential for different actors and stakeholders that depend on energy to support their livelihoods to thrive (Buechler et al., 2020). As seen in Table 3, a major aspect is to use solar energy to create electricity that can be used to pump ground- or water-surface water for food production.

Furthermore, as shown by Ibrik (2020), solar energy's impact reduces poverty in rural communities and increases drinking water and education access. While creating less demand for diesel-generated energy for rural farmers, solar energy increases water efficiency, which also can increase profits (Gupta, 2019). Furthermore, solar energy usage is likely to influence other behavioural changes that can positively impact the WEF nexus, e.g., harvesting water, composting, and willingness to grow more food crops (Buechler et al., 2020). However, as Al-Saidi and Laham (2019) shown, the deployment of solar energy can have a wide range of results on the WEF nexus depending on how the usage of solar energy is regulated, its implementation and the size and type of the projects.

One major trade-off for solar energy's role within the WEF nexus, concerning the impact on local water resources, was identified during the review process. Solar energy can increase long-term water insecurity due to increased energy access in water-scarce regions, leading to overusing local water resources, often for irrigating crops (Al-Saidi & Laham, 2019; Gupta, 2019). Therefore, solar energy usage can potentially create a trade-off between water and food security – increasing water usage for farmers, which increase food production, versus limiting the water usage, which undermines food production (Gupta, 2019). Still, the trade-offs and potential ways to mitigate the trade-offs cannot be fully established since two out of the four articles seen in Table 3 do not examine the trade-offs within the WEF nexus or potential impacts on local water resources of solar energy deployment.

Table 3. Case studies of general solar deployment

Author(s)	Context	Method	Synergies	Trade-offs
Ibrik (2020)	Two villages, Dir Ammar and Al-Birin, in the West Bank, Palestine Rural Small-scale solar energy	Real-time data collection after implementing rural solar energy electrification programs.	Solar energy creates energy security which leads to increased water security and in turn leads to increased agricultural production due to solar-powered irrigation and food security.	Not examined

Al-Saidi & Laham (2019)	India: State of Gujarat, State of Bihar, Karnataka State, Rajasthan State, Odisha Sate, West Bengal State Rural Small-and large-scale solar energy farming projects	Analysis of ongoing solar energy projects to farmers and their impacts.	Solar energy leads to increased access to groundwater, which leads to increased irrigation potential, leading to more food security.	Stress on groundwater resources due to overuse when irrigating extensively.
Gupta (2019)	Six districts in Rajasthan, India Rural 434 farmers (289 adopters and 145 non-adopters).	Hypothesis testing and analysis of a solar energy programme during the 2011-2015 period. Quasi-experimental difference-in-differences study design comparing solar pump adopters with control farmers.	Increased crop intensity in four districts and increased vegetable and fruit production in three districts leading to further food security.	Increased total water consumption. Stress on groundwater resources in two districts.

Buechler et al. (2020)	Rural and Urban Arizona and Zacatecas, Mexico. Semi-arid regions along the mountain chain the Sierra Madre. How small-scale solar projects impact the communities.	Multi-disciplinary comparative qualitative study. Interviews, participant observation, individual and focus group interviews, and stakeholder meetings.	Producing organic food becomes cheaper. Groundwater is pumped for irrigation. Power electric fences to keep animals away. from the food production. Saves freshwater by using rainwater or greywater instead.	Not examined

As seen in Table 4, the second category of the general solar deployment theme, similar results are found as in the first category. Tobasco-Chavero et al. (2019) examine the implications of using solar energy in an urban setting through four different model scenarios. Solar energy placed on rooftops can create self-sufficient energy for households in urban settings while having the potential to support urban agriculture. However, the authors stress the high environmental burdens solar energy can have during the construction phase and the associated impacts on WEF security. He et al. (2019) found that solar energy is more water-efficient than hydropower and a more reliable energy source in drought-prone regions. Therefore, solar energy should be considered over hydropower in regions with droughts or might face it in the future (He et al., 2019). Furthermore, solar energy can provide electricity to rural areas and help people sustain their food production through solar-powered irrigation (Roje et al., 2020). However, as mentioned previously, He et al. (2019) and Roje et al. (2020) stress the trade-offs with water within the WEF nexus when using solar energy unsustainably. Over usage of water resources due to increased access to solar energy, used to irrigate food crops, can, in the long-term, create groundwater depletion, hence again showcasing a trade-off between depleting water resources to create higher crop yields which are made possible by increasing the access to unregulated solar energy.

Table 4. Models of general solar deployment

Author(s)	Context	Method	Synergies	Trade-offs
Tobosco-Chavero et al. (2019)	Montbau neighbourhood, Barcelona Urban – Rooftop W(S)EF system – producing food and energy while harvesting rainwater.	Four different model scenarios based on urban features, climatic conditions, WEF demands, country and local conditions.	Increases the self-sufficiency for urban households – the solar energy is used for harvesting rainwater and using it for irrigating food production crops.	High environmental burdens during the construction phase.
He et al. (2019)	California Replacing hydropower with solar or wind energy	Trade-off frontier model and expansion path to analyse water constraints due to hydropower and the impacts of switching to solar or wind energy.	Using solar instead of hydropower use less water surface intensive and therefore more surface water will be available for irrigation. Drought resilience energy and better food production potential.	Solar and wind energy used unsustainable can create Groundwater depletion.

Roje et al. (2020)	José Painecura Hueñalihuen community located in the municipality of Carahue, Chile Rural Arid/semi-arid area.	Simulation of an integrated optimizer based on model predictive control (MPC) combining water and energy management systems equals integrated energy-water management system (EWMS) to measure water sustainability and crop yields for ten farmers.	Solar energy allows the water management system to function and therefore sustain crop yields through irrigation. Hypothetical rural electrification through solar-powered micro-grid.	Potential side-effects if water is overused and not allowed to recharge.

4.2 Co-location of Solar Energy and Agriculture in a Single Location: Agrivoltaics

For solar energy to be used on a large scale, it requires vast land areas. The need for such large land areas can, in some cases, cause competition with land that is used for agricultural purposes. An important question for large-scale solar energy deployment is therefore how to meet increasing energy demand without competing with land that can be used for food production (Ravi et al., 2016). According to the current literature of solar energy's role within the WEF nexus, Agrivoltaic Systems (AV) aims to integrate land used for solar energy production with agriculture. AV co-locates photovoltaic (PV) solar energy production with agricultural production and can improve land use and water efficiency (Barron-Gafford et al., 2019). Therefore, solar energy's role within the WEF nexus is essential when using agrivoltaic systems and showcases a generally positive impact on energy, water, and food security. However, the state of knowledge about agrivoltaics within the WEF nexus is sparse, as seen in Table 5, and the findings in this review should be considered accordingly.

An experiment involving three food crops by Barron-Gafford et al. (2019), as seen in Table 5, showcases strong synergies within the WEF nexus when comparing AV with non-AV plots. The experiment involves three different food crops that are grown on drylands. One of the food crops shows three times greater production under the AV than the non-AV land while reducing the water needed for irrigation due to less direct sunlight. Even though total food production differed depending on crops tested, one crop species resulted in slightly less production; total food production doubled under the AV than the non-AV growing environment while saving water needed to irrigate the crops and simultaneously create solar energy from the PV panels. Furthermore, the AV system cooled the PV panels during the daylight hours with 8.9-2 C, which created further efficiency for the PV panels.

In many parts of the world, current large-scale solar energy infrastructures exist in semi-arid or arid areas that are not suitable for many food crops. High-value xerophytic plants, such as aloe vera, can, according to Ravi et al. (2016), be grown on the same land as solar panels without decreasing the PV capacity while having low water usage needs. Combining land for solar energy production with xerophytic plant production can reduce the need to grow aloe vera crops where food crops can be grown. Simultaneously, more land and water will be available for food production through more efficient land and water use. In water-scarce regions, AV offers a way of reducing the water needs of farmers while providing them with more energy to use for food production. AV thus provides a potential solution to the conflict between land used for energy versus agricultural production while having the potential to improve water efficiency (Proctor, Murthy & Higgins, 2021).

Although the potential trade-offs identified in the previous section – ground- and surface-water depletion due to over-usage – are not examined in WEF studies focusing on agrivoltaics, the synergies and water-saving potential of the technology serve as a way of reducing overall water usage when co-locating food production with solar energy generation (Barron-Gafford et al., 2019; Neto et al., 2018). However, in arid regions, solar panels are often washed routinely to maintain optimal energy production. Even though the water used is less than other energy sources and relatively small, washing solar panels in large solar infrastructures located in desert regions may significantly impact the available local water budget. Therefore, in water-scarce regions, solar energy's water needs may significantly stress local water resources and potentially displace water that small-scale agriculture and domestic consumers depend on (Ravi et al., 2016).

Table 5. Solar energy usage in Agrivoltaics

Author(s)	Context	Method	Synergies	Trade-off
Barron-Gafford et al. (2019)	Biosphere 2 Agrivoltaics Learning Lab, Tuscon, AZ, USA Hot desert Site involved replicated rows of agricultural crops in traditional, open-sun growing conditions or under an Agrivoltaic system.	Comparison between the two different sites, one Agrivoltaic and one normal, given the same soil conditions, irrigation, crop species, and climate conditions.	Chiltepin fruit production three times greater, CO2 uptake 33% greater, no difference in water use efficiency. Water use efficiency 157% greater for Jalapeno. Tomatoes - 65% greater CO2 uptake and water efficiency, almost double food production.	None 11% lower CO2 uptake, slightly lower food production None
Neto et al. (2018)	Five states in Brazil: the states of Para (PA) in the north, Bahia (BA) in the northeast, Mato Grosso (MT) in the center-west, Sao Paulo (SP) in the southeast, and Rio Grande do Sul (RS) in the south. Analysis of one state from each of the five regions of Brazil due to the large variety between states.	SM model, photovoltaic solar roof tops, that integrates solar energy production, shade to cattle, and collection of rainwater.	Solar energy production while collecting rainwater and producing needed shade for cattle production.	Not examined.

Ravi et al. (2016)	Northwestern India Desert environment	Life Cycle Analysis (LCA) of a hypothetical Agrivoltaic system based on LCAs of a solar photovoltaic system and Aloe vera production system.	No reduction in PV capacity when co-located with Aloe vera production. Possibility of using the same water inputs for cleaning panels and for irrigating aloe vera production.	Water needs for cleaning the solar PV installation became higher.

4.3 Co-location of Solar Energy and Aquaculture in a Single Location: Aquavoltaics

Another way of solving the usage of land for energy versus food production is to use floatovoltaic systems and combine them with aquaculture. Floatovoltaic (FV) technology refers to solar photovoltaic energy systems deployed on water. These FV systems can be deployed over aquaculture systems – the farming of aquatic organisms – and thereby combine the generation of solar energy production and aquaculture, called aquavoltaics. Hypothetically, aquavoltaics can therefore increase food and energy production by using the water, instead of land, for energy generation, thereby saving land for agricultural purposes instead while producing food under the FV panels (Prince, Handler & Pearce, 2017). Like agrivoltaics, solar energy's role within the WEF nexus is essential for aquavoltaic systems to function since it is an essential part of the system. However, similarly with the previous section, research about aquavoltaic systems within the WEF nexus is sparse, and the current potential implications of such a system should be taken with precaution.

As seen in Table 7, aquavoltaics showcase strong synergies within the WEF nexus. For industrial aquaculture to function, large quantities of water are necessary to create water flows that cycle nutrient and maintain clean water. FVs reduce water evaporation when installed on the water surface and, therefore, significantly reduce the economic and environmental costs of creating large cycle nutrient flows and maintaining clean water. Aquavoltaic systems therefore create energy while simultaneously saving water by reducing water evaporation (Campana et al., 2019), thus creating a strong synergy within the WEF nexus. However, potentially severe trade-offs from aquavoltaic systems within the WEF nexus exist, as seen in Table 7. Since aquavoltaic systems are deployed on water, they block and absorb the sunlight, which many organisms depend on for survival. If done unsustainably, the increased shading can cause decreasing algae growth and plant life, eventually impacting the entire food chain and, therefore, adversely impact fishing and fish farming opportunities (Château et al., 2019).

Table 7. Solar energy usage within aquavoltaics

Author(s)	Context	Method	Synergies	Trade-offs
Campana et al. (2019)	Thailand Shrimp farm Water treatment ponds as site for floating PV.	Model Dynamic techno-economic simulation and optimization model. Several scenarios for floating PV systems to meet the electricity needs of a shrimp farm.	Energy production Moderate energy savings for water pumping. Reduction of evaporation losses.	Not found
Château et al. (2019)	Taiwan Milkfish pond	Model Dynamic mathematical model showcasing the biochemical processes of a milkfish pond that is covered by a floating PV system. Several scenarios with different extents of PV cover.	Energy production Possibility of covering 60% of the fishpond while maintaining over 70% of the fish production.	Trade-off between fish production and energy generation – with higher energy generation and FPV population the fish production declines due to less sun and a cooler environment. Under 60% FPV cover equals 10% reduction in fish production in winter and 5% in summer.

4.4 Solar-Based Greenhouse-Desalination System

Another role for solar energy within the WEF nexus is integrating a solar-based multi-generation system with a greenhouse-solar desalination system (Rabhy et al., 2019). The solar-based greenhouse-desalination system is an example of how water, energy, and food security can be further improved within one system while overcoming harsh land and climate conditions and low water availability in arid areas by providing adequate climatic conditions for plant growth while reducing the water needed for irrigation. Solar energy is the preferred energy source to provide such benefits since arid areas are usually located in favourable sun conditions (Salah et al., 2017). The system produces irrigating water for food production via solar desalination and dehumidification processes, while electricity is provided via PV cells. Brackish and seawater can therefore be used for agricultural purposes due to the solar distillers that transform it into freshwater that can be used for the crops in a fully climate-controlled greenhouse environment (Rabhy et al., 2019).

As seen in Table 6, the state of knowledge about solar-based greenhouse-desalination systems are higher than the two previous sections but still relatively low. Still, solar-based greenhouse-desalination systems have strong synergies within the WEF nexus. The primary trade-off identified is that the system might undermine the sunlight needed for optimal crop production, creating a trade-off between energy production versus food production (Karan et al., 2017; Loik et al., 2017). However, two out of the four studies do not examine the potential trade-offs of the solar-based greenhouse-desalination systems, indicating that more research is needed to examine the full trade-offs it might create.

Table 6. Solar-Based Greenhouse-Desalination Systems

Author (s)	Context	Method	Synergy	Trade-off
Karan et al. (2017)	Las Vegas, NV and State College, PA. Small-scale WEF system greenhouse system powered by solar energy that can provide a consistent supply of food for a family of four. Artificial light, heating, ventilation, air conditioning, water recycling.	Case study Within system approach – all changes occur within the greenhouse based on the predetermined resources. Quantitative modelling to determine each resource's influence.	Solar energy allows rainwater to be recycled that is used to irrigate food production crops.	Depends on enough sunlight and precipitation to ensure an efficient food production system.
Loik et al. (2017)	University of California Santa Cruz Arboretum. Glasshouse with Wavelength-Selective Photovoltaic Systems (WSPVs)	Case study – comparing WSPVs impact on tomato crop yield versus regular or dyed windows.	Small water saving under the WSPV light. WSPV reduces the potential for high light induced damage.	Slightly lower CO2 under the WSPVs.

Rabhy et al. (2019)	Borg El Arab City, Alexandria, Egypt. Transparent solar distillers (TSDs) used to supply freshwater to crops – integrated on the roof of an agricultural greenhouse. Case study	Performance of a TSDs system is numerically and experimentally investigated.	The technology can hypothetically be integrated on a roof of a greenhouse and thus allow sunlight for plant photosynthesis process and excess solar radiation to desalinate water used for plant irrigation.	Not examined
Salah et al. (2017)	Different climatic conditions of Borg-Elarab, Egypt. Stand-alone agriculture greenhouse (GH) integrated with Transparent Solar Stills (TSS) on the roof and equipped with a chilled water condenser.	Mathematical model to examine the GH for four different days (Coldest, hottest, maximum radiation, and minimum radiation).	Solar energy to reduce GH heating while producing freshwater from solar stills for irrigation. Also, condensers recover water from the plant transpiration.	Not examined

5. Discussion

For the first theme, general solar deployment, solar energy shows strong synergies within the WEF nexus. For many rural communities, the main issue is that their areas are too far away from a centralised electricity grid, and therefore, they often face energy, water, and food insecurity (Roje et al., 2020). General solar energy deployment has great potential to be scaled up. Current estimations suggest that micro-grids can provide more than 50 per cent of the additional electricity needed to reach universal energy access without adding any additional Greenhouse Gas (GHG) emissions (Madriz-Vargas, Bruce & Watt, 2018). Solar micro-grids can be used for drinking, cooking, water pumping, and irrigation while replacing the more common diesel energy generation commonly used in rural areas and thus provides a cost-effective decarbonised alternative to universal energy access (Roje et al., 2020; Ibrik, 2020). Besides having the potential to create energy, water, and food security, solar energy projects in rural areas can create positive spillover effects. The importance of increasing energy access and increasing water and food security potential is highlighted in Ibrik's (2020) article, which shows how increasing access to such resources can reduce poverty, increase access to education, and better profit-making amongst rural communities. Solar energy specifically allows these positive impacts to be reaped without polluting the environment and is, according to Buechler et al. (2020), likely to create positive behavioural changes such as harvesting water, composting, and growing more food crops. Therefore, by ensuring water, energy, and food security through solar energy deployment, strong spillover effects can have positive impacts on local communities, which showcase the importance of ensuring energy, water, and food security to improve community's welfare and livelihoods, which in turn can lead to increasing the willingness to engage in sustainable practices.

However, besides Al-Saidi and Laham's (2019) article, most studies only examined solar energy's impact on the WEF nexus in smaller-scale solar energy projects. The deployment of solar energy can have differing impacts on the WEF nexus depending on the size and type of project. With a significant trade-off identified throughout the first theme, the increased access to water resources which can lead to over-abstraction of water (Al-Saidi and Laham, 2019; Gupta, 2019), the potential impact of large-scale solar energy powered irrigation for food production could have potentially detrimental impacts on water security. This is especially relevant in already water-scarce regions where solar energy is likely to create a trade-off between ensuring water security in the long term and limiting water abstraction versus increasing food security in the short term and excessively using local water resources to irrigate food crops (Al-Saidi &

Laham, 2019). With many studies neglecting to examine the trade-offs fully, the full impacts of solar energy's role within the WEF nexus are yet to be established.

Moreover, an important point is not that solar energy deployment in itself causes stress to local water resources, but it is rather how the solar energy produced is used that can create potentially adverse impacts on water resources. Solar energy can be deployed in regions with little or no previous access to energy (Zaman et al., 2021), and the scaling-up potential the energy resource has is often what creates these potentially negative implications. When solar energy facilities are situated in areas with no large-scale or unreliable access to energy before, the knowledge about how to use the increased access to energy sustainably might not exist (Al-Saidi, M., & Lahham, N, 2019). Furthermore, the adverse impacts of rapidly expanding energy access to such regions are often neglected on an institutional level, leading to a lack of adequate monitoring, relevant regulations, and awareness about the potential downsides of over-using local water resources (Closas & Rap, 2017). Therefore, it is not necessarily the solar energy resource itself that creates this issue, but rather how it is used and regulated. If any other energy source would be deployed in such regions, the same impact would likely occur unless relevant regulations and awareness regarding sustainable water abstraction would be mainstreamed.

A specific way solar energy can be used, with strong synergies within the WEF nexus, is through agrivoltaics, as seen in section 4.2., by co-locating food crops under PV panels while improving water efficiency. Furthermore, agrivoltaics can potentially solve a major issue regarding solar energy expansion – the vastly increased need for more land (Hickel, 2019). With a growing world population and increasing consumption, substantially more land will be needed for food production in the future with the current global consumption pattern (Smith, 2018). However, as Barron-Gafford et al.'s (2019) study shows, the water and food improvements differed widely depending on what food crops are grown and where they are grown. For example, studies not deemed suitable to be included in this review found that lettuce crops in France average 1-19 per cent lower yield in the AV plot than the full-sun control plot, showcasing a trade-off between food and solar energy production regarding AV. However, a later study in the same region showcased a 20 per cent reduction in water usage in the AV plot, hence showcasing a synergy of solar energy and water security when using AV even though it might present a trade-off regarding food production (Proctor, Murthy & Higgins, 2021). Although showcasing large potential, such dissymmetry's shows that this technology is still in its infancy and scaling it up without extensive knowledge about local climate conditions, food crop types, and how these interact within an agrivoltaic system might result in non-desirable results.

As seen in section 4.3., another solution to using land for energy production or food production is the deployment of aquavoltaics. The primary advantage of FV is the water that can be used to cool the PV system, boosting the power conversion efficiency (Pringle, Handler & Pearce, 2017). In addition, the main issue with PV is the evaporation losses from water bodies that could be used for agricultural irrigation or other power production instead. FV reduces water bodies' evaporation rates significantly compared to traditional PV systems (Campana et al., 2019). Therefore, there are two major ways FV can mitigate water losses; they consume much lesser water than traditional fossil fuel energy systems; and, by deploying solar energy systems on water, water losses due to evaporation is mitigated by up to 70-85 per cent (Prince, Handler & Pearce, 2017). Such potential makes FV technology very promising; however, within the WEF nexus, a significant trade-off occurs when integrating FV and aquaculture into aquavoltaics. The system blocks sunlight to life under the water surface and therefore undermines food production (Château et al., 2019). Furthermore, the role of sunlight for aquatic ecosystems is poorly understood (Hunting et al., 2019), while blocking sunlight might adversely impact the growth of under the water surface life (Stallings et al., 2015). Deploying aquavoltaics on a large scale could cause detrimental effects to local water ecosystems, especially when much of water ecosystems are still unknown to humans. However, a possible way to mitigate this in a controlled setting is the potential of manipulating oxygenation zones. Such manipulation can result in greater biomass generation while additional nutrients increase biochemical oxygen demands growth rates (Pringle, Handler & Pearce, 2017). Still, just like with agrivoltaic systems, scaling up the usage of aquavoltaics should be done with precaution. A thorough examination of the impacts of water ecosystems, which might differ depending on the region, needs to be done before aquavoltaics can be deployed while ensuring sustainably.

Current research on solar-based greenhouse-desalination systems show strong synergies within the WEF nexus (Rabhy et al., 2019). With few or no trade-offs within the WEF nexus, the potential for solar-based greenhouse-desalination systems are vast. However, the technology is currently costly and might not be a viable option in many contexts (Karan et al., 2018). With more research and investments into such systems, solar-based greenhouse-desalination systems might become a prospect for ensuring reliable water, energy, and food security. An especially important part of the technology is its ability to overcome harsh land and climate conditions (Salah et al., 2017), which creates the potential for ensuing water, energy, and food security in areas that might otherwise become uninhabitable due to climate change. If the financial barrier to solar-based greenhouse-desalination systems would be overcome, it could serve as a way to adapt to the increasing desertification and changes in weather patterns caused by climate change.

6. Conclusion

Although solar energy's role within the WEF nexus is sparse since it only started gaining traction in 2015, an increasing number of articles has started to emerge in recent years. The state of knowledge about solar energy's role within the WEF nexus was highest for this study's theme general solar deployment and lowest for the aquavoltaics theme. This review shows that solar energy deployment is more complex than simply expanding the usage of renewable energy and that its impact on water and food security differs depending on usage, region, and local-specific considerations. In all studies, solar energy creates additional energy security, leading to better opportunities to access local water resources, thereby increasing water security, which can be used for crop irrigation and increase food security. A major trade-off for general solar deployment within the WEF nexus is the over-abstraction of water to irrigate food crops, thus creating a trade-off between long-term water security versus shorter-term food security. However, many studies did not fully examine the trade-offs or in which setting they occur. Agrivoltaics and aquavoltaic systems create strong synergies as well, and both offer water-efficient means of producing energy and food. However, aquavoltaics often undermine food production, while agrivoltaics impact on food production varies depending on what crops are grown and their location. Solar-based greenhouse-desalination systems, although the research on such systems is sparse, shows promising results. Solar energy provides the energy needed for the system to function, allowing for an autonomous system that recycles rainwater and uses it to irrigate crops functions. The main barrier to such a promising technology is the high financial costs. To conclude, the different themes created in this review study shows the diverse roles solar energy has within the WEF nexus, even with the sparse literature currently available. Furthermore, the diverse synergies and trade-offs highlighted in this review shows how deploying solar energy are more than only increasing energy security; it also impacts water and food security, which future decision-makers must consider.

Based on this review, several recommendations can be made. With sparse research about solar energy's role within the WEF nexus, more research is needed to identify the full scope of synergies and trade-offs and the necessary measures needed to exacerbate the synergies and mitigate the trade-offs. Since the research findings differed depending on context and region, new solar energy projects should analyse the implications of solar energy deployment with regional and context-specific considerations. Furthermore, future research projects should always include the potential trade-offs when deploying solar energy since this was something many of the studies included in this review lacked.

Overall, solar energy's role within the WEF nexus showed a positive impact, and solar energy deployment should continue for the world to reach crucial decarbonisation targets. With the right management techniques, regulations, and policies, potential trade-offs within the WEF nexus can be mitigated. Therefore, for policy practitioners, decision-makers, businesses, and others who work with solar energy deployment, the trade-offs solar energy might create within the WEF nexus must be considered. An essential part of this is to spread information about the trade-offs, especially the impacts on the ground- and water-surface bodies. Communities should be provided with preliminary information about stresses to local water resources when implementing new solar energy projects in areas that previously had limited energy access (Al-Saidi & Laham, 2019). Furthermore, the establishment of adequate water monitoring and adequate regulations on how much water a region or community are allowed to abstract is needed. Currently, most economical and technical feasibility studies regarding solar-powered groundwater irrigation fail to account for and evaluate groundwater resources in terms of quantity and quality throughout such a project, thus threatening long-term water security and, subsequently, food security. Adequate and recent data on how much water a solar-powered irrigation system use and the groundwater availability in a region should be incorporated in future planning processes (Closas & Rap, 2017).

Agrivoltaics showcased strong synergies within the WEF nexus. However, the technology is in its infancy, and different locations might showcase different synergies or trade-offs regarding AV within the WEF nexus. Therefore, more research is needed to establish which crops showcase the highest synergies or potential trade-offs within the WEF nexus when AV is deployed (Barron-Gafford et al., 2019). For aquaculture, to optimise the systems, light changes and adjustment through artificial means are often needed. Solar-powered lights would therefore provide a more optimal condition for aquaculture. Such measures would create a uniform and more predictable oxygen distribution, thus, improving food production capabilities (Pringle, Handler & Pearce, 2017), and should be further researched through a nexus approach. Furthermore, to avoid adverse effects on water ecosystems, the deployment of aquavoltaics should be done with precaution to ensure that the system does not undermine essential water systems.

7. Limitations

This review article was created, written, and completed by one author. A review written by a single author creates higher susceptibility to bias from the author when choosing literature to review. This was mitigated by sending the article to several outside reviewers for assistance before a completed manuscript was finalized. In addition, the systematic review methodology ensures that the study is replicable, and that minimal bias pertains the research process.

Using a qualitative conventional content analysis was determined appropriate for this research, as elaborated on in section 3. However, such a type of analysis often fails to fully understand the context that undermines the identification of key categories. The impact of this may result in findings that do not adequately represent the data. In addition, the conventional content analysis does not build on pre-existing theories, which was suitable for this review article. However, it undermines the ability to fully examine the literature used in this review article (Hsieh & Shannon, 2005). An in-depth analysis of the research studies is therefore recommended for future research projects.

Moreover, much literature covers the WEF nexus aspects without referring to the nexus approach specifically and might contain valuable information. However, assessing and reviewing the potential knowledge that might exist within such literature was out of the scope of this review paper, while the use of alternative keywords and snowballing methods was used to find additional literature that might not use specific nexus concepts.

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The author of this article has no competing interest to declare.

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