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Solar-powered irrigation as a curse for vulnerable water basins? A community case study using the water–energy–food security nexus

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The rise of solar-powered irrigation systems (SPIS) has shown promise in several developing countries. However, there is increasing concern about the consequences of easy access to energy in vulnerable groundwater basins. The agricultural sector in water-scarce Yemen relies heavily on groundwater resources, with solar energy recently enabling groundwater extraction for irrigation during the ongoing political instability. This community case study discusses the role of solar-powered irrigation systems (SPIS) within the water–energy–food security nexus (WEF-Nexus), based on community practices in the Sana'a Basin, Yemen. Using field surveys and expert perceptions, it highlights tradeoffs and repercussions associated with increased use of SPIS. Although farmers have embraced SPIS, capital investment costs are still the biggest obstacle to acquiring this technology. The increased use of SPIS will impact water use and cropping patterns, and can thus have long-term impacts on water security, food production, and equity issues. This paper proposes considerations for governance and policy to advance overall integrated water management and regulation of groundwater usage driven by SPIS. Establishing suitable frameworks for water extraction utilizing renewable energy can support the conservation of groundwater reserves and safeguard livelihoods under water scarcity exacerbated by the ongoing conflict in Yemen.

KEYWORDS

solar-powered irrigation, energy policy, water scarcity, groundwater depletion, water–energy–food security nexus

1 Introduction

Lately, increased academic attention has been given to the use of solar power in the water sector, particularly in agriculture. Solar energy is increasingly being used in agriculture to facilitate energy access, emissions reduction, and clean energy use by replacing diesel-powered pumps (Acosta-Silva et al., 2019; Aliyu et al., 2018). Solar-powered irrigation systems (SPIS), or solar pumps (SP), are being promoted as a way to optimize traditional water irrigation systems by reducing electricity consumption and (if feasible) minimizing water consumption (Senthil Kumar et al., 2020). Pairing SPIS with water-efficient irrigation systems (e.g., drip irrigation) can lead to rural development and resource conservation (Gao et al., 2017). However, experiences from many developing and arid countries have shown that solar energy for irrigation can lead to the over-extraction of water if SPIS are not appropriately regulated, such as limiting pump size, water metering, or mandating water use efficiency measures (e.g.,

precision irrigation systems; Gao et al., 2017). It is, therefore, important to apply a broader perspective of the water–energy–food security nexus (WEF-Nexus) to examine the cross-sectoral impact of the dissemination of solar energy in the agriculture sector of developing countries (Al-Saidi and Lahham, 2019; Gupta, 2019). At the same time, understanding the socio-political dimension of using agrivoltaics systems is highly necessary to define the roles and responsibilities of meaningful integration between agriculture and solar energy (Pascaris et al., 2021).

In Yemen, solar energy contributes to water provision for various users, including farmers who depend substantially on groundwater for agriculture. The country has endured prolonged instability due to civil conflicts, wars, economic decline, and severe water resource depletion (Lackner, 2019; Sady et al., 2013). Yemen's aridity, scarce water endowments, and mismanagement and overuse of supplies undermine water security. The ongoing conflict has considerably impacted water utilization and performance in the water and irrigation sectors (Burki, 2016). Prevailing unrest has reduced the availability of fuels and electricity, which typically power groundwater extraction and transport. This heightened scarcity of energy sources has made water resources more difficult to access and services less reliable. However, in certain areas, farmers have accessed new technologies like SPIS, which enable them to continue using groundwater.

This community case study focuses on Sana'a Basin, where water shortage poses considerable problems. Of global national capitals, Sana'a has frequently been identified as most prone to water depletion (Misiedjan et al., 2014). Solar energy presents an environmentally-preferable renewable resource, but observers indicate its complex impacts in Yemen (Aklán et al., 2019; Aklán and Lackner, 2021). While solar pumps can augment water access and conserve energy, they potentially influence aquifers like the sensitive Sana'a Basin. Amid current fuel scarcity, urban public water agencies increasingly utilize solar-driven groundwater pumping for domestic supply. Solar pumps for drinking water confer valuable impacts on accessibility, health, and hygiene. However, there is a need to investigate the impacts of using solar energy for irrigation on other critical issues, such as the regulation of SPIS use and its possible impacts on the ongoing over-extraction of groundwater resources.

Groundwater administration in Yemen lacks policies and regulations for novel solar technologies aiding extraction. Limited field data and analysis of SPIS further challenge management. This paper addresses this deficiency by analyzing local trade-offs of using SPIS in farming practices in Yemen. It uses field interviews and stakeholder perspectives on current SPIS practices and potential consequences for sustainably utilizing Yemen's constrained reserves. Unresolved overdraft risks deteriorate accessibility to water in the long run and thus affect livelihoods in the Sana'a basin. With rising SPIS prevalence in Yemen as an affordable clean option, this paper provides governance recommendations and donor approaches that can guide sustainable groundwater consumption by SPIS.

2 Context: trade-offs within the water–energy–food nexus of SPIS

The use of solar energy in agriculture is a cross-sectoral challenge with potential impacts on water, energy, and food security. Academic literature on renewables in the WEF-Nexus reveals many trade-offs

and synergies depending on the system design and innovation used (e.g., dual systems of agriculture and solar production, solar pumps combined with precision irrigation; Gupta, 2019). While renewable energy use can provide benefits for food and electricity access, its water-saving impacts are dependent on specific technology and regions (Ferroukhi et al., 2015). Therefore, the WEF-Nexus approach emphasizes the need for studying specific trade-offs and impacts related to the use of certain technologies or products that affect the three resources (Lee et al., 2023).

Solar applications in agriculture offer cross-cutting impacts, decreasing fossil fuel/grid reliance while boosting farmer resilience. This aids in climate change mitigation by reducing emissions and exposure to fuel cost volatility. Government energy subsidy spending, which is significant in the Middle East (GIZ, 2016), could be significantly lowered. Excess power fed into grids through power purchase agreements supports renewable targets and overall energy security. Regional renewable strategies incorporated solar into food production. Tunisia's 2008 Renewable Energy Plan promoted applications for agriculture/rural areas, envisaging the use of renewables in irrigation, desalination, and other on-farm activities (Bryden, 2017).

Renewables demonstrated economic merits and feasibility that can enhance agricultural production. Regionally, solar water pumps exhibited short payback spans of around 4–6 years with extensive longer-term savings (Chandel et al., 2015). Renewables enable various functions like water heating, abstraction, crop drying, grain grinding, greenhouse heating, and facility lighting (Chel and Kaushik, 2011). Coupled with increasing diesel costs, economically viable applications such as SPIS attract not only farmers but also decision-makers and financiers. However, analyzing SPIS sustainability is restricted by water availability, as it risks exacerbating scarcity as much as ameliorating energy access (Closas and Rap, 2017). Unregulated solar pumping risks require identification and mitigation via sustainably incentivizing policies and regulations governing all uses.

While solar energy use in agriculture can impact water availability, related policy objectives may differ by the context of potential/current uses. Figure 1 depicts four hypothetical setups of the SPIS decision-making dilemma in contexts representing resource potential/current utilization. In all SPIS scenarios, increasing solar use aims to enhance energy access. Agricultural land expansion feasibility/desirability depends on water availability. In arid environments, solar potential and optimal resource thresholds presumably surpass land/water. Under Scenario A, natural scarcity constrains land/water utilization exceeding optimal levels while solar potential remains largely untapped, as in Yemen. Scenario B represents larger, unexploited potential for land/water utilization and large but underdeveloped solar potential, as could apply to countries that are arid but abundant in water and arable land, e.g., Sudan. In wetter environments, land/water potential may surpass solar energy potential. Under Scenario C, agricultural potential is largely realized at the detriment of water, as in Spain/France, the USA, and Australia. Scenario D features underdeveloped agricultural/water utilization potential with lower solar potential, as in Japan and Brazil.

Bearing in mind the common non-restrictive goal of enhancing renewables' share, two major strategies underlie scenarios determining the integration between solar energy and agriculture:

- **Water saving and efficiency:** This objective implies that water security is the primary concern. Here, SPIS must contribute to

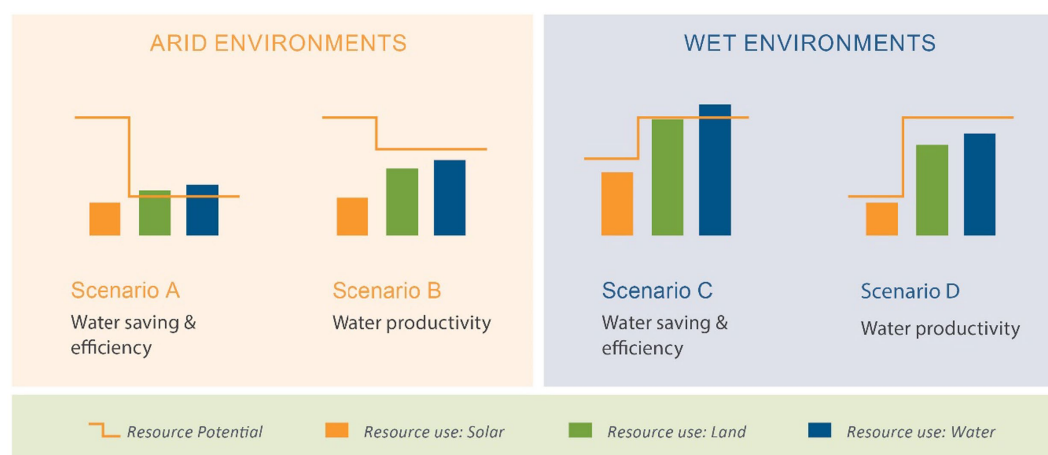


FIGURE 1
SEF objectives under various resource potential and use patterns scenarios.

reducing the overall water footprint by making the agricultural sector more water efficient or by reducing overall farmland size. There is no automatic link between increased solar power in agriculture and decreased water use. The decrease in water use can result from the substitution of agricultural land with solar panels. It can also result from improved monitoring and more integrated SPIS systems (e.g., encouraging water harvesting or promoting water saving and efficiency increases).

- **Water productivity:** Increasing water productivity means producing more agricultural output with the same water input. Here, food security is the key driver for SPIS projects. This can be achieved through hybrid systems that promote solar energy use in combination with better sustainable agricultural practices.

3 Community case study: background

3.1 The mounting environmental and humanitarian crises in Yemen

Yemen, a predominantly rural country with about 30 million people, has no lakes, permanent rivers, or significant water desalination capacity; rainfall and groundwater are Yemen's sole sources of water (Taher, 2016; Lackner, 2019). It is estimated that around 90% of groundwater resources are used by the agricultural sector, despite this sector accounting for less than 20% of GDP. Yemen faces extreme water scarcity due to overuse and population growth. The annual volume of renewable water per capita declined from 221 cubic meters in 1992 to 80 cubic meters in 2014, falling further to just 75 cubic meters in 2017 (FAO, 2021). Groundwater tables have severely declined, leaving the country in a state of extreme scarcity. For instance, in the Sana'a Basin, the water table was at a depth of 30 meters in the 1970s but descended to between 200 and 1,200 meters by 2012 (World-Bank, 2014).

Since 2011, the start of the Yemeni political uprising, the water supply situation in Yemen has been deteriorating (Lackner and Al-Eryani, 2020). During Yemen's ongoing conflict, the country's public water and electricity infrastructure served fewer households, estimated at 10% or less in 2018 (Aklan et al., 2019). All economic sectors, such

as agriculture, industry, and services, faced greatly increased expenses for irrigation, transportation, or marketing. This led to reduced production and exports (Al-Weshali et al., 2015; Clemens et al., 2012). Agricultural, industrial, and service outputs stalled, negatively affecting both public and private industry.

The conflict has affected water provision nationwide in terms of availability, accessibility, quality, and affordability. Evidence indicates decentralized water systems organized at the community level have exhibited more resilience compared to public centralized systems. In many locations, residents have opted to revert to sustainable practices like rainwater harvesting (Al-Saidi et al., 2020). While service levels are reduced and coverage has decreased compared to pre-crisis levels, the public water authority represents one of the few public institutions that has maintained some degree of operational continuity (Aklan et al., 2019).

Due to the current conflict, all power plants and the national network stopped working completely in 2016 (Rawea and Urooj, 2018). Private networks and household solar power have replaced the national grid, though few have sufficient storage or capability to operate equipment with high energy demands, such as refrigerators (Al-Saidi et al., 2020; Steenbergen and Aklan, 2016). The growing availability and financial accessibility of solar power, combined with years of intermittent or occasional electricity provision in towns and even less in rural areas, have led to wider solar adoption nationwide. More than 70% of households now use solar as their primary energy source (Aklan et al., 2019). Solar panels can be seen installed on nearly every house in Sana'a (Figure 2). Simultaneously, and to some extent supported by humanitarian organizations, solar water pumping has considerably expanded throughout the country for domestic supply and irrigation. However, solar use for agriculture has mainly been financed by well owners and operators, becoming more accessible to wealthier societal segments.

3.2 Solar energy as a coping strategy for the water–energy–food sectors

Irrigated area in Yemen has increased from 37,000 hectares (ha) in the 1970s to more than 400,000 ha in the 2000s. During the same



FIGURE 2
Newly installed solar panels on houses in Sana'a and SPIS at a farm in Sana'a Basin.

period, as irrigated areas increased 11-fold, the area supporting rain-fed agriculture declined by 30 percent (Closas and Molle, 2016). Among the most striking cases of unsustainable water management is the situation in the Sana'a Basin, where water resources serve the country's rapidly growing capital and high-value crops, such as *qat* (a mild stimulant widely used in Yemen) and grapes. Water extraction in the Basin is estimated to be five times the recharge levels (Taher et al., 2012; World-Bank, 2010). A further example is fruit production in the Tihama coastal plain; in the middle of Wadi Zabid, a significant area for banana cultivation, the irrigated area increased from 20 ha in 1980 to 3,500 ha in 2000. The number of drilling wells also increased by more than five times between 1987 and 2008, from about 2,421 to 12,339 wells (Al-Qubatee et al., 2017).

Water management policies and related national institutions have been weak. Farmers with extensive landholdings and powerful social connections have more, and unregulated, access to the resource than small landholders. Yemen has undergone a series of reforms since 1995, including the establishment of a National Water Resources Authority (NWRA) in 1995, the passage of a national water law in 2002, the establishment of a separate Ministry for Water and Environment in 2003, and the return of the irrigation sector to the Ministry of Agriculture, Irrigation and Fisheries (MAIF; Lackner, 2019).

In 2005, with donor support, the National Water Sector Strategy and Investment Program (NWSSIP) was announced, extolling important investments that have remained largely unfulfilled. While the NWSSIP addresses renewable sources such as rainfall and rainwater harvesting, it says nothing about using solar energy for water. An update was made in 2014, but the cabinet did not approve it due to the political crisis (NWSSIP, 2014).

In 2013, the total capacity of the national electric grid in Yemen was 1,535 megawatts (MW; Funder et al., 2012): 699 MW derived from diesel, 495 MW from steam, and 341 MW from gas power plants (Almekhlafi, 2018). The country's energy needs for lighting alone are estimated at 112 percent of the total generated energy (Rawea and Urooj, 2018). More than 50 percent of Yemen's population lacks access to the national grid, with the remaining population experiencing frequent power outages (Abdullah, 2018). Yemen's energy policy has largely been focused on diesel and gas electricity generation, which supplies cities but leaves most rural areas without any connection to the national grid. Yemen has high potential for renewable energy

sources, namely solar, wind, and geothermal (Almohamad, 2021). However, the country still lacks administrative strategies to promote and regulate sustainable energy resources. There are around 100,000 pumps in use in Yemen for irrigation purposes (NWRA, 2013). Replacing diesel and electric-powered pumps with SPIS would require clear rules and restrictions, particularly regarding the cultivation of the water-intensive *qat*.

4 Community case results: SPIS use in the Sana'a Basin

4.1 Study area and sampling

To understand the dissemination of SPIS in this region, field surveys were conducted in December 2020 and January 2021 among a stratified sample based on location (areas in Sana'a Basin with potential access to SPIS) and diversity (fertile areas with historically diverse cropping patterns). Therefore, the surveys were done with 88 farmers in Sana'a Basin, in the regions of Bani Husheish, Bani Mater and Hamdan. The study also undertook key informant interviews (KIIs) with 12 water, irrigation, and energy experts to ensure coherence between the data at the farmer level and professional- and administrative-level information. This approach facilitated a more profound understanding, from different perspectives, of the future of SPIS—including its uses and proper management—in Yemen. After a quality check on the collected data, participants were contacted by phone to verify unclear or incomplete points.

Sana'a Basin was selected as the study area because it is experiencing water scarcity and has deeper groundwater than other basins. Information on the use of SPIS in such a deep basin can be roughly extrapolated to different areas, with the assumption that SPIS use in shallower basins would be easier. To cross-check, a small data sample (10 farmers) was collected from Hadramawt, where the groundwater depth is <100 m. Due to the small size of this sample, the comparative insights are limited and used only to contextualize the case study results from the Sana'a Basin.

This community case study focuses on the Sana'a Basin, which spans nine districts, including Yemen's capital, with a 3,240 km² area and 4 million residents (Akalan et al., 2019). Sampled farmers from Bani Husheish, Bani Mater, and Hamdan have seen a drastic increase

in SPIS due to having flat and fertile land and rich farmers who can access SPIS. The basin has an arid climate, mild temperatures (12°–25°C), and annual rainfall averaging 240 mm. Most rain falls in two short seasons (March–April and July–August). Water demand has surged due to rapid population growth and agricultural expansion. Over 13,000 wells were in the basin by 2011, leading to groundwater depletion (Alwathaf and El Mansouri, 2012). Water abstraction exceeds recharge, causing annual water level declines of 4–8 meters. Agriculture consumes 90% of groundwater, with *qat* and grapes as primary crops (Foppen et al., 2005; Taher, 2016).

4.2 SPIS dissemination

SPIS installations increased from 0% in 2012 to 31% by 2020 (Figure 3). Pumping depths rose from 15 m (2014) to 500 m (2020; Figure 4). Due to war-related airport and seaport closures, annual SPIS adoption in Sana'a grew by 4.4%. If this continues, a complete conversion to SPIS could occur within 15 years, or 7 years if stability is restored.

During the war, groundwater levels stabilized, not due to SPIS, but due to reduced diesel pump use and higher-than-usual rainfall (2019–2020). Large landholders, primarily *qat* farmers, led SPIS adoption. In Bani Husheish, over 400 solar pumps were installed by 2017, making up 20% of wells.

SPIS adoption accelerated due to diesel shortages and high costs. By 2021, 30% of farmers in Sana'a used SPIS. Initially driven by war-related energy shortages, adoption is now motivated by SPIS's lower operational costs and reliability. Farmers report satisfaction, as SPIS maintain water access with minimal running costs.

Figure 4 shows the reported SPIS costs based on the farmers' survey (each column representing a solar pump for irrigation), as well as the pumping depth. The columns show that the number of SPIS increased from one in 2016 to eight in 2020. SPIS installation costs range from \$4,000 for shallow wells to \$100,000 for deep wells, with the cost increasing with depth. Brand, quality, and solar panel capacity

also influence prices. Some farmers report SPIS providing an equal or better water supply than diesel pumps. In Hadramawt, SPIS costs range from \$10,000 to \$17,000, making affordability a major barrier.

Diesel prices remain volatile due to war-driven import restrictions and black-market activity. By 2021, diesel prices had risen to 3–5 times pre-war levels, with some reaching up to 15 times higher. Farmers in *qat*-growing Sana'a were more willing to invest in SPIS due to higher profits, while Hadramawt farmers struggled with upfront costs. Many farmers retained their diesel systems for backup.

Qat farming expansion is outpacing other crops, raising concerns about long-term groundwater depletion (Al-Weshali et al., 2015). Farmers who previously cultivated non-*qat* crops are shifting to *qat* due to its profitability.

4.3 Perception of SPIS impact and regulation

While all farmers expressed interest in SPIS, 69% cited high initial costs as a significant barrier. Some regretted declining free SPIS systems in the past. Many wells are jointly owned, and time-based water allocations make SPIS challenging since output varies with solar radiation. This led 28% of surveyed farmers to hesitate in adopting SPIS, fearing unfair water distribution.

Development agencies, including FAO, IOM, UNDP, CARE, and OXFAM, have supported SPIS adoption, sometimes imposing depth limits. Larger landholders access more funding, while smaller farmers struggle financially. Some farmers sell assets like cars and gold to afford SPIS. Farmers receive little to no training on SPIS installation, operation, or maintenance, relying mostly on vendor information. Concerns include inconsistent product quality due to a lack of import standards and dishonest dealers.

Experts see SPIS as a solution to Yemen's unreliable electricity supply but worry about groundwater depletion without regulations. Unlike some policymakers, water experts fear over-extraction risks, as in other countries. Energy experts believe solar pumps could stabilize

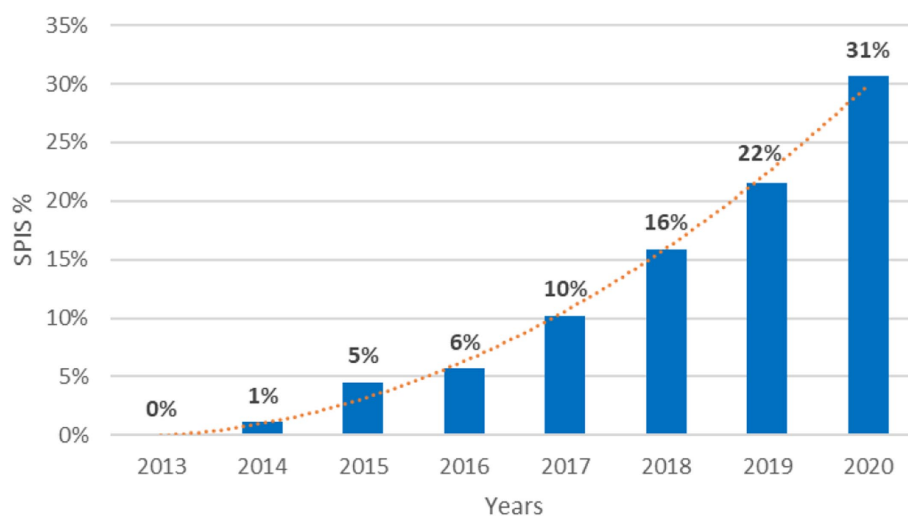


FIGURE 3

Cumulative installed SPIS (in percentage) compared to all groundwater pumps in the study area.

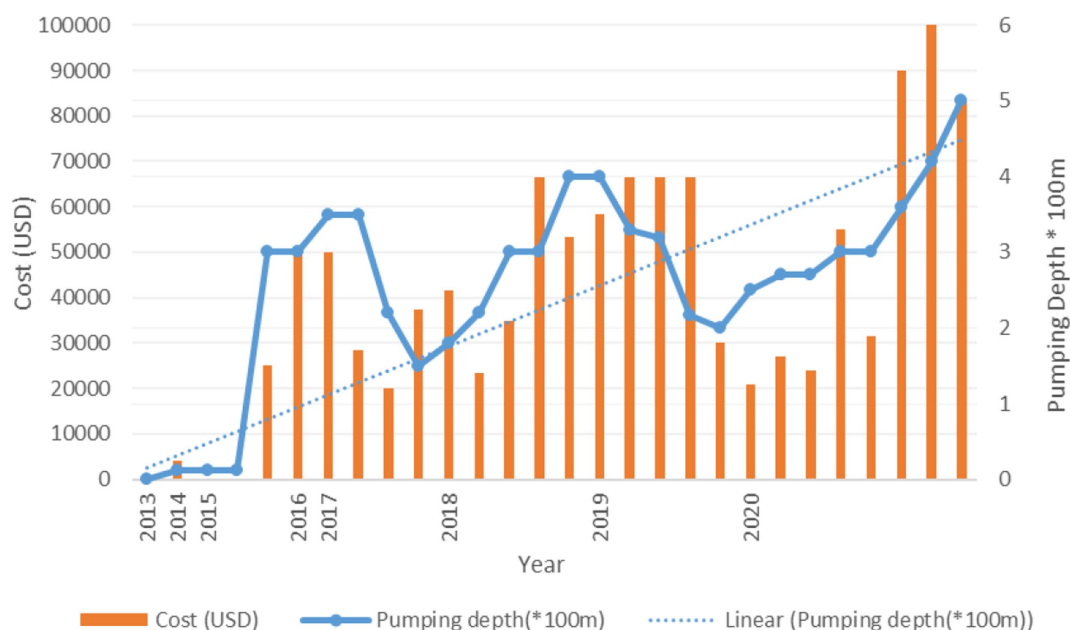


FIGURE 4
Installed SPIS, related costs, and pumping depth (2014–2020).

water levels by limiting pumping hours (8–10 h daily), but no study has assessed this in Yemen. Instead of subsidies, experts recommend technical support and water management training. Experts unanimously support SPIS, highlighting its economic and environmental benefits, particularly in rural areas. However, they stress the need for policies to prevent unsustainable groundwater use. Future studies should assess SPIS's long-term impact compared to traditional diesel systems.

4.4 Evidence on long-term repercussions

While this community case study cannot measure specific long-term impacts due to data limitations, it is crucial to link farmers' and experts' perceptions to secondary evidence on the long-term patterns. First, it is clear that the cost of a solar irrigation system increases significantly with the depth of the water table. In the case of the Sana'a Basin, where the wells are deep, costs for installing SPIS can reach up to US\$100,000. This method of irrigation, therefore, increases the gap between poor and wealthy farmers. Even where water can be reached at lesser depths, the price of SPIS installation is still beyond the means of most smallholders. SPIS are most accessible to the wealthiest farmers, those who own other businesses and/or grow the highest value crops. Note that men predominantly carry out farming activities in Yemen.

There are several equity implications of this trend. Farmers can justify irrigating the highest value crops, and more likely than not, they will expand their *qat* areas at the expense of basic food crop cultivation, such as sorghum, which negatively affects food security. Besides, irrigation costs, alongside other economic pressures, are likely to concentrate land ownership even further, as smallholders are forced to sell their assets, gradually worsening social differentiation. Policies focused on reducing inequality need to take these factors into

consideration when planning water management. The risk of unsustainable overexploitation of aquifers and, ultimately, their exhaustion is high throughout the country. The exhaustion of aquifers means not only an end to agriculture but also the end of a habitable area, ultimately leading to forced migration.

Second, while the hydrology of Yemen varies considerably, the risk that SPIS proliferation will likely worsen overexploitation of aquifers is particularly clear given the cautionary tale of historic diesel subsidies, which led to the overexploitation and dramatic decline of groundwater resources over decades (Akalan et al., 2019). All SPIS owners in the Sana'a Basin kept their old pumps (mostly diesel) as standby systems. Most current SPIS users rely on solar systems and use diesel pumps only when the SPIS supply is insufficient, mainly during the night, in the summer season, or on cloudy days. There is growing evidence that the low operational cost and available energy of SPIS contribute to the excessive extraction of groundwater, decreasing water tables, and negatively affecting water quality (Al-Saidi and Lahham, 2019; Gupta, 2019; Rathore et al., 2018). Most Arab countries are either in the category of extreme water scarcity or will be there soon. Often, hydrological infrastructure and rainwater harvesting are limited, and water reuse is not exploited, resulting in overuse of limited groundwater resources.

Another related concern is that farmers might irrigate more during the day, which lowers irrigation efficiency and water productivity. There are zero operational costs for SPIS, and it might not encourage water conservation (Kishore et al., 2014). Once installed, the SPIS has a relatively low cost per unit of generated power. Farmers try to maximize their groundwater use to recover the high capital costs of SPIS, either by expanding their irrigated area or by selling water to other farmers. This could lead to a race to the bottom unless regulations are put in place and enforced. In India, highly subsidized SPIS led to oversized capacities and, thus, some overexploitation (Shah et al., 2016; Shim, 2017). Most farmers in

Yemen are still practicing the old methods of flood irrigation, and few have modern irrigation systems. These issues need to be addressed systematically at the community and policy levels through comprehensive procedures and regulations.

Third, food security is a significant challenge in Yemen but addressing it should not come at the expense of the country's endangered water security. SPIS can increase food production by harnessing reliable and sustainable energy to provide timely irrigation. Additionally, solar energy can be oriented toward off-grid solutions through the modernization of on-farm facilities, such as solar pumping, heating, distribution, etc. (Ferroukhi et al., 2015). However, these benefits may be at risk, as many SPIS technical feasibility studies fail to appropriately evaluate available water resources and water use, leading to trade-offs within the water–energy–food nexus. Given that 70 percent of Yemenis still live in rural areas with significant dependence on agriculture, ensuring the use of the most appropriate and water-saving irrigation technology is very important. However, activating traditional rainwater harvesting systems and developing rain-fed agriculture are of equal importance, as many areas have insufficient groundwater to enable more than very minimal supplementary irrigation (Akalan et al., 2022).

5 Discussion: lessons for sustainable, solar-powered irrigated agriculture in Yemen

Alongside analyzing the implications of SPIS for resource security in Yemen, it is important to outline several overarching lessons from this important case of a highly vulnerable water basin. This section highlights key lessons and contextualizes them within academic literature across the broad issues of (1) integrating solar energy in agriculture into policies and applications; (2) coordination and multilevel regulation; and (3) capacity building and science-based assessment.

- **Integration:** To increase energy access while conserving groundwater and increasing irrigation efficiency and water productivity, there should be more SPIS integration. SPIS can be connected to the grid (if the water wells are not scattered) to sell the excess energy at a subsidized price for non-water extraction uses. This creates an opportunity cost for the inefficient or wasteful use of solar energy. Alternatively, any energy surplus can be directed toward other productive on-farm uses. SPIS applications can be integrated with monitoring systems (e.g., using cellular phones), while additional measures such as rainwater harvesting can be linked to support SPIS. Sustainable projects in this area (e.g., in India or Morocco) demonstrate the importance of linking solar energy use in agriculture to policies from other sectors, such as groundwater management plans and investments in aquifer recharge (Closas and Villholth, 2016; Al-Saidi and Lahham, 2019). Subsidies for solar installations should be reformed, such as lowering subsidies in water-vulnerable regions to encourage saving. Such subsidies can also be conditional upon purchasing micro-irrigation systems, as is the case in Morocco and some parts of India (Kingdom of Morocco, 2014; Shah et al., 2014; Bassi, 2018; Al-Saidi and Lahham, 2019).
- **Coordination and multilevel regulation:** National, governorate, and local authorities should coordinate their water management

policies to ensure priority access to water for domestic use, followed by livestock and other non-agricultural uses. None of the official authorities or their related policies/strategies, including the Ministry of Electricity and Energy (MEE), the Ministry of Water and Environment and the Ministry of Agriculture, Irrigation and Fisheries (MAIF), have addressed the issues associated with solar energy use in Yemen. In 2009, the MEE published a 10-page National Strategy for Renewable Energy and Energy Efficiency, but it has yet to be adopted and does not offer SPIS-specific guidance (MEE, 2009). There is a high need for multilevel regulation of SPIS use. At the national level, clear framework policies on water abstraction and permits are needed, as well as certification and standardization for SPIS systems. These can be combined with policies to promote solar energy use in agriculture. At a regional or basin level, the MAIF and NWRA should formulate specific regulations determining permissible pumping depths based on the actual groundwater level and renewable water availability in each basin. For instance, in the Sana'a Basin, SPIS should be allowed up to a maximum depth of 200 m (a safe depth for scarce and deep groundwater), with maximum outputs of up to 250 m³/day. At the local level, controlling pumping depth is necessary to manage actual water extraction, which is directly influenced by the number and size of solar panels installed, thereby determining the pump's capacity. The number of solar panels installed can be detected by satellite imagery, as well as from photographs taken by unmanned aerial vehicles, a technology that is now easily accessible.

- **Capacity building and evidence-based assessment:** As highlighted earlier in this study, enhancing the capacities of farmers to use water, solar energy, and arable land sustainably is important. This can be done at the extension services level, or through water user associations (WUAs) or similar institutions, working closely with farmers on building capacities and ensuring their representation. Financing organizations and civil society can play a significant role in promoting solar energy for domestic use, particularly in rural areas, while ensuring sustainable practices. Projects can be accompanied by training in equipment maintenance, as well as effective certification of the quality of the technology. At the same time, we need to understand the extent and impact of SPIS in Yemen, particularly the opportunities and limitations for different basins. One approach is to develop a SPIS risk map for the entire country to define high-risk areas. Coastal groundwater reserves, with lower depths, are likely to be more adversely affected by this technology than the highlands. There are a few studies about solar energy for domestic use (Abdullah, 2018; Al-Ashwal, 2019; Almekhlafi, 2018; Rawea and Urooj, 2018), but this has little bearing on the technology's applicability for agricultural water extraction. A 2019 UNDP report, the only study to discuss the use of SPIS in Yemen to date, identified the advantages of SPIS and promoted its use, but said little about the possible impact of SPIS on groundwater sources (UNDP, 2019).

6 Conclusion

Although the findings of this community case study suggest caution regarding the use of solar power for irrigation, it should

be emphasized that solar energy use in agriculture is largely perceived as a positive development in the conflict-ridden and resource-poor country of Yemen. Solar power is, in this way, providing basic services to the population, particularly for thousands of rural households that would otherwise not have access to this essential element for survival.

Concerning the sustainable management of Yemen's scarce water resources, the main finding of this study is that SPIS require better regulation and governance, alongside other water extraction mechanisms, primarily in agriculture but also for domestic and other uses. The field data collected for this study demonstrate that the use of SPIS has dramatically increased in the last decade in Yemen. The data also show that the use of solar energy for irrigation in solar-rich and groundwater-scarce Yemen can adversely affect groundwater resources, particularly in the absence of effectively implemented regulations. In other words, SPIS is yet another mechanism that, unless well managed, could worsen Yemen's overall water scarcity. The crucial determining factor for farmers about SPIS is the marginal cost of solar-powered pumping, which is almost negligible once they have made the initial investment. To mitigate negative repercussions and minimize trade-offs associated with disseminating SPIS in Yemen, several policy recommendations can be made for local and international actors.

- SPIS use should be incorporated into water management policies outlined by the national water institutions and enforced by national and local authorities. These policies should prioritize access to water for domestic use, maximize the benefits of rain-fed agriculture of high-yielding and drought-resistant staple crops, and allow irrigation with SPIS from groundwater only where replenishment of the water source is guaranteed.
- Central and local governments should implement a national awareness campaign on water management issues, including the risks of depletion of resources and the positive and negative potential impact of SPIS and other irrigation technologies.
- International funders need to emphasize the impact of solar power use on water issues. Solar energy access should remain a priority, particularly in remote and rural areas. At the same time, SPIS should be based on clear requirements for efficient irrigation, use limits, training, capacity building, and certification.
- Water and agricultural institutions should assess the impact, opportunities, and limitations of SPIS, producing an SPIS risk map for the entire country to define the areas of high risk. The coastal groundwater reserves, with lower depth, are likely to be more adversely affected by this technology than the highlands.
- Certification and quality control of imported SPIS systems are needed through joint action by international donors and the national authorities for standardization.
- National water institutions should formulate regulations for SPIS use, determining permissible pumping depths based on the actual groundwater level and renewable water availability, improve monitoring of use (e.g., using satellite and remote systems), and condition the use and subsidies on sustainable water management practices through modern irrigation technologies.

- Farmers' and communities' participation is necessary to improve capacities and awareness related to the use of SPIS and ensure sustainable and equitable use of SPIS.

Data availability statement

The datasets presented in this article are not readily available because they are owned by the Sana'a Center for Strategic Studies. Requests to access the datasets should be directed to musaedaklan@gmail.com.

Ethics statement

Ethical approval was not required for the studies involving humans because ethical approvals processes not existing in Yemen. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

MA: Validation, Funding acquisition, Formal analysis, Writing – original draft, Data curation, Investigation, Writing – review & editing, Resources, Conceptualization, Visualization, Methodology. HL: Methodology, Conceptualization, Validation, Investigation, Funding acquisition, Resources, Writing – review & editing, Writing – original draft. MA-S: Writing – review & editing, Conceptualization, Writing – original draft, Methodology, Formal analysis, Visualization.

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