

GIS-based method for assessing the viability of solar-powered irrigation

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ABSTRACT

To attain food security, sub-Saharan Africa needs to increase its use of irrigation to improve agricultural productivity and resilience to climate change-induced droughts and erratic rain patterns. Stand-alone solar-powered irrigation systems are a promising technology to power irrigation where grid electrification is unavailable. However, these systems' economic viability and sustainability are affected by spatially varying factors such as climate, water availability, and solar potential, making it challenging to plan their roll-out. This study addresses the planning challenge by developing a novel open-source reproducible geospatial methodology to determine irrigation water demand, peak power demand, life cycle cost, and locations where solar-powered irrigation systems would be cheaper than alternative off-grid irrigation technologies. The method considers spatial-temporal data for meteorological conditions, soil quality, water distance and depth, solar resource potential, technology efficiency and local equipment and fuel costs. Maize cultivation in Kenya is taken as a case study to demonstrate the method. We find the median peak irrigation water demand in Kenya to be 65,000 l/ha/day and the median peak power demand to be 2.6 kW/ha. The levelized cost of solar-powered irrigation systems ranges from US\$ 0.09/kWh to US\$ 0.25/kWh, making solar irrigation cheaper than diesel-powered irrigation in all Kenyan regions. The results from the method offer valuable insights to governments, farmers and investors on where water use regulations are required for sustainable water use, where subsidies and innovative financial models are needed for the affordability of solar irrigation and where alternative uses of energy from the solar systems beyond irrigation are possible.

1. Introduction

This paper investigates the spatial feasibility of solar-powered irrigation systems (SPIS) to improve agricultural productivity in sub-Saharan Africa (SSA). It develops a novel geospatial SPIS planning method and applies it in the case of maize farming in Kenya.

Crop yields in SSA are very low compared to the rest of the world [1]. A key reason for the low yields is that over 90% of the continent's agriculture is rainfed, making the sector vulnerable to climate change-induced droughts and erratic rainfall patterns [2]. This low agricultural productivity has affected the continent's food security, with over 300 million of its people categorised as food insecure by the Food and Agricultural Organization (FAO) as of 2020 [3]. To achieve food security and climate change adaptation, Africa could embrace irrigation in its agricultural systems—irrigation can increase yields by at least 50% and build resilience to climate shocks [4,5].

A primary challenge to implementing irrigation is the continent's low electrification rate of 48% with the majority of the unelectrified population being in rural areas where most agriculture happens [6–8]. An emerging solution for irrigation in low and medium-income

countries (LMICs) where electrification rates are low is the use of off-grid solar-powered irrigation systems (SPIS) [9,10]. However, planning for SPIS requires systems thinking, considering the food-energy-water nexus and both economic and environmental sustainability [11,12]. As the factors affecting SPIS's size, cost, profitability and sustainability vary spatially and temporally, geospatial tools can be useful to assess and visualise SPIS deployment potential and help governments, investors and farmers in planning and decision-making [13].

Existing peer-reviewed methods for sizing SPIS (e.g., [14–18]) follow a standard procedure of estimating the crop irrigation water requirements and then sizing the pump based on the water demand and the type, distance and depth of the water source to be used. In terms of SPIS sustainability, a review article by Agrawal et al. [19] lists 14 factors to consider in ensuring that the deployment of SPIS is environmentally sustainable, socially acceptable and economically viable. The economic factors are peak daily water requirement, depth or distance of water source, solar irradiance, system quality and after-sale services, the scale of farming, access to inputs and crop markets, utilisation factor and cost of alternative solutions. Environmental sustainability factors are water use efficiency, carbon emissions abatement

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and SPIS's end-of-life management. Social acceptability factors are threats to safety and security, system quality and after-sale services, technology awareness and co-benefits.

However, despite this knowledge on how to size and ensure the sustainability of SPIS being available, little has been done to apply it geospatially. Schmitter et al. [20] used a case study of Ethiopia to map the suitability of SPIS on a scale of one to five (where one is unsuitable and five is most suitable) using physical factors like slope, weather (e.g., irradiance), water depth and the distance to the nearest market. That study incorporates the various factors by giving them percentage weights based on expert knowledge. This, however, makes the method challenging to reproduce in other regions as new context-specific weighting will be required. Yu et al. [21] considered precipitation and slope of the ground surface as indicators when analysing the viability of SPIS for grassland irrigation in China. As precipitation and slope are not the only factors affecting SPIS viability, the study relies on background knowledge of other factors like irrigation water demand in China, making it hard to reproduce in other regions. Nilsson et al. [22] introduce a method for spatially estimating the power and energy requirements for groundwater irrigation in Uganda. However, the method does not consider surface water resources. In addition, the method in [22] does not provide a code for its reproduction in other regions and is not self-contained as it requires calculations for water requirements to be performed using the FAO AquaCrop application. No existing geospatial studies have assessed the SPIS utilisation factor, a key parameter in assessing the SPIS economic viability according to [19,23].

Therefore, although several researchers and scientific publications have provided insights on geospatial SPIS, different research gaps still need to be addressed. First, the existing methods are not easily reproducible due to their location specificity or reliance on pre-existing expert knowledge (*research gap 1*). Second, the existing methods do not consider both groundwater and surface water sources (*research gap 2*). Third, no study has geospatially assessed how the SPIS utilisation factor affects their levelized cost of electricity (LCOE) and cost competitiveness against other technologies (*research gap 3*).

This research proposes and demonstrates a novel geospatial SPIS planning method overcoming existing research needs in the literature. The novelty lies in an open-source, comprehensive, reproducible methodology for spatial sizing, life cycle costing and determining the utilisation factor of SPIS by considering spatial-temporal data for meteorological conditions, soil quality, water distance/depth, solar resource potential, technology efficiency, and SPIS costs. The research addresses *research gap 1* by building and availing Python code for the methodology publicly on [GitHub](#). This gap is further addressed by demonstrating the use of the method through a case study of Kenya and providing the relevant peer-reviewed geospatial datasets that can be used to reproduce the analysis for other regions. *Research gap 2* is addressed by having the developed methodology consider both groundwater and surface water sources and choosing to use whichever requires less energy. *Research gap 3* is addressed by geospatially calculating the LCOE of SPIS and comparing it to the LCOE of diesel-powered irrigation systems (DPIS), Kenya's most common off-grid irrigation technology. Furthermore, the gap is addressed by examining how the utilisation factor of SPIS affects its cost competitiveness with DPIS. The main contributions of the paper are:

- An open-source reproducible methodology is developed for spatially assessing SPIS viability by sizing, life cycle costing and determining how the SPIS utilisation factor impacts their cost competitiveness against other common off-grid irrigation technologies, such as DPIS.
- The results from the case study in Kenya offer insights into where water usage regulations will be required to avoid water over-abstraction, where SPIS is the most cost-competitive irrigation technology, where the SPIS utilisation factor needs to

be increased to improve their cost-competitiveness, and where subsidies and flexible payment plans will be required to enable farmers to acquire SPIS.

Kenya, a country in East Africa, was selected for the case study as agriculture is a vital sector of the country's economy, contributing directly to 33% of gross domestic product (GDP) and indirectly to 27% of GDP through linkages to other sectors such as manufacturing and distribution [24]. 78% of the country's food production is by smallholder farmers who rely on rainfed agriculture and are therefore exposed to climate shocks [25,26]. The country's frequency of droughts has increased from every 5–10 years to every 2–3 years [27]. With 83% of the country's land being arid and semi-arid land (ASAL), the effects of these droughts have been devastating to the country's food security. An ongoing drought, which began in late 2020, has since affected 14.9 million people (as of March 2022) [28]. Irrigation is, therefore, urgently needed for the country's food security. In the case study, maize is used as the reference crop. Two scenarios are studied: (1) an *average-case* scenario representing normal climatic conditions, and (2) a *worst-case* scenario representing drought. Openly available geospatial data are obtained, processed and applied for the case study, showing how this same methodology can be repeated for any other country across Africa and any other geography where the relevant geospatial data are available. The Kenya case study results can partly contribute to filling the gap identified by Mwendwa et al. [29] in estimating agricultural energy demand, which is needed for the country's sub-national and national energy planning.

The remainder of this paper proceeds as follows. In Section 2, the developed methodology is presented. Section 3 discusses the application of the method in the case study of Kenya, and the results of the application are shown in Section 4. The results are discussed in Section 5 and conclusions are drawn, and potential areas for future research are identified in Section 6.

2. Methods

This section outlines the equations underlying the developed methodology and how the methodology can be implemented using Python programming and QGIS.

2.1. Summary of the methodology

Fig. 1 summarises this study's methodology. First, the spatial reference evapotranspiration is determined using meteorological geospatial data. This is then multiplied by the crop coefficient to obtain the crop evapotranspiration, equivalent to the crop water demand. Then, to determine the net water needed from irrigation, the effective precipitation is subtracted from the crop water demand. The gross irrigation water demand is then obtained by considering the irrigation efficiency. With the demand determined, to size the SPIS, the available sources of water, solar resources, and pump efficiency are considered. Using the sized SPIS, the annual irrigation energy demand, the local SPIS costs and the expected drought frequency, the LCOE of the SPIS and that of alternative technologies are calculated and compared. Each step of the process is described in further detail in the sub-sections below.

2.2. Determining crop water demand

The FAO defines crop water demand as equivalent to crop evapotranspiration (ET_c) [17,30], which is a product of an area's reference evapotranspiration (ET_o) and the crop coefficient (K_c):

$$ET_c = K_c ET_o \quad (1)$$

To calculate ET_c , ET_o is first obtained using the standard Penman-Monteith equation [17]:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (2)$$

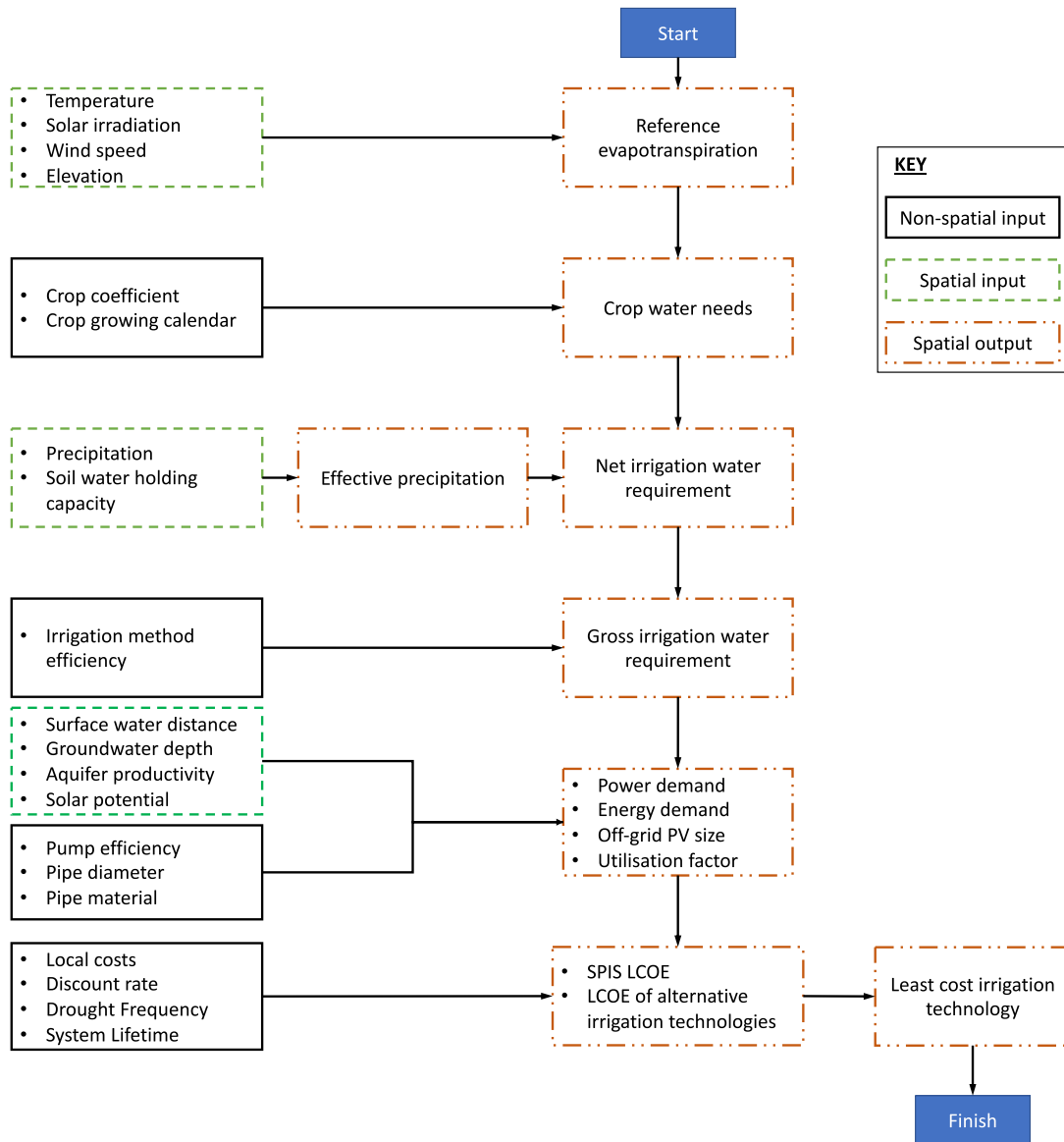


Fig. 1. A flow chart summarising the methodology.

where R_n is the net radiation at the crop surface in MJ/m²/day, G is the soil heat flux density in MJ/m²/day, T is the air temperature at 2 m above ground-level in °C, u_2 is the wind speed at 2 m above ground-level in m/s, e_s is the saturation vapour pressure in kPa, e_a is the actual vapour pressure in kPa, $e_s - e_a$ is the saturation vapour pressure deficit, Δ is the slope vapour pressure curve in kPa/°C, and γ is the psychrometric constant in kPa/°C.

The Penman–Monteith equation has been proven to work correctly for most locations and has provisions for making estimations where meteorological data is insufficient [17,31]. The equation has been used in studies such as [16,18,32]. Both the Penman–Monteith equation and the associated estimation of unavailable meteorological data are implemented using the Python ETo (PyETo) library [33]. The spatial inputs to PyETo are solar irradiation, minimum temperature, maximum temperature, average temperature, the location coordinates and elevation.

The other input to the ET_c calculation is K_c . Different crops have different K_c values as indicated by FAO [17]; additionally, the K_c for any given crop varies depending on its growth stage, commonly reaching its maximum during the mid-season [34]. The crop growth calendar is used to allocate the K_c value for each month accordingly.

2.3. Determining net irrigation water demand

The net crop irrigation water demand (ND) is the difference between ET_c and the effective precipitation (P_e):

$$ND = ET_c - P_e \quad (3)$$

P_e accounts for the fact that not all the rainfall received on a piece of land is effectively consumed by its crops. Due to surface runoff, evaporation, and percolation below the crop root zone, some rainwater is missed by crops [35]. The P_e is determined according to formulae developed by Ali et al. [36], which calculates the P_e based on climatic conditions, crop rooting and whether the crop is grown on dryland or wetland. For dryland crops, P_e is calculated as:

$$P_e = CP_t \quad (4)$$

where P_t is the total precipitation in mm/month and C is a multiplication factor based on soil type, climate and whether the crop is shallow or deep-rooted. For shallow-rooted crops (i.e., with root depth of up to two feet), C is between 0.8 and 0.95, while for medium to deep-rooted crops, it is between 0.7 and 0.9 [36]. When applying this method, the C values should be geospatially scaled according to soil available water

holding capacity (AWHC), which can be drawn from public datasets (e.g., [37]).

2.4. Determining gross irrigation water demand

Next, the gross irrigation demand must be determined. When sizing the SPIS, the pump must have a higher capacity than the net demand to accommodate for water losses and inefficiencies. Losses (i.e., where not all irrigation water is effectively consumed by the crop) are caused by factors like deep percolation, surface run-off, and water distribution method ineffectiveness. To calculate these losses, we use indicative values for both the conveyance efficiency (ϵ_c), which is dependent on both the type of soil and size of the farm, and the application efficiency (ϵ_a), which is dependent on the method of irrigation used, obtained from the FAO (i.e., 60% for surface irrigation, 75% for sprinkler irrigation, and 90% for drip irrigation) [38]. This study uses the conveyance efficiency for lined canals or pipes, which is 0.95 [38]. The gross water demand (GD) is then obtained according to:

$$GD = \frac{ND}{\epsilon_c \epsilon_a} \quad (5)$$

2.5. Estimating peak power requirements

Best-fit SPIS sizing depends on the irrigation water requirements, the type of water source used, the elevation head, solar irradiance, and the efficiency of the pumping system. Peak power demand (P) for a SPIS in kW is calculated as:

$$P = \frac{Q \rho g H}{\eta_{pump}} \times 10^{-3} \quad (6)$$

where ρ is the density of water (taken as 1000 kg/m³), Q is the pumped volume flow rate of water in m³/s, g is the acceleration due to gravity (taken as 9.81 m/s²), H is the total dynamic water head in metres, and η_{pump} is the efficiency of the pumping system [15]. Each of these input variables is calculated through different relationships, which are described in detail in [Appendix A](#).

2.6. SPIS sizing and utilisation

The most common way of SPIS sizing is the worst month method (WMM) described in [39]—the month with the highest energy demand is used for the sizing. The required PV system power rating is calculated as:

$$P_{pv} = 1.2 \times \frac{E_d}{PV_{out}} \quad (7)$$

where P_{pv} is the power rating of the PV system in kW, E_d is the monthly energy demand in kWh, and PV_{out} is the average solar generation potential for the month with the highest demand in kWh/kWp. The P_{pv} value obtained is scaled by a safety factor; in this case, a factor of 20% is used. Monthly energy demand (E_d) in kWh is estimated as:

$$E_d = P \times t_d \times d_m \quad (8)$$

The annual demand is calculated by adding up all the monthly demands. Using this, the utilisation (U) of the installed PV system is calculated as a ratio of energy demand to energy produced:

$$U = 100 \times \frac{E_d}{E_s} \quad (9)$$

where E_s is the energy produced in kWh, calculated as:

$$E_s = P_{pv} \times PV_{out} \quad (10)$$

where PV_{out} is the average solar generation potential for the respective month in kWh/kWp.

2.7. Levelized cost of electricity

The LCOE is calculated to determine the cost competitiveness of using SPIS for irrigation compared to alternative technologies. LCOE

is a standard benchmark for determining the lifetime cost of supplying electricity using a particular technology [40] and is calculated as:

$$LCOE = \frac{\sum_{t=1}^n \left(\frac{C_t + O_t}{(1+r)^t} \right)}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}} \quad (11)$$

where C_t is the capital expenditure in year t , O_t is the operational expenditure in year t including maintenance, n is the lifetime in years, r is the discount rate, and E_t is the electricity consumed in year t . The E_t values for this irrigation application are determined based on whether the year receives average rainfall or experiences drought. Where there are no reliable rainfall predictions, the drought frequency of a region can be used to approximate E_t .

Based on information from area-specific equipment sellers, the average capital cost per kW is calculated for both the surface and groundwater options; this is used to estimate the cost of the required irrigation system based on its size. The maintenance costs are estimated as a percentage of the capital cost depending on the irrigation technology. The fuel costs are calculated depending on whether the irrigation technology requires fuel.

2.8. Code development and data processing

This method was implemented as an open-source Python code available at the [project repository](#). It builds on the Agrodem code developed by Korkovelos et al. [41,42]. The following additions and expansions were made:

- The crop growing calendar was changed from one planting season a year to a biannual planting season to accommodate planting in the two rainy seasons.
- The crop coefficients for maize were adjusted to match the maize water demands in arid regions.
- The method for calculating effective rainfall was modified, as the method initially used in Agrodem was based on a study in the US.
- The method for calculating the friction head for surface water and groundwater sources was adjusted as the initial method had outdated assumptions.
- The methods for sizing the required solar PV, calculating the system utilisation factor, and determining the LCOE of the SPIS and other irrigation technologies were added.

The input to the Python code is a CSV file that must have monthly data on solar irradiation, maximum, minimum, and average temperature, precipitation, crop coefficient, wind speed at two metres, and solar potential. The CSV must also have spatial data on groundwater depth, elevation and soil water holding capacity. The CSV is generated by first dividing the study area into polygons, with each polygon representing a unit of analysis. The polygon size is decided by considering factors such as the distance over which there would be a significant variance of climatic and soil conditions, the processing time and the lowest resolution dataset used. Data from raster datasets can then be read into the polygons using spatial software such as QGIS. The polygons become the rows of the CSV developed.

3. Case study setup

This section discusses the sources of data for the case study and the assumptions made to implement the methods discussed in Section 2. The datasets used for the case study are shown in [Table 1](#). The input CSV files developed are in the [project repository](#).

3.1. Spatial resolution and scope

A total of 6138 hexagonal polygons of ~100 km² were used as the unit of analysis in this case study, as hexagons offer numerous

Table 1
Summary of datasets used in the case study.

| Dataset | Resolution | Year | Source | Coverage |
|---------------------------------|------------|-----------|-------------------|----------------|
| Protected Areas | Vector | 2006 | WRI [43] | Kenya |
| Land cover | 30 m | 2017 | RCMRD [44] | Eastern Africa |
| Min and Max temperature | 4.5 km | 2009–2018 | WorldClim [45,46] | Global |
| Precipitation | 4.5 km | 2009–2018 | WorldClim [45,46] | Global |
| Elevation | 90 m | 2007 | WRI [47] | Kenya |
| Solar potential and irradiation | 250 m | 1994–2018 | Solargis [48] | Global |
| Wind speed | 4.5 km | 1970–2000 | WorldClim [45,46] | Global |
| Groundwater depth | 5 km | 2020 | IGRAC [49] | Africa |
| Soil water holding capacity | 1 km | 2017 | ISRIC [37] | Africa |
| Lake and reservoirs | Vector | 2018 | RCMRD [50] | Africa |
| Rivers | Vector | 2016 | WRI [51] | Kenya |
| Dams | Vector | 2016 | WRI [51] | Kenya |

Table 2
Monthly K_c value for different stages of maize growth.

| Month of growth | 1 | 2 | 3 | 4 | 5 |
|-----------------|-----|-----|-----|-----|-----|
| K_c | 0.4 | 1.1 | 1.2 | 1.2 | 0.6 |

benefits over a rectangular grid in spatial analysis [52]. 6138 is more than double Kenya's 2427 administrative locations [53]. The climate and resident activities within an administrative location are usually uniform, and hence, the unit of analysis chosen for this study can be regarded as high-resolution.

Not all of Kenya's 582,646 km² landmass was considered in this study. Protected areas and water bodies were excluded as they are not viable for agriculture [54], reducing the considered area to 466,390 km² (~80% of the total area). While forest lands should not be considered viable for agriculture in Kenya, as the government is committed to preserving and increasing the country's tree cover [55], forested areas were kept under consideration here as the unit of analysis was 100 km², meaning that forests and farming can coexist in many locations.

3.2. Scenarios

Two scenarios were analysed in the case study: an average-case and a worst-case scenario. The average-case scenario used average precipitation and temperature data for the last ten years for which reliable and high-resolution data could be found (i.e., 2009–2018 from [45]). The worst-case scenario used the lowest rainfall and the highest temperature mean in the same time period to simulate drought. These two scenarios were used as evapotranspiration is directly proportional to temperature [56].

3.3. Crop selection and parameters

Maize was evaluated as the reference crop in this case study since it is grown by over 90% of Kenyan farmers and is the country's main staple food with consumption of 88–103 kg/person/year [57–59]. Maize also has one of the highest crop coefficients, meaning that an SPIS that can satisfy water demands for maize will also be able to satisfy the demands for other crops (i.e., vegetables, legumes) [17].

The crop coefficient for maize was determined using an FAO report [17], which states that maize in arid areas takes 140 days to grow, with 25 days in the initial stage, 40 days in the development stage, 45 days in the mid-season stage, and 30 days in the late season stage. According to [17,60], the K_c of maize is 0.3 at the initial stage, 1.2 at the mid-season stage and 0.6 at the late season stage. We extrapolated K_c values from these values throughout the growth period, as shown in Fig. 2. Additionally, we estimated the K_c values at different months by taking the highest value in the month as shown in Table 2.

The maize growing calendar used in this study was obtained from the FAO [61]. In Kenya, maize planting for the long rainy season commences in March. Given that maize typically requires five months

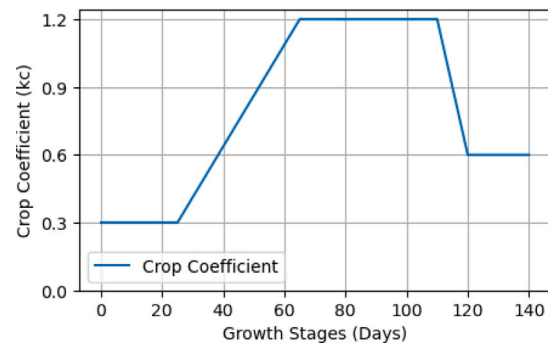


Fig. 2. Maize K_c at different days of growth.

Table 3
The biannual maize planting calendar used in the case study.

| Season 1 | | | Season 2 | | |
|---------------|------------|--------|---------------|------------|----------|
| Initial stage | Late stage | Break | Initial stage | Late stage | Break |
| March | July | August | September | January | February |

Table 4
Effective rainfall multiplier (C).

| AWHC | Effective rainfall factor (C) | |
|--------|-------------------------------|-------------|
| | Shallow rooted | Deep rooted |
| 10–20% | 0.83 | 0.74 |
| 20–30% | 0.845 | 0.76 |
| 30–40% | 0.86 | 0.78 |

to mature and about one month to prepare the land for the next growing season, we developed the biannual maize growth calendar shown in Table 3. For the first season, planting begins in March, and for the second season, planting begins in September. August and February are designated as the intermission months.

As discussed in Section 2.3, a multiplication factor C is required to calculate the effective rainfall. Values of C were calculated using an available water holding capacity (AWHC) raster dataset [37], which shows AWHC values for Kenya ranging from 14% to 32%. The effective precipitation factor C was scaled according to the decile in which the AWHC value fell, as shown in Table 4. Maize is a shallow-rooted crop according to [62].

3.4. Irrigation system

Drip irrigation was assumed to be the irrigation method as this reduces the water used for irrigation (i.e., thereby prioritising sustainability). In addition to reducing water use, drip irrigation has other advantages, such as weed growth reduction and plant nutrition optimisation [63].

The SPIS was assumed to work eight hours a day, as all parts of Kenya experience a consistently high solar capacity factor between 8 am and 4 pm throughout the year [64]. For code modularity, a month was assumed to be 30 days.

3.5. Levelized cost of electricity

The LCOE of SPIS was calculated and compared to the LCOE of diesel-powered irrigation systems (DPIS), the most common irrigation technology among smallholder farmers in Kenya [65]. The irrigation systems were sized for 0.47 ha farms, the average size for smallholder farms in Kenya [66].

Based on Kenya SPIS sellers [67–70], the average cost per kW of submersible SPIS (pumps for groundwater) was found to be KES 133,134 (US\$ 925) while that of a surface SPIS (pumps for surface water) was obtained as KES 155,433 (US\$ 1079). These costs include both the solar panels and the pump required to deliver a power of 1 kW. The cost average per kW of DPIS was obtained as KES 18,000 (US\$ 125) from prices in [71] by assuming a standard 70% loading for the generator. The conversion rate used was US\$ 1 = KES 144, the conversion rate for 22nd February 2024 [72].

The operation costs for the SPIS are mainly the maintenance of the pumping accessories, as the solar panels only require cleaning. For the SPIS maintenance costs, a rule of thumb of 1% of the capital costs was used according to Santra et al. [73]. For DPIS, operational costs include fuel and maintenance costs. The maintenance cost of DPIS was taken to be 5% of capital costs also according to Santra et al. [73]. The diesel fuel costs were calculated based on irrigation energy demand by assuming that 0.3 l of diesel produces 1 kWh of electricity according to [74]. The diesel cost per litre was KES 201.47 (US\$ 1.4), which was the cost as of January 2024 [75]. An escalation rate of 2% every year was used for the diesel price, according to Xie et al. [76]. The cost per kWh of electricity in January 2024 was KES 36.81 (US\$ 0.26) [77].

The lifetime in the LCOE calculation was taken to be 20 years, the lower end of the lifetime of solar panels [78]. The diesel pump and the solar pump will be replaced in year 10, as indicated by Islam et al. [79]. This 10-year replacement period aligns with the warranty period offered by one of the pump suppliers in Kenya [80]. The cost of replacing a solar pump was taken to be KES 25,000 (US\$ 174) per kW [81] while that of replacing the diesel pump was taken to be KES 18,000 (US\$ 125) per kW [71]. A discount rate of 13% was used based on the Central Bank of Kenya rate as of February 2024 [72].

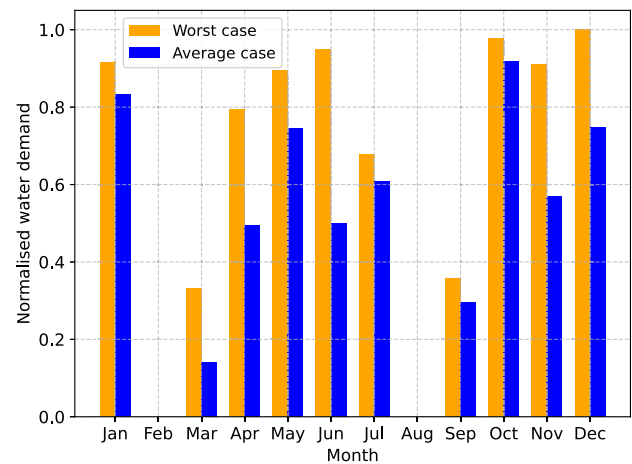
In calculating the energy demand for irrigation, two drought frequency scenarios were considered: two years and three years, as the drought frequency in Kenya is 2–3 years [27]. In the case of a 2-year frequency, the drought scenario was taken to happen every two years, and the same logic was used for the 3-year frequency scenario.

4. Results

This section discusses the results obtained by applying the methods discussed in Section 2 in the case study of Kenya. The results presented are for peak water needs, power demand, system utilisation factor and the LCOE for SPIS and DPIS. The results files can be found on the [project repository](#). The averaged results at the county level are shown in [Appendix B](#).

4.1. Water demand

[Fig. 3](#) shows the normalised average monthly peak water demand across the year. As expected, there was no water demand in February and August, the intermission months in the biannual growing cycle used. The highest water demands in the worst-case scenario are in December, while in the average-case scenario, these are in October. There are lower demands in March and September, corresponding to the months which are planting months. Beyond the planting months,



[Fig. 3](#). Normalised monthly average irrigation water demand for maize using a biannual cropping calendar. The normalisation was done by dividing the monthly water demands by the maximum monthly water demand.

April has the lowest water demand for both the average and the worst-case scenarios.

The spatial peak crop water requirements (PCWR) for the worst-case and average-case scenarios are shown in [Fig. 4](#). For the biannual cropping of maize considered in the study, all the Kenyan areas investigated would require some irrigation both in the average and the worst-case scenarios. The highest PCWR in the average case scenario would be 82,052 l/ha/day in a region in Turkana County in northern Kenya. In the worst-case scenario, the highest PCWR would be 75,093 l/ha/day, and it is also in an area in Turkana.

At the county level, in the average scenario, the highest PCWR is in Isiolo County (67,020 l/ha/day), followed by Turkana County (65,090 l/ha/day), both in northern Kenya. In the worst scenario, the highest PCWR is also observed in Turkana and Isiolo counties, with a PCWR of 73,340 l/ha/day and 69,765 l/ha/day, respectively. Generally, there is higher PCWR in north and northeast Kenya than in central, western, and coastal Kenya.

4.2. Power demand

The peak power demand (PPD) was calculated based on the month with the most demand. The spatial PPD for the average-case and worst-case scenario is shown in [Fig. 5](#). The maximum PPD for the average-case scenario is 5.9 kW/ha, observed in a region in Turkana County in northern Kenya. In the worst-case scenario, the maximum PPD is 6.5 kW/ha, also observed in an area in Turkana.

With the worst-case scenario SPIS sizing used, four counties would, on average, require SPIS greater than 4 kW/ha: Wajir, Mandera, Garissa, and Marsabit. Twenty-nine counties would mainly require SPIS smaller than 1 kW/ha. In terms of landmass, 22.5% of areas would require SPIS less than 1 kW/ha, 11.8% of areas would require 1–2 kW/ha, 27.1% of areas will require 2–3 kW/ha, and 34.3% will require SPIS greater than 5 kW/ha.

4.3. Utilisation factor

The SPIS annual utilisation factor was calculated as the percentage of annual energy consumption to the total annual energy production. The average monthly energy produced by the SPIS and the energy consumed for irrigation is shown in [Fig. 7](#). For the SPIS sizing based on the peak monthly power demand of the worst-case scenario, we observe that the average annual energy supply is 10,873 kWh/ha; the highest average monthly energy supply is 1029 kWh/ha in January; the highest average energy demand for the worst-case scenario is 694

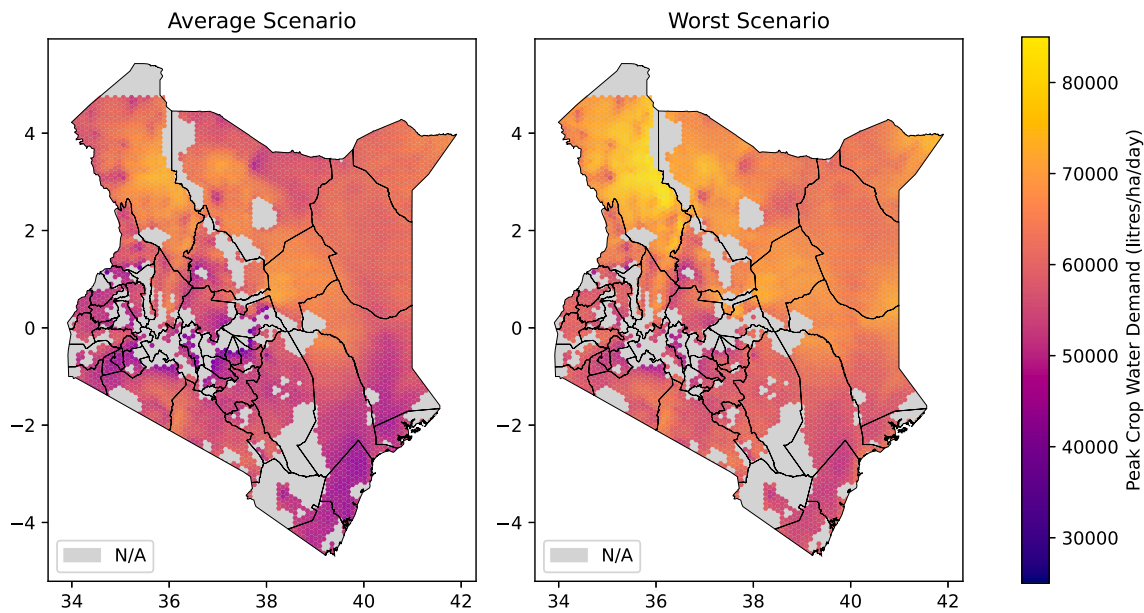


Fig. 4. Peak irrigation water requirements in litres/ha/day for average-case and worst-case scenarios. N/A represents protected areas and wetlands which were excluded from the analysis.

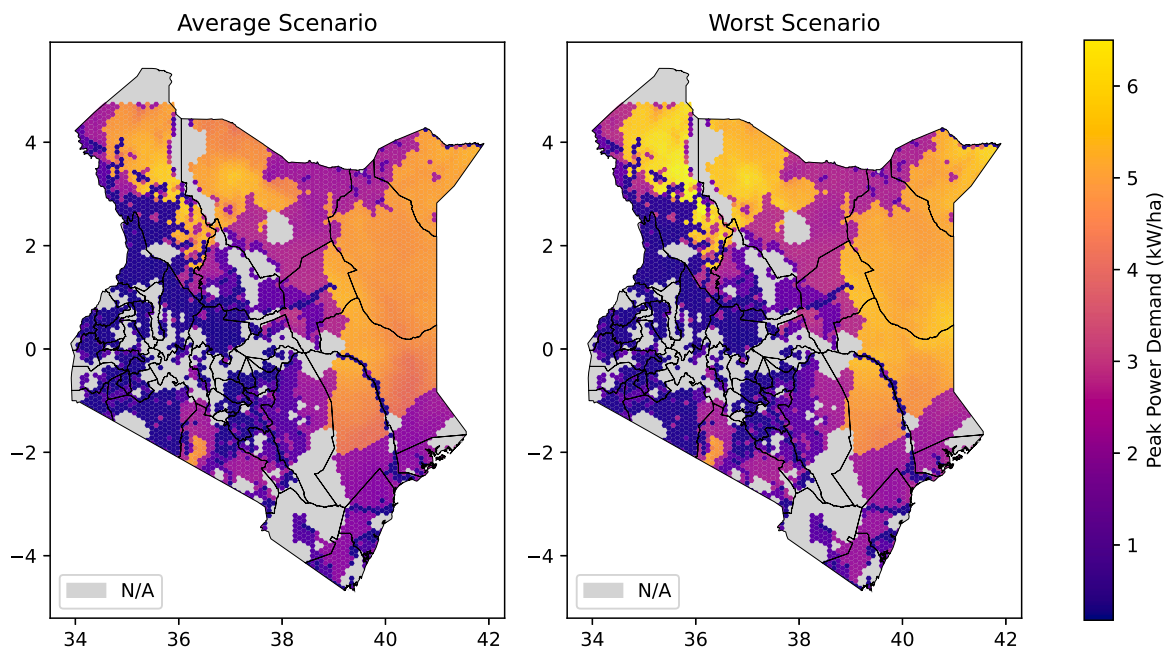


Fig. 5. Peak irrigation power demand in kW/ha for average-case and worst-case scenarios. N/A represents protected areas and wetlands which were excluded from the analysis.

kWh/ha in December while that of the average-case scenario is 611 kWh/ha in October; and the annual average demand for the worst-case scenario is 5416 kWh/ha while that of the average-case scenario is 4307 kWh/ha. The results for the spatial utilisation factors for the average-case scenario and the worst-case scenario are shown in Fig. 6.

In the average scenario, the highest annual utilisation factor is 54.8% observed in a region in Marsabit County, while in the worst-case scenario, the highest annual utilisation factor is 56.4% observed in a region in Tana River County. At the county level, in the average scenario, Marsabit County has the highest utilisation factor average of 46.9%, while Kisii County has the lowest at 13.2%. In the worst-case scenario, Kwale County has the highest average utilisation factor of 52.8% while Kisii County has the lowest at 33.1%.

Overall, in the average scenario, the utilisation factors across Kenya are as follows: 3.5% of areas have a utilisation factor of 10%–20%,

8.9% fall within the 20%–30% range, 31.3% have a utilisation factor of 30%–40% and 49.7% of areas have utilisation factors of 40%–50%. In the worst-case scenario, all the SPIS have a utilisation factor greater than 30%, with the majority (96%) having a utilisation factor greater than 40%.

4.4. Levelized cost of electricity

The results for the LCOE of SPIS for two-year and three-year drought frequency scenarios are shown in Fig. 8. The LCOE results for DPIS are shown in Fig. 9. The LCOE of SPIS ranges from US\$ 0.087/kWh to US\$ 0.219/kWh in the two-year drought frequency scenario and from US\$ 0.088/kWh to US\$ 0.25/kWh in the three-year drought frequency scenario. For DPIS, the LCOE ranges from US\$ 0.490/kWh to US\$

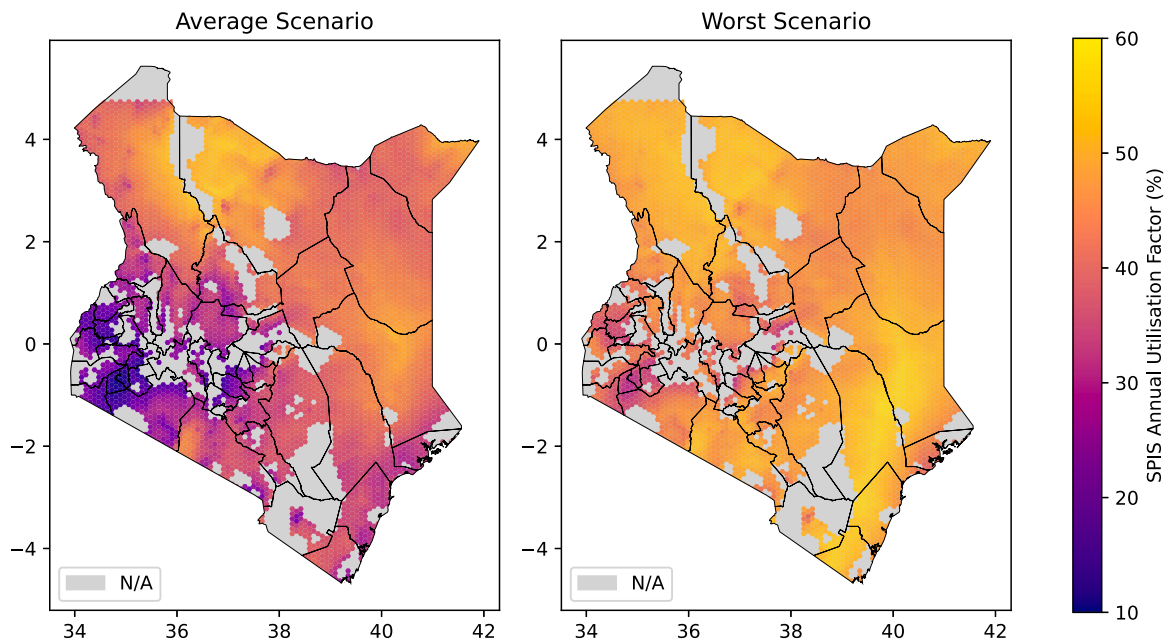


Fig. 6. Annual SPIS utilisation factor for average-case and worst-case scenarios. N/A represents protected areas and wetlands which were excluded from the analysis.

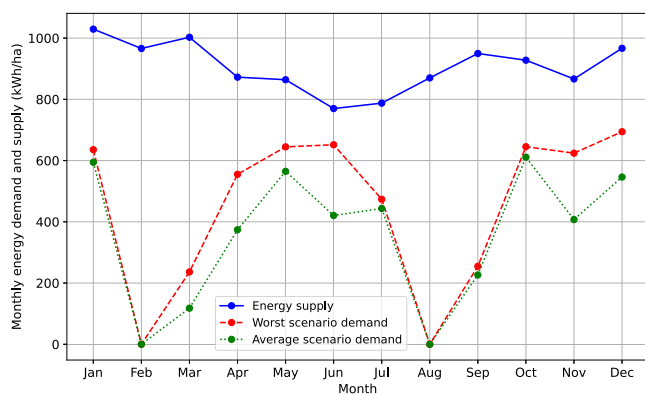


Fig. 7. Average monthly energy demand and supply in kWh/ha.

0.511/kWh in the two-year drought frequency scenario and from US\$ 0.490/kWh to US\$ 0.518/kWh in the three-year drought frequency scenario. SPIS is cheaper than DPIS for all the regions investigated. On average, the LCOE of SPIS is more than four times lower than that of DPIS in both the two-year drought frequency scenario and the three-year frequency drought scenario.

To demonstrate the relationship between the SPIS utilisation factor and LCOE, we used a standard SPIS size for the mean peak power demand of 3 kW/ha under different utilisation factors. Fig. 10 shows the results with a discount rate of 13% and a lifetime of 20 years. Fig. C.11 in Appendix C shows the relationships at double and half the 13% discount rate. We note that the utilisation factor impacts the LCOE of SPIS more than the LCOEs of DPIS and grid-powered irrigation. With this discount rate and lifetime, SPIS are cheaper than DPIS when the annual utilisation factor is greater than 9.5% and cheaper than grid-powered irrigation when the utilisation factor is greater than 17.5%. Doubling the discount to 26% increases the utilisation factors at which SPIS would be cheaper than DPIS and grid-powered irrigation to 18% and 34%, respectively. Halving the discount rate to 6.5% decreases the utilisation factors at which SPIS is cheaper than DPIS and grid-powered irrigation to 5.5% and 10.5%, respectively.

5. Discussion

The results of this work provide valuable insights into irrigation water demand, the required size and cost of SPIS, the expected SPIS utilisation factor, and where SPIS would be the least-cost technology to power irrigation. These are discussed in the sections that follow.

5.1. Water demand

The regions with the highest water demand in the drought scenario correspond to those identified to be drought-prone by Orindi et al. [82], the United Nations Development Program [83], and FAO [61]. This congruence verifies that the methods used in this paper for simulating the drought scenario are plausible.

Considering that the average smallholder farm in Kenya is 0.47 ha [66], and that the highest water demand is about 82,000 l/ha/day, it means the highest required water flow rate would be 5125 l/h if pumping is done for eight hours a day. This means that there are SPIS in the Kenyan market [67–70] that can satisfy the highest water demand in the country.

However, regions with high irrigation water demand should consider groundwater and surface water sustainability. A way to assess water sustainability would be to ensure that the total rate of water abstraction for all water uses in the area does not exceed the replenishment rate of the underground aquifer or surface source. Datasets such as [84], which gives aquifer productivity in l/s, can guide national or local governments to develop regulations on water use for irrigation.

5.2. Power demand

With 77.5% of regions investigated needing SPIS greater than 1 kW/ha, it means the SPIS for average smallholder farms (0.47 ha) would cost above US\$ 500 and above US\$ 2000 per farm for the 38% of regions with power demand greater than 4 kW/ha. The majority of farmers are unlikely to afford these high initial costs, considering that the majority of Kenyan counties have a gross county product (GCP) per capita of below US\$ 1400 [85]. Innovative financing models and subsidies will be necessary to make SPIS affordable to most farmers as recommended by FAO [86]. In regions with very high power demand

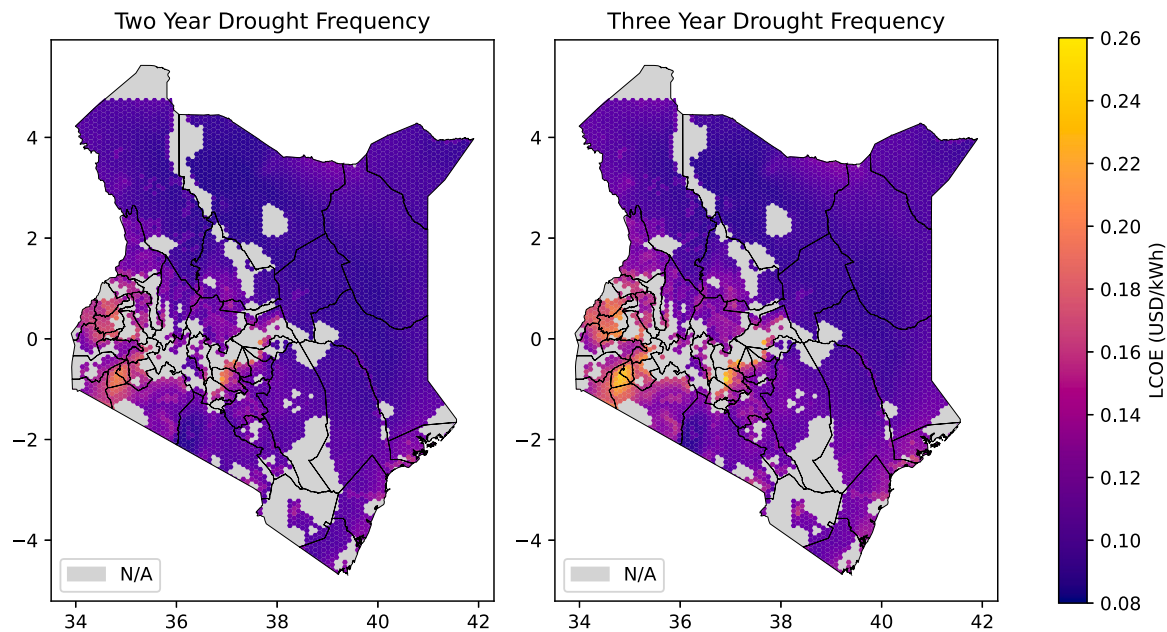


Fig. 8. Levelized cost of electricity of SPIS for two-year and three-year drought frequency scenarios at a discount rate of 13%. N/A represents protected areas and wetlands which were excluded from the analysis. The currency conversion rate used was US\$ 1 = KES 144, the rate for 22nd February 2024.

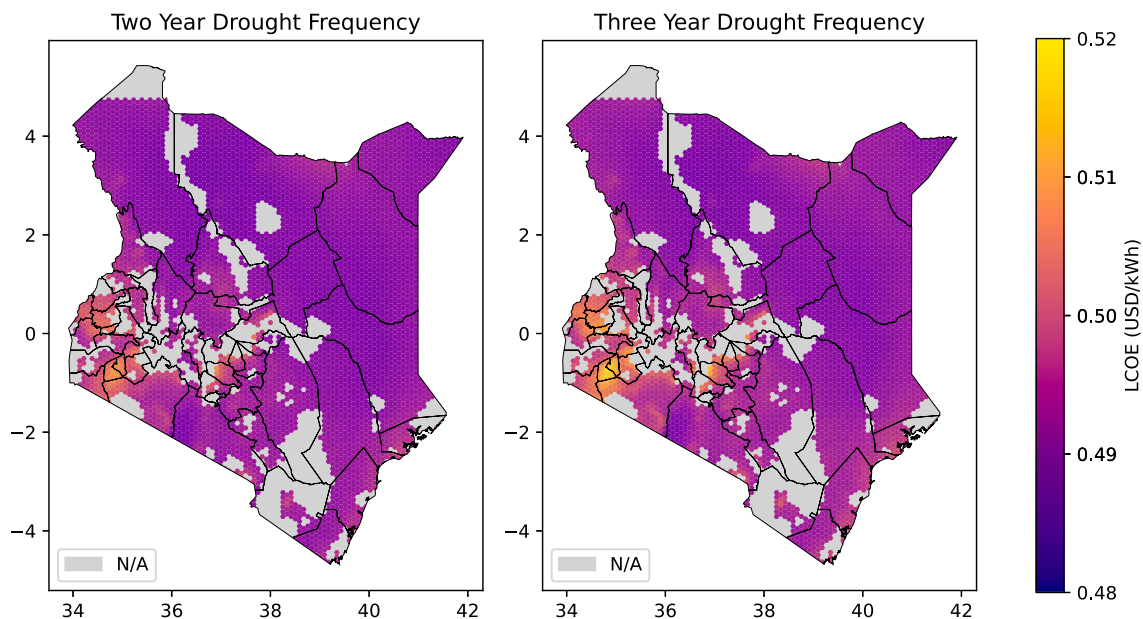


Fig. 9. Levelized cost of electricity of DPIS for two-year and three-year drought frequency scenarios at a discount rate of 13%. N/A represents protected areas and wetlands which were excluded from the analysis. The currency conversion rate used was US\$ 1 = KES 144, the rate for 22nd February 2024.

(i.e., >4 kW/ha), a cost–benefit analysis will be needed to determine whether it is “worth it” to use SPIS.

A way to optimise the SPIS sizing is needed to avoid the need for very large SPIS. The SPIS size can be reduced by: (1) reducing the peak water demand, which can be achieved by shifting the crop growing calendar to avoid the months with the highest demand or by practising deficit irrigation during the drought scenario, as discussed by [87,88], (2) reducing the system friction head by increasing the diameter of the pipes used, and (3) increasing the pumping system efficiency through technical innovation. Another option is sizing the SPIS for the average scenario and adopting a model such as that used in India, where entrepreneurs provide water-pumping energy as a service to farmers [89], especially during peak demand months and drought. Water storage could also be incorporated to pump and store water

during periods of low irrigation demand to cover the deficit during high water demand.

5.3. Utilisation factor

When a biannual cropping calendar is used, the annual utilisation factors are generally high (>30%) in most of Kenya’s regions. This high utilisation rate underscores the demand for power to irrigate Kenya’s agriculture so that it can be productive throughout the year. Additionally, the fact that the majority of the annual utilisation factors are below 50% means that there is an opportunity for the excess SPIS power to be used for alternative uses. These alternative uses could include the electrification of the local households and the provision of

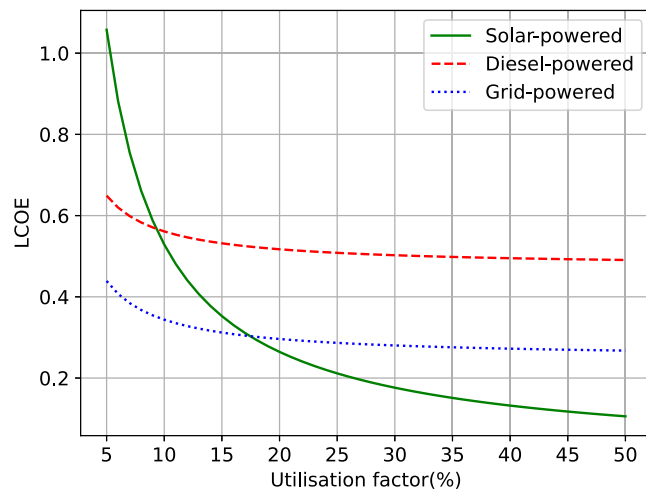


Fig. 10. Relationship between LCOE and utilisation factor for SPIS, DPIS and grid-powered irrigation at a discount rate of 13%. The mean peak power demand of 3 kW/ha was used for this simplified analysis.

drinking water for humans and livestock. Having the excess SPIS energy power alternative uses will further reduce their LCOE.

5.4. Levelized cost of electricity

Considering that IRENA's PV global weighted average for 2022 was \$0.049/kWh [90], we believe our SPIS LCOE range of \$0.09/kWh to \$0.25/kWh is plausible. Additionally, a study by Lorenzo et al. [91] for large-scale SPIS in seven countries in West Africa gives the LCOE in the countries to be in the range of \$0.067/kWh to \$0.174, which compares well with our results. Our LCOE for DPIS range of \$0.49/kWh to \$0.52/kWh was sanity checked against the diesel power LCOE of \$0.31/kWh given by Sigarchian et al. [92] in 2015, taking into account the fact that the price of diesel in 2024 is higher than it was in 2015.

As expected, the LCOEs for the three-year drought frequency scenario are higher than those for the two-year drought frequency scenario because having less frequent droughts reduces the energy demand for irrigation, increasing the LCOE. This difference in LCOE between the two scenarios is more for SPIS, where the majority of costs incurred are capital, and less for DPIS, where most of the costs are fuel costs depending on energy demand. We observe a bigger range in LCOE values for SPIS than for DPIS as the utilisation factor has more impact on the LCOE of SPIS than that of DPIS; this is again because the costs of SPIS are dominated by capital expenditure while those of DPIS are dominated by expenditure on fuel.

Whether SPIS has the least cost compared to DPIS will depend on the utilisation factor of SPIS. Considering that the SPIS utilisation factors are high in Kenya, SPIS is cheaper than DPIS in all regions. However, for farmers to benefit from SPIS in the long term, interventions such as flexible payment plans discussed in Section 5.2 will be required to afford the high upfront costs of SPIS.

6. Conclusions

This paper presents a novel open-source reproducible methodology for geospatially assessing the viability of solar-powered irrigation systems (SPIS). The methodology incorporates meteorological conditions, crop type, soil qualities, water sources, solar resource potential, and technology efficiency to estimate the size of SPIS required in various locations. Additionally, it uses local equipment and fuel costs to determine SPIS's levelized cost of electricity (LCOE) and compares this with the LCOE of other technologies. The methodology is tested and validated through a case study focusing on maize cultivation in Kenya.

The code for this methodology is publicly available on [GitHub](#), enabling its application to different regions and crops by leveraging geospatial data. The results from the methodology highlight areas of interest in SPIS development, allowing for better targeting of more detailed studies.

The study's findings highlight several key observations specific to Kenya. It emphasises the necessity of implementing water usage regulations in regions with high water demands to prevent water over-abstraction. Furthermore, innovative approaches to sizing SPIS are needed to meet the peak power demand during months with significantly higher demand than others. To ensure SPIS affordability for farmers, the paper recommends the provision of government subsidies for SPIS products and providing flexible payment plans to the farmers. Additionally, the study highlights the importance of alternative uses for energy from SPIS beyond irrigation to increase their utilisation and economic viability.

The methodology and findings have significant implications for long-term irrigation planning, especially considering the increasing occurrence of droughts and the unpredictability of rainfall patterns. Farmers can utilise this approach to accurately determine irrigation water demands and appropriately size SPIS. Governments can make informed decisions regarding subsidy allocation based on the required SPIS sizes in different regions and use this information for improved planning in the energy sector. Entrepreneurs, manufacturers, and financiers can identify opportunities for value creation using SPIS. The results generated by the method can be a starting point for achieving multiple benefits of food security, water sustainability, and electricity access.

Future work in this field encompasses expanding the analysis to cover more crops other than maize. Additionally, performing cost-benefit analyses will help determine SPIS profitability and payback time in different regions. Water sustainability considerations should also be integrated into the assessment of SPIS viability. Lastly, exploring the cost and technical aspects of using SPIS for alternative uses is essential. These research avenues will contribute to a more comprehensive understanding of the viability of solar-powered irrigation systems.

CRedit authorship contribution statement

Daniel Mutia Mwendwa: Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Alycia Leonard:** Writing – review & editing, Supervision, Conceptualization. **Stephanie Hirmer:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

I have shared a link for the GitHub repository containing the code, input and output files used for the case study of Kenya.

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Thanks to Dr Alexandros Korkovelos from the CCG programme for his insights and support.

Appendix A. Peak power demand equations

As discussed in Section 2.5, peak power demand (P) for a SPIS in kW is calculated as:

$$P = \frac{Q\rho gH}{\eta_{pump}} \times 10^{-3}$$

The input variables to this equation are calculated through the relationships described below.

- **Pump efficiency** (η_{pump}) is given by:

$$\eta_{pump} = \eta_{mech} \times \eta_{elec} \tag{12}$$

where η_{mech} is the mechanical efficiency of the pump and η_{elec} is the electrical efficiency of the pump. η_{mech} is assumed to be 70% while η_{elec} is assumed to be 81% (i.e., a motor efficiency of 85% and drive efficiency of 95%) according to [93,94], giving an overall pump efficiency of 57%.

- **Volume flow rate** (Q) depends on the total water demand per day and the number of hours the SPIS operates in a day as follows:

$$Q = \frac{GD}{d_m \times t_d \times 3600} \tag{13}$$

where d_m is the number of days in a month and t_d is the irrigation hours per day.

- **Total dynamic head** for groundwater pumping (H_{gw}) is estimated according to Eq. (9), and for surface water pumping (H_{sw}) it is estimated as per Eq. (10):

$$H_{gw} = H_{depth} + H_p + H_f \tag{14}$$

$$H_{sw} = (Z_{farm} - Z_{sw}) + H_p + H_f \tag{15}$$

where H_{depth} is the depth of the groundwater in metres and H_p is the pressure head (i.e., the pressure at which the water should reach the end of the pipe) [95]. $(Z_{farm} - Z_{sw})$ is the height difference between the source of water and the farm in metres, and H_f is the friction head (i.e., due to loss of pressure resulting

from friction in the transmission pipes). A decision metric is needed to decide whether to use groundwater or surface water; typically, the source with the least power demand is chosen. H_p for drip irrigation and sprinkler irrigation can be assumed to be 2 m based on [96].

- **Friction head** (H_f) is approximated using the Darcy formula:

$$H_f = 4K_f \times \frac{8lQ^2}{D^5\pi^2g} \tag{16}$$

where k_f is a Reynolds number-dependent empirical factor which describes friction loss, l is the length of the pipe in metres, D is the diameter of the pipe in metres, and g is the acceleration due to gravity. k_f can be obtained from a Moody diagram such as the one in [97] by deciding the pipe material to be used, its relative roughness, and the expected water flow rate Reynolds number [98]. As a starting point, a k_f of 0.013 can be used by assuming the use of PVC pipes with absolute roughness of 0.0015 mm [99] and a typical irrigation water flow Reynolds number of 5×10^5 was used [98].

- **Pipe diameter** (D) is estimated mathematically as:

$$D = \sqrt{\frac{4Q}{\pi \times v}} \tag{17}$$

where v is the maximum allowable water velocity in m/s. v can be assumed to be 1.5 m/s which is the maximum recommended velocity for water pipes according to [100,101].

Appendix B. Average irrigation parameters by county

See Table B.5.

Appendix C. Relationship between levelized cost of irrigation and utilisation factor

See Fig. C.11.

Table B.5

Table showing the averages for main irrigation parameters for Kenyan counties that require some irrigation. The table contains the values for peak water demand (in litres/ha/day) during a drought scenario, peak power demand (in kW/ha) during a drought scenario, annual energy demand (in kWh/ha) during a drought scenario, utilisation factor (in %) during a drought scenario, and the SPIS and DPIS LCOEs (in US\$/kWh) in a 2-year drought frequency scenario. The currency conversion rate used was US\$ 1 = KES 144, the rate for 22nd February 2024.

| County | Water demand | Power demand | Energy demand | Utilisation | SPIS LCOE | DPIS LCOE |
|----------------|--------------|--------------|---------------|-------------|-----------|-----------|
| Baringo | 63 652 | 0.5 | 911 | 47.1 | 0.12 | 0.49 |
| Bomet | 54 168 | 0.7 | 944 | 36.3 | 0.16 | 0.5 |
| Bungoma | 57 754 | 0.4 | 576 | 39.6 | 0.17 | 0.5 |
| Busia | 60 564 | 0.6 | 791 | 39.9 | 0.16 | 0.5 |
| Embu | 58 124 | 0.8 | 1266 | 48.8 | 0.12 | 0.5 |
| Garissa | 64 829 | 4.4 | 8041 | 51.6 | 0.1 | 0.49 |
| Homa Bay | 59 637 | 0.8 | 1174 | 41.5 | 0.14 | 0.5 |
| Isiolo | 69 765 | 2.9 | 5301 | 46.3 | 0.1 | 0.49 |
| Kajiado | 61 006 | 2 | 3589 | 49.3 | 0.11 | 0.49 |
| Kakamega | 59 642 | 0.5 | 653 | 37.4 | 0.17 | 0.5 |
| Keiyo-Marakwet | 63 289 | 0.4 | 626 | 45.2 | 0.14 | 0.49 |
| Kericho | 55 721 | 0.4 | 541 | 37.9 | 0.16 | 0.5 |
| Kiambu | 56 106 | 0.6 | 993 | 45.4 | 0.14 | 0.5 |
| Kilifi | 55 954 | 1.7 | 3055 | 52.1 | 0.12 | 0.49 |
| Kirinyaga | 56 675 | 0.4 | 600 | 43.7 | 0.14 | 0.5 |
| Kisii | 55 626 | 0.8 | 1049 | 33.1 | 0.19 | 0.51 |
| Kisumu | 61 777 | 0.8 | 1183 | 42 | 0.14 | 0.5 |
| Kitui | 60 437 | 1.8 | 3164 | 48.8 | 0.11 | 0.49 |
| Kwale | 57 074 | 1.5 | 2759 | 52.8 | 0.11 | 0.49 |
| Laikipia | 59 255 | 0.6 | 969 | 45.5 | 0.12 | 0.49 |
| Lamu | 60 911 | 2.3 | 3580 | 44.2 | 0.13 | 0.5 |
| Machakos | 58 836 | 0.9 | 1590 | 48.2 | 0.12 | 0.49 |
| Makueni | 60 558 | 1.1 | 1937 | 48.6 | 0.11 | 0.49 |
| Mandera | 67 242 | 4.5 | 7809 | 49.3 | 0.1 | 0.49 |
| Marsabit | 68 088 | 4 | 7412 | 49.7 | 0.1 | 0.49 |

(continued on next page)

Table B.5 (continued).

| County | Water demand | Power demand | Energy demand | Utilisation | SPIS LCOE | DPIS LCOE |
|--------------|--------------|--------------|---------------|-------------|-----------|-----------|
| Meru | 65 922 | 1.4 | 2140 | 39 | 0.13 | 0.5 |
| Migori | 59 062 | 0.6 | 920 | 39.8 | 0.15 | 0.5 |
| Mombasa | 61 321 | 1.3 | 2087 | 48.9 | 0.13 | 0.5 |
| Murang'a | 55 627 | 0.5 | 778 | 43.1 | 0.16 | 0.5 |
| Nairobi | 58 331 | 0.4 | 660 | 49.9 | 0.12 | 0.49 |
| Nakuru | 56 812 | 1.2 | 2107 | 43.9 | 0.12 | 0.49 |
| Nandi | 56 065 | 0.6 | 925 | 40.7 | 0.16 | 0.5 |
| Narok | 59 173 | 0.8 | 1252 | 43 | 0.13 | 0.5 |
| Nyamira | 53 941 | 0.5 | 705 | 33.8 | 0.18 | 0.51 |
| Nyandarua | 50 495 | 0.7 | 1076 | 40.8 | 0.13 | 0.5 |
| Nyeri | 54 474 | 0.4 | 521 | 39.1 | 0.17 | 0.5 |
| Samburu | 64 234 | 1.6 | 2806 | 46.8 | 0.11 | 0.49 |
| Siaya | 60 762 | 0.6 | 889 | 41.5 | 0.14 | 0.5 |
| Taita Taveta | 57 150 | 1.4 | 2397 | 51.1 | 0.11 | 0.49 |
| Tana River | 60 807 | 3.6 | 6607 | 52.4 | 0.11 | 0.49 |
| Tharaka | 60 789 | 0.5 | 847 | 48.3 | 0.12 | 0.49 |
| Trans Nzoia | 57 904 | 0.4 | 648 | 42.7 | 0.15 | 0.5 |
| Turkana | 73 340 | 3.4 | 6237 | 51 | 0.1 | 0.49 |
| Uasin Gishu | 59 176 | 0.5 | 718 | 45.8 | 0.14 | 0.5 |
| Vihiga | 57 875 | 0.4 | 510 | 34.8 | 0.18 | 0.51 |
| Wajir | 65 852 | 4.9 | 8718 | 48.3 | 0.1 | 0.49 |
| West Pokot | 64 690 | 0.5 | 804 | 47.1 | 0.12 | 0.49 |

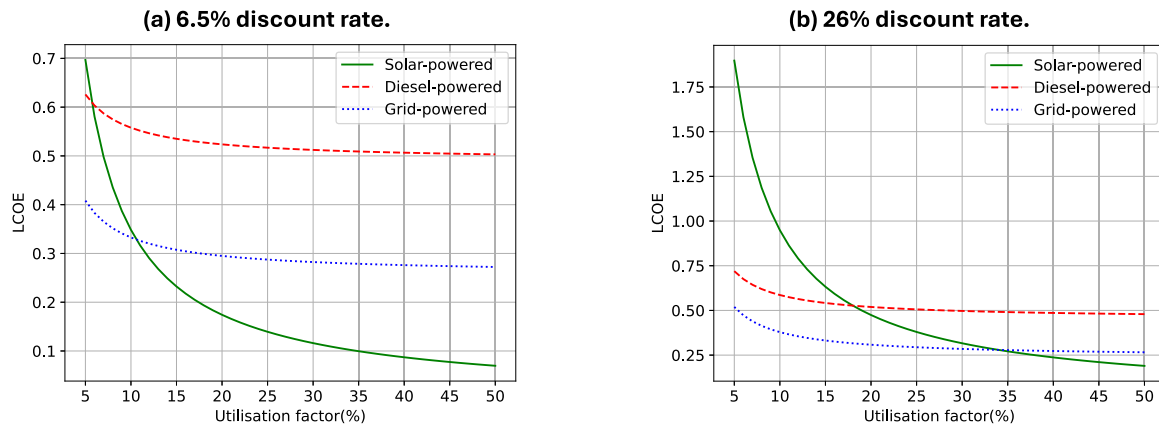


Fig. C.11. Relationship between LCOE and utilisation factor for SPIS, DPIS and grid-powered irrigation at discount rates of 6.5% and 26%. The mean peak power demand of 3 kW/ha was used for this simplified analysis.

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