Working Paper: Identifying energy solutions to support development of irrigated agriculture in Ethiopia

This working paper presents early findings from a country-level planning analysis that aims at identifying energy solutions to support the development of irrigated agriculture in Ethiopia. An integrated energy and irrigation planning framework is developed for this goal. Groundwater irrigation development potential and the recommended cost-effective energy solutions across the country are mapped.

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Irrigation farm using electricity in Koka, Ethiopia

Identifying energy solutions to support development of irrigated agriculture in Ethiopia

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Abstract

Sub-Saharan African countries have long been beset with energy poverty. While there are already many studies on how to improve access to modern energy services in the region, those energy planning analyses are dominated by residential energy demand, and not much attention has yet been paid to the productive use of energy in agriculture. This paper aims at filling this knowledge gap by presenting a country-level planning analysis in Ethiopia to inform investment decisions and policy discussions about the promotion of energy use in agriculture to support the development of irrigated agriculture in the country. Irrigation is considered as a promising option to boost agricultural production and enhance agricultural resilience in Ethiopia. However, the strong water-energy nexus in irrigated agriculture implies that irrigation development in Ethiopia is hampered by energy poverty. The challenging aspect of the planning analysis for productive use of energy in irrigated agriculture is that, in addition to access to energy, irrigation adoption is constrained by many other factors such as availability of water resources, land suitability, and market potential of irrigated crops. In this study, we put the analysis into an integrated irrigation-energy planning framework and used the integrated modelling approach to identify groundwater irrigation development potentials in Ethiopia under three energy solutions: grid-connected electricity, off-grid solar PV, and diesel energy The analysis shows that by 2030, there is a potential to add about 1.05 million hectares of groundwater irrigated area. Both on-grid and off-grid energy solutions will play an important role in the effort to develop groundwater-based irrigated agriculture in Ethiopia. Moreover, the application potential of the two off-grid energy solutions (solar PV and diesel) critically depends on the energy pricing policy of the country. A reform that removes the subsidies on fossil fuels will help promote the use of solar PV powered irrigation system significantly. Finally, Ethiopia is a country rich in renewable energy resources. Apart from solar energy, other sources of renewable energy available in Ethiopia include wind, geothermal, and micro-hydrology. There is also keen interest in investing in mini-grids. The approach developed in this study can be extended to accommodate these energy solutions, and this constitutes a topic that invites future research.

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1. Introduction

Ethiopia is home to 115 million people (World Bank, 2021). Although remarkable progress has been made in the past two decades, the country still faces several socioeconomic challenges, including energy poverty and food insecurity. Energy poverty in Ethiopia is characterized by low access to modern energy services. As of 2019, only 48 percent of the population in Ethiopia had access to electricity and in rural areas this percentage is even lower (World Bank, 2021). In terms of food insecurity, Ethiopia is one of the countries that are exposed to the highest risk of food shortage; 56 percent of the population is exposed to moderate or severe food insecurity risk (FAO, 2021). Irrigation plays an important role in reducing food insecurity as it allows agricultural production two to three times a year (compared to one or two production periods of rainfed systems), reduces the heavy reliance of subsistence agriculture on rains, and makes agricultural production resilient to rain failures.

While the issue of energy poverty and food insecurity are often discussed separately, there is a strong linkage between them. Like in many other activities, agricultural production has energy as an indispensable input and the level of energy use is key to agricultural productivity (Pimentel, 2019). Lack of energy services poses a barrier to the adoption of agricultural technologies and hampers the endeavour of boosting agricultural production. As of 2014, the level of agricultural mechanization – a heavy energy user in agriculture – in Ethiopia was only about 0.1 kilo watt per hectare (kW/ha), which fares poorly compared to other countries, for instance, India and China where agricultural mechanization was 2 kW/ha and 6 kW/ha in 2014 (Borgstein et al., 2020).

This paper presents a country-level planning analysis[1] in Ethiopia to inform investment decisions and policy discussions about productive uses of energy in the country's agriculture. Prospects to improve performance of the energy sector in Ethiopia have been discussed in a range of energy planning studies (e.g. Mentis et al., 2016; Mondal et al., 2018; Oyewo et al., 2021; Pappis et al., 2021). However, these analyses are dominated by the residential energy demand, which currently accounts for about 90 percent of total energy consumption in Ethiopia (Tiruye et al., 2021). Examples of agricultural productive uses of energy include irrigation, grain milling, cold storage, milk cooling, and coffee washing, among others. In this study, we focused on the productive use of energy in irrigated agriculture, or more accurately, the groundwater-fed irrigation, which is where the energy demand in irrigated crop production concentrates (Tidwell et al., 2014; Chen et al., 2018). The goal of our analysis is to identify cost-effective energy solutions to support the development of groundwater-based irrigated agricultural in Ethiopia.

Irrigation plays an important role in global food production, thanks to the high productivity associated with irrigated production. It is estimated that cropland equipped with irrigation accounts for 20 percent of the cropping area in the world but contributes to 40 percent of the total food production (UNESCO, 2020). Relative to other regions in the world, Sub-Saharan Africa, including Ethiopia, lags in development of irrigated agriculture with only 5 percent of cropland in Sub-Saharan Africa and 3 percent of cropland in Ethiopia currently under irrigation (FAO, 2016). The predominance of rainfed production exposes agriculture to the risk of erratic rainfall and limits the farming opportunity in dry season. In view of these barriers, irrigation development is widely perceived as an important means to improve agricultural production in Ethiopia and other Sub-Saharan African countries.

There are many factors that constrain wide application of irrigation in Sub-Saharan African countries, ranging from uncertain water and land resources conditions and market potential of irrigated crop products to lack of access to credit and complementary technologies (Villholth, 2013; Bjornlund et al., 2017; Mwamakamba et al., 2017). Energy poverty is not the sole, but undoubtedly an important constraint. The energy requirement of irrigation arises from water pumping and is a key determinant of the cost of irrigation and the economic feasibility of irrigation development. At the same time, the irrigation development potential in Ethiopia and other Sub-Saharan African countries is still a debatable issue (Xie et al., 2014; Altchenko and Villholth, 2015; Worqlul et al., 2017) as different institutions (both governmental agencies and international organizations) produce different and wide-ranging irrigation potential estimates depending on differences in their methodologies. This implies that the energy demand for irrigation is uncertain, while an energy planning analysis typically requires irrigation

[1] The irrigation water demand, energy requirement for irrigation and profits of production vary by crop. A major and unique challenge in country-level irrigation planning analysis is that it is hard to create scenarios in a national scale planning analysis to represent the crop mix in the future expanded dry season irrigated production. The crop mix has to be determined endogenously in the modelling. By contrast, in an irrigation planning analysis at community level, there is usually sufficient knowledge to project what crops farmers will cultivate once they have gained access to irrigation.

development potential as an input. For these reasons, energy and irrigation planning should not be viewed as two independent planning processes. Instead, they are correlated with each other and require simultaneous decisions.

This study used an integrated modelling approach to identify groundwater irrigation development potential in Ethiopia and cost-efficient energy solutions to support the irrigation development under combined biophysical and socioeconomic constraints. The three energy solutions included in the study are grid-connected electricity, off-grid solar PV, and diesel energy. Ethiopia launched the National Electrification Program (NEP) 2.0 in 2019. According to the program report, currently the irrigation in Ethiopia mainly relies on nonmotorized manual pumps and diesel-powered pumps. We anticipate that diesel pumps may continue to play an important role in future irrigation development in Ethiopia, while the application potential of nonmotorized manual pumps could be limited because of their labour-intensive nature. The program also calls for a diversification of energy sources for motorized water pumping for irrigation by promoting the use of solar energy and on-grid electricity. Other energy solutions for irrigation in Ethiopia such as wind-powered pumps and mini-grids (both hydro and solar) can contribute to meet energy demands in the sector in the country, a topic of future investigations as data on cost structures of these systems becomes available. Compared to diesel energy, solar energy is an emerging energy technology, which is renewable and clean, and has attracted much attention in recent years (Hartung and Pluschke, 2018). It is also expected that "access to grid-based services would offer several advantages, including energy and costs savings, and reliable services" (MoWIE-NEP2.0, 2019).

2. Methodology

Most parts of sub-Saharan Africa have tropical climate with alternating rainy and dry seasons. Currently, the crop cultivation is concentrated in the rainy season. Irrigation helps extend crop production into the dry season, which is the main irrigation season. We thus use the saturation adoption level of irrigation which can be reached in the dry season to define the irrigation development potential of the country. The saturation level of irrigation adoption is estimated by considering the constraints of land suitability, quantity of renewable groundwater resources and economic profitability of the irrigated crop production. The planning horizon is set to 2030. To reflect the spatial variability in weather, land and water resources and accessibility to power grid, high-resolution spatial data on these variables are used to inform the analysis. More details about the methodological framework is given below.

2.1 Irrigation cost estimation

The irrigation water requirement, energy demand for irrigation, and profits of production vary by crop. It is hard to create scenarios to represent what the crop mix would look like nation-wide as irrigation is expanded in the future. The crop mix is therefore treated as unknown in this national scale planning analysis and is modelled endogenously. To this end, it is necessary to specify prior to the analysis a list of irrigable crops to be included in the analysis. The irrigable crops here refer to crops considered to be most suitable to be produced under irrigated conditions in dry season. There is conventional wisdom that farmers tend to use irrigation to cultivate high-value crops (Xie et al., 2014). We use maize, wheat, vegetables, and pulses as irrigable crops in this study, which reflect the common crops under irrigation in Ethiopia. We first estimate the irrigation costs under each energy solution in irrigated production of each irrigable crop and in each land pixel across the country.

The irrigation cost in this study is calculated as present value of irrigation cost flows during a 25-year period, which is the typical life span of solar panels.

The irrigation cost ($CIRR_{cst}$) consists of three components and is calculated as

$$CIRR_{cst} = C\_energy_{cst} + C\_pump_{cst} + C\_borehole_{cst} \tag{1}$$

where $CIRR_{cst}$ is irrigation cost in year t (USD/ha), C_energy_{cst} is the energy-related cost in year t (USD/ha), C_pump_{cst} is pump cost in year t (USD/ha), and $C\_borehole_{cst}$ is the cost related the borehole in year t (USD/ha).

The energy cost is further comprised of initial installed costs including capital expenditures for acquisition of equipment and costs for installation, maintenance, fuel, and replacement of equipment (World Bank, 2018). To estimate these energy-related costs, we sized the water pumping system by following the approach by Xie et al. (2021). First, we estimated the gross irrigation water demand and energy requirement for water pumping during the growing season of each irrigable crop. The daily gross irrigation water demand (irrigation water withdrawal) in month i is calculated as (Allen et al., 1998):

$$D_{gross,i} = (ET_{0,i} \cdot k_{c,i} - P_{eff,i})/(ndays_i \cdot \eta_{irr}) \quad (2)$$

where $D_{gross,i}$ is the daily mean net irrigation water demand in month i (mm H_2O), $ET_{0,i}$ is the monthly reference evapotranspiration (mm H_2O), $k_{c,i}$ is the crop coefficient in month i, $P_{eff,i}$ is the effective rainfall in month i (mm H_2O), $ndays_i$ is the number of days in month i, and η_{irr} is irrigation efficiency.

Effective rainfall, $P_{eff,i}$, is estimated by using the method proposed by the US Department of Agriculture Soil Conservation Service (Smith, 1992):

$$P_{eff,i} = \frac{P_i(125 - 0.2P_i)}{125} \quad for\ P_i \leq 250mm/mo$$

$$P_{eff,i} = 125 + 0.1P_i \quad for\ P_i > \frac{250mm}{mo} \quad (3)$$

where P_i is the monthly precipitation in month i (mm H_2O).

With estimated irrigation water demand, the daily average energy requirement for irrigation water pumping in month i, E_i, is calculated as

$$E_i = \frac{D_{gross,i} \cdot A \cdot 10 \cdot \rho \cdot g \cdot H}{3.6 \times 10^6 \cdot \eta_{pump}} \quad (4)$$

where A is farm size or irrigated area in hectares (assumed to be 1 ha), 10 is a factor used to calculate the conversion of gross irrigation water demand (expressed in mm H_2O) to gross irrigation water demand in cubic meters (m^3 H_2O)[2], ρ is the density of water (in 1,000 kg/m^3), g is the gravity of the Earth (9.8 m/s^2), H is the total dynamic head (m), η_{pump} is the energy efficiency of the motor and the pump, and 3.6×10^6 is the conversion factor from joules to kWh.

The rated power of solar panels in solar irrigation system is calculated as

$$P_{array\_STC} = max\{E_i/(h_i \cdot df)\} \quad (5)$$

where P_{array_STC} is the rated power of the solar array under standard testing conditions (kWp[3]), subscript i denotes the month in the growing season, E_i is the daily mean energy requirement for irrigation in month i (kWh), h_i is the peak sun hour (hr) in month i, and df is a derating factor (0.77).

The initial cost of the solar PV system is calculated as

$$C_{solar\_ini} = P_{array\_STC} \cdot C_{solar\_installed} \quad (6)$$

where C_{solar_ini} is the initial capital cost of solar module (USD); $C_{solar\_installed}$ is the installed cost of solar module (USD/Wp).

There is no fuel cost in solar irrigation and the maintenance cost is assumed to be 2 percent of the initial installed costs. The assumption used here is formed by synthesizing information from various sources, including from discussions with water and energy specialists in Ethiopia.

The rated power of diesel generator is calculated as

$$P_{disel\_gen} = \frac{E_{max}}{h_{diesl\_gen}} \quad (7)$$

[2] To calculate the water demand in cubic meters, it is necessary apply a multiplier of 0.001 to convert water depth in millimetres to water depth in meters, and a multiplier of 10000 to convert irrigated area in hectares to irrigated area in square meters. Therefore, the overall conversion factor is 10 (= 0.001 * 10000).

[3] The size of a solar system is measured in kWp (kilowatt peak). It is the amount of power produced under standard laboratory test conditions, which broadly equate to bright sunshine. So a 1 kWp system will produce 1 kW of electrical power in bright sunshine.

where P_{disel_gen} is the rated power of the diesel generator (kW), E_{max} denotes daily mean energy requirement in peak month (Kwh), and h_{diesel_gen} is daily operation hours of the diesel generator (hr) which is numerically equal to peak sun hours in the peak month (hr).

The initial capital cost of diesel irrigation is calculated as

$$C_{diesel\_ini} = P_{diesel\_gen} \cdot C_{diesel\_installed} \cdot 1000 \tag{8}$$

where C_{diesel_ini} is the initial capital cost of diesel irrigation (USD) and $C_{diesel\_installed}$ is the installed cost of diesel generator (USD/Watt).

The annual maintenance cost of a diesel generator is assumed to be 20 percent of the initial capital cost. As for solar, this assumption is formed by synthesizing information from various sources, including from discussions with water and energy specialists in Ethiopia.

The annual fuel cost in diesel irrigation is calculated as

$$C_{diesel\_fuel} = \frac{\sum_{i=1}^{n} E_i \cdot ndays_i}{e} \cdot Pr_{diesel} \tag{9}$$

where C_{diesel_fuel} is the annual diesel fuel cost (USD), E_i is the calculated daily mean energy requirement (kWh) in month *i*, $ndays_i$ is the number of days in month *i*, e is diesel consumption per kWh ≈ 0.4 l/kWh and Pr_{diesel} is diesel fuel price (USD/liter).

As noted before, energy planning in Ethiopia is dominated by household energy demand. The planning horizon of this analysis is 2030. According to the Ethiopia National Electrification Program 2.0, access to on-grid electricity will be extended to locations up to 25 km from the current grid lines. A 25km-wide buffer zone was therefore created, and it is assumed that access to on-grid electricity is available in this buffer zone and in land pixel with population density greater than 200 people per km^2 (using assumptions provided by Pappis et al., 2021).

The energy cost under on-grid energy solution is calculated as

$$C_{electricity} = \sum_{i=1}^{n} E_i \cdot ndays_i \cdot Pr_{electricity} \tag{10}$$

where $C_{electricity}$ is the electricity cost (USD), and $Pr_{electricity}$ is electricity tariff (USD/kWh). In addition, a one-time connection fee is charged at the beginning of the project.

The initial capital cost for a pump is calculated as

$$C_{pump\_ini} = P_{pump} \cdot C_{pump} \cdot 1000 \tag{11}$$

where C_{pump_ini} is the initial capital cost of pump (USD), P_{pump} is rated power of pump (kW and is the same as P_{diesel_gen} in equation 7) [4], and C_{pump} is unit capital cost of pump (USD/Watt). It is assumed that pump-related costs are identical under energy solutions and that the annual maintenance cost of a pump is 5 percent of the initial capital cost. We further assumed that a replacement of the pump occurs in the middle of the life span of the solar irrigation system (year 13). These are simplifying assumptions as in practice, there is likely to be considerable variation in actual costs and lifetime of individual pumps. However, the lack of sufficient data prevents us from incorporating this into the model of this national level analysis.

The capital cost of borehole construction at year 0 is calculated as

$$C_{borehole} = D_{borehole} \cdot VC_{borehole} + FC_{borehole} \tag{12}$$

where $D_{borehole}$ is drilling depth of borehole (m), $VC_{borehole}$ variable cost per meter in borehole drilling (USD/m), and $FC_{borehole}$ is fixed cost in borehole drilling (USD). This is informed by our assessment that drilling depth is the

[4] That is, it is assumed that the power ratings of diesel generators and electric pumps are the same.

major factor that influences costs, which are assumed to be independent of the type of energy solution. It is assumed that there is a borehole in each farm, which implies the command area of a borehole is 1 hectare. Borehole maintenance costs are considered to be insignificant and omitted.

The spatial input data used in this step of analysis are listed in Table 1.

Table 1: Spatial input data used in cost estimation

Data type	Source
Solar irradiance	PVGIS (https://ec.europa.eu/jrc/en/pvgis)
Precipitation	CHIRPS (https://www.chc.ucsb.edu/data/chirps)
Reference evapotranspiration	CGIAR-CSI (https://cgiarcsi.community/data/global-aridity-and-pet-database/)
Groundwater depth and productivity	British Geological Survey (https://www2.bgs.ac.uk/groundwater/international/africangroundwater/mapsDownload.html)
Powerline grid	World Resources Institute (https://www.wri.org/initiatives/energy-access-explorer)
Population density	WorldPop (https://www.worldpop.org)

The precipitation data from CHIRPS (Climate Hazards Group InfraRed Precipitation with Station) and reference evapotranspiration[5] data from CGIAR-CSI are used to estimate irrigation water demand (Equation 2 &3). Solar irradiance data from PVGIS (Photovoltaic Geographical Information System) are used for solar system sizing (Equation 5). Groundwater maps of Africa from the British Geological Survey provide estimates of groundwater depth in terms of rest water level, which is the main component of total dynamic head H in Equation (4). The total dynamic head also includes the drawdown, or water table lowering caused by water pumping. The drawdown is estimated using the Theis equation (1935). The spatial data showing 25 km buffer zone from powerlines of the electricity grid in Ethiopia is obtained from the World Resources Institute's Energy Access Explorer and population density data from WorldPop are used to delineate area with access to on-grid electricity.

The values of main non-spatial input parameters used in this study are shown in Table 2. As indicated, the values of some of the parameters are derived by synthesizing information from various sources. This implies that there is greater uncertainty associated with the values of these parameters. Reducing this uncertainty relies on the advance in data collection technologies and more survey efforts. Moreover, among these parameters, diesel fuel prices and electricity tariff are two parameters to which the results of the study are most sensitive. More discussions about the two parameters and an analysis on their sensitivity are provided in section 2.4.

Table 2: Non-spatial input parameters for cost estimation

Parameter	Value
Irrigation efficiency η_{irr}	0.5 (FAO, 1997)
Energy efficiency of pump η_{pump}	0.6 (Phocaides, 2007)
Derating factor of solar module df	0.77 (World Bank, 2018)
Installed cost of solar module $C_{solar\_installed}$ (USD/Wp)	1.2*

[5] Evapotranspiration is the "loss of water from the soil both by evaporation from the soil surface and by transpiration from the leaves of the plants growing on it" (https://www.britannica.com/science/evapotranspiration)

Installed cost of diesel generator $C_{diesel\_installed}$ (USD/kW)	250*
Unit capital cost of pump C_{pump} (USD/Watt)	0.7*
Diesel fuel price Pr_{diesel} (USD/liter)	0.57 (GIZ, 2019) & Global Petrol Prices (2021)
Electricity tariff $Pr_{electricity}$ (USD/kWh)	0.03 (Global Petrol Prices, 2021)**
Variable cost of borehole drilling $VC_{borehole}$ (USD/m)	65 (Xenarios and Pavelic, 2013)
Fixed cost of borehole drilling (USD)	2350 (Xenarios and Pavelic, 2013)
Capital discount rate	10%*

* Parameter values are determined based on authors' judgements by synthesizing information from literature and expert meetings.
** A one-time connection fee of $125 per line drop is also assumed.

2.2 Simulation of groundwater irrigation expansion

The cost estimation is followed by a simulation analysis to assess groundwater irrigation development potential across the country, and at the same time identify cost-effective energy solutions to support such irrigation development. The modelling approach used in the simulation analysis is schematically shown in Figure 1. It involves extending an irrigation planning framework we developed previously (Xie et al., 2021). Various approaches have been proposed to assess the irrigation development potential in Africa at national and continental scales. These include the attempt to use GIS (Geographic Information System) tools and MCE (Multi Criteria Evaluation) techniques to delineate areas with land suitability for irrigation (Worqlul et al., 2017; Schmitter et al., 2018) and to evaluate water budgets to determine the scale of irrigated agricultural production that water resources can support (Altchenko and Villholth, 2015). The irrigation planning method we proposed integrates the use of the land suitability and water budget analysis tools and takes into account the economic feasibility of the irrigated crop production. It is described briefly below. More details can be found in Xie et al. (2021).

The development process of groundwater is essentially decentralized. We introduced agent-based modelling techniques in the design of our irrigation planning model to simulate the decision of irrigation adoption at farm level. A class of agents are defined on a 1km by 1km land grid within a geographic domain with land suitability for groundwater irrigation development. The land suitability domain is derived through a GIS multi-criteria land suitability analysis and by using terrain, groundwater depth, groundwater productivity, groundwater storage and access to market as evaluation criteria (Xie et al., 2018). The land pixels in this suitability domain have a score ranging from 34 to 90 with 100 as the highest possible score and 1 as the lowest possible score. The criteria used for computing the irrigation suitability scores, the range of parameters and scores, the aggregation methods, and the data sources are described in detail in Xie et al's 2018 paper (pages 799 to 800). The higher score indicates a better land suitability for groundwater irrigation development. Each 1km land pixel is viewed as a farm, an autonomous entity for irrigation decision. The farm size therefore refers to the land area in each land pixel used for rainfed annual crop production which is assumed to be left fallow in the dry season. Here we also assume that irrigation adoption will only occur on existing cropland and ignore the possibility of cropland expansion. The farm size in a land pixel is estimated by using data on existing crop extent and crop pattern (You et al., 2014) by removing the land area for non-crop use, and cropland area for perennial crop production and already equipped with irrigation. The spatial distribution of the estimated farm size that is used in this study is shown in Figure 2 (b).

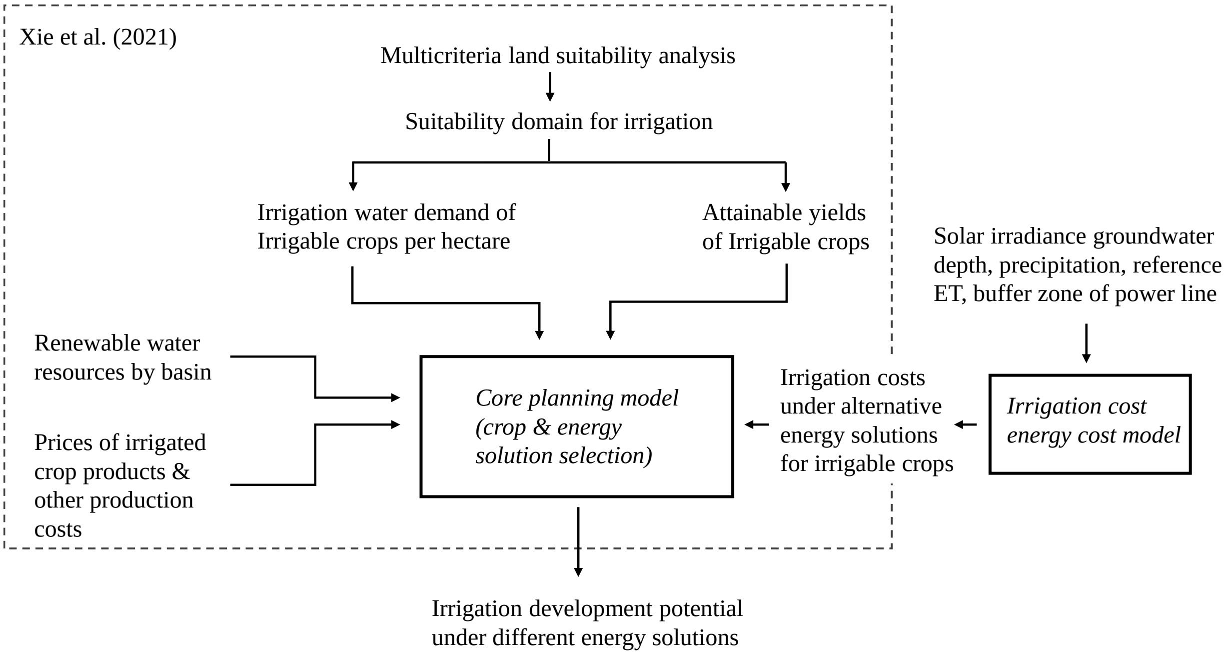


Figure 1 Modelling expansion of groundwater irrigation

(a) Land suitability (b) Farm size

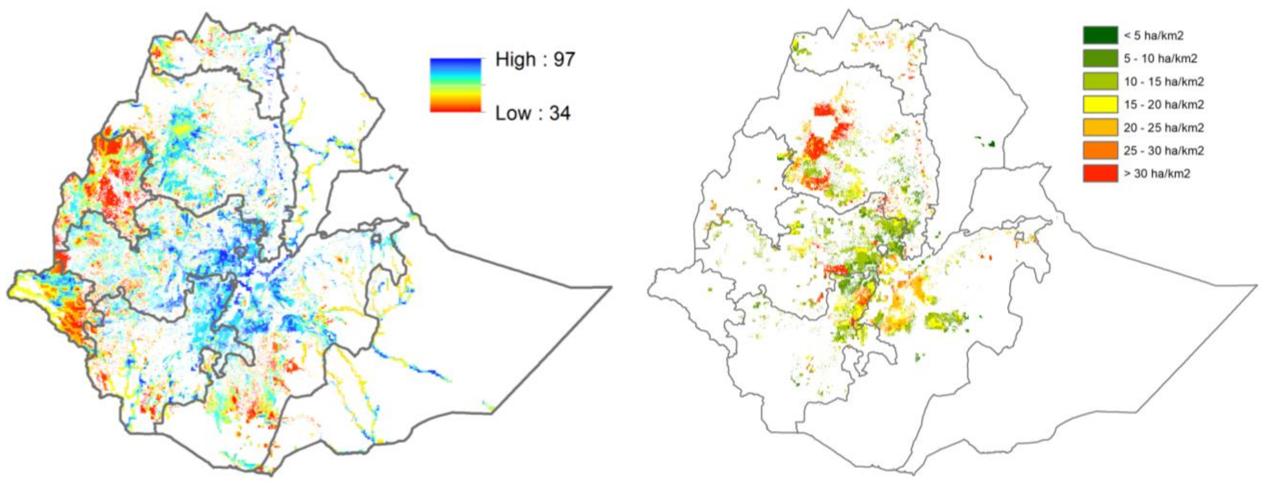


Figure 2 Land suitability for groundwater development and farm size distribution

In the irrigation planning model, the farmer's willingness to adopt irrigation is modelled as a probabilistic function of the land suitability for irrigation of the farm, or the probability of adoption is assumed to be linearly correlated with the land suitability score. The success rate of adoption is further evaluated according to water resources and market conditions. That is to say, in addition to land suitability, the expansion of irrigation is also constrained by the quantity of renewable groundwater resources and economic profitability of irrigated crop production. Note that increased production from irrigation expansion may lead to a drop in crop prices, which affects the profitability of irrigated production and ultimately causes a stopping of the irrigation expansion. This supply-price relationship and the resulting constraining effect are simulated in our model. In this sense, irrigation development in our model can be viewed as a process for farmers to compete for renewable water resources and market shares of irrigated crop products. Specifically, the economic return of adopting irrigated crop production is calculated as the net present value (NPV) of the 25-year irrigation project. In the NPV evaluation, the estimates of attainable yields of irrigated crop (Figure 3) are predicted through a spatial interpolation analysis by interpolating IFPRI's

Spatial Production Allocation Model (SPAM) yield estimates (You et al., 2014), using the Random Forest approach[6] (Jeong et al., 2016). Demand functions for four irrigable crops representing market conditions farmers who enter into the irrigated production by 2030 may face and during the lifespan of the irrigation project are derived from IFPRI's IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade) model (Robinson et al., 2015). They are used to model the supply-price relationship of the irrigated crop products. Estimates for irrigation cost are generated in Section 2.1, and the non-irrigation component of the crop production costs are estimated using a profit margin approach (You et al., 2014), where profit is defined as a certain share of the revenue. In our water balance constraint evaluation, the irrigation water demand by crop are estimated using the method described in Equation (2) and Equation (3) and is aggregated to seasonal level. Pixels on a 10km by 10km land grid are used to represent groundwater basins (Figure 4). The annual basin-wide safe yields of groundwater for irrigation are calculated from groundwater recharge map developed by MacDonald et al. (2021).

(a) Maize (b) Wheat

(c) Vegetables (d) Pulses

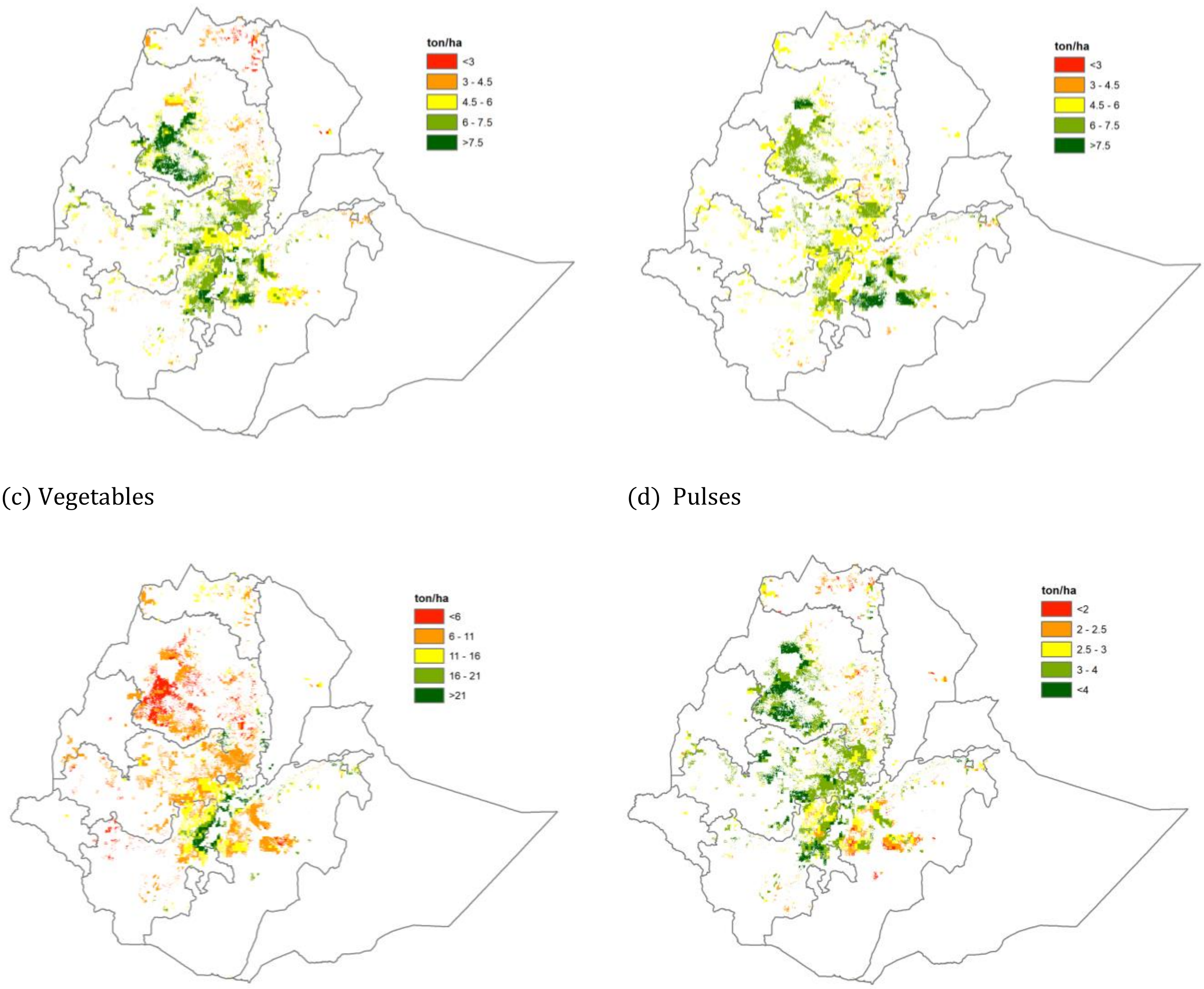


Figure 3 Attainable yields of irrigated crops

In this study, we extend the national irrigation planning approach by allowing farmers to not only choose crops for irrigated production but also the energy solution that is most cost effective. A key assumption in this is that farmers always choose to cultivate the crop that is most profitable – growing one annual crop per season The results from the preceding cost estimation analysis are used to inform the decision on selection of energy solutions.

[6] A Random Forest approach is a classification algorithm consisting of many decision trees to reach at a single result, trees that start with a basic question and split the data further based on the response to the questions. It then creates an uncorrelated forest of trees, whose prediction power is better than of an individual tree.

In this way, the model is capable of reporting the placement of energy solutions used to support the groundwater irrigation development.

There is stochasticity in the simulation introduced by the assumption that the probability of adoption is linearly correlated with the land suitability. In the application of the model, the model is run in a Monte Carlo setting and reports the probability of successful adoption of groundwater irrigation, including the adoption probability under three energy solutions, on the 1km farm grid. The adoption probability of each farm pixel is calculated as:

$$p_{adopt} = \frac{n_{adopt}}{N_{sim}} \tag{13}$$

where p_{adopt} is the adoption probability of groundwater irrigation in the pixel, n_{adopt} is the number of realizations in which groundwater irrigation is adopted successfully in the pixel, and N_{sim} is the number of total realizations.

2.3 Sensitivity analysis

As noted in section 2.1, we provide sensitivity analyses to demonstrate the sensitivity of the model to the input parameters of diesel fuel price and electricity tariff. In this sensitivity analysis, we run the model under a set of alternative diesel fuel price and electricity tariff values (column 3 in Table 3). The diesel fuel price and electric tariff used in this study (see Table 2 and also listed in column 2 of Table 3) are derived from historical levels between 2018 and 2021. Ethiopia is one of the countries with the lowest diesel price and electricity tariff in Sub-Saharan Africa (World Bank, 2021). Energy prices in Ethiopia are heavily subsided (Whitley and Van der Burg, 2015). The prices used in the sensitivity analysis are higher and proposed to reflect the costs of the energy services. The results of the sensitivity analysis thus also serve to illustrate how an energy subsidy reform could shift the portfolio of energy options in irrigation development. It also allows assessing sensitivity given global diesel price spikes such as those caused by the recent Russia-Ukraine war. Note that considering the difficulty in forecasting long-term diesel prices and uncertainty over potential future declines of solar PV cost, we assume a constant diesel fuel price, electricity tariff, and installed cost of solar PV during a 25-year lifespan of an irrigation project.

Table 3: Diesel price and electricity tariff in sensitivity analysis

	Historical	High
Diesel fuel price Pr_{diesel} (USD/liter)	0.57	0.9 (Parry, 2021)
Electricity tariff $Pr_{electricity}$ (USD/kWh)	0.03	0.09 (Global Petro Prices, 2021)

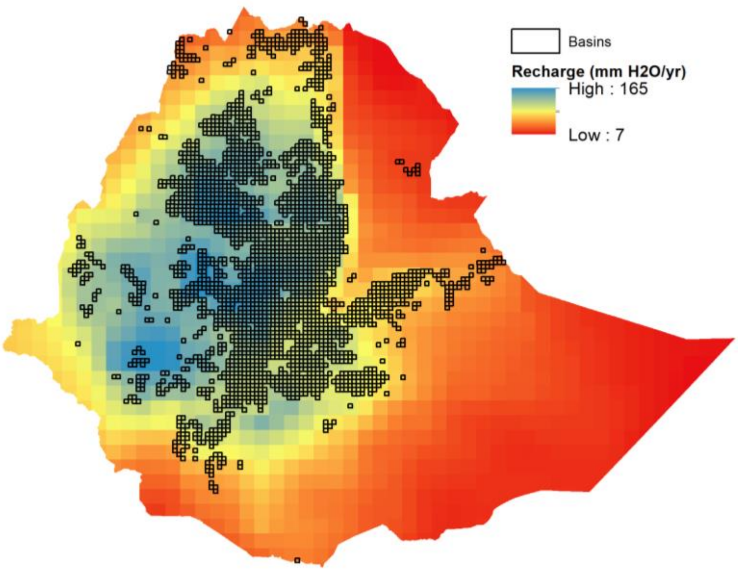


Figure 4 Groundwater basins and recharge in Ethiopia

3. Results

The most cost-effective energy solutions identified through the cost estimation analysis at base case historical levels for diesel fuel price and electric tariff are shown in Figure 5. Electric grid expansion was assumed to be limited within the 25 kilometre radius from the current grid lines as per the country's national electrification plan. As evident on these maps, the cost effectiveness of each energy solution for irrigation varies substantially under different cropping systems. However, in general, on-grid electricity has an advantage in areas close to the electricity transmission network and with high population density, while among the two off-grid energy solutions (diesel and solar PV), solar irrigation tends to be more cost effective in the north and in the eastern lowlands. It appears that solar PV is more cost-effective for market oriented crops such as vegetables and maize (and partly wheat), as achieving sufficient return on investment on the solar panels and pump requires crops that fetch higher prices. Pulses require less water for irrigation and fetch lower prices compared to the other crops, resulting in diesel being more cost effective for them in areas away from the current grid lines.

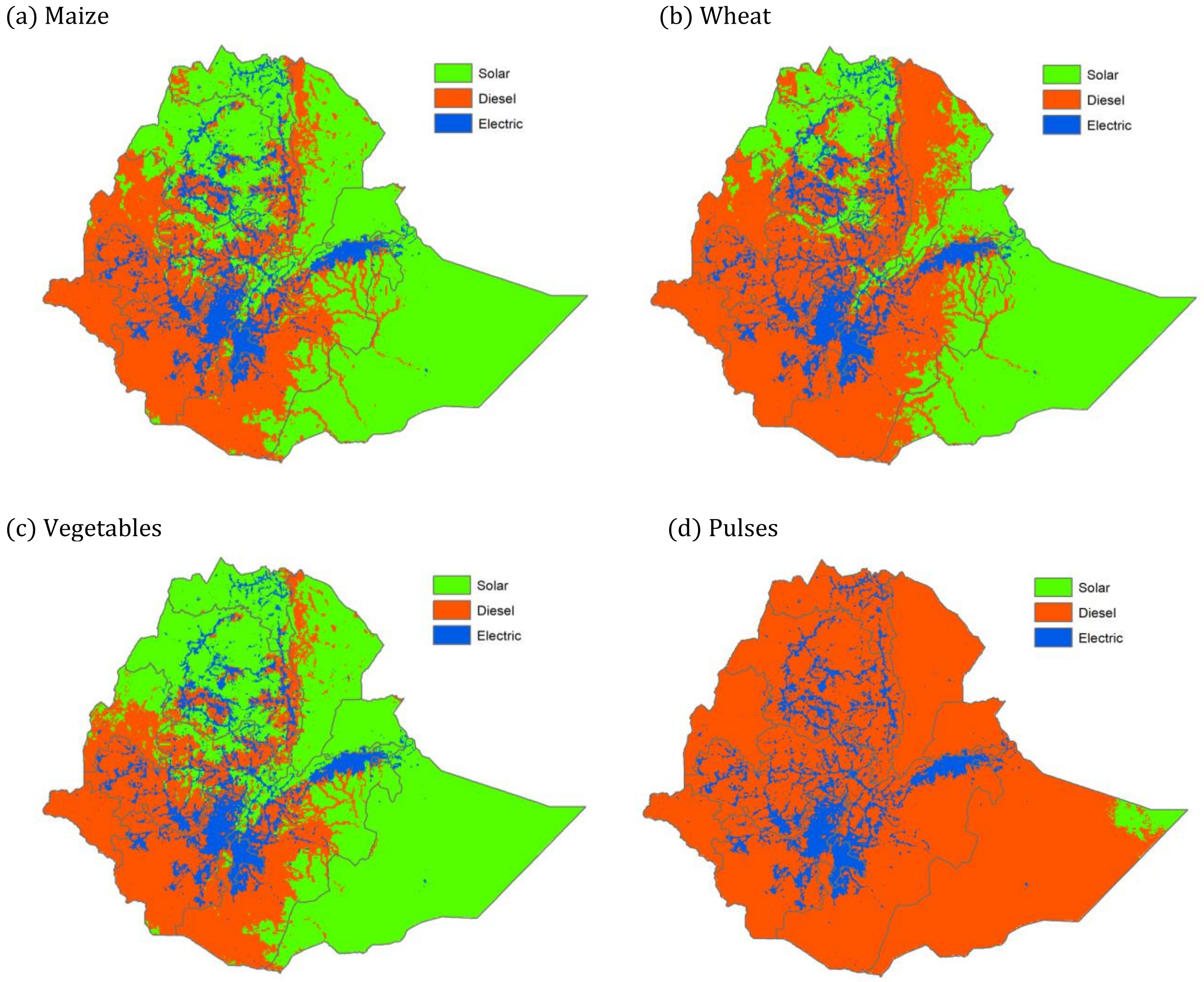


Figure 5 Most cost-effective energy solution identified through cost estimation analysis and based on diesel fuel price and electric tariff derived from historical data

Further modelling results on the adoption probability of groundwater irrigation are shown in Figure 6(a), taking into account combined land suitability, water availability and economic viability constraints. The identified dominant cost-efficient energy solutions are shown in Figure 6(b). Here the dominant cost-efficient energy solution refers to the energy solution with the highest predicted adoption probability in each land pixel. The expected potential areas, which are calculated according to the adoption probability and irrigated areas at farm level and aggregated to region level, are shown in Table 3. It is estimated that the total groundwater irrigation development potential in Ethiopia is about 1.05 million hectares, consisting of 0.26 million hectares where solar irrigation is most cost efficient, 0.34 million hectares in which diesel irrigation is most cost efficient and 0.46 million hectares where on-grid electricity is the most cost-efficient energy solution for irrigation.

(a) Adoption probability (b) Dominant energy solutions

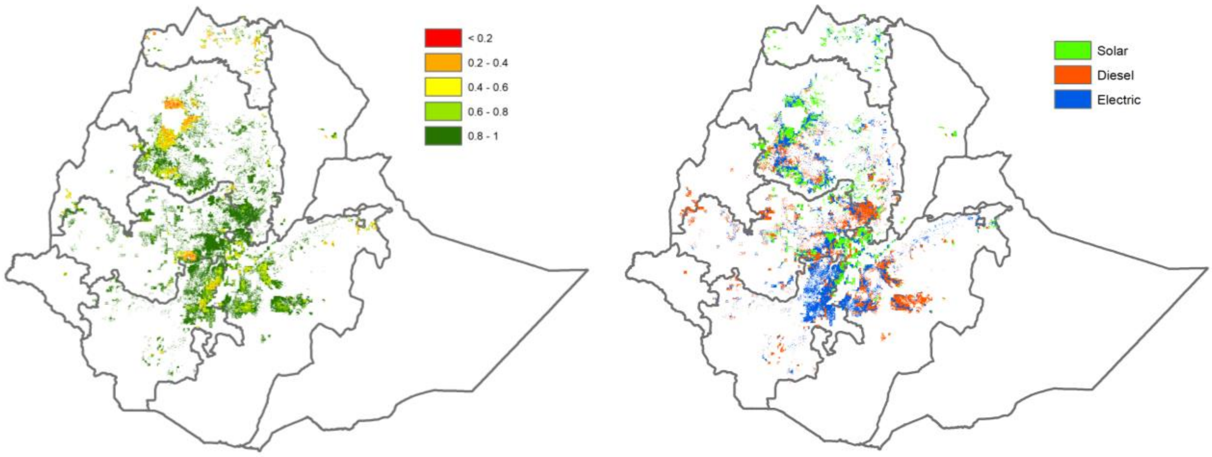


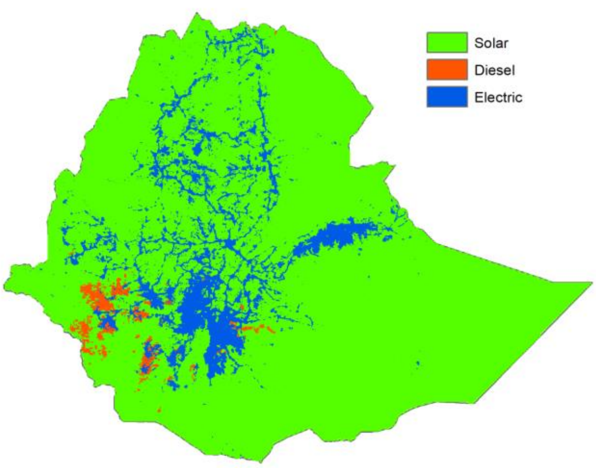
Figure 6 Adoption probability and dominant energy solutions in groundwater irrigation development in Ethiopia - based on diesel fuel price and electric tariff derived from historical data.

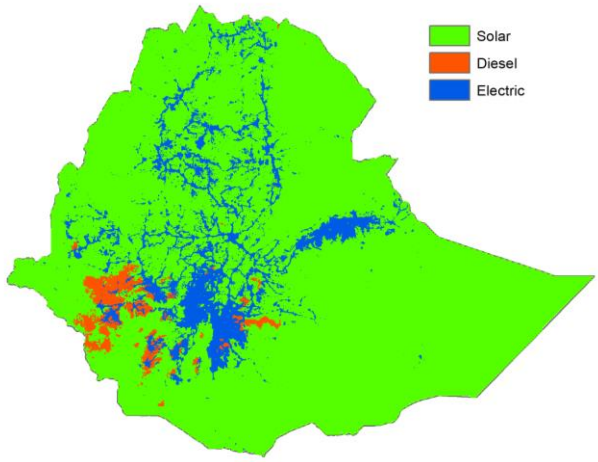
Table 3 Expected values of areas with groundwater irrigation development potential under three energy solutions (in hectares) - based on diesel fuel price and electric tariff at historical levels

Region	Solar	Diesel	Electric	Total
Addis Ababa	13	0	39	52
Afar	1,121	118	35	1,274
Amhara	138,212	97,372	145,280	380,865
Benishangul Gumuz	2,780	6,642	1,645	11,067
Dire Dawa	0	0	0	0
Gambela	0	720	204	923
Hareri	0	3	581	585
Oromia	93,636	202,227	185,062	480,926
Somali	139	0	102	240
SNNPR	5,562	28,996	113,737	148,295
Tigray	19,587	34	9,889	29,510
Total	261,050	336,112	456,574	1,053,736

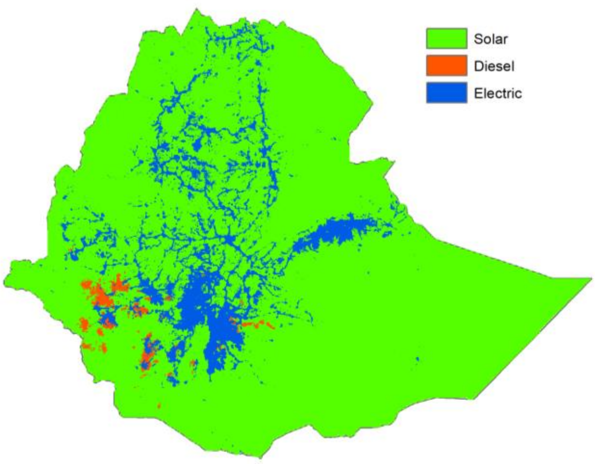
The results under alternative high diesel fuel price and electric tariff scenario are shown in Figure 7, Figure 8, and Table 4. The estimates for total adoption probability and total expected potential area are almost identical, and so do the estimates for on-grid electric pumping systems. On the other hand, the high diesel price leads to a dramatic change in the application potential of two off-grid energy solutions. The adoption potential of solar irrigation systems increases to 0.59 million hectares while the application potential of diesel irrigation systems drops to only 9 thousand hectares (compared with an irrigation potential of 0.26 million hectares and 0.34 million hectares with solar and diesel under the 'historical prices' scenario).

(a) Maize (b) Wheat





(c) Vegetables



(d) Pulses

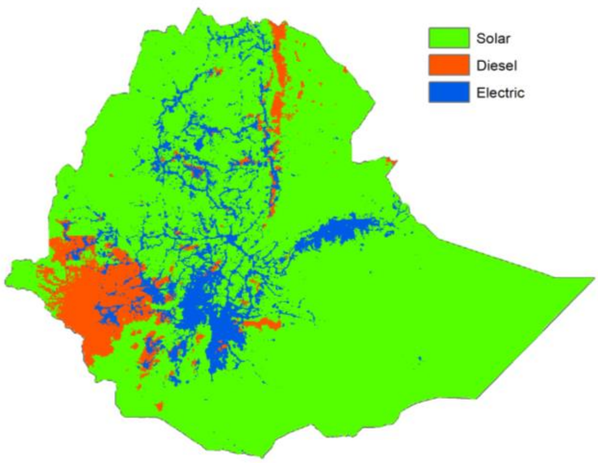
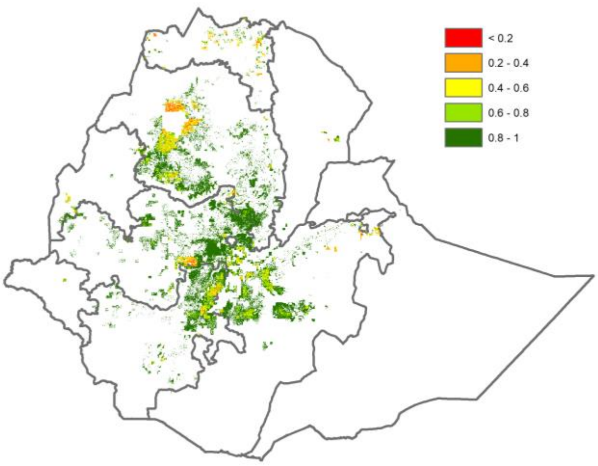


Figure 7 Most cost-effective energy solution identified through cost estimation analysis and under high diesel fuel price and electric tariff scenario

(a) Adoption probability



(b) Dominant energy solutions

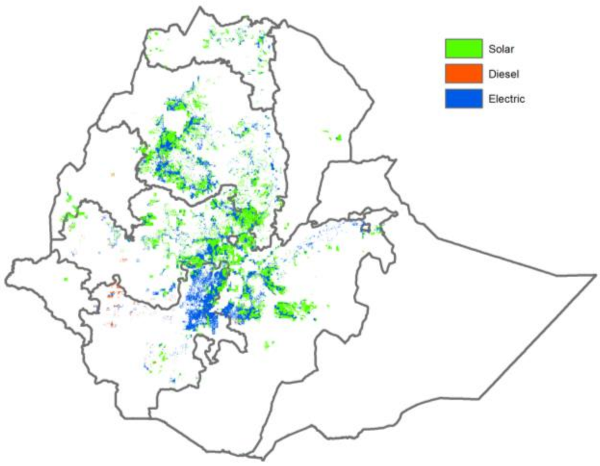


Figure 8 Adoption probability and dominant energy solutions in groundwater irrigation development in Ethiopia under high diesel fuel price and electric tariff scenario.

Table 4 Expected values of areas with groundwater irrigation development potential under three energy solutions (ha) – under high diesel fuel price and electric tariff scenario

Region	Solar	Diesel	Electric	Total
Addis Ababa	13	0	39	52
Afar	1,237	0	33	1,270
Amhara	235,215	662	144,591	380,468
Benishangul Gumuz	8,200	258	1,548	10,006
Dire Dawa	0	0	0	0
Gambela	530	189	204	923
Hareri	5	0	572	577
Oromia	291,225	2,874	184,928	479,027
Somali	134	0	102	235
SNNPR	28,997	5,710	113,548	148,255
Tigray	19,607	0	9,849	29,455
Total	585,163	9,692	455,414	1,050,269

4. Conclusion

Sub-Saharan African countries have long been beset with energy poverty. While there are already many studies on how to improve access to modern energy services in the region, those energy planning analyses are typically focused on residential and/or total energy demand, and not much attention has yet been paid specifically to the productive uses of energy in agriculture. This paper aims at filling this knowledge gap by presenting a country-level planning analysis in Ethiopia to inform investment decisions and policy discussions about the promotion of productive uses of energy in agriculture to support the development of irrigated agriculture in the country. Irrigation is considered as a promising option to boost agricultural production and enhance agricultural resilience in Ethiopia. However, the strong water-energy nexus in irrigated agriculture implies that irrigation development in Ethiopia is hampered by energy poverty. The challenging aspect of the planning analysis for productive uses of energy in irrigated agriculture is that, in addition to access to energy, irrigation adoption is constrained by many other factors such as availability of water resources, land suitability, and market potential of irrigated crops. In this study, we formulated an integrated irrigation-energy planning framework to identify groundwater irrigation development potentials in Ethiopia under three energy solutions: grid-connected electricity, off-grid solar PV, and diesel energy, and under combined biophysical and socioeconomic constraints. The analysis shows that by 2030, there is a potential to add more than 1.05 million hectares of groundwater irrigated area in Ethiopia using diesel, solar, or grid electricity. Both on-grid and off-grid energy solutions will play an important role in the effort to develop groundwater-based irrigated agriculture in Ethiopia. The cost-effectiveness of each energy solution is found to vary by crop and by location, but overall, on-grid electricity is the most cost-effective energy solution in areas close to the electricity transmission network. At the same time, there is considerable groundwater irrigation development potential that is located outside the service area of electricity grid where the groundwater irrigation development needs to rely on the use of off-grid energies. Compared to diesel energy, solar PV tends to have an advantage in the north and in eastern lowlands, which could constitute the focal region for solar irrigation investment.

The analysis also reveals the challenges in making decision to provide cost-effective energy solution for expanding groundwater irrigation. The application potential of the two off-grid energy solutions critically depends on the energy pricing policy of the country. A reform that removes the subsidies on fossil fuels will help promote the use solar PV powered irrigation system significantly.

Finally, as a caveat about the limitation of the study, the above findings are subject to uncertainty which arise from the key assumption and input data used in the study described in Section 2. This invites future endeavours to improve the model when better data and knowledge is available. Moreover, in this study we only consider three energy sources. Ethiopia is a country rich in renewable energy resources (Hailu and Kumsa, 2021; Tiruye et al., 2021). Apart from solar energy, other sources of renewable energy available include wind, geothermal micro-hydrology etc. There is also keen interest in investing in mini-grids (NARUC, 2021). The modelling framework applied in this study can be extended to accommodate these energy solutions.

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