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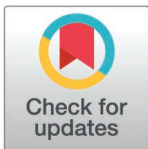
Energy options for irrigated agriculture and their impacts on returns: Evidence from Ethiopia

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Abstract

Irrigated agriculture often relies on modern energy technologies, but farmers must choose between options with different costs, benefits, and long-term returns. This study employs a mixed-methods approach combining a comprehensive household- and plot-level survey conducted in Ethiopia during 2016/17 with qualitative evidence from focus group discussions and key informant interviews, as well as bio-physical and climatic data linked to geo-referenced household and plot locations. The quantitative dataset includes 464 rural households and 1,037 irrigated plots across four regions and ten districts of Ethiopia. Because farmers self-select into different irrigation energy technologies, simple comparisons of returns across users may produce biased estimates. To address this issue and strengthen causal inference, the study applies a multivalued treatment effects framework using the Inverse Probability Weighted Regression Adjustment (IPWRA) estimator to construct counterfactual outcomes and compare net returns across irrigation energy systems. Results show that while diesel pumps yield the highest total value of production per hectare, the estimated mean net returns are higher with electric pumps and manual systems. Increased fuel and maintenance costs are the main reasons for the low net return of diesel pump systems. These findings underscore the importance of promoting affordable, reliable, and sustainable irrigation energy technologies to address high energy costs, a significant constraint on improving agricultural productivity and farm net returns in smallholder irrigation systems, while supporting rural electrification, climate-resilient agriculture, and sustainable irrigation development in Ethiopia.

1. Introduction

Improved access to irrigation water plays a remarkable role in the sustainability of rural livelihoods. It has direct and indirect benefits for poverty alleviation, resilience,

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Data availability statement: The data underlying the results presented in this study are available in the [Supporting Information](#) files. The de-identified dataset and accompanying Stata do-files required to replicate all analyses and results reported in the manuscript are provided without restriction. These files were drawn from a larger dataset collected as part of the first author's PhD dissertation at the Center for Development Research (ZEF), University of Bonn.

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and sustainable development. The direct benefits operate through localized and household-level effects, while indirect benefits function through aggregate-level (regional and national) impacts [1].

Access to improved irrigation enables rural households to diversify their livelihood since it creates options for extended production across the year, increases agricultural yield, and generates employment opportunities [1–5]. The increased income helps stimulate and integrate the rural economy via stronger links to input and output markets [1]. Furthermore, the participation of farm households in water users' associations builds their social capital and networks [4]. Irrigators usually grow high-value marketable crops such as fruits and vegetables during the dry season. Consumption of such high micronutrient crops can provide essential nutrition benefits to farm households. Households also increase their consumption of animal products due to the higher income and improved livestock productivity [6]. As a result, investment in irrigation acts as a production and supply shifter with a strong and positive effect on growth, benefiting people with low incomes in the long run [6,7].

Recognizing the contribution of irrigation access to poverty alleviation and in building resilience, over the past three decades, the government of Ethiopia, with support from development partners, has embarked on an aggressive strategy of irrigation expansion that includes a range of different projects. Investment in the irrigation sector comprised over 1/3rd of the total budget of the Ministry of Agriculture's Agricultural Growth Program (AGP 2011–2016) [8], and the area under irrigation increased three-fold between 2004 and 2015 [9]. In 2019, at least 13 ongoing large-scale irrigation projects with a combined area of more than 400,000 hectares were under construction (Ministry of Agriculture, personal communications, 2019). Gebregziabher et al. [10] reported that between August 2004 and December 2010, around 800,000 motor pumps were imported into the country to help equip these irrigation projects.

In parallel with the introduction of various technologies and the expansion of irrigation schemes across the country, several reforms and institutional development efforts have been undertaken in the irrigation sector. Institutional changes in the irrigation sector have been aimed at decentralizing and devolving the governance structure for the past three decades. These reform initiatives are evident at the macro and sub-sectoral levels [11]. Macro-level institutional reforms of the water sector include developing water laws and water policies, preparing national and regional water plans, and reorganizing administrative institutions. At the sub-sectoral level, the reforms include devolving responsibilities through water management transfer and participatory water management.

The recent expansion is supported by both surface and groundwater irrigation projects. Ethiopia has 12 major river basins with a total annual runoff volume of 122 billion m³ of water, and an estimated groundwater potential of 2.6 billion m³ [5]. The exploitation of groundwater for irrigation purposes has several advantages (e.g., availability of water on demand, the potential for decentralization, etc.) over systems that rely on surface water, which typically require dam construction and the development of substantial canal infrastructure. As such, the government has developed policies to facilitate groundwater irrigation development and support agricultural

transformation in the country, such as allowing duty-free importation of irrigation pumps and agricultural machinery [12]. Developing and expanding groundwater irrigation, however, also requires equipment with pumping solutions that include manual, diesel, petrol, electricity, and solar-powered technologies.

Recently, the Ethiopian government has articulated a strong commitment to developing solar and other renewable energy resources, as outlined in various national policies, laws, and regulations. To support this vision, it has introduced a range of incentives to promote the adoption of solar irrigation pumps, including improved access to finance and duty and tax exemptions. A ban on petrol and diesel-powered pump imports enacted in May 2023 marked a significant structural shift in the country's irrigation strategy, towards cleaner and more sustainable technologies [13]. However, trade data (HS code 8413) suggests that imports of petrol and diesel-powered pumps remain substantial, with 268 shipments recorded between October 2023 and September 2024 [14]. And while a number of stakeholders have piloted solar pump initiatives across Ethiopia, these efforts have not yet reached scale. Serious implementation challenges persist, including limited institutional capacity and resource constraints, which hinder the ability to effectively respond to growing farmer demand for affordable and reliable energy for irrigated agriculture [13,15]. Existing research on irrigation in developing countries is increasingly focused on the adoption rates of alternative water-lifting technologies among smallholder farmers [10,16,17]. Literature on the impacts of access to irrigation on rural households' returns is also well established [18,19]. Despite this, empirical evidence on the relationship between energy technology choice and net agricultural returns is remarkably scant, although farm profitability likely varies across water-lifting technologies. Dittoh et al. [20] examined the potential of small pumps in Ghana and found that using pumps is far more beneficial than manual and gravity irrigation systems. Meanwhile, Balana et al. [21] found that using watering cans is associated with higher investment returns and lower risk due to the low cost of this approach, while smallholder farmers using diesel pumps have higher net income. The higher revenue per plot that is sometimes obtained from irrigation with simpler technologies highlights the influence of fuel and initial investment cost barriers that hamper the take-up of motorized pumps, especially among capital-constrained smallholder farmers [20,21].

Investment costs for irrigation pumps powered by different energy sources can vary widely across locations, reflecting local fuel availability and technical considerations such as feasible pumping depth, lifting capacity, and efficiency. For example, Scott and Sharma [22] studied electricity supply and groundwater development trends over two decades in India and found heavy reliance on diesel power owing to insufficient electricity supply, as well as pricing issues. Similarly, Rubio-Aliaga et al. [23] reported that diesel pumps are often preferred over solar PV pumps because seasonal irrigation needs may not align with the timing of solar generation and because diesel systems typically require lower upfront investment. More broadly, high energy costs and limited electricity access – which increase dependence on diesel and petrol pumping – continue to constrain the adoption and effective use of water-lifting technologies across much of sub-Saharan Africa [24].

A study conducted across various countries in Sub-Saharan Africa by Xie et al. [25] found that solar-powered pumps can be more cost-effective than diesel pumps for groundwater irrigation. Recent evidence from Ethiopia further shows that solar-powered mini-grid irrigation systems can provide a viable alternative to diesel-based irrigation by reducing operational costs and improving long-term economic viability, although affordability and infrastructure constraints remain important challenges [15]. In Ethiopia, farmers often prefer motorized pumps because of their productivity advantages, although financial constraints remain a major barrier to adoption [26].

Despite these important insights, prior studies do not generally differentiate across irrigation technologies and focus mainly on technology adoption and willingness to pay, without isolating the effect of irrigation energy source choice on net agricultural returns. Thus, limited attention has been given to understanding how energy-related factors influence farm net returns across different irrigation systems. This gap is particularly important in Ethiopia, where low grid connectivity, rising fuel prices, and high capital costs continue to constrain irrigation expansion and agricultural intensification. At the same time, recent policy efforts promoting solar and renewable energy technologies are creating new opportunities for

a different irrigation development path. This transition is particularly relevant given growing evidence that such energy options may improve both the economic and environmental sustainability of irrigated agriculture in Ethiopia [15].

This study contributes to the literature in three important ways. First, it is among very few studies, so far as we are aware, to compare net returns across multiple irrigation energy technologies using rigorous counterfactual estimation approaches. Second, it combines household survey and plot-level data with qualitative evidence and geo-referenced biophysical information to provide a more comprehensive assessment of irrigation energy choices and farm performance. Third, it generates policy-relevant evidence to inform Ethiopia's ongoing transition toward cleaner and more sustainable irrigation energy systems.

The findings highlight clear differences in energy cost structures, crop choices, input use intensities, and net farm returns among farmers using manual, diesel, and electric pumps, as well as gravity-based canal irrigation. Electric motor pumps generate the highest net returns, followed by manual pumps, while diesel pumps are associated with lower net returns due to high fuel and maintenance costs. These results underscore the importance of reducing energy-related constraints to improve agricultural productivity and the economic returns of irrigation investments among smallholder farmers.

The paper is organized as follows. Section 2 presents the data sources and empirical strategy. Section 3 reports the descriptive and econometric results. Section 4 discusses the findings. The final section summarizes the findings and discusses their policy implications.

2. Methodology

2.1 Data and study areas

The data for this study come from a cross-sectional survey of smallholder irrigators in four regions of Ethiopia, i.e., Tigray; Amhara; Oromia; and Southern Nations, Nationalities, and Peoples (SNNPR) regions. The survey was conducted in 2016/17 to analyze the economics of irrigation systems from technological and management perspectives. The sample is composed of 464 irrigation farm households and their plots (both irrigated and rainfed); these plots were used during *Meher* (the main rainy season which lasts from June to September) as well as the irrigation season (November to May) of 2015/16. In total, information was gathered on 1,037 irrigated and 1,580 rainfed plots; in this paper, we only consider production from the irrigated plots. The survey gathered information on household and farm-land characteristics, crop production, input use, irrigation technologies and management systems, crop sales, labor use, livestock, access to credit, soil conservation, household income, expenditure and consumption, social protection, and shocks. It also contains detailed information on the sources of energy used to lift irrigation water, ownership status of the pump, rental cost (if rented), year of purchase, price, installation cost, source of finance, cost of fuel or electricity, and maintenance costs. Details of the study locations, sampling techniques, agro-ecological zones, and types of irrigation are described in Bekele et al. and Bekele and Mekonnen [27,28]. It is worth noting that the adoption of solar-powered irrigation technologies was very limited in Ethiopia at the time of the survey. Recent studies show, however, that solar powered irrigation pumps offer an inexpensive and effective alternative to electric- and diesel-powered motor pumps [13,15,25,29–33].

The survey data were further merged with temperature and precipitation data for the period 1981–2016 based on georeferenced farm household-level latitude and longitude coordinates, as described in Bekele and Mekonnen [27]. The GPS coordinates of households were also used to obtain average slope of the farms, distance to rivers and streams, and electricity transmission network data. Data on the price of diesel during 2016/17 was obtained from the Ethiopian Central Statistical Agency.

Furthermore, in-depth focus group discussions (FGDs) and key informant interviews (KII) were conducted with irrigator farmers and community representatives, respectively, to obtain deeper insights on irrigation practices common in the different study locations. The FGD included a water master, a member of the local water user committee, an irrigation guard, a member of the local women's forum, an elder, a religious leader, a development agent, and an ordinary farmer. The KIIs

were used to collect village-level information pertaining to access to services, irrigation services, agricultural input and output prices, and perceptions of the relationship between irrigation and livelihoods.

Ethics statement. Ethical approval for the study was obtained from the Research Ethics Committee at the Center for Development Research (ZEF), University of Bonn, Germany, prior to data collection. Research clearance was also granted by the relevant governmental bodies in Ethiopia, including the then Ministry of Water and Energy, the Ministry of Agriculture and Natural Resources, as well as the respective regional bureaus. Community-level approval was secured through consultations with local administrative authorities and community leaders. At each study site, the research team engaged with *kebele* administrators and community elders, who provided consent for the study to proceed.

In our data collection, informed verbal consent was obtained from all participants prior to their involvement in the study. Since the interviews were conducted in local languages across all study areas, the consent process was explained in the local language and documented by trained enumerators on the survey form, with a checkbox indicating that verbal consent was granted. For households where the head was not literate, enumerators explained the consent information in the local language, and a community representative or local government official (most often an extension worker) served as a witness. Participants were provided with a clear explanation of the study's purpose, procedures, potential risks, and their rights, including the right to withdraw at any time without any negative consequences.

Verbal consent was documented by trained enumerators and the researcher (the first author of this paper) during the household surveys, focus group discussions, and key informant interviews. The study included only adult participants: household and plot-level surveys and focus group discussions were conducted with adult farming household heads, while key informant interviews were carried out with farmers, local irrigation experts, and government officials who have in-depth knowledge of irrigation systems and practices in Ethiopia.

Given the rural and low-literacy context of the study areas, verbal consent was considered the most appropriate approach and was reviewed and approved by the Institutional Review Board (IRB) of the Center for Development Research (ZEF), University of Bonn, which authorized the use of verbal rather than written consent due to literacy constraints and cultural appropriateness. The study adhered to the ethical principles outlined in the *Guidance for Ethical Clearance* of the Center for Development Research (ZEF), University of Bonn, for research ethics.

Data collection was conducted from December 2016 to March 2017, focusing on the 2015/16 production year. The objective of the study was to analyze the economics of irrigation, with a particular emphasis on the technologies in use and irrigation management. Additional information regarding the ethical, cultural, and scientific considerations specific to inclusivity in global research is included in the Supporting Information ([S1 Checklist](#))

2.2 Econometric approach

Analyzing the impact of the energy source a particular farmer uses for irrigation on her/his returns requires estimation relative to an unobserved counterfactual: what would the return from an alternative irrigation energy source have been if the farmer had adopted another instead? We use other farmers, who make different energy choices, to approximate this counterfactual. Unfortunately, a naïve comparison across farmers may lead to biased estimates of impact owing to sample selection. To estimate the impact of using various types of energy sources on net returns, this study primarily follows a multivalued treatment effects approach [34–38]. This method allows us to estimate the treatment effects when there are more than two levels of treatment. Inverse Probability Weighted Regression Adjustment (IPWRA) estimation method is used to estimate the Potential Outcome Means (POM) of net returns associated with each irrigation energy source and to conduct pair-wise comparison to find Average Treatment Effect on the Treated (ATT). The method enables us to compare the outcomes between each pair of treatment options (gravity (canal), manual pump, diesel motor pump, electric motor pump, and pressurized irrigation system)[37–39]. In addition, the propensity score method is applied [40–43]. PSM allows construction of counterfactuals using observational data that reduce two sources of bias in the observational data, bias due to lack of distribution overlap and different density weighting. Unlike multivalued treatment estimators such as IPWRA,

the focus of propensity score matching estimators is often the effect of a binary treatment on some outcome variables. In our case, the impact of each energy source to access irrigation as a binary treatment on net return.

Multivalued treatment effects approach: Inverse Probability Weighted Regression Adjustment (IPWRA). IPWRA estimation method is utilized to define the average net return of each treatment group (gravity (canal), manual pump, diesel motor pump, electric motor pump, and pressurized irrigation system) and make pair-wise comparisons to find ATT. This approach helps reduce validity threats arising from selection bias due to observable confounds that may be correlated with the outcome variables. Specifically, IPWRA uses probability weights to obtain outcome-regression parameters that account for the missing data problem arising from the fact that each subject is observed in only one of the potential outcomes. A first model is used to predict treatment status, and a second then considers outcomes as a function of treatment status, with outcome-regression parameters used to compute averages of treatment-level predicted outcomes. The contrasts of these averages then provide estimates of the treatment effects. Because IPWRA estimation technique has the double-robust property, only one of the two models must be correctly specified for the IPWRA estimator to be consistent.

As a first step, the conditional probability model is constructed to predict the probability that irrigated plot i ($i = 1, \dots, N$) being in each treatment group k (1 = gravity, 2 = manual, 3 = diesel, 4 = electricity, 5 = pressurized system). Hence, we can write the conditional probability as follows:

$$T_{ik} = \begin{cases} 1 & \text{if } \tau'_k Z_i + \epsilon_{ik} > 0 \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where T_i denotes as treatment status of plot i ; $k = 1, 2, 3, 4, 5$ (indicates alternative status--energy sources); Z_i is a vector of observed characteristics for plot i , including household, farm, village, irrigation scheme, and biophysical characteristics; τ_k vector of parameters associated with treatment alternative k ; and ϵ is the error term. It is assumed that the error term ϵ_{ik} is independently and identically distributed (iid) and follows a logistic distribution. Thus, we use the multinomial logit model to estimate the probability that plot i is in treatment level k according to the following model:

$$P\left(T_i = \frac{k}{Z}\right) = \frac{\exp(\tau'_k Z)}{1 + \sum_{j=2}^5 \exp(\tau'_j Z)} \quad (2)$$

The basic assumption of this model is that selection is based on observable characteristics of the households, farm, village, scheme characteristics and bio-physical factors. There is sizable common support between the conditional probability densities of the plots in all alternative groups (treatment levels). The IPWRA estimator is well suited to account for selection into different irrigation alternatives based on observed characteristics.

In the next step, we examine the net return of each alternative in year 2015/16, using a linear specification, to specify the potential-outcome model with five treatment groups as follows:

$$NetReturn_{ki} = \beta_k + \alpha_k XH_i + \delta_k XF_i + \sigma_k XV_i + \nu_k XS_i + \vartheta_k XC_i + \epsilon_{ki} \quad (3)$$

Where $NetReturn_{ki}$ is the potential net return (USD/ha) for plot i under irrigation alternative k , that is modeled to be a function of a vector of exogenous factors (X) which include: household characteristics (XH), farm characteristics (XF), village characteristics (XV), scheme characteristics (XS), agro-ecological and climate characteristics (XC) and ϵ_{ki} is the error term.

In our application of the IPWRA estimation, a multinomial logistic model is employed to predict the treatment status, and the outcome variable (net return/ha) is then modelled as a linear function of the covariates for each of the five treatment categories.

Estimation of average treatment effects on the treated. The ATT indicates how the average outcome would change for irrigators who adopted one particular irrigation alternative had they instead adopted another irrigation alternative. The ATT is the average effect of adopting irrigation alternative k rather than alternative l among irrigators who actually adopted

alternative k . In our case, this represents the difference between the net return earned under a particular irrigation alternative and the potential net return these same irrigators would have earned had they adopted another irrigation alternative. The pairwise ATT can be expressed as:

$$ATT_{k,l} = E(Y_i(k) - Y_i(l) | T_i = k). \quad (4)$$

Where $Y_i(k)$ denotes the potential net returns for plot i under irrigation alternative k , $Y_i(l)$ denotes the potential net return for the same plot under irrigation alternative l and $T_i = k$ indicates that plot i actually received treatment k . Thus, $ATT_{k,l}$ represents the average difference between the net returns of irrigators who adopted alternative k and the net returns they would have obtained had they instead adopted alternative l . With five irrigation alternatives, $k, l \in \{1, 2, 3, 4, 5\}$, with $k = 2, 3, 4, 5$, allowing pairwise comparisons across the five alternatives. While comparing the outcomes between each pair of treatment alternatives, the basic assumption is that prices of goods are held constant.

The treatment and outcome models include a set of covariates expected to jointly influence irrigation energy technology adoption and farm net returns, based on previous empirical studies and the conceptual understanding of factors affecting irrigation technology choice and farm performance. These covariates include household characteristics - XH - (household head age, education, household size and total livestock ownership), farm characteristics - XF - (plot fragmentation, plot size, agricultural input variables (fertilizer and improved seed use)), market access and institutional variables - XV - (transport access and land allocation), and agro-climatic characteristics - XC - (Meher rainfall variability and NDVI). In this IPWRA estimation, a multinomial logic model is first employed to predict the treatment status, and the outcome variable (net return/ha) is then modeled as a linear function of the covariates. Details of all explanatory variables are provided in [Table 1](#).

Matching methods. Propensity score matching (PSM) methods [40–43] are widely used to estimate the treatment effects when all treatments confounders are measured. The propensity score is the conditional probability of assignment to a treatment given a vector of covariates, including the values of all observed treatment confounders. The first step of PSM is estimation of the propensity score using probit – which is the model we use – or logistic regression. For each irrigation energy alternative, a binary treatment indicator T_i is defined, taking the value 1 if plot i uses the particular irrigation energy alternative being considered and 0 if it uses any of the other alternatives. Thus, the propensity score, $P_r(T_i = \frac{1}{X_i})$, is defined as the conditional probability of receiving the particular treatment, given a set of observed covariates. The conditional probability that plot i receives the particular treatment, conditional on observed characteristics X , is given by:

$$P(X_i) = P_r(T_i = 1 | X_i) \quad (5)$$

After obtaining the estimated propensity scores, step 2 consists of matching treated and comparison observations to create a new sample in which observations have approximately similar probabilities of receiving the treatment. Among the many matching algorithms, we employed the nearest neighbour approach, which identifies the comparison observation with the closest propensity score to that of each treated observation. In addition, to assess the robustness of our findings, we employed additional matching algorithms, including kernel matching and radius matching with a caliper, as reported in the Supporting Information ([S2](#) and [S3 Tables](#)).

The matched sample is intended to improve comparability between the treatment and comparison groups with respect to observed covariates. Under the conditional independence assumption, treatment assignment is assumed to be independent of potential outcomes conditional on these observed covariates. Finally, in step 3, outcomes are compared between the treated observations and their matched comparison observations to estimate the average treatment effect on the treated (ATT). Then, the ATT is:

$$ATT = E[Y_i(1) | T_i = 1, P(X_i)] - E[Y_i(0) | T_i = 1, P(X_i)] \quad (6)$$

Table 1. Summary statistics of explanatory variables included in the analysis.

Variable Name	Mean	Std. Dev.	Min	Max
Household Human capital				
Sex of the household head, 1 = male, 0 = otherwise	0.92	0.27	0	1
Age of the household head (in years)	44.20	12.07	20	85
Education level of the household head (in years)	5.29	5.01	0	19
Family size, (in number)	6.10	2.19	1	15
Years of experience in using irrigation water	9.32	8.64	2	71
Number of training participated in 2015/16	1.11	2.10	0	15
Frequency of contact to extension worker in 2015/16, (in number)	17.97	43.45	0	265
Household physical capital				
Livestock ownership (in TLU)	5.05	5.60	0	51.61
Village level characteristics				
Walking distance to woreda market (in min, one way)	35.09	34.63	0	120
Distance to the nearest grid (in m)	6385	4866	0	26229
Local price of diesel (USD)	0.67	0.01	0.65	0.69
Distance to the nearest river or stream (in m)	4597	4624	0	19410
Plot Characteristics				
Irrigation plot size (in ha)	0.40	1.3	0.01	40
1=if the soil type is loamy	0.60	0.49	0	1
Average slope	2.28	3.34	0	22.00
1=if it is allocated by government	0.41	0.49	0	1
1=if improved seed was used	0.44	0.50	0	1
1=if pesticides/herbicides applied	0.58	0.49	0	1
1=if fertilizer was used	0.70	0.46	0	1
Climate variables				
<i>Meher</i> precipitation coefficient of variation	23.22	6.88	15.107	36.46
<i>Belg</i> precipitation coefficient of variation	16.23	8.43	7.376	34.44
Mean annual temperature (in °C)	17.14	1.32	14.937	21.03
<i>Meher</i> mean total precipitation (in ml)	670.04	273.49	338.66	1179.47
<i>Belg</i> Mean total precipitation (in ml)	262.13	98.86	90.91	419.08
Elevation (in m)	1854	322.00	1245	2780
Types of energy used to lift irrigation water				
1=Gravity	0.52	0.50	0	1
1=Manual	0.07	0.26	0	1
1=Diesel pumps	0.27	0.45	0	1
1=Electric pump	0.05	0.22	0	1
1=Pressurized	0.08	0.28	0	1
Number of observations(plots/households)	1037/464			

Source: Author's computation based on survey data.

Note: Summary statistics by energy alternatives is provided in Supplementary Information [S1 Table](#). All values are in USD at the exchange rate in January 2017.

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where $Y_i(1)$ denotes the potential net return for treated plot i under the particular irrigation energy alternative being evaluated, $Y_i(0)$ denotes the potential net return for the same plot under the other irrigation alternatives, $T_i = 1$ identifies plots using the particular alternative, and $P(X_i)$ is the estimated propensity score. Our PSM analysis was implemented in Stata using the `psmatch2` and `teffects psmatch`.

We employed IPWRA and PSM to estimate the impact of energy source choices on net returns from irrigation. These methods were selected primarily because our analysis is based on cross-sectional data, which limits the applicability of panel-based approaches such as fixed-effects or difference-in-differences (DiD) models that require repeated observations over time or a clearly defined treatment timeline.

We specifically chose the multivalued treatment effect framework within IPWRA because it allows for the estimation of treatment effects when there are more than two categories—in our case, multiple irrigation energy sources. This approach enables us to estimate the mean net returns associated with each energy type and to conduct pairwise comparisons to compute the Average Treatment Effect on the Treated (ATT). Moreover, IPWRA's doubly robust nature—combining both treatment and outcome models—helps mitigate selection bias in observational data and yields consistent estimates as long as either model is correctly specified. This makes IPWRA particularly well-suited for our context, where selection into irrigation energy alternatives based on observed characteristics is an important consideration.

PSM was used as a complementary robustness check, allowing us to compare outcomes across different energy source user groups while controlling for observable differences in household, farm, village, scheme, agro-ecological, and climatic characteristics.

There are several limitations to each of these approaches. IPWRA relies on the correct specification of at least one of the models to ensure consistency, while PSM may be biased by unobserved confounders and often suffers from loss of sample size due to the matching process. Both methods assume that selection into treatment is based on observable characteristics; as such, they only address selection bias to the extent that the observed covariates included in the models adequately account for treatment selection.

Indeed, the validity of the estimates in these frameworks relies on several key assumptions holding, including the conditional independence (ignorability) assumption and the overlap (common support) assumption. First, the conditional independence assumption requires that, conditional on observed covariates, treatment assignment is independent of potential outcomes. In this study, the plausibility of this assumption is strengthened by including a rich set of household, plot, village, climatic, market access, and bio-physical characteristics in both the treatment and outcome models. Second, the overlap (common support) assumption requires that households have a positive probability of adopting different irrigation energy technologies conditional on their observed characteristics (see S1–S5 Figs in [S2 File](#); S6–S10 Figs in [S3 File](#) in the Supporting Information for details). To assess the plausibility of this assumption, we examined propensity score distributions and conducted covariate balance diagnostics before and after weighting. The balance statistics indicate substantial improvement in covariate comparability after weighting and suggest reasonable overlap across treatment groups (refer to S11–S15 Figs in [S4 File](#); S4–S8 Tables in [S1 File](#) in the Supporting Information).

Furthermore, the IPWRA estimator is doubly robust, meaning that treatment effect estimates remain consistent if either the treatment model or the outcome model is correctly specified. Nevertheless, because the analysis relies on observational cross-sectional data, bias arising from unobserved confounding factors cannot be completely ruled out.

Net return definition, cost exclusions, and value of labor. Net return in this study is defined as the difference between the value of total output (with all units of production imputed at market price whether they were sold or not on the market) and total variable costs of farm operation (including the cost of seed, fertilizer, agro-chemicals, fuel, electricity, hired labor, imputed costs of household and exchanged labor, and maintenance costs). Capital expenditure to set up the dams or river diversions of gravity systems, the cost of construction of distribution canals for such gravity systems, the cost of manual, diesel and electric pumps, and the cost of installing pressurized systems were not included in the net return. These are farm gate returns excluding taxes and transportation costs to sell output to markets. These costs were excluded from the net return calculations because the analysis focused on annual operating profitability and recurrent production costs. Capital investments represent one-time expenditures and differ across irrigation technologies in terms of useful lifespan, replacement schedules, and depreciation patterns. Therefore, incorporating these costs into annual net returns would require additional assumptions regarding annualized depreciation and equipment lifespan. Consequently,

the estimated net returns presented in this study reflect annual operational performance rather than full lifecycle profitability. Technologies with relatively high upfront investment costs, such as large-scale canals and pressurized irrigation systems, may therefore generate lower returns if annualized capital costs are included.

Household and exchange labor were valued using household-estimated local wage rates to approximate their opportunity costs and ensure comparability with hired labor costs in the calculation of net returns. This approach captures local labor market conditions and seasonal variation in labor demand. Since labor requirements differ substantially across agricultural activities and irrigation technologies, the estimated net returns reflect not only differences in productivity and operating costs but also differences in labor use intensity and associated opportunity costs.

3. Empirical results

3.1 Descriptive results

3.1.1 Irrigation use and energy options in Ethiopia. About 52 percent of the irrigated plots in the sample use gravity to convey water from the source to their plots. Diesel-based motor pumps are used to lift water onto 28 percent of the sampled plots. Electricity is used in 14 percent of the irrigated plots, with 8.4 and 5.3 percent using pressurized and electric motor pumps, respectively. Manual water lifting methods such as pedal pumps, rope, and washer pumps or watering cans are used on 7 percent of the irrigated plots (refer [Table 1](#)). As is common throughout sub-Saharan Africa, in Ethiopia, pumps are mostly imported, especially from China and India. And though the situation may change in the future as rural electrification advances, most irrigation pumps currently operating in rural Ethiopia are diesel-powered [13], as shown by the above percentages.

Groundwater and rivers are the main sources of water for irrigation in Ethiopia, with ponds and springs playing a minor role. In the study sample, all electric pumps, 77 percent of manual pumps, and 46 percent of diesel pumps use groundwater. About 23 percent of manual pumps and 50 percent of diesel pumps are used in plots that use rivers as their source of irrigation water. Finally, about 4 percent of diesel pumps are used on plots that source their water from ponds and springs.

As [Fig 1](#) depicts, the majority of manually operated pumps (65 percent) irrigate from shallow wells with a depth of less than 7 meters. About 45 percent of diesel-powered irrigation wells are deeper than 7 meters. On the other hand, 85 percent of irrigators that use electric pumps withdraw water from wells that are deeper than 50 meters. These differences in well depths by pump types have implications for the amount of water that can be obtained from the well, energy costs, and farm net returns. The cost of a manually drilled well ranges from USD 18 to USD 200 and is significantly lower than motorized drilling, which costs approximately USD 1,200 to USD 1,600 at a depth of 6–12-meters. Farmers who have

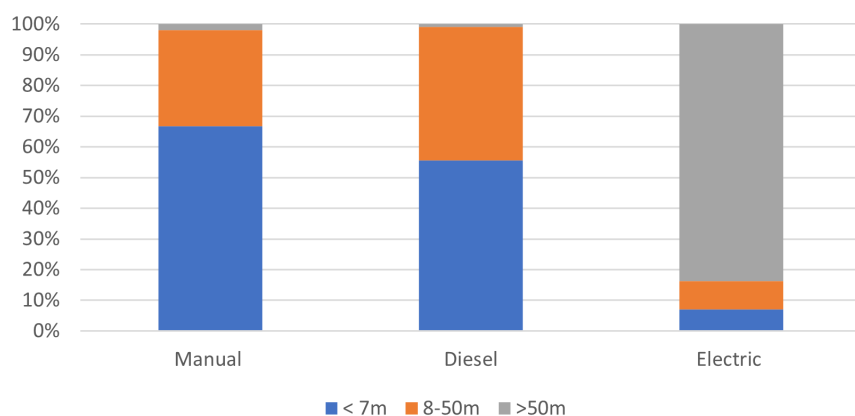


Fig 1. Depth of groundwater by energy source.

<https://doi.org/10.1371/journal.pwat.0000601.g001>

developed private irrigation are often able to obtain assistance from *Kebele* (the smallest administrative units in Ethiopia) and *Woreda* (district, the third-level administrative division of Ethiopia) offices to dig and prepare shallow wells and boreholes.

In the study sample areas, most diesel pumps (88 percent) were found to be solely owned by the irrigating household, while 9 percent were jointly owned with other households, and 3 percent by farm associations. Electric pumps, on the other hand, tend to involve significant collective action, as 53 percent of them were owned by farm associations and 30 percent were jointly owned with other farm households. Six in ten manual pumps were owned by households while four in ten were jointly owned with other households.

Electric pumps are the most expensive pumps to purchase, at a price of around USD 435 (Table 2). The cost of installation and accessories is highest for diesel pumps, with large variation observed among the minimum (USD 0) and maximum amounts paid (USD 404). The cost of fuel and electricity was reported to be USD 421 and 416 on average per hectare for diesel and electric pumps, respectively, in the irrigation season of 2015/16 (Table 2). On average, farmers who did not own a pump paid USD 76 and USD 47 per irrigation season to rent diesel and electric pumps, respectively.

Annual repair and maintenance costs were highest for diesel pump users, averaging around USD 186, as shown in Table 2. This finding was supported by focus group discussions (FGDs) with irrigation water users and key informant interviews with *woreda* and *kebele*-level irrigation experts. These discussions revealed that a major challenge associated with motor pumps in the study areas is the lack of accessible and reliable repair and maintenance services. Generally, repair and maintenance costs vary significantly depending on the size, model, and frequency of use of the pump. In addition to these costs, several construction-related issues were reported, including the collapse of dug wells during construction and drilling failures caused by rocky soil conditions. These findings are consistent with those reported by Balasubramanya et al. [44].

Another issue worth highlighting is the volatility of fossil fuel prices on the international market. The average price of diesel in Ethiopia was 0.64 US dollars per liter in 2016/17 (at the time of the survey). The increasing cost of diesel was a concern voiced by many diesel irrigators. The use of diesel fuel is also more expensive in rural areas due to the remoteness of the sites and high transport costs. In FGDS, farmers pointed out that they had to buy diesel from retail sellers who raised their prices well above the official rate. This rising cost of fuel, plus transportation and other operation and maintenance costs, was making the use of diesel irrigation pumps expensive and less attractive. Volatility of energy prices was less of an issue for those using electric-powered motor pumps, given the low price of electricity in Ethiopia at the time (which has recently increased substantially, however). An additional difference between the two power sources is the long-run effect of diesel consumption on the environment. Since the main source of electricity in Ethiopia is hydropower energy, emissions from electrical pump use are much lower than those from diesel pump use. Studies have shown that a major source of greenhouse gas emissions in rural areas is from use of fossil fuel energy for operating irrigation pumps, especially diesel-powered ones [45–47].

Table 2. Key characteristics of pump irrigation systems and related costs.

	Manual		Diesel		Electric	
	Mean	SD	Mean	SD	Mean	SD
Years of experience in using the pump (yrs)	5.9	10.2	4.78	3.97	7.29	3.34
Price of the pump	142.68	210.34	370.39	224.75	434.85	220.49
Installation cost	5.31	6.00	62.88	97.98	19.83	37.63
Fuel/electricity cost per hectare	0.00	0.00	420.65	440.03	416.36	500.47
Repair and maintenance	35.63	47.93	185.84	319.54	27.62	24.22
Cost for rent	0.00	0.00	76.41	86.35	47.11	48.62

Note: All values are in USD at the exchange rate in January 2017.

<https://doi.org/10.1371/journal.pwat.0000601.t002>

Pressurized irrigation systems, mainly observed in Kobo-Girana and Golgol Raya Valley, require substantial initial infrastructure investment and depend heavily on reliable electricity supply. FGDs revealed that worn-out pipes, clogging, and frequent power interruptions increasingly reduce system performance and farmer returns over time. The cost of electricity in these systems ranges from 228 USD to USD 479 per season per hectare, in Koba Girana and Golgol Raya, respectively (Table 3).

For gravity-based systems, both small-scale traditional and large-scale irrigation schemes were included in the sample. Rivers are the main source of water for the small irrigation schemes, while both dams and rivers play significant roles in supporting large and medium irrigation schemes (Table 4). The small systems typically rely on diversion weirs made from local materials that require annual maintenance. Furrow irrigation is more common in small irrigation schemes while flooding irrigation is more common in large and medium irrigation schemes (Table 4). The average operation and maintenance cost is small in gravity-based irrigation systems, at around 9 USD/ha/irrigation season (Table 4).

3.1.2 Cropping patterns. Fig 2 shows the distribution of crops grown in the study areas during the 2015/16 irrigation seasons, in areas serviced by different energy options. The major crops were vegetables, such as onion, tomato, cabbage, and pepper, which accounted for 35 percent of the plots included in the study, followed by perennials (26 percent) such as the stimulant leaf *chat/qhat*, false banana (*enset*), banana, and coffee. The share of vegetables, roots, and tubers was higher for irrigated plots using manual and diesel pumps, compared to plots using pressurized pumps, electric pumps, and gravity methods. Given the higher market prices, these cropping choices have important implications for farm net return. On the other hand, the share of grains grown on irrigated plots was higher where pressurized pumps, electric pumps, and gravity methods were in use (Fig 2).

Gravity irrigators complained about the mismatch between the command area under irrigation and the amount of water distributed during the irrigation seasons. As we learned in FGDs, the reliability of the irrigation water supply is affected by the number of irrigators drawing water from a single source. Large surface systems with many irrigators showed difficulty

Table 3. Operation and maintenance of pressurized irrigation schemes.

	Golgol Raya (Alamata)		Koba Girana (Kobo)	
	Mean	SD	Mean	SD
Year of irrigation experience	4.06	2.62	10.66	2.22
Electricity cost/ha/ irrigation season (USD)	479.06	361.88	227.84	167.09
Operation and repair cost/ha/ irrigation season (USD)	33.09	48.95	16.04	14.75

Note: All values are in USD at the exchange rate in January 2017.

<https://doi.org/10.1371/journal.pwat.0000601.t003>

Table 4. Characteristics of gravity (canal) irrigation schemes.

		Small	Large/medium
Source of irrigation water (%)	River	82.2	47.12
	Dam	14.14	52.88
	Pond	3.66	0.00
Techniques applied in the farm (%)	Flooding	38.74	61.83
	Furrow	61.26	38.17
Mean of year of irrigation experience		12.38 (9.21)	12.32(10.40)
If contributed at the initial stage (%)		65.00	38.00
Average O&M cost in labor days/ha/irrigation season (in USD)		7.59 (9.24)	7.56(10.08)
Mean O&M cost in cash/ha/irrigation season (in USD)		9.14 (19.66)	9.86(12.08)

Standard deviations in parenthesis.

<https://doi.org/10.1371/journal.pwat.0000601.t004>

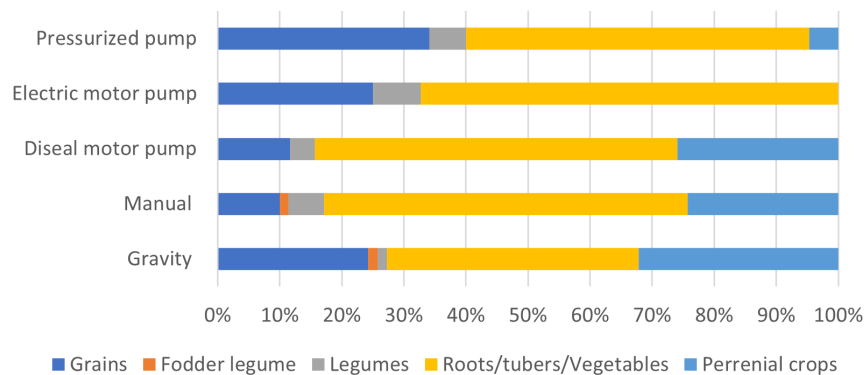


Fig 2. Crop produced in irrigation season by energy type.

<https://doi.org/10.1371/journal.pwat.0000601.g002>

in delivering water throughout the dry season. Farmers indicated that water shortage forced them to shift from cultivating high value crops to traditional crops that were less sensitive to supply interruptions and required smaller amounts of water.

3.1.3 Input use and value of production of irrigation using various energy sources. Table 5 presents statistical summaries of variables on input use and the value of production from irrigated plots, by irrigation energy source. The highest total value of production appears in the irrigated plots using diesel pumps, whereas the highest net return is observed from the manually operated irrigation systems (Table 5). High fuel costs to power pumps and maintenance costs

Table 5. Average input uses and value of output from plots irrigated with various energy options (in USD per season).

Input type	Gravity	Manual	Diesel	Electricity	Pressurized system
Cost of local seed per hectare	13.76 (0.90)	14.68 (2.39)	13.82 (1.21)	15.49 (2.27)	16.58 (2.76)
Cost of improved seed per hectare	19.37 (46.61)	18.63 (22.97)	24.49 (18.34)	28.03 (43.07)	25.73 (27.74)
Cost of chemical fertilizer per hectare	133.54 (5.77)	140.40 (16.87)	185.73 (9.41)	102.16 (12.56)	92.11 (9.77)
Cost of agro-chemicals per hectare	49.49 (4.39)	29.55 (9.95)	52.92 (6.78)	59.67 (13.63)	41.50 (5.16)
Family labor days (in adult equivalent) per hectare	109.14 (2.72)	120.82 (8.95)	129.59 (5.84)	118.55 (10.73)	110.54 (8.38)
Hired labor days per hectare	26.16 (3.19)	33.37 (13.72)	76.20 (9.60)	81.45 (15.04)	41.50 (8.23)
Exchange labor days per hectare	4.35 (0.81)	0.32 (0.32)	1.65 (0.62)	2.67 (1.23)	7.75 (2.96)
Total labor days per hectare	142.99 (4.13)	145.89 (13.68)	182.29 (8.91)	172.58 (12.24)	165.35 (10.31)
Total cost of labor per hectare	325.68 (9.22)	295.41 (23.29)	318.61 (19.43)	343.35 (33.71)	313.50 (19.99)
Total value of output per hectare	1483 (1570)	1914 (1887)	2083 (2102)	1640 (1734)	1969 (2078)
Total net value of output per hectare	658 (794)	1114 (1118)	1097 (1346)	715 (925)	1054 (1144)
Number of observations	537	73	283	55	87

Note: Standard errors in parenthesis.

<https://doi.org/10.1371/journal.pwat.0000601.t005>

are the main reasons for the low net returns of diesel pumps compared to manual pumps. The lowest total production cost as well as net return is observed in the group that used gravity-based canal irrigation, possibly because of limited water availability in these systems, which pushes irrigators to shift from growing high value crops to traditional cereal crops. This result is consistent with prior studies [20,48–50] that find motor pump users earning higher returns than canal irrigation users.

There are also statistically significant differences in input uses between irrigated plots that used different energy sources. Cost of fertilizer per hectare was highest on irrigated plots using diesel pumps, followed by plots using manual pumps, gravity, electricity, and pressurized systems (Table 5). On the other hand, the seed cost varied less across plots using different energy types (see Table 5). Expenditure on agro-chemicals was lowest among plots that used manual pumps. Finally, our results show that the amount of labor needed in irrigated agriculture averages 155 labor-days but differs substantially according to energy technology used. The daily wage rate multiplied by the total labor days yields the total cost of labor. The most labor was hired by diesel and electric motor pump users. Insights from the focus group discussions suggest that irrigators hire labor from rainfed farmers within the same *sub-district* and from neighboring *sub-district* that have limited irrigation opportunities.

3.2 Econometric results

3.2.1 Factors affecting adoption of various types of energy source to irrigate. The results of the first stage of the propensity score matching (PSM) - probit estimation - are presented in Table 6. The results show diesel-powered irrigation pump adoption is higher among younger irrigators, whereas older household heads are more likely to use gravity irrigation. The introduction of motor pumps to access irrigation is a very recent phenomenon in Ethiopia, and younger farmers are typically less risk-averse and are more willing to try new technologies [51,52]. Larger family size is also associated with the use of pressurized irrigation systems, while households with frequent contact with extension workers are more likely to adopt manual water-lifting technologies.

Ownership of a larger number of livestock and land holdings is also positively related to the probability of using diesel irrigation pumps. These variables proxy for greater wealth, and the relationship suggests that wealthier households are perhaps better able to adopt and finance the purchase of motor pumps. The result is consistent with previous studies by [53,54]. Expectedly, irrigators who transport their output to market using modern vehicles, who are also wealthier, have a higher probability of adopting manual and electric pumps as well as a pressurized system to irrigate. Besides indicating wealth, access to transportation (and hence markets) may facilitate farmers' use of advanced energy technology in irrigated agriculture, as this eases access to inputs and allows farmers to quickly bring fresh produce to market.

Interestingly, households with a greater number of plots are more likely to adopt manual pumps, perhaps indicating the need to balance labor requirements across multiple plots. As expected, higher diesel prices increase the likelihood of adopting manual and electric pumps and decrease the use of diesel pumps. Distance to the nearest stream or river has a negative and significant association with adopting gravity irrigation and using manual and diesel pumps, which is consistent with such farmers needing reliable access to water.

Finally, the results show that plots located in areas with higher *Meher* season rainfall variability have a higher probability of adopting manual and diesel pumps and are less likely to use gravity irrigation. Canal irrigation system, which is usually based on river diversions and small dams, itself relies on the amount of rainfall in the previous season, making it susceptible to the vagaries of nature, though to a lesser extent than rain-fed farming. On the other hand, groundwater-based irrigation is less directly susceptible to short term rainfall variability as it relies on water stored underground and recharged over longer time periods. This may reflect the value of modern irrigation technology for managing weather risks.

3.2.2 Estimation of the impact of various energy options on net return. Multivalued treatment effect results: As the first step to estimate the impact of adopting various energy sources for irrigation, we construct a conditional probability model to estimate the probability that each irrigated plot is assigned to each given alternative (see S1–S5 Figs in S2 File and S6–S10 Figs in S3 File in Supporting Information). In the second step, we estimate the conditional means of net

Table 6. Parameter estimates of adoption of water lifting technologies by energy option: first stage PSM.

Variables	Gravity	Manual	Diesel	Electric	Pressurized
Household characteristics					
Age of the household head (in years)	0.012*** (0.004)	-0.007 (0.007)	-0.02*** (0.005)	-0.005 (0.010)	0.011* (0.006)
Education level of the household head (in years)	-0.007 (0.010)	0.024 (0.017)	0.01 (0.012)	0.013 (0.025)	-0.021 (0.014)
Family size, (in number)	-0.033 (0.025)	0.011 (0.034)	-0.023 (0.027)	0.060 (0.072)	0.107*** (0.040)
Frequency of contact to extension worker in 2015/16, (in number)	0.000 (0.001)	0.004** (0.002)	-0.002 (0.002)	0.001 (0.002)	-0.002 (0.002)
Total household land holding(ha)	-0.038 (0.026)	-0.016 (0.029)	0.048** (0.024)	-0.059 (0.134)	-0.013 (0.046)
Livestock ownership (TLU)	0.004 (0.012)	-0.044* (0.026)	0.024** (0.011)	-0.030 (0.046)	-0.032 (0.025)
Fragmentation (no of plots)	-0.057** (0.024)	0.082** (0.032)	0.019 (0.024)	-0.023 (0.099)	-0.127** (0.051)
1=If the household owns vehicle	-0.58*** (0.125)	0.624** (0.279)	-0.059 (0.159)	0.534** (0.228)	0.583*** (0.161)
Village level characteristics					
Price of diesel	-3.16*** (0.483)	12.405*** (3.229)	-6.492*** (0.850)	8.35** (3.564)	-1.08* (0.605)
Distance to nearest national grid electric transmission (in meter)	0.001*** (0.001)	-0.001** (0.001)	-0.001*** (0.001)	-0.001 (0.001)	-0.001*** (0.001)
Farm characteristics					
Irrigation plot size (in ha)	0.041 (0.053)	-0.050 (0.222)	-0.037 (0.051)	0.191 (0.452)	-0.304 (0.319)
1=If fertilizer applied	0.214* (0.124)	-0.505*** (0.171)	-0.124 (0.135)	-0.017 (0.345)	-0.203 (0.204)
1=If improved seed used	-0.248* (0.140)	0.288 (0.210)	-0.048 (0.154)	0.166 (0.353)	0.345 (0.216)
Bio-physical characteristics					
Average slope	0.09*** (0.019)	-0.022 (0.025)	-0.12*** (0.025)	-0.113 (0.074)	0.014 (0.026)
Meher precipitation coefficient of variation (CV)	-0.27*** (0.021)	0.447*** (0.105)	0.365*** (0.033)	0.184 (0.394)	-0.026 (0.023)
Mean average temperature	0.932*** (0.094)	-1.788*** (0.467)	-1.50*** (0.132)	-0.147 (0.633)	0.357*** (0.125)
Normalized difference vegetation index (NDVI)	-1.54*** (0.567)	3.491*** (1.328)	1.19 (0.751)	-2.494 (2.248)	-1.160* (0.684)
Distance to stream or river in meter	-0.001*** (0.001)	-0.001* (0.001)	-0.001*** (0.001)	0.001 (0.001)	0.001 (0.001)
Constant	35.1*** (7.167)	-166.4*** (43.04)	-77.2*** (11.91)	118.58** (54.49)	9.03 (9.52)
Pseudo R2	0.39	0.25	0.44	0.51	0.32
F-p value	0.00	0.00	0.00	0.00	0.00
No of observations	537/1025	73/1025	285/1025	55/1025	87/1025

Note: The first stage was estimated using a probit specification. Standard errors in parenthesis. *, ** and *** indicate statistical significance at 10%, 5% and 1%, respectively.

<https://doi.org/10.1371/journal.pwat.0000601.t006>

farm return using IPWRA estimators. We then calculate pairwise comparisons to estimate the ATT between the different irrigation alternatives. These pairwise comparisons indicate how the net farm returns of irrigators using a particular alternative would differ had they instead used another alternative. The pairwise differences denote the changes in the net farm return with respect to the change in different alternatives (going from one alternative to another). [Table 7](#) presents the potential outcome means (net farm return in hundreds of USD/ha) of each energy option and the pair-wise comparison of ATT results. In our specification, the full list of covariates used to predict alternative (treatment) status includes age and education level of the household head, household size, access to extension service (number of contacts per year), assets used as proxies for wealth (tropical livestock units (TLU) and irrigated farm size), number of plots per household, whether the household uses a vehicle to transport its output, land acquisition (1 =allocated), whether fertilizer and improved seeds were used, the coefficient of variation of Meher season precipitation, and NDVI in the year 2016.

[Table 7](#) reports results for the multivalued treatment effect estimation of the impact of various energy options on the net returns from irrigated agriculture. It presents the estimated mean potential outcomes (i.e., the expected net farm returns)

Table 7. Estimated average potential net return (in hundred USD/ha) and average treatment effect ATT of adoption of various energy options for irrigation, from multivalued IPWRA.

Outcome	Average potential outcome $POM_t = E(y_t)$		Average treatment effect on the treated (ATT) $ATT = E\{y_1 - y_0, t=1...5\}$	
	Mean	SE	Mean	SE
Gravity (1)	6.56***	0.66		
2 vs 1			4.49***	1.46
3 vs 1			4.39***	1.24
4 vs 1			-2.14	32.17
5 vs 1			7.73***	2.98
Manual pump (2)	14.93***	4.06		
1 vs 2			-8.47***	4.08
3 vs 2			-6.74	4.16
4 vs 2			1.64	36.23
5 vs 2			-5.37	4.69
Diesel pump(3)	8.19***	0.85		
1 vs 3			-1.73***	0.91
2 vs 3			6.74	4.16
4 vs 3			8.39	36.01
5 vs 3			1.38	2.65
Electric motor pump(4)	16.58	36.00		
1 vs 4			-10.12	36.00
2 vs 4			-1.64	36.23
3 vs 4			-8.39	36.01
5 vs 4			-7.01	36.11
Pressurized irrigation system(5)	9.57***	2.44		
1 vs 5			-3.11	2.47
2 vs 5			5.37	4.69
3 vs 5			-1.38	2.65
4 vs 5			7.01	36.11

*, ** and *** indicate statistical significance at 10%, 5% and 1%, respectively.

<https://doi.org/10.1371/journal.pwat.0000601.t007>

(USD/ha) for each irrigation alternatives, as well as the average treatment effect on the treated. In our case, we have five energy alternatives: canal, manual, diesel, and electric pumps and pressurized irrigation systems.

The econometric results comparing the net returns earned from irrigation with various energy options are generally not consistent with those found in the descriptive analysis. Though irrigators with electric motor pumps have the highest net return (16.5 hundred USD/ha), the estimation is not statistically significant. One possible reason is the small sample size of farmers using electric pumps, which limits statistical power to estimate impacts. Thus, measures of estimated returns are imprecise, with wide confidence intervals, and should be interpreted cautiously. The limited number of observations for electricity users can be attributed to the broader issue of limited electricity access in the country. As a result, the adoption of electric irrigation pumps and pressurized irrigation systems remains very low.

Using manual lifting technology generates the second highest net crop return (around 15 hundred USD/ha), and a significantly higher net return than these farmers would have earned had they adopted gravity irrigation. This is consistent with previous studies done in other locations in sub-Saharan Africa and South Asia [20,55]. The third highest net return is obtained by irrigators in pressurized irrigation systems (950 USD/ha), followed closely by diesel motor pump users (800 USD/ha).

Operation and maintenance costs of irrigation systems have a significant impact on the net returns from irrigated agriculture. As previously discussed, although diesel motor pump users tend to achieve the highest total value of production, their net returns are diminished due to the high costs of annual repair, maintenance, and fuel. This finding is supported by discussions with irrigation water users, which revealed that—beyond the high operational costs—a key factor driving up expenses is the lack of accessible and reliable repair and maintenance services for motor pumps in the study areas.

The lowest net return is obtained by canal irrigators (656 USD/ha) and farm households in this kind of irrigation system would have been better off had they adopted any of the other irrigation alternatives, except electric motor pumps. For instance, using manual and diesel irrigation lifting technologies would have increased the per-hectare net return of farmers using gravity-based irrigation by 450 and 440 USD/ha. This result supports the findings from focus group discussions on crop choice, which pointed to cultivation of lower-valued crops by gravity irrigators, as a means of coping with irregular irrigation water supply in gravity irrigation systems. In these systems, it is difficult to deliver water to all farmers throughout the dry season.

This result is in contradiction with a study by Solomon and Ketema [56], which found that diversion irrigation technologies have a strong poverty reduction potential. A point worth noting is that the majority of these gravity/canal irrigated plots are located within irrigation command areas where decisions on energy options were decided during the construction of the schemes, and a shift to a different energy alternative would require significant collective action and mobilization—hence the switch to the energy options that fetch high net returns is not easy and straightforward.

Binary propensity score matching (PSM) estimation results: As the results of the multivalued IPWRA estimation may be sensitive to the underlying assumptions, PSM approach was used as a robustness check for the estimated treatment effects. The matching variables used are the same as the variables presented in the multivalued treatment effect section. We find that there is a considerable overlap in common support. Unlike the multivalued IPWRA analysis, which allows comparisons across the five irrigation alternatives, the binary PSM analysis compares users of each irrigation energy alternative with users of all other energy alternatives.

Table 8 reports the estimates of the average adoption effects estimated by the matching method. We find results generally similar to those obtained from the multivalued IPWRA analysis. Irrigators using gravity irrigation generate 1.82 hundred USD/ha lower net returns than they would have generated under the other irrigation alternatives. The average net farm returns of plots currently irrigated using diesel and electric pumps would increase by 2.26 and 4.29 hundred USD/ha, respectively, if these irrigators had instead used the other irrigation energy alternatives.

Robustness checks and identification diagnostics: Additional robustness checks were conducted to assess the validity and stability of the IPWRA and PSM estimates. First, overlap/common support diagnostics based on

Table 8. Average treatment effects from nearest neighbor propensity score matching.

Outcome	Average treatment effect on the treated (ATT), $ATT = E\{y_1 - y_0, \epsilon_{1...5}\}$	
	Mean	SE
Gravity vs others	-1.82*	1.00
Manual pump vs others	2.86	1.86
Diesel pump vs others	2.26**	1.09
Electric pump vs others	4.29***	1.44
Pressurized system vs others	1.16	1.80

Note: The values are in hundred USD/ha. *, ** and *** indicate statistical significance at 10%, 5% and 1%, respectively.

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propensity score distributions were examined across irrigation energy technology groups, indicating reasonable overlap among treatment categories, although overlap was relatively weaker for electric pump users because of the smaller sample size in this category (Supporting Information S1–S5 Figs in [S2 File](#) and S6–S10 Figs in [S3 File](#)). Second, covariate balance diagnostics were assessed before and after weighting/matching using standardized mean differences and summary balance statistics. The results show substantial reductions in standardized bias and pseudo R^2 values after weighting/matching across the treatment comparisons, suggesting improved comparability between treatment and comparison groups and reduced in observed covariates (Supporting Information S11–S15 Figs in [S4 File](#); S4–S8 Tables in [S1 File](#)).

To further assess the robustness of the findings, additional matching algorithms, including kernel matching and radius matching with a caliper, were employed to examine the sensitivity of the estimated treatment effects to alternative matching specifications and the choice of matching algorithm.. The results from these robustness checks were consistent with the main findings and are reported in the Supporting Information ([S2](#) and [S3 Tables](#)).

4. Discussion

The findings of this study highlight important trade-offs across irrigation energy technologies in Ethiopia. Although electric motor pumps generated the highest estimated net returns, the estimates were not statistically significant because of the relatively small number of electric pump users in the sample. Nonetheless, the results suggest that electric irrigation technologies may offer important economic advantages where reliable electricity access and institutional support systems are available.

Another important finding of the study is that manually operated irrigation systems generated the second-highest net returns. The relatively strong performance of manual systems appears to be driven by their low operational and maintenance costs. Unlike diesel-powered systems, manual technologies do not require fuel expenditures and involve relatively limited repair costs, making them economically attractive for many smallholder farmers. These findings suggest that lower-cost irrigation technologies may continue to play an important role in supporting profitable irrigation among resource-constrained households, particularly in areas where access to electricity, financing, fuel, and maintenance services remains limited.

Another important issue worth highlighting is the volatility of fossil fuel prices, particularly diesel prices, and their implications for irrigation technology adoption and profitability. The econometric results indicate that higher diesel prices significantly reduce the likelihood of adopting diesel-powered irrigation systems while increasing the probability of adopting manual and electric irrigation technologies. Although diesel motor pump users often achieve relatively high production values, their net returns are substantially reduced by high fuel, repair, and maintenance costs, making these systems

particularly sensitive to energy price fluctuations. Beyond their economic implications, diesel-powered irrigation systems are also associated with greenhouse gas emissions and local air pollution arising from fossil fuel combustion, raising concerns regarding their long-term environmental sustainability. Recent evidence from Ethiopia on the viability of solar mini-grid irrigation as a replacement for diesel-powered irrigation further suggests that reducing dependence on diesel-based systems through alternative technologies may generate both economic and environmental co-benefits through lower fuel consumption and reduced emissions [15].

Similarly, farmers using electric and pressurized irrigation systems frequently reported power interruptions that reduced system performance and farm net returns. Together, these findings suggest that continued increases in diesel fuel prices could further reduce the relative profitability of diesel-powered irrigation systems and strengthen the economic attractiveness of lower-cost and less fossil fuel-dependent alternatives, particularly manual lifting technologies and, where electricity access is available, electric irrigation systems.

The findings also have important implications for Ethiopia's ongoing transition toward cleaner and more sustainable irrigation energy systems, including recent restrictions on diesel- and petrol-powered irrigation pumps. While transitions toward electric and solar-powered irrigation systems may improve long-run economic return and environmental sustainability, the results demonstrate that such transitions require substantial complementary investments in rural electrification, reliable energy supply, maintenance services, financing mechanisms, and institutional coordination. Without these supporting investments, scaling electric irrigation technologies in remote rural areas may remain difficult.

5. Conclusion and policy implications

Remarkable national economic growth in Ethiopia in recent decades has led to ambitious plans to expand access to irrigation and modern energy in rural areas, despite limited evidence on the value of alternative irrigation technology strategies and options. This study aimed to enhance understanding of different energy options to support irrigation, and to compare the net returns and relative costs of these alternatives. We leveraged data collected through a cross-sectional survey conducted in 2016/17, and applied multivalued treatment effects approach, specifically the Inverse Probability Weighted Regression Adjustment (IPWRA) method, to estimate mean net returns from each irrigation energy source and to make pairwise comparisons to estimate the Average Treatment Effect on the Treated (ATT). In addition, propensity score matching (PSM) was employed as a robustness check. Qualitative analyses supplemented and deepened insights obtained in the econometric analysis. The results can be used to inform and target policies aimed at increasing adoption rates and net farm returns associated with different irrigation energy alternatives.

Descriptive results revealed that there are statistically significant differences in input use across irrigated plots using different energy types. For instance, the use of hired labor is more common among irrigators who use diesel and electric pumps, partly due to the higher share of market-oriented production in these types of irrigation which may require harvesting within a short period of time to supply local traders and aggregators. The choice of energy options in irrigated agriculture in Ethiopia is influenced by observable household, plot, village as well as bio-physical characteristics.

The multivalued treatment effect findings show that using electric motor pumps in irrigation leads to the highest net crop returns among the alternatives, yet the result is not statistically significant. Using manual lifting technology generates the second highest net crop return (around 15 hundred USD/ha), and a significantly higher net return than these farmers would have earned under gravity irrigation. The result implies that using manually operated lifting technologies can be a viable option for farmers who have plots located near water supplies but lack access to electricity. Irrigators in pressurized irrigation systems and those that use diesel motor pumps have the third and fourth highest estimated mean net returns per hectare, at 960 USD/ha and 800 USD/ha, respectively.

Several caveats, however, are needed before generalizing the findings regarding the relatively high estimated net farm return associated with electric pumps. First, the majority of manually operated pumps (65 percent) irrigate from wells less than 7 meters deep, while about 45 percent of the wells used for diesel powered irrigation are more than 7 meters deep.

On the other hand, 85 percent of irrigators using electric pumps withdraw water from wells more than 50-meters deep. These differences in well depths across pump types have implications for the amount of water available from the well, related energy costs, and farm net returns.

Second, most diesel pumps in the sample (88 percent) are solely owned by the irrigating households, while electric pumps involve significant collective action, as 53 percent of them are owned by farm associations and 30 percent are jointly owned with other farm households, with less than 17 percent solely owned by a household. Collective action issues related to water allocation, irrigation system governance, and operation, if not properly addressed, can impede the performance of pressurized electric irrigation and gravity systems relative to individually operated motor or manual pumps. Third, high fuel and maintenance costs are the main reason for the low net returns of diesel pumps. Fourth, focus group discussions with farmers show two major problems affecting the performance of the pressurized irrigation systems included in this study: (i) worn out pipes and laterals which result in clogging and impede water delivery, and (ii) frequent and long-duration power outages, which were reported by owners of individualized electric pumps as well. Farmers in the FGDs reported that these challenges could compromise their ability to cover electricity costs. As such, further investigation is needed concerning the design and delivery of reliable and affordable electric irrigation systems, and the institutional and governance support they require. In this regard, current efforts to introduce and scale up solar pumps and solar mini-grid based irrigation through public-private partnerships in Ethiopia should be studied carefully to draw relevant lessons.

In the short term, we recommend making the importation and distribution of various pump technologies as competitive as possible by addressing key bottlenecks—particularly foreign currency shortages and limited financing mechanisms—while promoting efficiency and encouraging a gradual transition to cleaner technologies. In the medium term, scaling up solar irrigation should be prioritized through targeted investments, increased public-private collaboration, and the adoption of innovative financing models. In the long term, expanding access to affordable and reliable rural grid infrastructure will be crucial to support wider adoption of electric irrigation systems across the country.

To accelerate the transition to solar-powered irrigation in Ethiopia, stronger enforcement of the diesel pump import ban and better market monitoring are needed to align practice with policy. Institutional capacity and coordination across government agencies must be improved to reduce confusion for stakeholders and attract private investment. Regional governments, responsible for implementing small-scale irrigation, require financial and technical support to meet farmer demand. Scaling up solar pump pilot projects and conducting rigorous market assessments will help identify national potential. Efficient business models along with improved access to finance for farmers and entrepreneurs, are essential to make solar irrigation affordable and scalable.

Overall, while the study makes a significant contribution to literature, it is not without limitations. It relies entirely on cross-sectional data collected, which limits to some extent the ability to establish causal relationships. To enhance the robustness of future research, collecting panel data or leveraging natural experiments would be valuable. These approaches would enable the use of quasi-experimental methods—such as difference-in-differences—to more accurately assess the impact of energy choices on irrigation outcomes and household welfare, even if experimental randomized controlled trials (RCTs) are deemed practical. Such studies should make comparisons across both existing energy sources and emerging renewable energy options.

Supporting information

S1 Table. Summary statistics of explanatory variables included in the analysis by irrigation energy source.
(XLSX)

S2 Table. Average treatment effects estimated using kernel matching.
(XLSX)

S3 Table. Average treatment effects estimated using radius caliper matching.
(XLSX)

S1 File. S4 Table–S8 Tables. Covariate balance diagnostics before and after weighting/matching, including standardized mean differences and summary balance statistics. S6 Table. Operation and maintenance of pressurized irrigation schemes. S7 Table. Characteristics of gravity (canal) irrigation schemes.
(ZIP)

S2 File. S1 Fig–S5 Fig. Conditional probability for a plot being irrigated using various irrigation energy practices.
(ZIP)

S3 File. S6 Fig–S10 Fig. Overlap (common support) diagnostics for IPWRA and PSM estimators.
(ZIP)

S4 File. S11 Fig–S15 Fig. Covariate balance diagnostics before and after weighting/matching across irrigation energy technology groups.
(ZIP)

S1 Data. Irrigation and Energy selected variables (.csv format).
(DTA)

S2 Data. Irrigation and Energy selected variables (.dta format).
(CSV)

S1 Do. Stata do-file for Irrigation and Energy analysis.
(DO)

S1 Checklist. Inclusivity in Global Research Questionnaire.
(DOCX)

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