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Global crop-specific energy demand for irrigation

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Global irrigation expansion is expected to enhance agricultural productivity in underperforming cultivated areas, yet its associated crop-specific energy requirements remain insufficiently quantified. Here, we present a spatially distributed, physically based framework that estimates crop-specific irrigation energy consumption at 10 km resolution worldwide. Currently, irrigation consumes about 1.38×10^9 gigajoules per year, of which three-quarters are used by surface irrigation systems and one-quarter by pressurized systems. Six crops—wheat, rice, maize, cotton, sugarcane, and vegetables—account for 60% of the total irrigated area and energy use. A sustainable expansion of irrigation in rainfed areas would increase irrigation energy consumption by approximately 17%, mostly in the Global South. These findings highlight that the magnitude of irrigation energy demand depends on system type, pumping depth, and climatic aridity. This study links crop-specific irrigation energy costs with productivity gains, guiding integrated planning for sustainable, climate-resilient food production.

Growth in the demand for agricultural products, accelerated by the combined effects of population growth, dietary shifts, and recent "green energy" policies, entails an increasing need for land, water, and energy for crop production[1–4]. Increased agricultural output can be achieved either through the expansion of cultivated land (i.e., "agricultural expansion") or by raising yields through "agricultural intensification"[1,5], although a combination of both approaches has typically occurred worldwide[6]. Intensification, generally achieved through fertilizers, irrigation, and other agrotechnology[2], is often regarded as the preferred path to protect natural habitats and biodiversity while meeting food demand[1,7,8].

Agricultural production more than tripled between 1960 and 2015[9], while the cultivated area expanded by only 12%[10,11]. This remarkable growth was largely achieved through the intensification of agricultural inputs, including fertilizers, mechanization, and irrigation[9]. Among these drivers, irrigation stands out because it directly governs the availability of the most limiting resource for crop growth—water. Unlike fertilizers or machinery, which improve yield only where sufficient moisture already exists, irrigation determines whether cultivation is possible at all, defining both the extent and productivity of agricultural land. Indeed, irrigation has historically played a crucial role in increasing yields, stabilizing food production, and enhancing the resilience of agricultural systems. It enables crops to rely on a more predictable water supply and mitigates heat stress, making irrigation a key adaptation tool in regions most affected by climate change[12]. Over the last five decades, more than 40% of the global increase in food production has been obtained from irrigated land, which has doubled in area[13,14]. Currently, irrigated agriculture accounts for approximately 16–20% of all arable land worldwide[12,15] and about 5.5% of the total energy consumption in the agricultural sector[16]. Irrigation, therefore, remains the cornerstone of global food security, underpinning the stability of yields and ensuring production under increasingly variable climate conditions. The potential for further irrigation expansion still exists in several parts of the world, particularly where land and water resources are available, offering opportunities to close yield

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gaps, enhance food resilience, and strengthen agricultural sustainability.

Recent studies have shown that only about 50% of currently rainfed farmland affected by water scarcity could be sustainably irrigated, in the sense that irrigation water requirements could be met without depleting environmental flows or groundwater stocks[17]. Potential for sustainable irrigation expansion exists across every continent (except Antarctica), with particularly strong potential in Sub-Saharan Africa and Eastern Europe, where irrigation development has historically been limited by economic and institutional barriers rather than by physical water scarcity – a condition referred to as "economic water scarcity"[18,19]. While global patterns of physical water scarcity are expected to shift under climate change[20], the persistence of economic water scarcity will continue to depend on socio-economic development and institutional capacity, including the presence of reliable energy infrastructure to meet irrigation water demand. These hydrologic and institutional constraints determine not only where irrigation expansion is possible but also where it can be considered sustainable in the long term.

Several international reports, including those by the Food and Agriculture Organization (FAO)[21,22], the International Energy Agency (IEA)[16], and the World Bank[23], emphasize that local energy limitations strongly constrain irrigation expansion. Historically, areas unsuitable for gravity irrigation began to be irrigated only with the advent of diesel engines or electric motors, depending on the available energy source. Yet, energy limitations persist as a major challenge in many rural areas of developing countries and, at times, in remote regions of developed ones. The feasibility of expanding irrigation, therefore, depends not only on water availability but also on the capacity to provide sufficient energy to withdraw, lift, pump, and apply water to agricultural land[24]. In this context, energy access becomes a critical determinant of irrigation development, particularly in areas affected by economic water scarcity, where water resources may exist but remain underutilized due to a lack of energy infrastructure. The availability of energy is thus a key enabling factor for sustainable intensification, influencing where irrigation can serve as an effective climate-adaptation strategy to cope with rainfall variability and heat stress[20,25].

Irrigation energy demand and water use vary widely across regions because they depend on multiple interrelated factors. The irrigation source, irrigation system, field size, and field properties, along with crop type and local hydrological conditions, determine the overall energy and water needs of irrigation[26]. Groundwater-based irrigation systems typically require more energy than surface-water systems because of the additional pumping head, while pressurized systems such as sprinkler or drip irrigation are more energy-intensive than surface methods[26]. Field characteristics—including slope, soil texture, and field size—affect conveyance efficiency and water delivery, thereby influencing both energy consumption and water use. These physical and management differences are critical to understanding the heterogeneity of irrigation requirements and demonstrate the need for spatially explicit, crop-specific assessments that capture how local conditions and technologies modulate irrigation energy demand worldwide.

Despite the clear importance of both water and energy for irrigation, their combined influence on agricultural productivity remains poorly quantified. How much energy is currently required for irrigation for each crop? How much additional energy is needed for sustainable irrigation expansion for these crops, and where? While global data exist on total energy use in agriculture[16,27] and on total irrigation energy demand[28], comprehensive crop-specific estimates of irrigation energy requirements are still missing. Moreover, it is not yet clear how irrigation energy demand varies geographically with respect to crop type, water source, irrigation system, and pumping depth. These knowledge gaps highlight the need for more detailed and integrated assessments that combine hydrological, agronomic, and energy dimensions to evaluate irrigation sustainability.

This article quantifies the energy requirements in irrigation, where the energy computed is directly related to irrigation itself, encompassing the processes of water withdrawal, conveyance, and application under different irrigation systems and sources. It also evaluates the potential additional energy needed to sustainably expand irrigation to rainfed areas for the most widespread irrigated crops, using multiple global crop distribution datasets. In addition, the analysis quantifies associated irrigation water consumption, thereby coupling crop-specific energy and water requirements under both baseline and sustainable expansion scenarios. By linking the spatial variability of irrigation energy and water requirements with potential increases in crop production, the study provides an integrated framework for analyzing the food–energy–water nexus. The results identify regions where water availability is sufficient, but energy limitations may restrict irrigation expansion, offering insights for sustainable agricultural intensification and energy planning. Ultimately, this global assessment contributes to understanding how energy and water constraints interact to shape the feasibility of irrigation development under future resource and climate pressures. Moreover, the results of this paper can support a more accurate evaluation of the return on investments in irrigation system expansion by considering the revenue potential linked to the type of crop harvested.

Results

The energy demand for irrigation under the baseline scenario

We quantify the total annual energy required for irrigation using a spatially distributed (10 km x 10 km resolution), physically based approach that accounts for crop type, irrigation system, water source, energy source, and local climatic conditions. Global estimates aggregate crop-level energy demand for both the current distribution of irrigated areas (baseline) and a sustainable irrigation expansion scenario. We perform the analysis at the global scale on currently cultivated areas[15] including areas cultivated with double cropping, using a square grid of approximately 10 km at the equator (chosen to balance spatial detail and computational efficiency in long-term, global-scale modeling) and spatially distributed data for hydroclimatic variables, field size[29], soil properties[30], spatially distributed map of irrigation[31] and crop distribution datasets, including Monthly Irrigated and Rainfed Cropped Areas MIRCA2000[32], MIRCA-OS[33], FAO/IIASA Global Agroecological Zones GAEZ[34–36] and the Spatial Production Allocation Model SPAM[15,37,38] (Table 1). We find that, presently, considering the most up to date global datasets of irrigated areas by Mehta et al.[31], about 395 million hectares worldwide are irrigated (55 million ha are double cropped) (consistent with previous studies[39,40]), and account for about 1450 km^3 per year of irrigation water consumption and about 4.2×10^{15} kcal per year of crop calorie production (Table 2), in agreement with[32,41]. The total water withdrawal for irrigation corresponds to about 2611 km^3 per year (Table 2), in line with existing datasets[39] and previous studies[27,42–45](supplementary information). Irrigated land is mainly located in the Indo-Pakistani belt (36%), China (27%), and the Middle East (11%). The energy was computed in gigajoules (GJ). We estimate that the global irrigation energy demand is 1.38×10^9GJ per year, considering an average weighted efficiency of diesel and electric pumps. Total energy demand rises to 2.05×10^9GJ per year if we consider diesel pumps (with an efficiency of 21%) as the only technology for mechanized water lift worldwide, while if electric pumps (with an efficiency of 56%) are used in electrified areas, and diesel pumps elsewhere, the total energy demand for irrigation would drop to 1.34×10^9 GJ per year. Although this represents only about 0.1% of total global anthropogenic energy consumption[16,27,28], irrigation remains a notable energy component within agriculture. Energy use in the agricultural sector comprises both direct uses—such as machinery operation, irrigation pumping, and on-farm activities—and indirect inputs, primarily

Table. 1 | Irrigated area, blue water withdrawal, and irrigation energy use across crop distribution datasets

DATASET	Reference year for crop distribution	Number of Crops considered in this study (including crop groups)	Irrigated area [Mha]	Blue water withdrawal [km^3 per year]	Average Energy for irrigation [10^6GJ per year]
MIRCA	2000	21	348.8	2228.3	1217.5
	2005	21	382.1	2424.1	1358.2
	2010	21	388.4	2424.3	1412.0
	2015	21	412.4	2593.4	1503.9
SPAM	2000	19	244.2	1699.4	783.1
	2005	42	260.0	1834.5	881.1
	2010	42	276.8	1945.1	913.3
	2020	42	286.9	1999.8	885.7
SPAM updated*	2020*	42	395.8	2611.2	1381.4
GAEZ	2000	26	321.4	2264.3	1246.7
	2010	26	395.7	2734.5	1524.1

The table reports total irrigated area, blue water withdrawal, and average irrigation energy use for the MIRCA, SPAM, and GAEZ crop distribution datasets at different reference years. The number of crops or crop groups included in each dataset is listed, as reported in supplementary data 2. The asterisk marks the SPAM2020 updated dataset used for the main results of this study.

Table. 2 | Irrigated area, blue water, production, and energy requirements for irrigation by crops

Crop	Irrigation system	Irrigated area [Mha]	Blue water withdrawal [km^3 per year]	Caloric content [10^{12}Kcal]	Energy - surface irrigation [10^6GJ per year]	Energy - sprinkler system [10^6GJ per year]	Energy - drip irrigation [10^6GJ per year]	Total energy for Irrigation [10^6GJ per year]
Wheat	SU-SP	61.3	322.4	328.1	142.4	49.8	0.0	192.2
Rice	SU-SP-DR	82.3	778.5	262.6	163.4	0.0	0.0	163.4
Maize	SU-SP	43.2	237.5	537.3	135.5	60.3	0.0	195.8
Sugarcane	SU-SP	12.9	181.4	950.7	136.4	28.6	0.0	165.0
Cotton	SU-SP	16.5	105.3	39.1	36.5	16.4	1.6	54.4
Vegetables	SU-SP	22.5	111.5	399.1	38.5	15.2	3.4	57.1
Other Crops	(see supplementary data 11)	157.2	874.7	1684.4	378.0	160.6	14.8	553.4
Total		395.8	2611.2	4201.2	1030.7	330.9	19.8	1381.4

SU stands for surface irrigation, SP for sprinklers irrigation and DR for drip irrigation. Second crops refer to the total harvested area of all crops grown in double cropping systems or during the secondary growing period. *Total irrigated area includes 55Mha of double cropping. ** Calorific value omitted as these crops are not consumed as food.

fertilizer production. In subsequent sections, we show that these local factors largely explain where and why irrigation energy demand is highest.

Energy use for irrigation concentrates in the Indo-Pakistani Belt (0.52 × 10^9GJ per year), the US "corn belt" (0.37 × 10^9GJ per year), and the MENA region (Middle East and North Africa) (0.10 × 10^9GJ per year) (Fig. 1). In those regions, the high energy demand is due to a combination of multiple factors, including the largest proportion of irrigated areas, the types of crops being irrigated, and the pedo-climatic characteristics of the region. These factors contribute to the highest demand for blue water in the world, consequently leading to higher energy requirements for irrigation. The countries that show the highest irrigation energy consumption per unit irrigated area are the United Arab Emirates (26.3GJ ha^{-1}), Jamaica (22.0GJ ha^{-1}), Nicaragua (21.5GJ ha^{-1}), and Mexico (18.8GJ ha^{-1}). Such high values typically arise from one or a combination of deep groundwater lifting, arid or semi-arid climates with high evaporative demand, and widespread use of pressurized irrigation systems, all of which elevate the energy required per hectare compared to gravity-fed or shallow-lift surface systems.

Energy demand varies not only with the energy source used and the amount of applied blue water, but also with the type of irrigation systems employed and the water source used for irrigation. Notably, irrigation systems play a crucial role in determining irrigation energy demand due to their varying efficiency and operating pressures. Despite its higher efficiency, sprinkler systems require more energy per unit area than surface irrigation, because of its higher operating pressure and friction losses in the pressurized conduits (Table 2; Table 3). Thus, out of the total irrigation energy demand (1.38 × 10^9GJ per year), approximately (0.92–1.03) × 10^9GJ per year is contributed by surface irrigation systems (over an area of 350.1 Mha), while 0.33 × 10^9 GJ per year is consumed by sprinkler irrigation (over a much smaller area of 34.4Mha) (Table 2). For instance, wheat irrigated with a sprinkler system withdrawing surface water with a diesel pump consumes on average 8.35GJ ha^{-1}, compared to 0.50GJ ha^{-1} with a surface irrigation system (Table 3). This difference is less evident when groundwater is used. Drip irrigation systems are less energy-intensive than sprinkler systems because of their higher water efficiency and lower operating pressures (Table 3). However, based on the latest global data available, drip irrigation currently covers only about 4Mha, representing a small fraction (i.e., <1%) of irrigated land. Moreover, drip irrigation is not suitable for all crops[46] and still encounters difficulties in being adopted in some areas[47,48]. According to our estimates, drip irrigation consumes approximately 2.0 × 10^7 GJ per year (Table 2), which is an order of magnitude smaller than other systems. Nonetheless, owing to their superior efficiency in minimizing freshwater withdrawals, drip irrigation systems are rapidly expanding worldwide, often in conjunction with greenhouse, hydroponic, and aquaponic systems[49]. Assuming a 5%, 10%, and 20% replacement of surface irrigation with sprinkler irrigation, the total energy demand for irrigation increases to 1.39 × 10^9GJ per year, 1.48 × 10^9GJ and 1.66 × 10^9GJ per year,

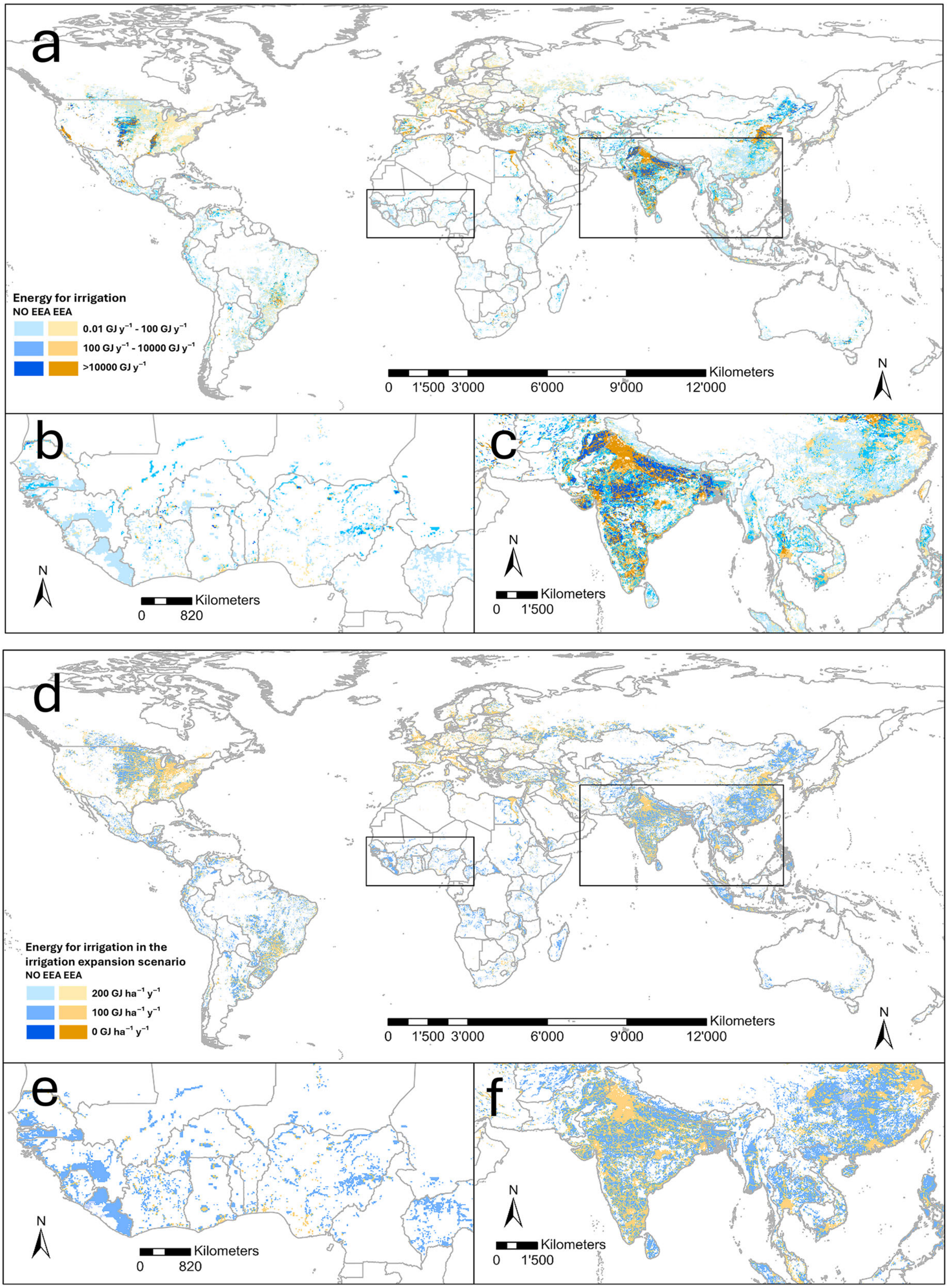

Fig. 1 | Global irrigation energy demand and energy availability for irrigated areas according to SPAM2020 crop distribution maps. a Total irrigation energy demand under the baseline scenario, with areas lacking evidence of energy availability (NO EEA) shown in shades of blue and areas with evidence of energy availability (EEA) shown in shades of orange. Spatial resolution: 5 arcmin (approximately 10 km at the equator). Zoomed-in views of regions highlighted in panel a, showing total irrigation energy demand under baseline scenario for West Africa (**b**) and South Asia (**c**). **d** Irrigation energy use per hectare for the baseline scenario, with areas lacking evidence of energy availability (NO EEA) shown in shades of blue and areas with evidence of energy availability (EEA) shown in shades of orange. Spatial resolution: 5 arcmin (approximately 10 km at the equator). Zoomed-in views of regions highlighted in (**d**), showing detailed irrigation energy use per hectare under baseline scenario for West Africa (**e**) and South Asia (**f**). The country boundaries map is the intellectual property of Esri and is used herein under license for the purpose of Cartographic visualization. Copyright © 2026 Esri and its licensors. All rights reserved.

Table 3 | Crop specific irrigation energy use per hectare

Energy source	Diesel						Electric					
Water source	Surface water			Groundwater			Surface water			Groundwater		
Irrigation system	Surface	Sprinkler	Drip	Surface	Sprinkler	Drip	Surface	Sprinkler	Drip	Surface	Sprinkler	Drip
Wheat	0.50	8.35		12.05	28.07		0.19	3.13		4.52	5.66	
Rice	1.24			17.79	14.68		0.47			6.67		
Maize	0.53	8.01		13.89			0.20	3.00		5.21	6.63	
Sugarcane	1.36	18.12		42.98	55.62		0.51	6.80		16.12	18.45	
Cotton	0.51	6.81	3.45	11.57	17.03	6.49	0.19	2.55	1.29	4.34	5.90	2.43
Vegetables	0.65	9.41	5.05	12.56	18.96	9.24	0.24	3.53	1.90	4.71	7.85	3.46

The table reports irrigation energy use per hectare for selected crops, separated by energy source, water source, and irrigation system. Values are shown for diesel and electric pumps using surface water or groundwater for surface, sprinkler, and drip irrigation systems.

Table. 4 | System specific irrigation energy use in selected locations in Nigeria and Egypt (from Fig. 2)

Energy source	Water Source	Irrigation system	Energy in N [GJ ha-1]	Energy in E [GJ ha^{-1}]
Diesel	Surface	Surface	1.6	0.3
		Sprinkler	16.7	2.9
	Groundwater	Surface	10.6	9.1
		Sprinkler	40.1	11.8
Electric	Surface	Surface	0.6	0.1
		Sprinkler	6.3	1.07
	Groundwater	Surface	4.0	3.4
		Sprinkler	15.0	4.5

The table reports irrigation energy use for representative locations (N and E) in the two countries (Nigeria and Egypt), distinguished by energy source, water source, and irrigation system. Values show how system design and water source combine to produce different energy needs in each setting.

respectively. Having established the dominant role of irrigation systems and water sources in shaping energy demand, we next quantify how these patterns manifest across crops (supplementary data 11).

Six crop types alone account for about 60% of the total irrigated area, according to the SPAM2020 dataset[37], namely wheat, rice, maize, cotton, sugarcane, and vegetables. About 0.55 × 10^9GJ per year is required for the irrigation of the 3 most cultivated and widespread cereals, namely wheat (13.9% of the total energy consumption for irrigation), maize (14.2%), and rice (11.89%), followed by sugarcane (11.9%) and fruits (tropical and temperate, ≈6%) (supplementary data 11). The most energy-intensive crops are sugarcane (12.8GJ ha^{-1}), tropical fruit (7.8GJ ha^{-1}), and oil crops (6.4GJ ha^{-1}), mainly due to their higher water demand, while for wheat the specific energy per hectare is 3.1GJ ha^{-1}. These differences are largely explained by crop water demand interacting with system choice and source (e.g., pressurized methods and groundwater lifting), reinforcing that technology and hydrology modulate crop-level energy intensities. The average specific energy across the crops considered in this study is about 3.4GJ ha^{-1} (supplementary data 11). Crop-specific energy requirements for the 6 most irrigated crops are here mapped for each (i) type of irrigation, (ii) water source (i.e., surface water and groundwater), and (iii) energy inputs (i.e., diesel vs electric engine), as shown in Table 4 for the points in Fig. 2.

Further, we analyzed the role played by the type of water source used. Groundwater withdrawals typically require more energy than surface water withdrawals (e.g., from rivers or lakes), due to the additional energy required for lifting water from the water table to the surface. About 61% of irrigated land uses water from surface sources, corresponding to 16% of the total energy demand, while the remaining is withdrawn from aquifers, consistent with a previous study[50]. In some regions, groundwater sources play a key role, as in the Middle East and in India, where it is depleting groundwater stocks due to unsustainable withdrawals[19,51,52]. In cases where groundwater is used as the water source, we quantified that approximately 80% of the total energy is required to lift water from the aquifer to the surface. This percentage decreases to 36.3% for sprinkler irrigation and 31.5% for drip irrigation. Conversely, distributed losses account for about 9% of the energy demand in sprinkler systems but remain below 3% for surface and drip irrigation. Meanwhile, operating pressure is the predominant contributor to energy consumption for drip and sprinkler irrigation, contributing approximately 66% and 55%, respectively.

The energy demand for irrigation under the sustainable irrigation expansion scenario

We evaluate the possibility of expanding irrigation to currently non-irrigated cultivated areas, where the crop water requirements can be sustainably met by the local water availability without depleting

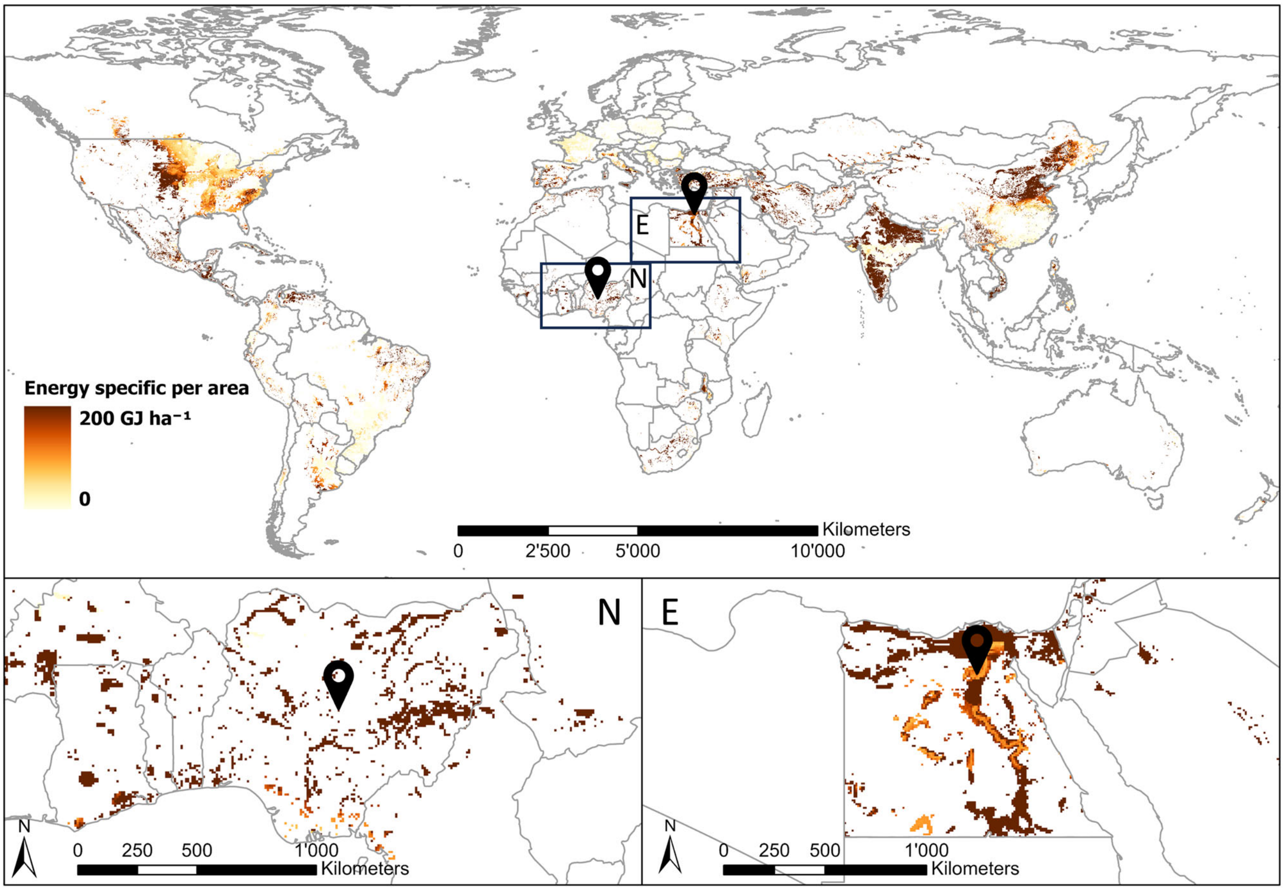

Fig. 2 | Crop-specific irrigation energy use for maize. The figure shows the spatial distribution of energy use for irrigated maize, with markers N and E indicating the selected locations in Nigeria and Egypt. These locations correspond to the pixels for which system-specific energy values are reported in Table 4. Energy use is expressed as gigajoules per hectare and mapped at high spatial detail to highlight local variation. The country boundaries map is the intellectual property of Esri and is used herein under license for the purpose of Cartographic visualization. Copyright © 2026 Esri and its licensors. All rights reserved.

environmental flows or groundwater stocks[17]. Approximately 110 million hectares are identified as suitable for potential sustainable irrigation expansion. These areas are mainly located in Africa (+39.6 Mha), Eastern Europe (+26.3 Mha), and Asian Russia (+11.0 Mha). Wheat, maize, and barley are the main crops planted in areas where irrigation may be sustainably expanded, which altogether account for about 40 Mha. We estimate that, overall, roughly 600 km^3 per year of water would be required in these additional irrigated areas, representing a 23% increase with respect to the current global irrigation water consumption. Wheat, maize, and rice are the crops demanding the highest amount of additional water (in total about 235 km^3 per year).

In the irrigation expansion scenario, we assume a proportional growth of irrigation systems, whereby the distribution of surface, sprinkler, and drip systems remains consistent with each country's current mix. This avoids imposing technological transitions and reflects plausible infrastructure development pathways. The total additional energy required worldwide to sustain suitable expansion of irrigated areas for the 42 crops is 0.24×10^9 GJ per year, about 17% more than in current conditions. Indeed, in the extreme scenario of complete electrification of the irrigation system, the baseline and additional energy required drops down to 0.87×10^9 GJ per year, while it increases to 2.31×10^9 GJ per year in the case of diesel being the only available energy source. In the expansion scenario, five countries—Ukraine, Canada, Cote D'Ivoire, Nigeria, and Kazakhstan—alone would account for over 40% of the additional global energy demand for irrigation (Fig. 3). This reflects the large extent of rainfed croplands identified as suitable for sustainable irrigation expansion. The highest relative increases in energy demand, however, are expected in the Baltic region (Latvia, Lithuania, and Estonia) and in sub-Saharan Africa (Cote D'Ivoire, Togo, and Rwanda), where even modest irrigation expansions lead to sharp rises compared to current energy demand levels. The total production from irrigated areas in the irrigation expansion scenario will account for 4.8×10^{15} kcal globally ($+6.2 \times 10^{14}$ kcal).

Energy availability for sustaining irrigation expansion

Energy availability, along with freshwater availability, plays a critical role in determining the feasibility of irrigation adoption. However, unlike water, which must be readily accessible locally because of the challenges and the cost associated with long-distance transport, energy can be transported (by power lines or fuel trucks) over considerable distances. Currently, only a small fraction of the energy used for irrigation comes from electricity, while most systems still rely on diesel pumps, which have a lower efficiency and a higher impact on the environment. Local electrical energy availability can facilitate the adoption of irrigation. Therefore, here we evaluate the extent to which the additional irrigation energy demand from expanded irrigation would occur in areas with limited access to electricity (based on IEA data[53]). To that end, we compare the country-specific values to the global average of per capita energy supply. Our analysis reveals that 30 of the top 50 energy-demanding countries (in terms of irrigation energy) fall below the global average. For example, Nigeria, which requires one of the highest amounts of energy for sustainable irrigation expansion and is expected see high rates of population increase, is

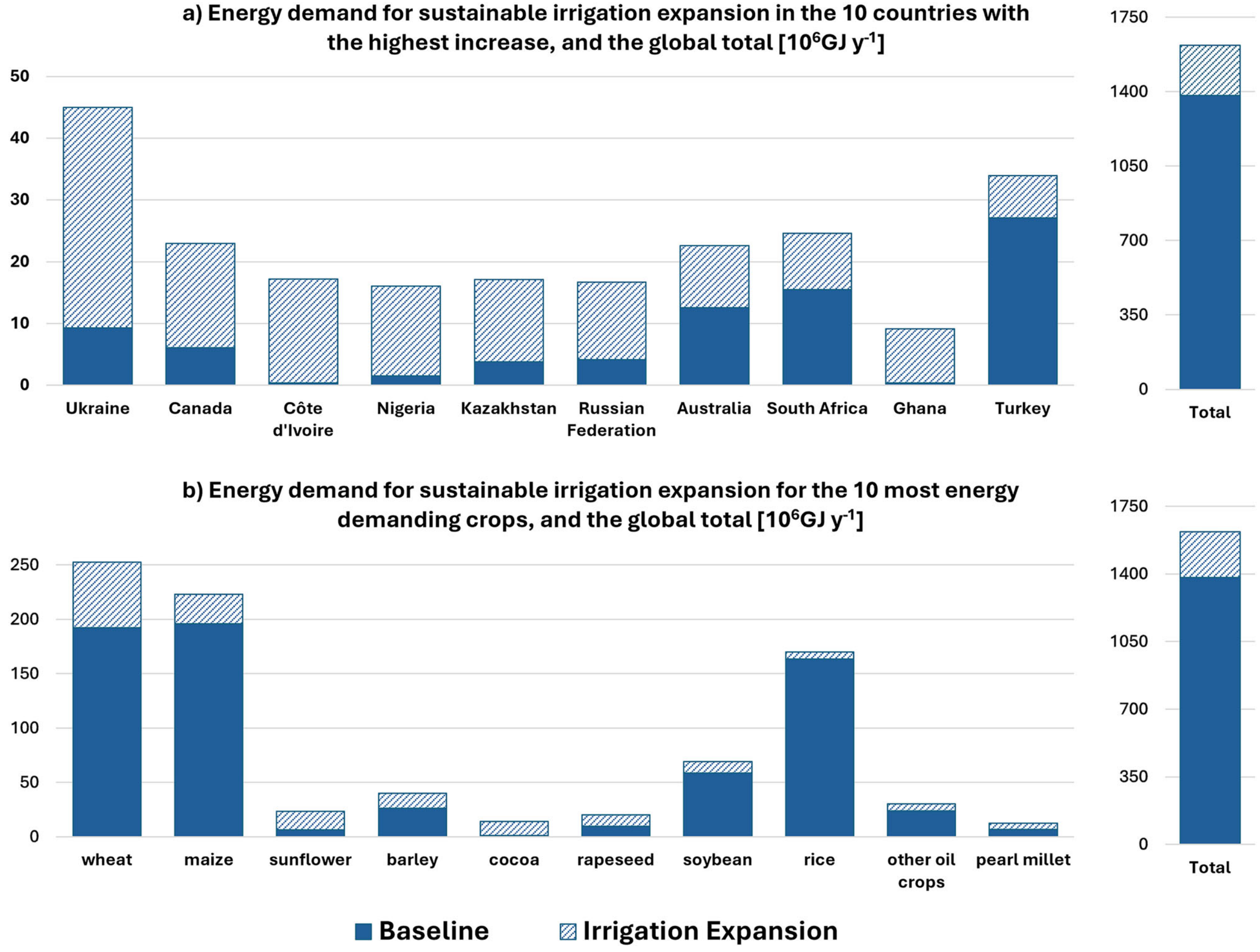

Fig. 3 | Current and additional irrigation energy demand under a sustainable expansion scenario. a Countries with the highest increases in irrigation energy demand, shown with baseline values and additional demand from expansion. **b** Crops with the highest energy demand under the expansion scenario, also showing baseline and additional values. Solid bars indicate current demand, and hatched bars indicate the increase from expansion.

already affected by energy poverty (in 2020, only 60% of its population had access to electricity). Irrigation expansion in Nigeria is estimated to require an additional 14.5×10^6 GJ per year to increase food production in by up to 3.8×10^{14}kcal per year, which could meet the yearly food requirement of about 300 million people (with a daily intake of 3343 kcal per day accounting also for food losses and feed-to-meat/milk/egg conversions for animal products), corresponding to about its population. Energy appears to be a major constraint on irrigation expansion also in the case of Niger, where the energy requirements for irrigation expansion are relatively low, and only 20% of the population has access to electricity[53].

Moreover, to identify the extent to which irrigation energy demand can be met by electricity, we also evaluate access to electrical power based on the presence of either (i) a power grid[54] or (ii) artificial night sky brightness[55]. By overlapping the irrigation energy demand map (Fig. 1) with the map of electrification, we identify the areas where electric energy is more likely to be available for irrigation because of the existence of a power supply network or of night lights. Currently, about 53.3% of the energy demand for irrigation occurs in areas with evidence of electrification, a fraction that increases to about 85% when considering a buffer of 10 km around those areas. In the irrigation expansion scenario, however, approximately 50% (i.e., 0.80×10^9 GJ per year) of the total energy requirement is in areas with evidence of electrification (Fig. 4). In the case of Eastern Europe, where the sustainable irrigation expansion scenario triples irrigated area, about 72.6% of the additional irrigation energy demand is in areas with evidence of electrification (96.4% if we considered a buffer of 10 km). This is in contrast with Sub-Saharan Africa, where a more than 3-fold increase in the energy demand for irrigation is expected to occur (from about 0.03×10^9 GJ per year to 0.11×10^9 GJ per year) in areas with only 18.9% evidence of electrification (43.8% if we consider a buffer of 10 km). Thus, our results (Fig. 4) identify the areas where an expansion of the electric grid, microgrid development, or use of diesel pumps will be necessary to support irrigation expansion.

Specific energy per calorie unit

Lastly, we quantified the irrigation energy demand per unit crop calorie produced by irrigation, either for human or animal consumption[56]. These results show the different amounts of food produced by energy consumption for irrigation around the world. In the current irrigation scenario, the MENA region exhibits the highest irrigation energy consumption per unit food produced, partly because of the highest water costs (i.e., the highest irrigation water requirements and average crop (blue) water footprint[57]). The highest increase in calorie production is expected in the Sub-Saharan region (about 60% increase), the area most affected by malnutrition. Thus, a sustainable expansion of irrigation in this region may represent an important step forward in tackling malnutrition. The crops that are major contributors to the additional calorie production are sorghum, millet, groundnuts, and maize, with groundnuts, chickpeas, and yams

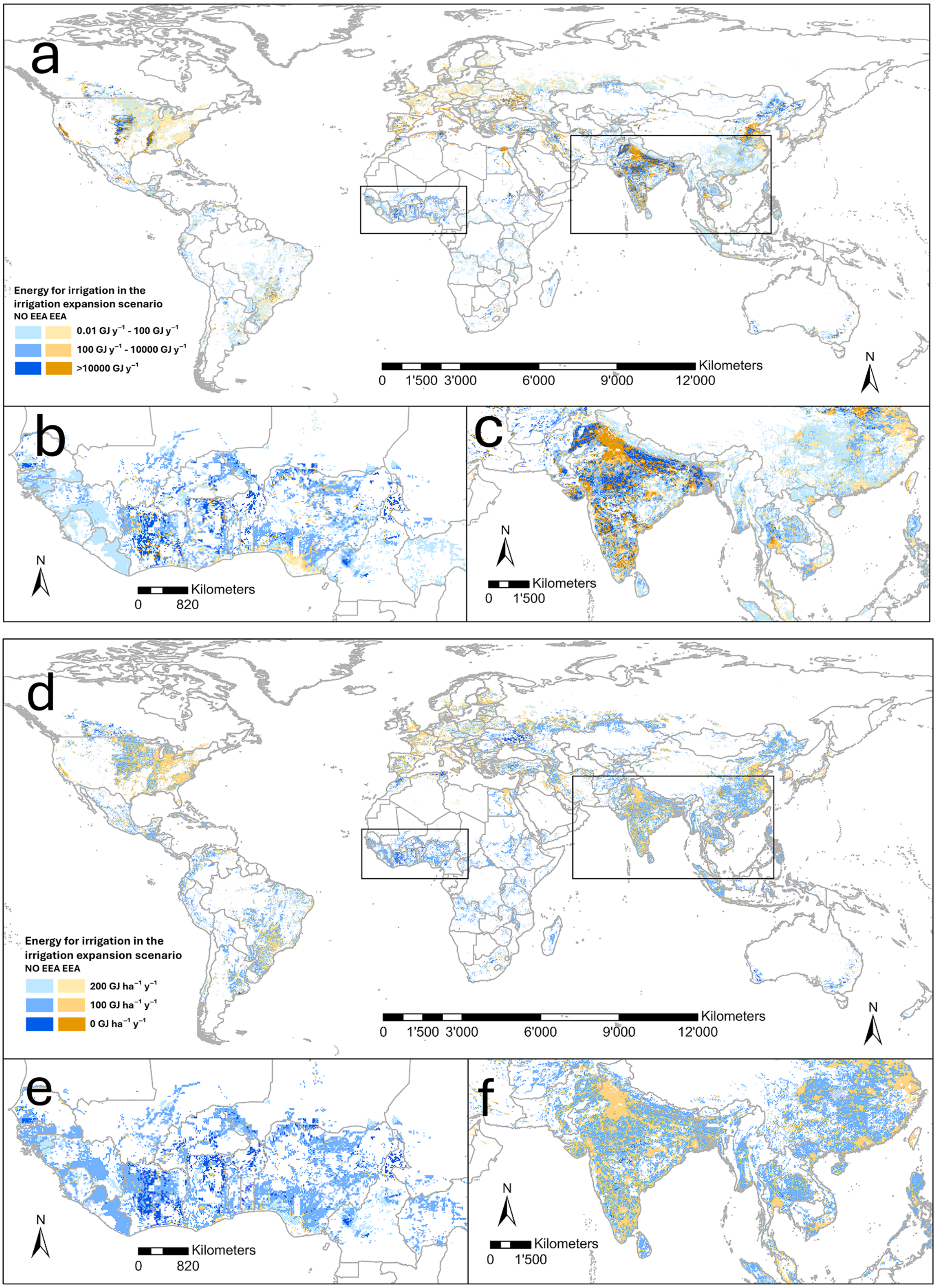

Fig. 4 | Combined irrigation energy demand and energy availability under baseline and sustainable irrigation expansion scenarios. a Total energy demand as the sum of baseline and sustainable irrigation expansion scenario areas, highlighting areas with no evidence of energy availability (NO EEA) in shades of blue, and areas with evidence of energy availability (EEA) in shades of orange. Spatial resolution: 5 arcmin (approximately 10 km at the equator). Zoomed-in views of regions highlighted in panel a, showing total energy demand for West Africa (**b**) and South Asia (**c**). **d** Specific energy demand per hectare of irrigated area as the sum of baseline and sustainable irrigation expansion scenario, highlighting areas with no evidence of energy availability (NO EEA) in shades of blue, and areas with evidence of energy availability (EEA) in shades of orange. Spatial resolution: 5 arcmin (approximately 10 km at the equator). Zoomed-in views of regions highlighted in (**d**), showing specific energy demand per hectare for West Africa (**e**) and South Asia (**f**). The country boundaries map is the intellectual property of Esri and is used herein under license for the purpose of Cartographic visualization. Copyright © 2026 Esri and its licensors. All rights reserved.

showing a substantial increase, compared to current (baseline) conditions.

Comparison with existing datasets and alternative crop distribution datasets

Three global crop distribution datasets−MIRCA, SPAM, and−are used in their various temporal versions from 2000 to 2020 (Table 3), along with an updated version of SPAM 2020 incorporating recent irrigated area data, to assess how uncertainties in crop and irrigation distribution affect energy estimates. These datasets cover different crops and crop groups, as reported in the supplementary data 2, and span from 2000 to 2020, providing a broader perspective on irrigation trends. Despite variations in temporal coverage, all datasets consistently indicate a global expansion of irrigated areas over time, leading to a corresponding increase in water withdrawals (Table 3) and energy demand for irrigation. Notably, all observed variations fall within the range outlined in our uncertainty analysis, reinforcing the robustness of our findings, except for the SPAM datasets[37], which include a lower total irrigated area compared to the other datasets. Among these, the SPAM2020 updated dataset is used as the reference for the main results presented in this study. Moreover, we compare our estimates with previous assessments of cumulative energy for irrigation (i.e., accounting for all crops together). Specifically, we present the information reported by IEA[16], Liu et al. (2016)[27], and Qin et al. (2024)[28]. IEA data reports 'Energy for agriculture and forestry' and provides energy usage for the entire agricultural sector, not just irrigation. Liu et al. (2016) specifically reported the energy estimate only of electric energy usage in agriculture, lacking specific data on energy consumption for irrigation. This results in our estimation to be about 18% of the IEA data, and 60% of those by Liu et al. (2016)[27], respectively (Fig. 5). Lastly, our estimation of energy for irrigation is 26% lower than the estimates reported by Qin et al. (2024) that use a similar approach. This difference arises because we used water demand data obtained from a hydrological model to calculate irrigation energy, leading to a slightly different global water withdrawal distribution (Fig. 5). We also conducted a country-wise comparison of energy consumed and water withdrawal with Qin et al. (2024)[28]. While our study includes 158 countries compared to their 151, the total water withdrawal differs by 7%. Although 27 countries have similar water demand estimates (±7%) in both studies, variations in the remaining countries stem from differences in irrigated area datasets, study period, and water demand sources. These discrepancies translate into energy consumption differences. For instance, estimates for the United States and Brazil vary by less than 10% between the two studies, whereas for India and Egypt, our estimates are 30% lower. In these latter countries, our estimates of water withdrawals are consistent (i.e., within 2%) with the values reported by Aquastat[39] (supplementary data 6) but show a larger discrepancy (>10%) compared to Qin et al. (2024)[28] (supplementary data 6 and 10). Although our estimates of water withdrawals are higher, the associated energy requirements are lower, likely due to differences in the spatial distribution of the crop maps used and the way double cropping, which is a prominent practice in these countries, has been accounted for.

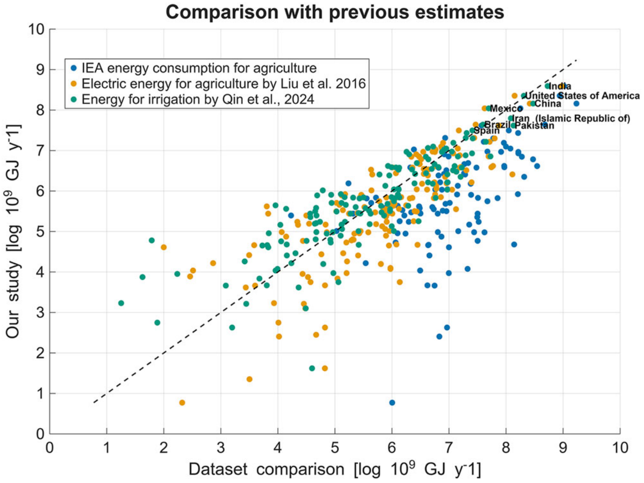

Fig. 5 | Comparison of country-level irrigation energy estimates from this study with previous global datasets. Each point in this represents a country, while labels are shown only for the eight most energy-consuming countries to avoid overcrowding of information in the figure. The comparison includes three sources: (i) total agricultural energy use reported by the International Energy Agency (IEA) (blue points), (ii) electric energy for agriculture from Liu et al. (2016) (orange points), and (iii) irrigation energy estimates from Qin et al. (2024) (green points). The dashed line indicates the 1:1 relationship. Since these datasets represent different components of agricultural energy use, perfect agreement is not expected. For complete country-level details, refer to supplementary data 10.

Our comparison demonstrates how crop types and their spatial distribution influence the estimated global energy demand for irrigation. As crop distribution continuously evolves to meet market demands and emerging needs, these changes, in turn, impact the total estimated energy required for irrigation. Indeed, unlike previous analyses[28], our estimation of irrigation energy demand is crop-specific, enabling us to assess variations in energy consumption among different irrigated crops. This approach enhances our ability to predict the impact of crop shifts on irrigation energy consumption, thereby improving strategies for agricultural production at both regional and global scales. Nevertheless, we acknowledge the need for more accurate input data to improve assessments at finer local resolutions (see assumptions and limitations).

Uncertainty and sensitivity analysis

Uncertainty and sensitivity analysis are important tools for assessing the robustness and reliability of the results obtained from model simulations (see Method).

We conducted a long-term annual energy assessment based on yearly specific withdrawn volume of water (WD), while keeping static the spatial crop distribution to analyze energy estimates and its fluctuations. The mean annual consumptive BW volume during this period is 2611.2 km^3 per year (supplementary data 6). Over the 31-year period, WD varied from a minimum of 2229 km^3 per year in 1993 to a peak value of 2906 km^3 in 2002, with all values falling within ±20% compared to the mean value. As expected, the yearly variations in withdrawn volume were found to be associated with negligible fluctuations in average total head (TH) of ±1%, and a standard deviation of our global energy estimates equal to 0.12×10^9 GJ per year. The lowest energy requirement, 1.07×10^9 GJ per year, was associated with the lowest WD of 1993, while the highest (i.e., 1.56×10^9 GJ per year) occurred in 2006.

Moreover, we examined the uncertainty associated with a relative variation in TH of ±1%, and in the withdrawn water volume (WD) of ±20% according to the long-term interannual fluctuations, and a variation in pump efficiency (PE) of ±40% (See methods). The uncertainty associated with our global energy estimate is $\pm 0.25 \times 10^9$GJ per year, with a central estimate of 1.38×10^9GJ per year. Therefore, the coefficient of variation corresponds to 18.5%. Irrigation systems consume $1.03 \pm 0.23 \times 10^9$ GJ per year (surface irrigation), $0.33 \pm 0.08 \times 10^9$ GJ per year (sprinkler), and $0.02 \pm 0.005 \times 10^9$ GJ per year (drip). In the sustainable irrigation expansion scenario, the uncertainty associated with our global energy estimate is $\pm 0.29 \times 10^9$GJ per year, with a central estimate of 1.62×10^9GJ per year. Therefore, the coefficient of variation corresponds to 17.8%. Approximately $1.13 \pm 0.25 \times 10^9$ GJ per year may be consumed by surface irrigation systems, $0.46 \pm 0.10 \times 10^9$ GJ per year by sprinkler irrigation systems and $0.023 \pm 0.006 \times 10^9$ GJ per year by drip irrigation systems.

For the sensitivity analyses, we varied the values of the four main variables within the same plausible ranges. and found that a 40% variation in pump efficiency is associated with values of global energy demand for irrigation ranging from 0.93×10^9 GJ per year to 2.18×10^9 GJ per year. Similarly, we considered a 20% variation in the total volume of water withdrawn, to account for interannual climate fluctuation[41,58]. This causes our estimate of the total energy demand for irrigation to range between $1.04{\times}10^9$ GJ per year to 1.57×10^9 GJ per year. Lastly, we considered a variation in the total head up to ±20%, leading to total energy estimates ranging from $1.10{\times}10^9$ GJ per year to 1.56×10^9 GJ per year.

Lastly, we also acknowledge that in many cases, surface irrigation using surface water sources may occur solely due to gravity. As a result, the energy demand for surface irrigation systems using surface water—accounting for approximately 11% of the total irrigation energy demand—is zeroed. In this case, energy demand for surface irrigation systems decreases from 1.03×10^9 GJ per year to 0.92×10^9 GJ per year for the baseline scenario, and from 1.14×10^9 GJ per year to 0.98×10^9 GJ per year for the irrigation expansion scenario.

Discussion

This study presents a spatially distributed, physically based approach that couples crop water requirements with water and energy parameters to quantify crop-specific energy demand for irrigation under baseline and sustainable expansion scenarios. Unlike previous global assessments that consider aggregated agricultural energy use[27,28], this analysis isolates the crop-specific, direct energy required to withdraw, lift, convey, and apply irrigation water. This allows for linking energy use with blue water requirements and productivity gains, offering an integrated view of the food–energy–water nexus and guiding sustainable irrigation planning at regional and global scales. We find that current irrigation consumes about 1.38×10^9 GJ per year, with three-quarters from surface systems and one-quarter from pressurized systems accounting for about 0.1% of the total energy consumption by human societies globally (≈600×10^9 GJ per year[16]). Energy for irrigation is only a part of the total agricultural energy required, accounting for about 6% of the total agricultural energy in the baseline scenario (supplementary data 8, 9, 10), and up to 7% in the irrigation expansion scenario. In fact, energy in the agricultural sector is used both directly – e.g., for machinery and irrigation – and indirectly to produce fertilizers, which account to 40% of the energy demand in the agricultural sector[16]. Post-harvest energy use includes energy for food processing, storage, and transport of agricultural products to markets. While irrigation accounts for a relatively small fraction of energy consumption in agriculture globally, regional differences matter. In the MENA region, for example, high dependence on deep groundwater extraction and the large irrigation water requirements due to the arid climates result in the highest energy consumption per hectare.

Understanding crop-specific energy requirements is essential for designing irrigation investment strategies that align with local development priorities. Crops differ significantly in water and energy needs depending on their physiology, growing season, and irrigation method. In regions prioritizing income generation, energy-efficient systems may be best suited for high-value crops. Where food and nutrition security are the focus, reliable irrigation for nutrient-dense staple crops, vegetables, legumes, or other micronutrient crops may be prioritized. Environmental goals may also influence technology choices, such as selecting solar or grid-powered pumps over diesel, where emissions reduction is a priority. The crop- and pump-specific spatial patterns (as shown in Table4 for the points in Fig. 2 for maize as an example) can support better planning for pump selection, solar sizing, and financing, ensuring investments are environmentally and economically sound. Investment for expanding irrigation goes in support of making energy available, as reported in different cases, such as in Rwanda, Niger, and Bangladesh[59]. Therefore, by linking energy needs to specific crop types, stakeholders, governments, donors, and/or NGOs can better align interventions with desired outcomes. This spatially explicit analysis of crop-specific energy demand for irrigation highlights areas where investments in energy infrastructure might be necessary to support irrigation expansion. Such expansion can lead to increased crop yields and improved resilience of agricultural production. In fact, irrigation is often considered a key adaptation strategy to address the intensification of extreme hydroclimatic conditions under climate change, as it increases the reliability of water availability for crop production[20,25]. Moreover, the evaluation of the value generated by irrigation in agriculture requires an assessment of the provision costs, which are strongly contributed to by energy consumption. This research allows for a more accurate, crop-specific global assessment of the value of water in agriculture across different regions of the world[60], providing a supporting tool to better estimate the return on investment (ROI) in areas suitable for irrigation expansion.

The provision of energy to power the food production chain has been crucial to agricultural development since the industrial and the green revolutions and played a key role in improving food security conditions[9]. In many rural areas, the absence of reliable and affordable electricity limits irrigation potential more than water scarcity itself. Access to energy, whether from electrification or from diesel engines, has allowed for the irrigation of areas where the use of a gravity system was not an option. The Nigeria's Fadama Development Project deployed 50,000 low-cost motorized pumps, increasing returns per hectare by 65–500% and achieving 40% economic rates of return[59]. Similarly, in Bihar, India, reforms combining solar irrigation subsidies with improved rural energy delivery have substantially expanded irrigation access Bihar[61]. These experiences demonstrate that the right mix of finance, technology, and institutional design can overcome traditional barriers to adoption. However, renewable solutions face persistent challenges: high upfront investment, limited access to credit, and weak maintenance ecosystems[62]. Aligning loan structures, tariffs, and service guarantees with agricultural cash-flow cycles remains essential for widespread diffusion.

Most of the additional energy demand required to sustainably expand irrigation is concentrated in agricultural areas where access to energy infrastructure remains limited or unaffordable, but the socio-economic benefits of irrigation could be especially high. Energy constraints arise in two distinct but equally limiting forms: in areas where no energy infrastructure is available, and in areas where energy exists but is inaccessible due to high costs, unreliability, or socio-economic barriers. Our spatial analysis (see Fig. 4) highlights that many regions with physically available water (i.e., under economic water scarce conditions) remain uncultivated or under-irrigated because the energy needed to pump and distribute water is missing, as observed in parts of China where irrigation development is constrained by energy poverty[63]. Notably, five countries—Ukraine, Canada, Côte d'Ivoire, Nigeria, and Kazakhstan—alone account for over 40% of the projected global increase in irrigation energy demand under the expansion scenario (Fig. 3). Our results represent a baseline estimation of the energy needs, which must be complemented with low-carbon energy planning to ensure environmental sustainability. Addressing this gap requires significant investment in off-grid renewable solutions such as solar-powered systems[64,65]and power grid expansion, which often entail high upfront financial costs, while grid-powered electric pumps, which are efficient and low cost to operate but require reliable infrastructure, often lack in rural areas. Meanwhile, continued reliance on diesel pumps, though widespread and flexible for rapid deployment in remote areas, significantly contributes to greenhouse gas emissions, carrying considerable environmental impacts. If the sustainable irrigation expansion scenario were implemented using predominantly diesel-powered systems, it could substantially increase the carbon footprint of food production, thereby conflicting with global climate goals. This underscores the need to design irrigation expansion strategies that are tailored to local energy contexts and that balance the trade-offs between water-use efficiency and managing energy intensity. By integrating crop-specific water and energy demand with spatial constraints, our study offers a tool to identify where irrigation expansion is technically viable and where targeted interventions are most needed.

It is to be noted that most places suitable for irrigation expansion currently have little or no access to energy through power lines (Fig. 4). The lighting map and the electrification lines used in this study are only a proxy of electrical energy availability. In fact, nocturnal lighting is concentrated in urban areas and is typically absent or sparse in rural areas where most irrigated agriculture takes place. Similarly, the power grid network indicates the presence of electrification but does not reflect power availability at the local scale. In such areas, agriculture commonly relies on alternative energy sources, primarily fossil fuels, which are associated with lower efficiency and higher environmental impacts[28]. In Sub-Saharan Africa, for example, less than 20% of the additional irrigation energy demand in the expansion scenario falls within areas with observable electrification. This aligns with long-standing patterns of energy poverty that hinder agricultural intensification even where land and water are available[9,15]. Renewable sources such as solar and wind power offer more sustainable and environmentally friendly alternatives. Interestingly, IEA reports that electrified pumps are replacing diesel pumps worldwide[16], thus promising to reduce energy consumption for irrigation. bringing it closer to its lower boundary, estimated in this study. Where national grids are sparse or unreliable, decentralized renewable systems can provide feasible alternatives to meet irrigation energy needs while contributing to rural electrification and lowering carbon footprints[66–69]. While we acknowledge that land tenure, financial feasibility, and policy readiness are additional prerequisites for implementation, our maps and estimates help prioritize locations where the biophysical foundations of sustainable intensification are already present. These insights can inform multi-criteria decision frameworks, guide climate-smart agricultural investment planning, and support the design of food-water-energy nexus strategies that avoid over-allocation or environmentally unsound development.

At the same time, improving energy access for irrigation must be accompanied by robust resource governance to avoid rebound effects. Historical evidence shows that when water and energy become more accessible, total withdrawals often rise rather than decline[70]. In our study, "sustainability" refers specifically to the water dimension—meeting crop water requirements without breaching environmental flow or groundwater constraints. Other dimensions, such as soil salinization, habitat alteration, and the carbon intensity of energy sources, were not specifically addressed as the potential rebounding effects of further increasing water withdrawals as soon as energy is made available. Empirical examples from Murray–Darling Basin (Australia), where a large-scale transition from surface to pressurized systems reduced water withdrawals, significantly increased energy use for agriculture[71]. Such cases highlight the importance of jointly considering water and energy efficiency in irrigation planning. In this direction, we have considered three different scenarios of replacement of traditional surface systems with sprinkler systems for 5,10 and 20% of their extent. Moreover, our crop-specific results, presented in Fig. 2, may help in a better assessment and understanding of the energy implications associated with such shifts. We also note risks and unintended consequences of such expansions. In energy-poor regions, large private investments in irrigation can accelerate deployment but risk unequal access and externalization of water risks if governance is weak[72]. Large-scale land acquisitions for commercial farming in water-rich areas, often termed 'land grabbing', can exacerbate inequality and local water stress if not subject to transparent governance[73]. Similarly, rapid diffusion of pressurized systems without reliable low-carbon power may raise both costs and emissions.

Although this study employs the most recent global datasets, assumptions about pump type, energy source, irrigation system, and efficiency where finer data were unavailable were necessary. Infrastructure realities and data limitations inevitably shape the interpretation of our estimates. These variables are applied uniformly at the country scale, and shares of system types and water sources are held constant in the expansion scenario. Limited information on actual irrigation practices, efficiencies, and infrastructure conditions adds further uncertainty. In some regions, for example, farmers rely on tractors or tillers to power pumps, often at low energy efficiency, or operate aging systems with performance far below design specifications. Similarly, the global distribution of pressurized distribution systems remains poorly documented, and large-scale inter-basin transfers are rarely accounted for in global models. Our analysis also assumes that most surface irrigation from surface water is gravity-fed, though some regions employ energy-intensive conveyance and inter-basin transfers—such as China's South-to-North Water Diversion (≈9.5 billion $m^3\ y^{-1}$)[74], the California State Water Project (≈3 billion $m^3\ y^{-1}$)[62], and Libya's Great Man-Made River (≈1.34 billion $m^3\ y^{-1}$)[75]—totaling about 0.5% of global irrigation withdrawals. Our uncertainty range for TH partially encompasses these effects. On-farm inefficiencies—tractor-driven pumps, poor maintenance—likely increase real energy use beyond modeled estimates. Furthermore, our electrification proxies capture presence, not reliability or affordability. Finally, sustainability here refers specifically to blue-water availability and excludes other dimensions such as salinization risk, habitat alteration, or energy-source sustainability. Climate change is not explicitly modeled, though projected to have a 15% increase in blue-water demand by 2071–2099[76], remain within our uncertainty bounds.

Despite these limitations, the framework provides a decision-ready basis for integrating energy considerations into irrigation planning. By explicitly quantifying energy for irrigation and linking it to spatial and crop-specific conditions, we identify where sustainable irrigation expansion is physically feasible yet constrained by energy access, and how much energy would be required under different technological pathways. Technological choices determine both energy intensity and emissions; coupling irrigation planning with low-carbon energy strategies is essential for climate-compatible agricultural development[26]. Lastly, we need to stress that, currently, 40-50% of irrigation is unsustainable (i.e., irrigation water consumption exceeds local water availability) due to 'blue water scarcity'[19]. This study does not account for the possible removal of irrigation from currently irrigated areas affected by blue water scarcity. However, in the future, such areas are expected to either reduce the irrigation water withdrawals (e.g., by adopting deficit irrigation) or shift towards non-conventional water sources.

Methods

The quantification of the total annual energy for irrigation is carried out both in the baseline irrigation scenario and in an irrigation expansion scenario. To this end, we first calculate the energy required to irrigate a single 'prototype' field, and then we accumulate the energy demand of all cultivated fields on a global scale. Results are provided in terms of energy required for irrigation for each of the main crops, considering the three most widely used irrigation systems (surface, sprinkler, and drip irrigation) and the different water sources (surface water and groundwater) for a long-term climate series of 31 years from 1993 to 2023.

A prototype field accounting for the average field size for each crop with a suitable crop-specific irrigation system is used to calculate the energy cost of irrigation (supplementary information). We use a crop-specific classification of suitable irrigation systems based on Jägermeyr et al.[46]. Most crops are irrigated with sprinkler and surface irrigation (supplementary data 11). Rice is irrigated only with surface irrigation, whereas crops such as pulses, sunflower, soybean, cotton, coffee, and temperate fruits are commonly irrigated with any of the three systems. In these cases, for each crop we consider the irrigation system that is consistent with the distribution of crops and associated irrigation method, using information reported by Jägermeyr et al.[46], (supplementary data 11).

Energy estimation

The energy required to irrigate each single field can be computed following Daccache et al.[77], as:

$$E_{sf} = \frac{TH \cdot \gamma \cdot WD}{PE \cdot IE} \quad (1)$$

Where TH is the total head of the pump, γ is the specific weight of water (9805 N m^{-3}), WD is the water demand by crops, PE (%) the pump efficiency, including the hydraulic efficiency and the mechanical efficiency, and IE the efficiency of the irrigation system, which accounts for the fact that a fraction of the irrigation water withdrawn from the source is not used (i.e., evapotranspired), but it is lost in surface runoff, soil drainage or losses from leaky conveyance canals or conduits[78]. In the absence of a globally distributed dataset detailing the types of pumps used for irrigation, average Pump Efficiency (PE) has been set equal to 31.5% in this study. This value is estimated as a weighted average of the efficiency of diesel and electric pumps. Indeed, pump efficiency can vary from 21% to 56% for diesel and electric pumps, respectively[24,79,80]. To assess the weighting of the two systems, we consider that only 30% of irrigated fields are currently located in areas with evidence of electrification. We account for uncertainty in the pump efficiency in the sensitivity and uncertainty analysis, and we performed simulations considering a fully diesel and a fully electric scenario. *IE* values have been derived from Jägermeyr et al.[46],.

The total head required to lift and apply irrigation water from its source is the sum of elevation head (EH), operating pressure head (OP), and friction losses (FL),

$$TH = EH + OP + FL + DD \quad (2)$$

The elevation head, EH, is the difference in elevation between the ground surface and the water source used for irrigation. The elevation head is calculated in different ways depending on the water source (either groundwater or surface water). In the case of groundwater sources, EH is the depth of the groundwater table in that cell, taken from Y. Fan et al.[81], and DD is the drawdown cone. DD is computed considering an average drawdown cone for confined and unconfined aquifers using the Cooper-Jacob equation (supplementary information). To account for uncertainty in the elevation head due to seasonal and annual groundwater fluctuations, potential increases in water table depth from water withdrawal, and observed changes in groundwater depth over the last 15 years, we applied an uncertainty margin of ±50%.

In case the source of water for irrigation is surface water (such as rivers or lakes), energy may be required to lift the water from the water source to the ground surface. Then, additional energy is required to convey surface water for irrigation if gravity flow to the irrigated field is not an option. In this study, it is assumed that extra energy is not required to convey the water from the withdrawal point to each field, because this is simply done by gravity and not in pressurized pipelines. Therefore, the total elevation head (EH) for surface water sources was assumed to range from 0 (no energy input required) to 5.0 meters globally, with an average of 2.5 m taken as the average head to lift the water from the surface source to the irrigation channel, after which it flows by gravity. The assumption is motivated by the maximum load that is withdrawn by centrifugal pumps that are commonly used for irrigation purposes[82,83], and making the same assumptions as[84]. In this analysis, the fraction of irrigated area with either groundwater sources or surface water sources is obtained from FAO's Global Map of Irrigation Areas version 5[85].

OP is the operating pressure set by the requirements of the irrigation system (surface, sprinkler, or drip) and the specific devices[86]. The following average operating pressures head for each irrigation type are considered, 0.0 meters of water[77] for surface irrigation since the water is distributed over the field by gravity, for sprinkler irrigation, 35 meters of water and 70 meters of water as an average of operating pressure for different types of sprinkler application devices for small and large fields respectively[87], for drip irrigation, 27 meters of water of operation pressure[88]. Lastly, FL accounts for energy dissipation due to friction[86]. Specifically, it is assumed that no friction losses are already accounted for in the baseline head needed to lift the water from the source (a surface water body) to the ground surface (i.e., in EH). In the case of sprinkler irrigation, friction losses are calculated as explained in the supplementary information, following Daccache et al.[89,90], while for a drip irrigation system, losses are accounted for in the operating pressure[88].

The water demand, WD, is the average water requirement (in volume over time) of the irrigated area. In each cell, we used the WATNEEDS model[41] to calculate the irrigation water requirement (IWR) of each crop. The model is run continuously for the period from 1993 to 2023. A three-year pre-run was performed to remove the dependency on baseline conditions (Chiarelli et al., 2020[41]). Yearly results of green and blue water are averaged over the 31-year period to produce the long-term time series of crop irrigation demand. The model uses inputs of spatially and temporally distributed information on climate, soil, and crop characteristics to solve a daily vertical soil water balance to determine crop water requirement (CWR) of each crop and the fraction of CWR that needs to be met by irrigation (IWR)[41]. CWR and IWR are based on estimates of potential evapotranspiration and actual evapotranspiration integrated over the growing season and are therefore expressed as depths of water (i.e., lengths, in millimeters). The model is run for different crop types according to available crop distribution rainfed-irrigated datasets, as detailed below. Crop lists for each dataset and crop parameters used in this study are reported in Supplementary Data 1 and 2. WD is then calculated as the sum across all crops of the product of crop-specific values of IWR and irrigated area. In order to account for the seasonal variation of WD, a sensitivity analysis has been run considering a variation of ±30% for the same. Blue water consumption at the country scale has been checked against available datasets[27,39].

Crop datasets and global irrigation demand assessment

The regional and global assessment of the energy required for irrigation is computed by multiplying the energy associated with every single field by the total number of fields within each grid cell and cumulating them regionally or globally.

The number of fields in each cell is calculated as the ratio between the average field size[29] and the prototype field size. In case the prototype field is bigger than the average land parcel size, the prototype is adapted to the smaller parcel size (supplementary information). The irrigated area in each cell of the global grid is obtained considering different spatially distributed crop distribution datasets, including those by SPAM, GAEZ, and Mirca. Detailed information on crop lists for each dataset and crop parameter,s including crop coefficient (Kc), growth stage duration, and the datasets used to derive planting and harvesting dates are reported in the supplementary data 2. Lastly, we also develop an updated dataset by linear scaling pixel-level irrigated areas from the SPAM global dataset[37] based on relative expansion reported by Mehta et al.[31], in order to better reflect recent trends in irrigation expansion. This interpolated dataset is referred to in this study as SPAM2020 updated.

Crop-specific energy per hectare

For the six most irrigated crops worldwide, namely cotton, maize, rice, sugarcane, vegetables, and wheat, which cover approximately 75% of the total irrigated areas, we provide crop-specific energy demand maps per hectare under different scenarios involving (i) the irrigation system adopted, (ii) the type of water source used, and (iii) the type of energy source used. These maps are generated considering an average field size of 100 hectares in each location as per the SPAM datasets[37].

Considered scenarios

The global demand for energy to irrigate is here computed under two different scenarios: (i) the baseline irrigated scenario and (ii) the sustainable irrigation expansion. The first scenario describes the current trends in terms of irrigated areas, irrigation system and crop distribution, including double cropping. In the second scenario, we evaluate the additional energy required to expand irrigation to areas where irrigation is needed, and water for irrigation is available, without depleting environmental flows or groundwater stocks. We do not consider expansion of irrigated areas during the second growing season, and we kept constant the share between surface and groundwater withdrawals. A field is considered to be irrigated if it is under a green water scarcity condition[19], which means that rainfed conditions would meet less than the required threshold of the crop's water requirement, accounting for a 10% reduction in yield (supplementary information).

We highlight that in this scenario, irrigation is expanded only in those areas where blue water is available for sustainable irrigation. Those areas have been identified by Rosa et al.[19], as areas currently undergoing economic water scarcity. Economic water scarcity conditions are a situation in which renewable blue water is locally available to meet the demand of irrigation, domestic, and industrial uses, but no irrigation occurs because of a lack of economic or institutional capacity. Economic water scarcity typically occurs in rain-fed croplands that are suitable for sustainable irrigation expansion. To delineate economically water-scarce areas, we compare blue water demand at irrigation expansion, including the additional blue water withdrawals for irrigation expansion, industrial, and domestic uses taken from Mekonnen and Hoekstra[91] and blue water availability (accounting for environmental flow and upstream water withdrawals), following Galli et al.[92]. If blue water demand (baseline + irrigation expansion) is lower than the water availability, it is possible to sustainably provide additional irrigation to currently rainfed areas. Climate change variability and potential economic development are not included in the scenario definition, as they fall outside the scope of this analysis. However, we provide our estimates under two contrasting scenarios: one where electrification fully meets the demand and another where diesel fuel remains the sole energy source for pumping, thus reflecting the diversity of energy sources that can be adopted for irrigation expansion. Supplementary data 1 provides a summary of the input data and scenarios considered.

Energy availability

At first, a country-scale comparison is carried out considering per capita energy consumption for each country. Additionally, a spatially distributed analysis was performed using an electrified network and nightlights maps to check where irrigation demand can be satisfied by the electrification grid. While spatially distributed analysis provides greater geographic precision in identifying water demand and water sources, it's worth noting that energy, unlike water, can be easily transported between locations. Country-scale data on supply energy per capita is taken from the IEA dataset[16], while two different datasets are combined to identify the electrified areas where electric energy for irrigation may be directly locally available. We consider that electric energy is available in the presence of either the electrified grid network or a nightlight. Thus, we overlap the maps of energy demand for both baseline and irrigation expansion scenarios with the map of energy availability, obtained by merging the map of artificial night light[55] with the electrified grid network[54]. For the night light dataset[55], energy is considered available if the total brightness of a pixel is above the natural light (1.7 to 14 μcd m^{-2}; blue), while the available vector file of electrified grid network[54] is converted into a raster file at 0.5 arcmin resolution (approximately 1 km at the equator) considering each pixel crossed by an electrification line as a pixel with available energy to be used for irrigation. To check the robustness of our analysis a 10 km buffer is introduced, under the hypothesis that electricity is available not only in the pixel with evidence of nightlight and/or electrified line, but also for all the closest pixels.

Sensitivity analysis and uncertainty analysis

This work represents an attempt to calculate crop-specific energy demand for irrigation at the global scale using a physically based approach. We carry out a detailed literature review to find the best value to be assigned to the different parameters used in the assessment. Our crop-specific assessment of energy for irrigation is based on global crop distribution data. We acknowledge the uncertainty in the exact spatial distribution of crops on the global scale, as different datasets exist and often do not fully agree, both in terms of crop typology and the distinction between rainfed and irrigated conditions. Our calculations are primarily based on the latest SPAM dataset, as it includes the widest range of crops, and has been updated with the most recent irrigation distribution maps by Mehta et al. (2024). However, we also provide energy demand estimates using crop distribution data from three additional datasets (MIRCA, GAEZ, and SPAM) for the respective time periods they cover.

We perform a yearly long-term energy assessment considering the yearly specific WD to study the energy estimation and the fluctuation of the main terms, TH and WD of Eq. (1), and we perform a statistical analysis to evaluate the mean and standard deviation. Those results are used in a preliminary uncertainty assessment on our global estimate, considering all variables in Eq. (1) having a Gaussian distribution centered on the mean and being random variables obtained as the product of independent variables.

Moreover, a sensitivity analysis was performed varying the most uncertain parameters, including (i) the total elevation head (TH), (ii) the average pump efficiency (PE), and (iii) the volume of water withdrawn (WD). Specifically, the total elevation head was varied up to ±20% to account for fluctuation of the groundwater table[93–95] and the initial head in case of groundwater and surface withdrawal, respectively; the average pump efficiency was varied of ±40% to account for the range in the efficiency related to the most common types of pump adopted[24,79,80], and the volume of water withdrawn was varied of ± 20% as a results of our yearly analysis, to include interannual climatic variability that affects the crop water demand[32,41,57].

Validation and comparison

To validate our estimates of the energy required for irrigation, we compare them to values reported in the literature for specific crops and at specific locations. To that end, we identify about 50 unique values reported in 14 previous studies (see the supplementary information for the list of the articles considered and the supplementary data 3 -Validation for the description of location, geographic coordinates, type of crop, type of irrigation method, and energy used for irrigation). The information covers 20 different locations and 15 different crops. A buffer of approximately 30 km is applied around each location. For 75% of the modeled specific energy demand in those 50 locations, the values are either close to (i.e., within a 20% error margin) or fall within the range of observed values.

Finally, a country-scale comparison of the total amounts of water withdrawals, electrical energy, and total energy used in agriculture is conducted, relying on existing literature[27] and datasets, such as those provided by the International Energy Agency (IEA)[16]. We highlight that

IEA reports data on total energy consumption in agriculture, fisheries, and forestry for selected partner countries. Thus, energy input for irrigation represents only a fraction of the total energy demand in the agriculture sector.

Limits and assumptions

Although we have used the most current data available, we acknowledge that our analysis on a global scale may be influenced by the necessary assumptions we have made using such data. To address these potential limitations, we perform both uncertainty and sensitivity analyses of the results with respect to the main parameters. Specifically, the spatial and temporal resolution of the analysis is determined by the availability of input data. All calculations are performed with a spatial resolution of 5 arcminutes (approximately 10 km at the Equator), except for the comparison with energy availability on the electric line, which is conducted at 0.5 arcminutes (approximately 1 km at the Equator). More detailed data would be required for a more accurate estimation, including data on the type of pumping system adopted, the irrigation system implemented, and the water sources used. For instance, due to the lack of specific data on pump types, their energy sources, and efficiencies, we use an average pump efficiency. Furthermore, in the absence of detailed information, pump types and water sources have been uniformly assigned to each crop, as well as the spatial distribution of irrigation systems, available at the country scale for all irrigated areas. It is also important to note that surface irrigation systems using surface water may operate through gravity, which we have accounted for in the sensitivity analysis, reducing the total energy demand by about 10%. Moreover, in our uncertainty analysis, we have taken these limitations into account, expressing the range of variation and providing crop-specific spatially distributed maps of different systems, energy sources, and pump efficiencies. Lastly, in the expansion scenario, we have kept constant the proportions of different irrigation systems, water sources, and pump types. While our estimates provide a useful approximation of global energy demand for irrigation by crop, some discrepancies may arise at local or regional levels.

Data availability

The energy-specific maps for the 6 most irrigated crops generated in this study and the raw data related to Fig. 1a, 1b, 4a, and 4b are available at: https://figshare.com/s/ca1f768e6781eb69b949.

Code availability

The MATLAB code for the computation of the crop-specific irrigation energy demand is available at: https://figshare.com/s/ca1f768e6781eb69b949.

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Author contributions

D.D.C., P.D., and M.C.R. designed the research; D.D.C., H.N., A.U., and I.L. performed the research; D.D.C., P.D., and M.C.R. analyzed the data; and all authors contributed to writing the paper. A.F. and H.N. contributed to the review of the paper.

Competing interests

The authors declare no competing interests.

Additional information

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