International Water Management Institute

Technical Brief

Groundwater irrigation in India's rice-wheat system: Quantifying the energy-carbon-productivity nexus and decarbonization pathways

Hidden cost of groundwater irrigation

The unchecked expansion of groundwater irrigation in India, coupled with poor irrigation water-use efficiency, has driven groundwater depletion across large parts of the country, particularly acute in the north-western states (Sikka et al., 2020). The significant loss of groundwater storage in the north-western Indian region (1 to 3 m/year depletion) has made it a global groundwater depletion hotspot (Devineni et al., 2022). This has been driven by water intensive expansion of rice-wheat and sugarcane cropping systems alongside power subsidies that offer little motivation for efficient water use in the region. For instance, the area under rice and wheat in the state of Punjab increased from 4.6% to 47.6% and from 29.5% to 49%, respectively, during 1966-67 and 2010-2011, resulting in a rapid depletion of groundwater levels. With climatic and anthropogenic-driven water demand, groundwater pumping is likely to increase in the future, potentially exceeding the monsoon groundwater recharge (Dangar & Mishra, 2023). This unchecked and continuous groundwater storage depletion is expected to pose a severe threat to the nation's food security (Jain et al., 2021).

While groundwater irrigation has led to severe depletion, it has simultaneously led to a sharp rise in energy consumption, particularly within the agricultural sector. In the process of water lifting, groundwater irrigation consumes significant electrical or fossil-fuel energy alongside generating carbon emissions, depending on the type of pump and its energy source.

A farmer in a paddy field, West Bengal, India (*photo*: Chhandak Pradhan/IWMI)

Additionally, energy subsidies, whether through a flat tariff or free electricity in some regions, lead to zero marginal pumping costs, providing no incentive for efficient water use and have burdened state utilities with heavy subsidy costs. In addition, groundwater pumping leads to significant carbon emissions, with estimates showing 32– 131 million tons of CO_2 emissions from groundwater pumping (Mishra et al., 2018; Rajan et al., 2020). However, crop-specific estimates of groundwater irrigation pumping and the associated emissions are not available for the country. With a growing emphasis on the sustainable management of limited water resources, improving agricultural productivity, and achieving net-zero targets, there is a need for quantifying the crop-specific energy consumption associated with groundwater irrigation and its environmental implications.

This technical brief presents district-level estimates of groundwater irrigation energy consumption, energy productivity, and associated Carbon (here, CO_2) emissions of two major crops, rice and wheat. This study will serve as an entry point for recommending mitigation pathways for informing policy and management decisions on crop choices to support judicious energy use, thereby indirectly abating emissions.

Methods: A data-driven assessment framework

This methodology assesses district-level energy consumption for groundwater pumping used to irrigate rice and wheat, based on a reference period of 2018–2020. It excludes other energy inputs to the farming system, such as those associated with developing on-farm irrigation infrastructure, fertigation, and field operations like tilling and harvesting. Districts where rice or wheat occupies less than 5% of the gross cropped area are excluded from the analysis. The detailed steps for calculating energy consumption, energy productivity, and carbon emissions are outlined in the following sections and illustrated in Figure 1.

Step 1: Calculation of groundwater abstraction for irrigation
As district-wise and crop-wise groundwater abstraction for irrigation information is not available, groundwater pumping was derived from crop irrigation requirements and the groundwater-irrigated area. The district and crop-wise groundwater pumping volumes were estimated by multiplying each crop's gross irrigation requirement, based on methodology accounting for crop season, coefficients, and reference ET (Amarasinghe et al., 2025), by its groundwater-irrigated area. The gross irrigation requirement of each crop was calculated by dividing the net irrigation requirement by irrigation efficiency. In the present study, the crop irrigation demand is assumed to be met completely. In this study, irrigation efficiency for the groundwater irrigated areas was taken as 50% for rice and 60% for wheat (Patle et al., 2016).

For rice, which is grown across three seasons, season-wise groundwater pumping volumes were estimated and then aggregated annually. For wheat, this is not an issue, as it is grown almost entirely in the post-monsoon rabi season under irrigation. While season-wise crop irrigation coverage data is available, source-wise irrigation coverage (surface water or groundwater) is not available at the crop or season level. Season-wise irrigation coverage was therefore apportioned in the same ratio as the overall source-wise split. Data on crop area, irrigation coverage, and irrigation source were sourced for the period 2018-2020 from the Directorate of Economics and Statistics (DES), Department of Agriculture and Farmers Welfare, Ministry of Agriculture and Farmers Welfare, Government of India.

Step 2: Assessment of dynamic pumping head
To calculate, the energy used in pumping, the dynamic pumping head was considered, with the total dynamic head (H) equal to the sum of the pumping head required to lift and deliver the required amount of irrigation water to the point of use and head losses in the pump assembly. The depth to the groundwater table was calculated by averaging the depths to groundwater levels during the pre- and post-monsoon periods, using Central Ground Water Board (CGWB) monitoring well data, for each district.

Step 3: Estimation of energy required for groundwater pumping
The energy required for groundwater pumping for irrigation depends mainly on the mass of water to be pumped, the total dynamic head, and the overall efficiency of the pumping system. This was estimated using the following equation:

$$E_{ij} = \frac{9.8 \times H_i \times GWPV_{ij} \times \rho}{3.6 \times 10^6 \times pe_i}$$

where E^{ij} is the energy required for groundwater pumping for irrigating j^{th} crop in i^{th} district (KWh); H_i = dynamic head (m); $GWPV_{ij}$ = groundwater pumping volume (m^3); p is the density of water (1000 kg/m^3); pe_i = overall weighted pump efficiency (%) for each district i; The overall pump efficiency in this study was taken as 35 and 25% for the electric and diesel pumps respectively, as adopted in multiple studies where the values range between 30%-40% ictric and 20%-30% in diesel (Patle et al., 2018; Mishra et al., 2018; Nelson et al.,2009; Shah 2009). For each district, the weighted overall pump efficiency was calculated based on the coverage percentage of electric and diesel pumps, as reported in the Fifth Minor Irrigation Census.

Step 4: Estimation of energy productivity for groundwater pumping
Finally, energy productivity was calculated by dividing the total crop production (in tonnes) attributable to the groundwater-irrigated area by the energy used in groundwater pumping, as calculated above. To estimate this, district-level crop yield (tonnes/hectare) was multiplied by the groundwater-irrigated area (hectares) in that district to derive the corresponding production. This production figure was then divided by the energy used in groundwater pumping to arrive at energy productivity.

A key assumption underlying this calculation is that district-level crop yield is available as a single value and does not distinguish between yield achieved under groundwater irrigation, surface irrigation, or rainfed conditions. This means that districts with similar yields can show very different energy productivity values, depending on how much of their irrigation comes from groundwater. A district that relies more heavily on groundwater irrigation will show lower energy productivity than a district with the same yield that relies less on groundwater because more of its production depends on groundwater pumping.

Step 5: Estimation of carbon emissions
Based on the energy consumption and distribution of the pump source of energy (diesel/electric) in the district, total carbon emissions were calculated by multiplying the groundwater pumping energy requirement of each crop by the respective emission factor of electricity (grid) and diesel fuel.

In this study, the emission factor for diesel pumps was taken as 0.0732 kg C per kWh (0.268 kg CO_2/kWh) (Nelson et al., 2009), and a grid emission factor of 0.71 kg CO_2 per kWh for electric pumps, representing a coal-dominated electricity generation system, as estimated by the Central Electricity Authority (CEA), Government of India.

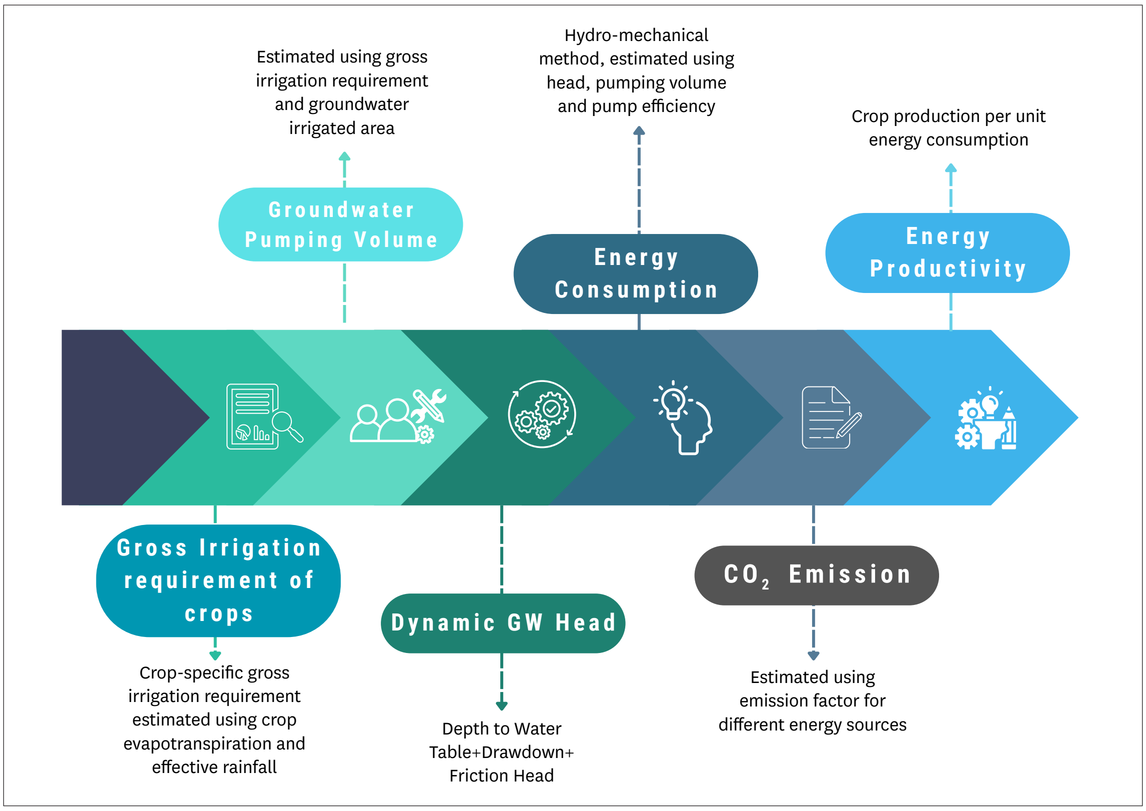


Figure 1. Summary method for estimating energy productivity and CO_2 emission

Key Findings

1. Energy consumption in groundwater irrigation and associated CO_2 emissions

At the national level, groundwater-based irrigation for rice and wheat consumed about 36.1 million MWh (mMWh) of energy annually, resulting in 20.6 million metric tonnes (MMT) of CO_2 emissions. Wheat accounted for the larger share, 25.7 mMWh (14.5 MMT CO_2), reflecting its near-total dependence on irrigation as a crop grown in the dry post-monsoon rabi season, while rice accounted for 10.4 mMWh (6.1 MMT CO_2). Rice and wheat combined contribute more than half of the total emissions (~39 MMT) from groundwater-based irrigation pumping nationally. Five states - Uttar Pradesh, Madhya Pradesh, Punjab, Rajasthan, and Haryana - together account for 76% of national groundwater pumping energy use and a similarly large share of associated CO_2 emissions (~21 MMT), reflecting their status as the country's principal rice-wheat growing belt.

Rice (Figure 2) - Uttar Pradesh, Punjab, and Andhra Pradesh together account for the largest shares of rice energy use and emissions, but their patterns diverge sharply relative to area. Uttar Pradesh cultivates the largest share of the country's rice area (29.6%) yet accounts for a proportionately smaller share of energy (21.7%) and an even smaller share of CO_2 emissions (13.2%). This lower energy requirement reflects two related factors: eastern rice-growing states such as Uttar Pradesh, Bihar receive a higher share of their crop irrigation requirement from rainfall, reducing the volume that needs to be met through groundwater pumping, and these states also tend to have shallower groundwater levels, which lowers the energy needed to lift a given volume of water. Punjab shows the opposite pattern: with only 13.1% of national rice area, it accounts for 18.1% of energy use and 21.7% of CO_2 emissions, disproportionately higher on both counts, reflecting lower rainfall contribution to irrigation and deeper groundwater levels from decades of sustained rice cultivation, both of which raise the pumping energy required per unit of rice area. Andhra Pradesh follows a similar energy-intensive trajectory (12.3% area vs. 17.6% energy).

On CO_2 emissions, the pump-source mix and its associated emission factor come into play. Uttar Pradesh's CO_2 share (13.2%) falls even further below its area share than its energy share does, because the state relies predominantly on diesel pumps. Based on the current grid emission factor, diesel pumping results in lower total CO_2 emissions per unit of energy than grid electricity, even after accounting for diesel pumps' lower efficiency, since India's coal-dominated grid carries a substantially higher emission factor per kWh than diesel combustion. Punjab and Andhra Pradesh, by contrast, rely almost entirely on electric pumps, which compounds their already higher energy use with a higher emission factor, further inflating their CO_2 share relative to area. Though this should not be read as diesel being the cleaner option overall: diesel pumping carries other costs, including local air pollution, dependence on imported fuel, and lower pump efficiency, which raises the energy required for the same irrigation output. As India's electricity grid progressively decarbonizes with a growing share of renewable generation, emissions from electric pumping are expected to decline over time, which could shift this relative positioning between states.

These state-level patterns are also visible at the district scale (Figure 1b and 1c). For both rice and wheat, energy and emission hotspots are concentrated in the districts of Uttar Pradesh, Punjab, Haryana, Rajasthan, and Madhya Pradesh, with additional rice-specific hotspots in West Bengal, Telangana, and Andhra Pradesh, districts marked by intensive groundwater irrigation, deeper water tables, and high irrigation demand.

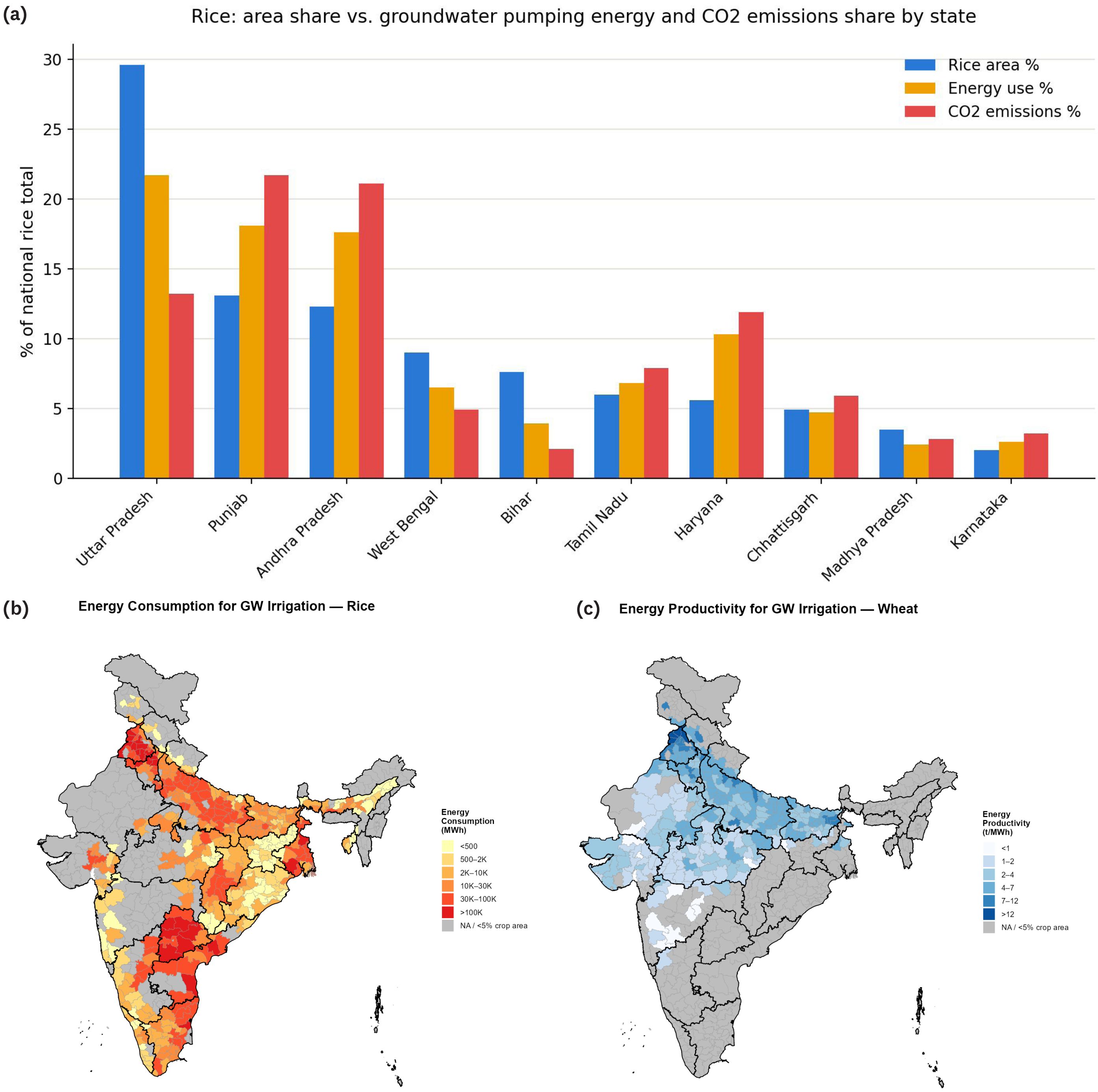


Figure 2. State-wise rice-cropped area share compared with groundwater pumping energy use share and CO_2 emissions share (a) and district-level median groundwater irrigation pumping energy consumption (b) and associated CO_2 emissions (c)

Wheat (Figure 3): A comparable but sharper divergence appears in wheat. Unlike rice, rainfall contributes little to meeting wheat's irrigation requirement, since the crop is grown almost entirely in the post-monsoon rabi season under dry conditions, so unlike the rice case, differences in energy use across wheat-growing states are driven primarily by groundwater levels and pump type rather than variation in rainfall dependence. Uttar Pradesh again shows 38.4% of national wheat area against just 27.9% of energy and 17.5% of CO_2, consistent with shallower groundwater and predominantly diesel-based pumping, as discussed for rice. Madhya Pradesh stands out as the clear outlier with only 21.8% of wheat area but accounts for 31.8% of energy use and 38.2% of CO_2 emissions, nearly double its area share on the emissions front, and the largest such gap of any state for either crop. This points to considerably deeper groundwater levels in Madhya Pradesh's wheat-growing districts, compounded by a near-total reliance on electric pumps, which raises both the energy required per unit of area and, through the higher grid emission factor, the associated emissions. Rajasthan (9.5% area vs. 13.4% energy, 14.3% CO_2) and Gujarat (2.8% area vs. 5.2% energy, 6.6% CO_2) show the same pattern at a smaller scale, both being predominantly electric-pump states with relatively deep groundwater.

Further, the analysis reveals substantial regional differences in the energy used for pumping groundwater for irrigation and associated carbon dioxide (CO_2) emissions across India (Figure 1). For both rice and wheat crops, the high-energy and emission hotspots are concentrated in north-western and western parts of India, particularly in Uttar Pradesh, Punjab, Haryana, Rajasthan, and Madhya Pradesh. For rice crops, additional high-energy-consuming districts are densely clustered in West Bengal, and the southern states of Telangana and Andhra Pradesh. These regions are characterized by intensive groundwater-irrigated areas, deeper groundwater levels, and high irrigation demands.

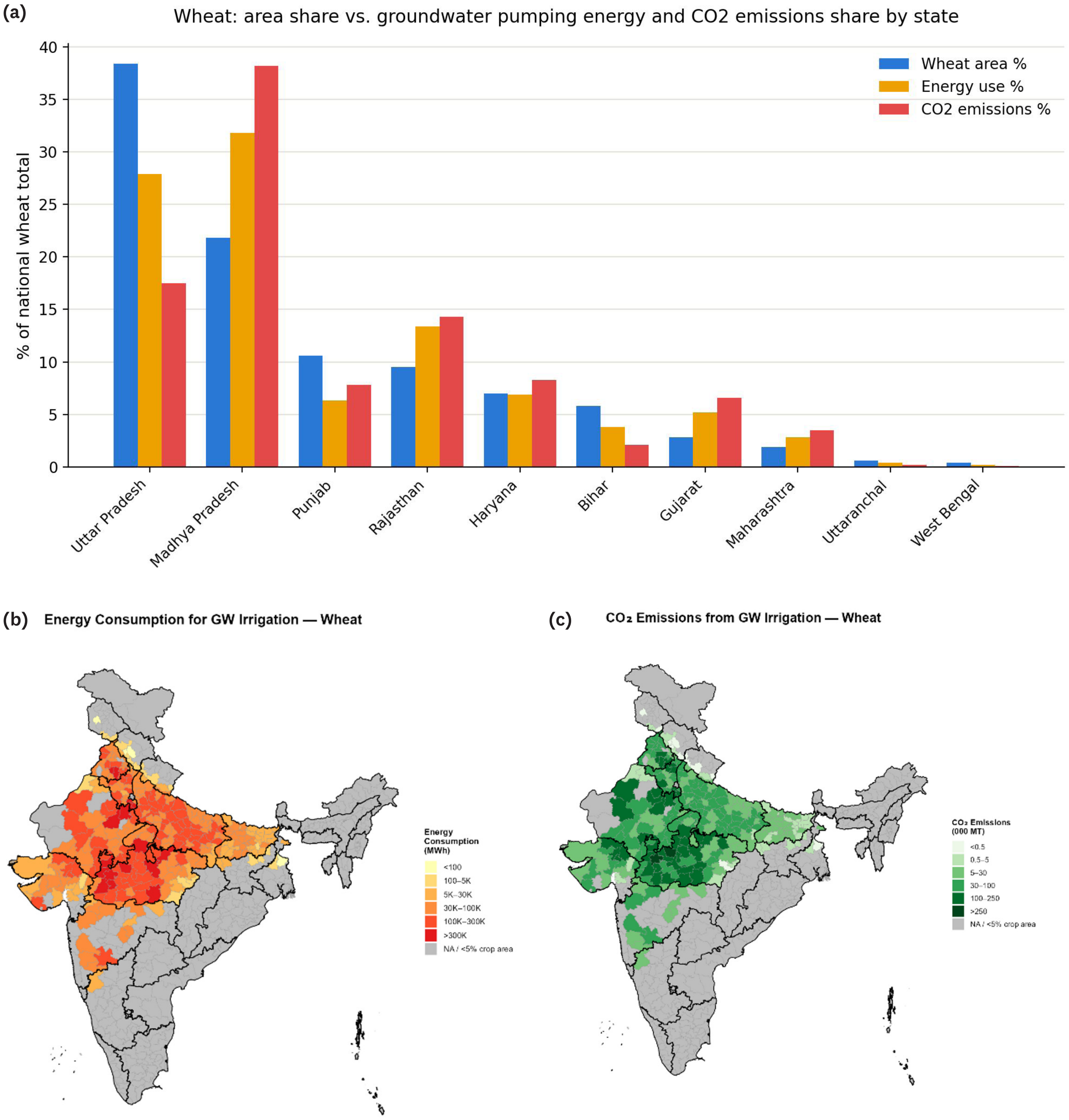


Figure 3. State-wise wheat-cropped area share compared with groundwater pumping energy use share and CO_2 emissions share (a) and district-level median groundwater irrigation pumping energy consumption (b) and associated CO_2 emissions (c)

A woman farmer transplanting paddy in Rangareddy district, Telangana, India (*photo:* Tanmoy Bhaduri/IWMI)

2. Energy productivity and performance of Indian States

District-level analysis of energy productivity (EP) for groundwater irrigation pumping in rice and wheat shows substantial regional variation (Figure 4). Energy productivity, tonnes of produce per unit of energy consumed for groundwater pumping, ranges from about 1 to 16 t/MWh (5th–95th percentile) across most districts, underscoring the wide variation driven by differences in crop yield, agroclimatic conditions, groundwater table depth, and pumping requirements across regions.

EP for rice and wheat also differs markedly in geographic pattern and magnitude. Moderate to high EP values for rice (>10 t/MWh) are concentrated in the eastern Indo-Gangetic plains of West Bengal and Bihar, in Odisha, and in a few districts of the southern peninsular region. In contrast, low-EP rice districts (<5 t/MWh) are mostly found in regions with deeper groundwater tables or lower crop yields, such as Punjab, Haryana, Gujarat, Rajasthan, Jharkhand, and parts of the southern peninsular states. At the state level, West Bengal recorded the highest rice energy productivity (7.2 t/MWh), followed by Bihar (7.0 t/MWh) and Uttar Pradesh (6.0 t/MWh) during 2018–2020.

Among major wheat-growing regions, the highest-EP districts (>10 t/MWh) are concentrated in Punjab and Uttar Pradesh, with western and central states showing lower EP overall. At the state level, Punjab's wheat recorded the highest energy productivity (7.3 t/MWh), followed by Uttar Pradesh (4.5 t/MWh) and Haryana (4.2 t/MWh), which is largely attributable to higher wheat yields in these states relative to their groundwater pumping energy requirement.

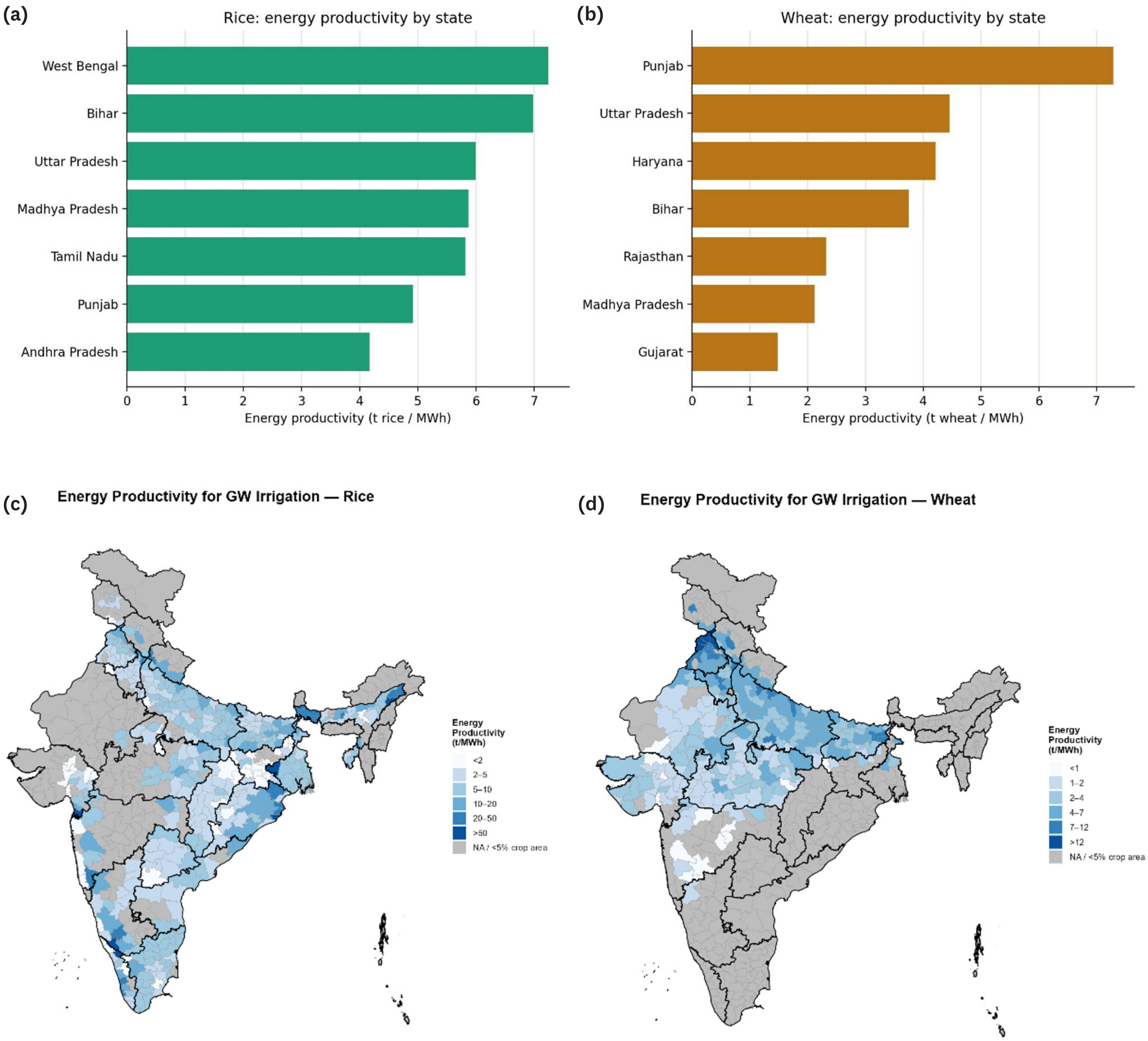
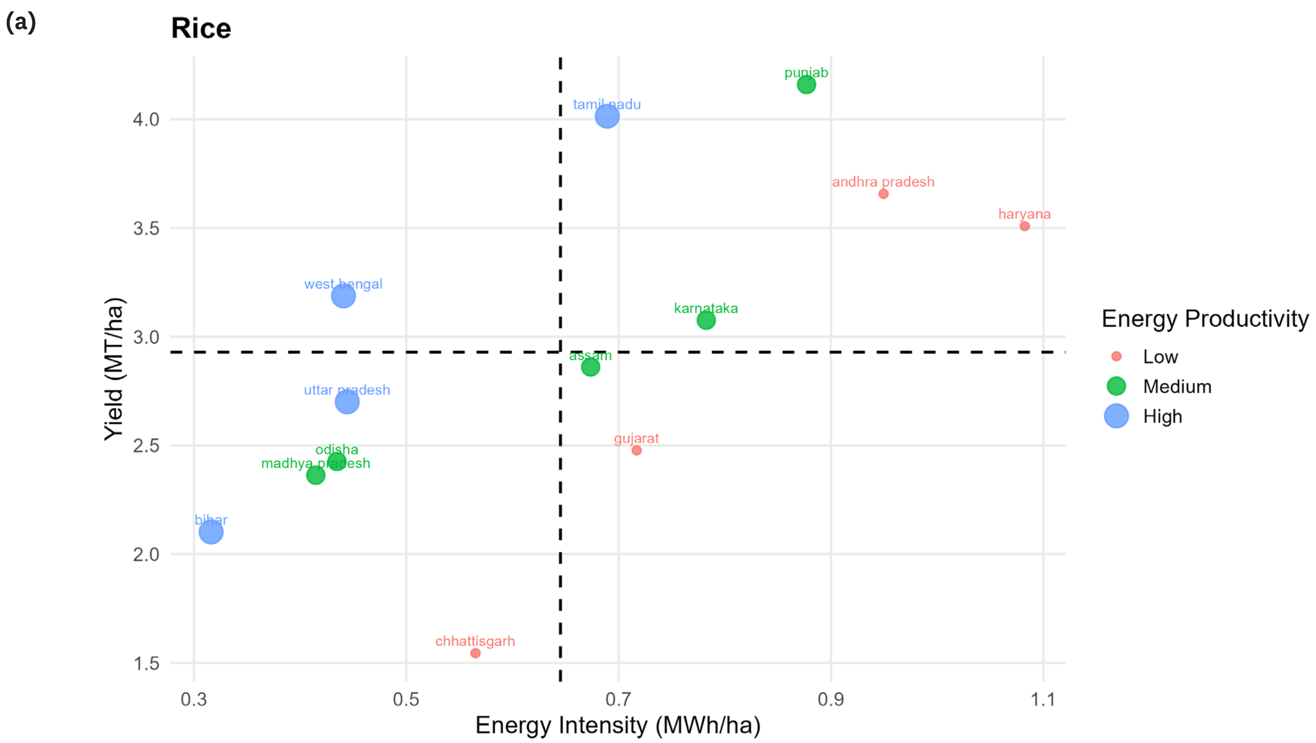


Figure 4. Average (2018-2020) State and median district-level energy productivity (tonnes of produce per unit of groundwater pumping energy) for (a, c) rice and (b, d) wheat

To assess the joint performance of energy use and productivity, states were classified into four quadrants based on crop energy intensity (energy consumption per unit groundwater-irrigated area) and yield from the groundwater-irrigated area (Figure 5).



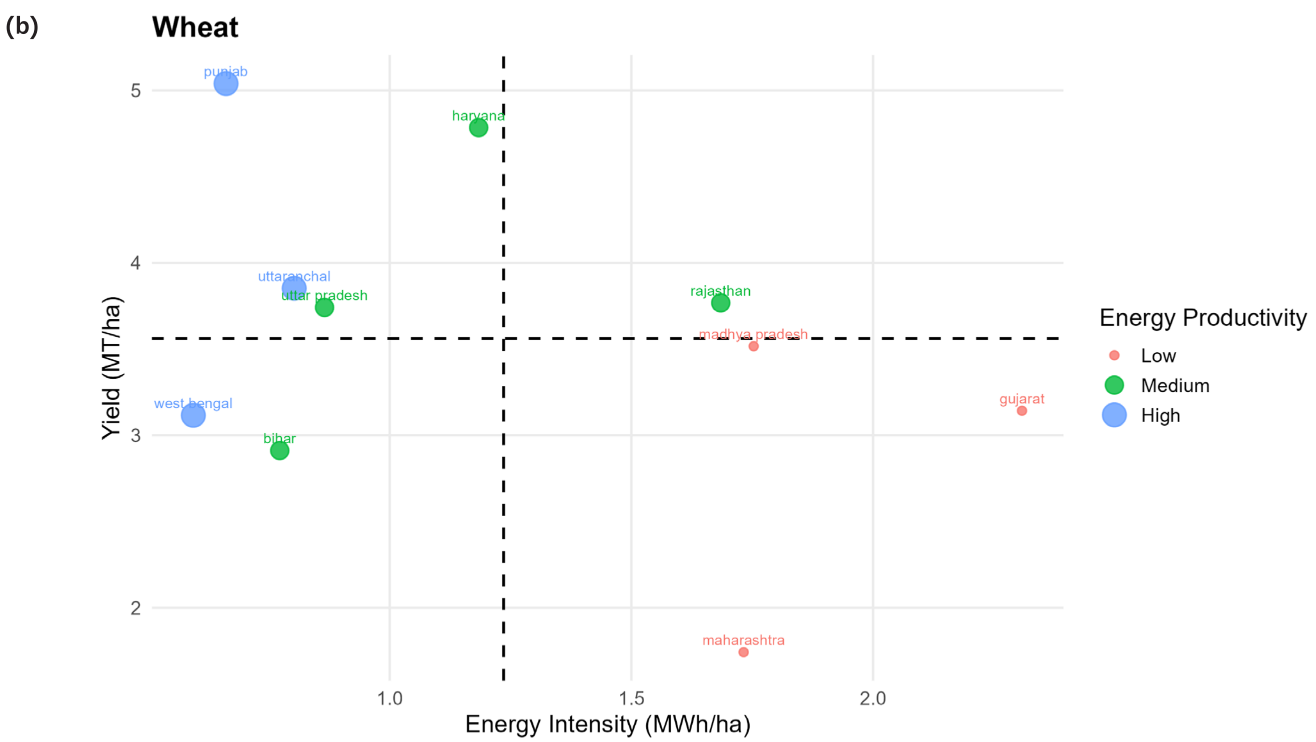


Figure 5. State-wise relationship between (a) rice, and (b) wheat energy intensity (energy per unit area) and yield, with bubble size representing energy productivity. The dashed x-axis and y-axis represent the mean energy intensity and yield, respectively.

Rice: Comparing rice energy intensity (energy consumption per unit groundwater-irrigated area) and rice yield from the groundwater-irrigated area across states (Figure 5a) shows that north-western states like Punjab and Haryana, along with Tamil Nadu, Andhra Pradesh, and Karnataka, achieve high yield but at the cost of high energy intensity from deep groundwater extraction, with Haryana and Andhra Pradesh showing a comparatively lower output-input ratio (EP) within this group. West Bengal stands out as the most favourable case, combining a relatively high yield (3.2 MT/ha) with low energy intensity, reflecting shallower groundwater and high rainfall in the state. At the other end, Gujarat and Assam fall in the undesirable high-energy, low-yield quadrant, reflecting poor performance on both fronts and representing the greatest scope for integrated interventions in crop management, pump efficiency, and irrigation scheduling. States such as Odisha, Uttar Pradesh, Madhya Pradesh, Bihar, and Chhattisgarh fall in the low-yield, low-energy-intensity quadrant, suggesting that production in these states is constrained more by irrigation access and water management than by energy availability, offering greater opportunity for improving irrigation water productivity through better water management rather than energy-focused interventions.

Wheat: The rice pattern does not fully carry over to wheat (Figure 5b), as wheat is mostly irrigated and grown in post monsoon dry season. Punjab sits in the most desirable quadrant, achieving the highest wheat yield (5.1 MT/ha) at low energy intensity, followed by Uttar Pradesh and, marginally, Haryana, both combining above-average yield with comparatively low energy use. Rajasthan is the exception among high-yield states, achieving a high yield (3.8 MT/ha) only at a correspondingly high energy cost. At the other end, Madhya Pradesh, Gujarat, and Maharashtra fall in the high-energy, low-yield quadrant, with Maharashtra showing the weakest yield performance (1.8 MT/ha) among the major wheat states assessed, representing the greatest scope for integrated interventions. Bihar is the only major state in the low-energy, low-yield quadrant, suggesting that, as with the comparable rice-growing states, irrigation access and water management, rather than energy input, remain the binding constraint on yield. Overall, wheat productivity gains in most leading states appear less tightly coupled to groundwater depth than rice, with the states of greatest concern for wheat (Madhya Pradesh, Gujarat, Maharashtra) narrower in number than for rice.

A solar powered irrigation system in Bihar, India (*photo:* Ayush Manik/CCAFS)

Mitigation pathways and transitioning to low-carbon agricultural irrigation

The above results highlight that a 'one-size fits all' mitigation strategy is unlikely to be effective, and a combination of site-specific low-carbon, high-productivity transition pathway is required, as discussed below.

a) Decarbonization of irrigation energy sources
Indian irrigation is powered predominantly by grid electricity, of which roughly 50–60% is still generated from coal gas and diesel, making agriculture a significant contributor to national CO_2 emissions. The Pradhan Mantri Kisan Urja Suraksha evam Utthaan Mahabhiyan (PM-KUSUM), launched in 2019, is India's flagship policy response, aiming to expand solar-powered irrigation and reduce dependence on diesel.

To quantify its potential impact, sanctioned solar pump data (from PM-KUSUM scheme) for Uttar Pradesh (state with largest rice and wheat area) were analyzed under two scenarios: (a) 5% de-dieselization under PM-KUSUM Component B, meaning 5% of existing diesel pumps are replaced with solar pumps; and (b) 50% solarization of the electric share under the feeder-level solarization component (PM-KUSUM-FLS), meaning 50% of existing electric pumps are converted to solar. Relative to the 2018–2020 baseline, the PM-KUSUM Component B scenario reduced CO_2 emissions by 3.4%, corresponding to 0.03 million MWh (mMWh) in energy savings and 11.19 million L (ML) in diesel savings, assuming 1 L of diesel produces 2.68 kWh of pumping energy (derived from 10.7 kWh of thermal energy at 25% system efficiency). The PM-KUSUM-FLS reduced CO_2 emissions by 16.5%, indicating reduced grid dependency. This shows that the scheme's components, if strategically deployed according to each state's existing irrigation-energy mix, could meaningfully advance net-zero emission targets.

b) Improve irrigation system efficiency
Water-efficient practices, micro-irrigation, Alternate Wetting and Drying, and Direct Seeded Rice, reduce irrigation water demand and, in turn, groundwater consumptive use, lowering energy demand independent of pump type or efficiency. The central government promotes this shift through Per Drop More Crop (PDMC), the micro-irrigation component of the Pradhan Mantri Krishi Sinchayee Yojana (PMKSY), and other programs incentivizing the adoption of DSR and AWD practices for rice.

Our model simulation for Uttar Pradesh shows that raising rice irrigation efficiency from 50% to 60% can reduce CO_2 emissions by about 16%. This also means there can be 0.37 mMWh of savings in pumping energy, equivalent to the electricity savings from the grid or 138 ML of diesel savings.

c) Improve pump efficiency
Most agricultural pumps in India operate well below optimal efficiency. Improving the efficiency of electric and diesel pumps alone can meaningfully reduce energy consumption and associated emissions. This is the objective of the Bureau of Energy Efficiency's Standards & Labelling programme for agricultural pump sets, alongside its Agriculture Demand Side Management (AgDSM) initiative, which promotes replacement of old pumps with BEE star-rated, energy-efficient models.

Our model simulation shows that improving diesel pump efficiency alone from 25% to 35% in Uttar Pradesh reduces CO_2 emissions by about 19%. In terms of energy, this intervention can reduce the pumping energy requirement by 0.54 mMWh, easing the burden on the grid or diesel requirements by 201.4 ML, if the source is diesel fuel.

d) Crop diversification
Shifting from water-intensive crops to less water-demanding alternatives improves energy productivity and reduces emissions per tonne of food produced. The Crop Diversification Programme (CDP), a sub-scheme of the Rashtriya Krishi Vikas Yojana (RKVY), supports this transition in Punjab, Haryana, and western Uttar Pradesh by incentivizing farmers to shift paddy area toward pulses, oilseeds, maize, and other less water-intensive crops.

The above pathways and analyses are presented as individual interventions, but they are not mutually exclusive, as decarbonizing the energy source, improving irrigation efficiency, and improving pump efficiency can be implemented together and sequentially. Combined, they can be expected to yield higher overall savings than any single pathway alone, although the combined reduction will be less than the simple sum of the individual percentages, since each subsequent measure acts on an already-reduced energy base. Taken together, when combined, these pathways can substantially improve energy productivity, reduce carbon emissions, and enhance energy reliability for farmers.

Yatin Kumar, a farmer and irrigation service provider, sets up irrigation pipes on his farm in Bihar, India (*photo:* Tanmoy Bhaduri/IWMI)

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Authors

Smaranika Mahapatra, National Researcher, International Water Management Institute (IWMI), New Delhi, India (s.mahapatra@cgiar.org)
Mohammad Faiz Alam, Senior Regional Researcher, IWMI, New Delhi, India (m.alam@cgiar.org)
Manikanta Radhakrishna, Researcher, Technical University of Munich (TUM), Munich, Germany (m.radhakrishna@tum.de)
Alok Sikka, Emeritus Scientist, IWMI, New Delhi, India (a.sikka@cgiar.org)
Gokul Prasad, Consultant, IWMI, New Delhi, India (g.prasad@cgiar.org)
Upali Amarasinghe, Emeritus Scientist, IWMI, Colombo, Sri Lanka (u.amarasinghe@cgiar.org)

Author Contributions

Conceptualization: Smaranika Mahapatra, Mohammad Faiz Alam, Alok Sikka, Upali Amarasinghe; Methodology: Smaranika Mahapatra, Mohammad Faiz Alam, Alok Sikka, Upali Amarasinghe; Software: Smaranika Mahapatra, Manikanta Radhakrishna; Validation: Smaranika Mahapatra, Mohammad Faiz Alam, Manikanta Radhakrishna, Alok Sikka, Upali Amarasinghe; Formal analysis: Smaranika Mahapatra, Mohammad Faiz Alam, Manikanta Radhakrishna; Investigation: Smaranika Mahapatra, Mohammad Faiz Alam; Resources: Alok Sikka, Upali Amarasinghe; Data curation: Smaranika Mahapatra, Mohammad Faiz Alam, Manikanta Radhakrishna, Gokul Prasad, Upali Amarasinghe; Writing – original draft: Smaranika Mahapatra, Mohammad Faiz Alam, Manikanta Radhakrishna, Alok Sikka, Upali Amarasinghe; Writing – review & editing: Smaranika Mahapatra, Mohammad Faiz Alam, Manikanta Radhakrishna, Alok Sikka, Upali Amarasinghe; Visualization: Smaranika Mahapatra, Mohammad Faiz Alam, Manikanta Radhakrishna; Supervision: Alok Sikka, Upali Amarasinghe; Project administration: Alok Sikka; Funding acquisition: Alok Sikka.

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International Water Management Institute (IWMI)

Headquarters
127 Sunil Mawatha, Pelawatte,
Battaramulla, Sri Lanka

Mailing address:
P. O. Box 2075, Colombo, Sri Lanka
Tel: +94 11 2880000
Fax: +94 11 2786854
Email: iwmi@cgiar.org
www.iwmi.org