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Water, Energy and Carbon Tradeoffs of Groundwater Irrigation-Based Food Production: Case Studies from Fergana Valley, Central Asia

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Abstract: In arid environments, water shortages due to over-allocation of river flow are often compensated by lift irrigation or pumping groundwater. In such environments, farmers using pumped irrigation can deploy on-farm energy-efficient and water-saving technologies; however, pumping water requiring extra energy is associated with carbon emissions. This study explores how to increase crop production using pumped irrigation with minimal energy and carbon emissions. The purpose of this research is twofold: first, to examine on-farm energy consumption and carbon emissions in gravity and groundwater irrigation systems; and second, to explore system-level alternatives of power generation and water management for food production based on the results from the farm-level analysis. This study employs a novel system-level approach for addressing water, energy, and carbon tradeoffs under pumped irrigation using groundwater. These tradeoffs are assessed at farm and system levels. On-farm level estimates showed that farm-level interventions were insufficient to produce mutual gains. According to the results of the system-level evaluation, system-level interventions for water and energy conservation, the use of renewable energy to pump water for irrigation, and river basin scale cooperation are all required to maintain crop production while reducing energy consumption and carbon emissions.

Keywords: water-energy-carbon nexus; groundwater; water-energy productivity; carbon dioxide emissions; renewable energy; Central Asia

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1. Introduction

Increased agricultural production is critical to ensuring food security for the world's growing population. This requires more agricultural farm inputs, including water and energy, and carries associated soil, water, and atmosphere pollution risks due to increasingly poor-quality return flows and greenhouse gas (GHG) emissions. Over time, the return flows and emissions may also accelerate global changes in the biosphere, negatively impacting the environment and depletion of non-renewable fossil energy resources. Consequently, agricultural development, aimed at obtaining short-term benefits, increases the risk of failures in the future for the environment and human life [1].

The unsustainability of agricultural development has become a much-researched subject [1–3]. One challenge for the intensification of food production in arid regions is the vulnerability and over-allocation of river flow, which causes farmers to shift to pumped irrigation, using available water sources, including groundwater [4–9]. The pumped irrigation ensures the reliability of water supply according to crop water requirements; however, pumping water makes irrigation energy- and carbon-intensive, increases greenhouse gas emissions, and accelerates climate change [10–12].

Pumped irrigation includes lift irrigation schemes and pumping groundwater for irrigation. Lift irrigation schemes implement an inter-basin water transfer in three stages: pump water from a source to the highest level; then transport water by gravity up to the irrigation zone; and finally, distribute water between farmers. In Uzbekistan, where over 50% of the irrigated land is under lift irrigation, water delivery for crop production is the third major consumer of the national electricity generated. Similarly, in Tajikistan, lift irrigation schemes occupy 40% of the irrigated land. In these schemes, water losses from irrigation canals and farm fields recharge relevant aquifers and raise the groundwater table.

Groundwater is an essential source of irrigation in many countries. In the USA and India, 60% of irrigation already relies on groundwater [4,13,14]. Although pumping groundwater accounts for only 3%, 3.6%, and 6% of total emissions from agriculture in China, Iran, and India, respectively [4,5,15], there are regions where groundwater abstraction has become the major consumer of generated electricity and source of carbon emissions [8].

In addition, groundwater irrigation often leads to storage depletion. Global estimates of groundwater depletion vary from 145 (±40) km^3/yr [16] to 283 (±40) km^3/yr [17]. In regions with intensive agriculture, groundwater depletion follows a significant increase in energy use [4,6,18]. The northern states of India and the North China Plain are examples of such regions where groundwater depletion has caused an increase in energy consumption and carbon emissions [8,19,20]. Due to the depletion of groundwater sources, according to Qiu et al. [20], energy consumption and carbon dioxide emissions in the North China Plain grew by 22% and 42%, respectively, from 1996 to 2013. In such regions, the sustainability of food production is associated with the restoration and stabilization of the groundwater table.

There are several opportunities to stabilize groundwater levels and reduce carbon dioxide emissions. Fishman et al. [21] found that appropriate crop selection and improved irrigation water use in areas with depleted groundwater would reduce groundwater abstraction by two-thirds and stabilize groundwater levels. Another opportunity is efficiency-oriented programs that can reduce water and energy losses and carbon emissions and benefit the environment. Handa et al. [22] found that improving pumping efficiencies reduced energy consumption (by 19% and 34%) and carbon dioxide emissions (by 20% and 52%) in two study regions in Oklahoma, USA, between 2001–2017. El-Gafy and El-Bably [23] obtained similar results for on-farm irrigation pumps in El-Behera, Egypt.

Several studies focusing on the operation of irrigation systems have linked the on-farm adoption of water-saving technologies to carbon dioxide emissions [24–28]. Thus, Guo et al. [26] found that drip irrigation increases the mean carbon dioxide effluxes and the cumulative CO_2 emissions compared with flood irrigation during the maize-growing season. In contrast, Gao et al. [27] demonstrated that subsurface drip irrigation increases water and nutrient use efficiencies and reduces weed pressure; moreover, in combination with fertigation, it can lead to significant emission reduction. Edwards et al. [29] reached a different conclusion, indicating that intensive crop surface and subsurface drip irrigation have negligible impacts on GHG emissions in loamy sand soils. In other words, on-farm level evidence is mixed, and the carbon input severity of water-saving technologies depends on the biophysical factors and other farming practices.

Another opportunity is shifting to alternative energy sources for pumping groundwater [30]. Mishra et al. [30] found that environmental benefits, such as reduced carbon dioxide emissions, can be obtained by switching from electric or diesel pumps to solar or wind power. This off-farm level consideration had no link with efficiency-oriented programs at the farm level. System-level assessments, from electricity generation for pumping irrigation water to field levels of food production, are lacking in the literature on carbon emissions.

This study examines the sustainability of pumped irrigation using a system-level approach through linking water and energy use at the on-farm level to the appropriate off-farm level mobilization of natural resources and carbon emissions to supply water and energy for on-farm crop production. The impact of water cooperation at the basin/system level on the sustainability of crop production is assessed at the on-farm level in groundwater irrigation areas. Thus, it facilitates the analysis of tradeoffs between water, energy, and carbon in groundwater irrigation areas. The research question is: how to reduce energy use and carbon emissions in crop production using pumped irrigation. The hypothesis is that combined analyses of water, energy, and carbon tradeoffs from field to system-level can result in sustainable crop production in groundwater irrigation areas. The objectives of this study are (1) to compare on-farm level energy use and related carbon emissions in gravity and groundwater irrigation systems; and (2) to examine alternatives of electricity generation and use, irrigation, and food production at a system-level based on these farm-level findings. The novelty of this study lies in the system-level approach to addressing water, energy, and carbon tradeoffs for pumped irrigation, including lift and groundwater irrigation.

2. Materials and Methods

2.1. Challenges in Food Production Due to Water-Energy-Carbon Nexus

The Aral Sea Basin, spread across the southern part of Central Asia, has a fast-growing population. The population is expected to rise from 57 million in 2020 to 83 million in 2050, making food crop production a priority for farming in irrigated lands where over 90% of the region's agricultural products are produced. Population growth will increase the demand for more water withdrawal. At the same time, the flow of the main rivers in the region is projected to decrease due to climate change and melting glaciers upstream. Thus, by 2050, the annual unmet demand in the Amudarya and Syrdarya River Basins is projected to increase to 50% and 35% of the total water demand, respectively [31]. Considering that over 40% of the irrigated land downstream of the rivers is under lift irrigation, food production in the region is projected to become highly dependent on the availability of water, the energy to lift water, and a sustainable environment, which also requires water for its functioning. Under these conditions, the interlinkages between water, energy, and carbon have become critical considerations for sustainable food production and an environmentally friendly strategy. Food production in the basin depends on river flow, which is transboundary. Much of the flow of the Syrdarya (over 73%) and Amudarya (over 88%) rivers originate in upstream countries—Kyrgyzstan, Tajikistan, and Afghanistan, while productive farmlands requiring irrigation are located primarily in downstream countries—Uzbekistan, Turkmenistan, and Southern Kazakhstan.

Reaping the benefits of such an environment requires close cooperation between riparian states in the upstream hydropower development and food crop production downstream of the rivers [32]. There is high demand for such collaboration, as 95% of the hydropower potential is undeveloped in the upstream of the Amudarya in Tajikistan and 87% in the upstream of the Syrdarya in Kyrgyzstan [33]. Increasing hydropower generation upstream in the future could boost the electricity market in the region; however, it might reduce the quantity of water available for agriculture in the summer months. While downstream crop producers are concerned about upstream hydropower development, hydropower is very important for the upstream economy and potential for the region's future [34].

At the beginning of the 1990s, the previously united regional power supply system collapsed. The downstream states preferred access to water than hydropower from upstream and, facing energy shortages, focused on internal thermal power development using fossil energy resources. The electricity supply from upstream hydropower stations was replaced with local thermal power stations. This strategy causes rapid depletion of fossil resources, including natural gas, in Uzbekistan, where reserves are available for only 20–30 years. In addition, the shift from hydropower to thermal power increases carbon dioxide emissions, contributing to climate warming and melting glaciers upstream. Thus, focusing on thermal power in the downstream states causes depletion of fossil energy resources and increases

CO_2 emissions, contributing to glacier melting and subsequent depletion of river flow upstream. This dilemma of water and energy tradeoffs and its impact on the agriculture and environment of the region is still not well studied [35,36].

The government of Uzbekistan, foreseeing an increase in water scarcity in agriculture, has prioritized the widespread adoption of drip irrigation. The area under drip irrigation is planned to increase from 44,000 ha to 600,000 ha by 2030, with reduced irrigation demand by 1500 million m^3 of water [37], which could be reallocated to another water-short irrigated area or allowed to flow to the Aral Sea. This may cause a gradual lowering of the groundwater table in many systems where irrigation water losses are the primary source of groundwater recharge. This may produce several gains, such as reducing unproductive evaporation from the groundwater table and creating free capacities in the aquifers, which can be used to store floodwater. The river has excessive flows in high water years. The shortcoming is that lowering the water table would make developing groundwater less attractive for farmers due to the increased energy demand for pumping. Current water savings may be achieved at the cost of future groundwater development. In such cases, groundwater depletion can be arrested by managed aquifer recharge activities in the winter seasons, for example, by using hydropower releases from the upstream reservoirs [38]. Irrigation in CA is already energy-intensive. Currently, irrigated agriculture is solely based on river flow, which is delivered to farm gates by a multi-level system of canals, often receiving water through inter-basin water transfers. This strategy of reallocating water resources from one basin to another, developed in the past (during the Soviet time with no borders between the riparian countries), is widely applied in the region and has resulted in low water-use efficiency of 0.3–0.4; water losses from the canals and the agricultural fields fill aquifers and raise groundwater levels.

Inter-basin water transfers have often been achieved by lifting water from one basin to another, requiring energy to pump water. Consequently, the electricity to pump irrigation water amounts to 12% of the total power generated in Uzbekistan. Thus, low water-use efficiency and high energy consumption make agricultural water management a critical starting point for sustaining national food production.

Developing farmer-driven groundwater irrigation under such conditions can improve water and energy efficiencies. Despite the government's water policy prioritizing water-saving by introducing drip irrigation or advancing furrow irrigation, groundwater development for agricultural purposes remains essential, especially for irrigated land in piedmont areas and river valleys, often under lift irrigation. One of the advantages of groundwater development over lift or small pump irrigation is that farmers using groundwater decide when to irrigate and how much water to apply.

Farmers cultivate grapes outside of canal command areas where groundwater is 20–40 m deep. They acquire water from lift irrigation schemes, if available, or pump groundwater. Lift irrigation schemes pump water from a river to a height of 50–200 m and more to the highest point. Water is transported by lift canals, usually long-distance by gravity, and then distributed between farmers for irrigation. That is why groundwater irrigation is less energy-intensive than lift irrigation, with an average value of 0.2–0.4 kWh/m^3 versus 0.3–0.6 kWh/m^3, respectively, indicating the regions where groundwater irrigation may produce water and energy savings. When the lift irrigation infrastructure is aged, the difference in the energy intensity between lift irrigation and the groundwater becomes higher. There are also risks of increasing salinization and depletion of groundwater, especially in drought years. Thus, the issues are complex and require system-level analyses of power generation, irrigation, food production, and the environment.

2.2. Study Area

This study was carried out in the Fergana Valley, where the Syrdarya River begins, by the confluence of two tributaries, the Naryn and Karadarya. These two main tributaries and small rivers, flowing into the valley from the south and north, are the primary water sources for irrigation. At the same time, losses from the riverbeds, irrigation canals, and agricultural fields recharge groundwater. Borisov [39] estimated that the total storage of groundwater, including renewable and non-renewable, in the Fergana Valley exceeds 100 km^3; despite this significant potential, groundwater is being developed and applied for irrigation to cover a shortage of canal water only. Two representative farms growing grapes using gravity and groundwater irrigation were selected for comparative analysis (Figure 1).

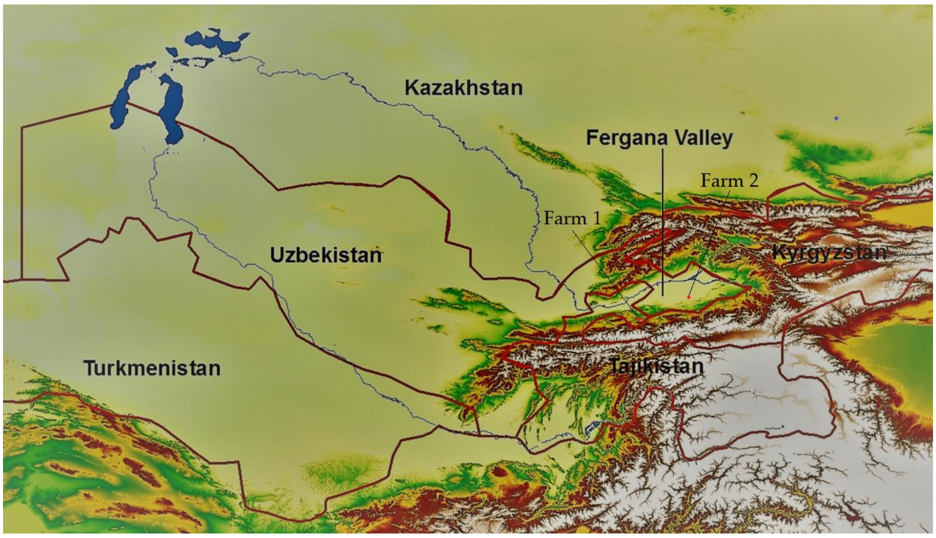


Figure 1. The Aral Sea basin and the location of the study farms.

The two farms selected for this study have different practices for growing grapes. Farm 1, situated in the western part of the valley in Soghd Province of Tajikistan, has GPS coordinates of 40°08′40″ N and 69°38′47″ E. The farm has a total land area of 630 ha, of which 86 ha is allocated to grape cultivation. The farmer's vineyards are grown in rows using trellis on sandy loam soils, underlain by gravel deposits, with gravity furrow irrigation applied from the Khodjabakirgan River. Farm 2 is located in the Fergana Province of Uzbekistan with GPS coordinates of 40°28′40″ N and 71°35′36″ E. In the early 1990s, the farmer received land from the government through a long-term lease. The 10-ha area is under groundwater/well irrigation, with 6 ha under grapes, while the remaining are young orchards. The farm's soil is sandy loam underlain by gravel 50 cm below the ground surface. There is approximately 500 ha of land under the same production technology of grape cultivation in the same area.

These two sites represent two different farming systems. Farm 1 has an extensive land area, is relatively well-supplied with machinery, and applies gravity irrigation. Farm 2 is a family farm in a smaller area, relies extensively on manual labor, uses a mini tractor for soil tillage, and practices groundwater irrigation. While Farm 1 applies row planting of vineyards and gravity irrigation by furrows made along the rows, Farm 2 uses intensive crop cultivation practices—grape vines at the height of 2 m cover the entire area. Such a canopy dramatically increases solar energy harvest, while plant roots occupy the whole inter-row space, up to a depth of 50 cm. This canopy shape and root distribution allow plants to effectively use solar energy, water, and nutrients. The farmer applies a low rate, high-frequency irrigation, using groundwater along the short furrows with a width of 60 cm, thereby moistening the entire inter-row space shaded by leaves. Due to the indicated differences, including the farming practices used in grape production, the form of ownership, management, and irrigation techniques, the yield levels achieved by Farm 2 are significantly higher than those of Farm 1.

2.3. Data and Methods

This study used a two-step approach to analyze water-energy-carbon tradeoffs. First, we carried out field studies at the farm level to estimate the linkages between the shift from gravity to groundwater irrigation and the changes in energy consumption and GHG emissions. Since farmers gradually move from cotton and wheat to high-value crops, orchards, and vegetables, we selected farms growing grapes, an essential source of revenue for farmers from the Fergana Valley and the region. We then evaluated system-level alternatives to make farming practices more sustainable, including intensifying crop production, introducing water- and energy-saving technologies, and shifting to renewable energy sources.

2.3.1. Farm Inputs

To assess the gains and shortcomings of introducing groundwater irrigation, farming practices and inputs, including irrigation water, were monitored during 2013–2014. All farming practices and inputs were recorded daily. Daily climate data for this period were obtained from the Fergana weather station. Field-level water monitoring included: (1) measuring irrigation applications by using Cipolletti and Thomson weirs, at field level and furrow level, accordingly; (2) Cipolletti weirs were also applied for measuring tail-end water discharges that occurred during irrigations; and (3) measuring soil moisture content for depths of 0–0.15, 0.15–0.30, 0.30–0.50 and 0.50–0.75 cm using soil sampling and air-drying methods. Phenology observations included measuring soil crop cover and plant height in major plant development phases.

The evapotranspiration from the grape fields was estimated using the water balance method using formula as follows:

$$ET = I + P - Fl + \Delta SM \tag{1}$$

where ET—evapotranspiration from a grape field; I—total irrigation applied; P—effective precipitation, Fl—field losses of irrigation water, ΔSM—change of soil moisture content in the plant root zone.

Soil moisture content was determined before and at the end of the crop-growing season as well as before and after irrigation applications. Deep percolation losses were estimated as the difference between the volume of water applied for irrigation and the amount of irrigation water accumulated in the plant root zone.

Table 1 shows the inputs applied with the emission potential for 2013–2014 for both farms.

Table 1 indicates the differences in farming inputs at Farm 1 and Farm 2. Intensive farming practices in grape cultivation, applied at Farm 2, require 3.7 times more labor than in Farm 1; soil tillage practices are applied using a mini tractor of 15 horsepower in Farm 2 and a tractor of 80 horsepower in Farm 1. These practices, monitored at the farms, are as follows: (a) soil tillage of interrow spacing and making furrows in spring; (b) soil cultivation after each irrigation at Farm 1 and four times per season and reshaping furrows at Farm 2; (c) applying herbicides and insecticides three times per year in the grape-growing season. Accordingly, the total diesel fuel consumption amounted to 56 l/ha and 60 l/ha at Farm 1 and Farm 2. These figures are within the range given for grape cultivation by Karimi and Moghaddam [41] and Osman and Engindeniz [42].

Furthermore, the irrigation application technique, another critical input in productivity, differed in the farms under consideration. Farmers applied eight irrigations per cropping season at Farm 1 and 15 irrigations at Farm 2. Although the recommended irrigation schedules were similar because of the same soil and climate conditions, the actual irrigation schedules differed (Figure 2).

Table 1. Farming inputs with emission potential used for grape production per hectare. Adapted from Abdurakhmanov et al. (2019) [40].

Farm Inputs	Unit	Farm 1 (Gravity Irrigation)	Farm 2 (Groundwater Irrigation)
Irrigation water application	m^3	8588 *	7891 **
Electricity	Megajoules (MJ)	0	14,349
Diesel	MJ	3153	3379 ***
Labor use	Hours	371	1387
Agrochemicals			
Nitrogen (N) base	Name/fraction (%)/kg	Urea (N content −46%)/46 kg	Ammonium nitrate (N content −35%)/400 kg
Phosphorus (P) base	Name/fraction (%)/kg	0	0
Potassium (K) base	Name/fraction (%)/kg	0	0
Sulfur	Kg	1	0
Insecticides	Kg	1	6
Herbicides	Kg	0	0
Fungicides	Kg	1	1
Manure	Kg	607.4	0
Farm machinery			
Tractor (capacity/weight/assumed average life span/total area serviced)	hp/kg/years	80 hp/3700 kg/10 years (MTZ-80 model)/70 ha	30 hp/1430 kg/10 years (VU-304 model)/15 ha
Plough (weight/life span/total area serviced)	kg/years	cultivator: MTZ-80-PRVN 2.5: 510 kg/10 years/70 ha	300 kg/10 years/15 ha
Chisel (weight/life span/total area serviced)	kg/years		350 kg/10 years/15 ha
Others (weight/life span/total area serviced)	kg/years	20 kg/10 years/70 ha	20 kg/10 years/15 ha

* Source of water is the unregulated flow of the Khodjabakurgan River, ** source of water is a well, belonging to the farmer and pumping groundwater from a depth of 40–45 m, *** diesel fuel is used at both farms for the operation of tractors for soil tillage and other farming practices. Notes: energy consumed is given for field level only.

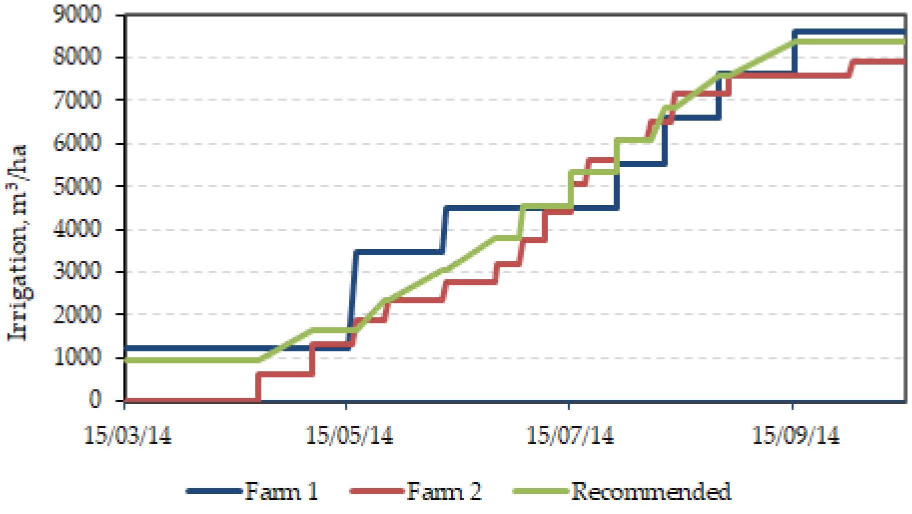


Figure 2. Integral irrigation applications in Farm 1 and Farm 2 as well as based on recommendation. Modified from Abdurakhmanov et al. (2019) [40]. Data of the recommended irrigation schedule (green line) is adapted from Domullodjonov (1988) [43].

Figure 2 shows that the total irrigation application was higher at Farm 1, and the amount of water applied to Farm 2 was less than the recommended volume. The recommended irrigation applications were calculated based on climate conditions, soil properties, groundwater table depths, and the relevant irrigation efficiency factors [43]. In both farms, farmers themselves, based on the status of plants, soil moisture depletion, and availability of irrigation water, decided when to irrigate and how much water to apply. The prolonged intervals between irrigation applications were in practice, especially from the second half of June until the end of July when grape bushes did not receive irrigation water for 47 days. Such interruptions in water supply occurred due to the unregulated flow of the Khodjabakirgan River. In contrast, groundwater use for irrigation allowed timely irrigation at Farm 2.

2.3.2. Energy Use and Greenhouse Gas Emissions

The study made the following assumptions:

- Water, energy, and carbon tradeoffs and conclusions based on grape production apply to other crops.
- The ages of the vineyards were 25 years and 8 years for Farms 1 and 2, respectively. The study assumed that vineyards in this age range do not have different productivity potential if properly maintained farming inputs [44]. Thus, comparative evaluations can be undertaken.
- The analysis applied the straight-line method of depreciation of agricultural machinery.
- According to Siyal et al. [45], energy inputs for surface water delivery by canal systems in the lower Indus basin in southern Pakistan average between 3 and 4 KJ/m^{3,} and carbon emissions are 0.22–0.30 g/m^3. These values are insignificant compared to on-farm energy consumption and carbon emissions in the gravity and groundwater irrigation systems. Considering the low energy inputs found in similar systems, energy inputs for water delivery by canal systems in the study areas were excluded from further analyses.

Water and energy use and GHG (CO_2-equivalent) emissions were the basis for assessing tradeoffs between water, energy use, and carbon emissions. Farm inputs and operations used in grape production contribute to CO_2 emissions. The amount of carbon dioxide equivalent (i.e., CO_2-e) depends on the type of GHG emitted from the farming inputs and respective conversion factors given in Table 2.

Table 2. Conversion factors of farming inputs into energy and CO_2-e.

Energy and Emission Sources	Energy (MJ/ha)	Emission Factor (kg of CO_2-e/ha) per Unit of Input	References
Labor use (MJ/h)	1.96		Özkan et al. [46]
Electricity (kwh/ha)	3.6	0.279 *	Özkan et al. [46]; DCC [47]
Diesel(l)	56.3	0.0745 *	Singh et al., 2002 [48]; DCC [47]
Water (m^3)	11.02		Acaroğlu and Aksoy [49]
Agrochemicals			
N (kg)	60.6	4.77	Singh et al. [48]; Lal [50]
P (kg)	11.1	0.73	Singh et al. [48]; Lal [50]
K (kg)	6.7	0.55	Singh et al. [48]; Maraseni et al. [51]
Insecticides (kg)	199	18.7	Liu et al. [52]; Scherbak et al. [53]
Fungicides (kg)	92	14.3	Liu et al. [52]; Velthof and Rietra [54]
Sulfur (kg)	1	0.33	Mondani et al. [55]
Manure (kg)	0.3	0.0075	Singh et al. [48]
Farm machinery (kg)	62.7	9.6	Pimentel [56]; Maraseni et al. [57]
Output: grapes	11.8		Kumar et al. [58]

* Emission factor per MJ of the input.

Energy and CO_2 emissions were from electricity and diesel, agrochemicals, and agricultural machinery production.

2.3.3. Energy Requirement and CO_2 Emissions for Groundwater Pumping

Electricity consumption for pumping water is monitored using the meter. In scenario analyses, the energy required for groundwater pumping was calculated using Equations (2) and (3) borrowed from Robertson [59] and Shah [4], respectively:

$$Energy\ (\mathrm{kWh}) = \frac{Volume\ \left(\mathrm{m}^3\right) \times H\ (\mathrm{m})}{367 \times \eta \times (1 - T\&Dlos)} \tag{2}$$

$$H = gwd + drawdown + friction \tag{3}$$

where *Energy* is the energy demand (kWh), *Volume* is the volume of groundwater lifted per annum; *H* is the total dynamic head (Equation (3)); *gwd* is the initial groundwater depth; *drawdown* is 3 m, and *friction* losses are 20%; *T&Dlos* is transmission and distribution losses; and η is the efficiency of the pump set (%), including the pump, the driver, and the motor.

In Uzbekistan, 89% of the electricity generated is from thermal power plants (TPPs), and 11% is from hydropower power plants (HPP). Meanwhile, 91% of the electricity produced at the TPPs is from natural gas, 2% from black oil, and 7% from coal. According to UzbekEnergo, the transmission and distribution losses of electricity in Uzbekistan are 11%, while pump set efficiency is 30%. Natural-gas-based electricity TPPs have an average efficiency of 28%, and coal-based TPPs have 25%.

The estimation of CO_2 emissions is based on the amount of electricity generated at the TPPs to support irrigation water pumping. The rate of natural gas consumption in the overall production of electricity for Uzbekistan is 0.276 m^3/kWh for conventional power plants and 0.188 m^3/kWh for new plants. The carbon dioxide emissions per unit of electricity from power plants ranged between 0.542 kg of CO_2-e for traditional once-through systems and 0.368 kg of CO_2-e for circulation systems. The Fergana Valley, where more than 10 million people live, covers a deficit in electricity supply from Kyrgyzstan, where electricity generation is assumed to be produced entirely by HPP. The estimations of CO_2 emissions from electricity generation by HPP are based on Scherer and Pfister [60], where CO_2 emissions are correlated to the relevant reservoir/electricity generation ratio area. Emissions of CO_2 are determined using this correlation separately for upstream, midstream, and downstream hydropower.

2.3.4. Energy and CO_2 Emissions from Agrochemicals

The agrochemicals considered in this study include fertilizers and chemicals used for controlling pests and weeds. The study derived the history of agrochemical use from monitoring activities and farm records. Farm 2 deployed ammonium nitrate (NH_4NO_3) with 35% N content, whereas Farm 1 applied urea with 46% N content. For the production, packaging, delivery, and application of chemical fertilizers, emissions were assessed following the emission factor given in Table 2.

2.3.5. Energy Use and CO_2 Emissions from Agricultural Machinery Production

According to Pimentel [56], approximately 83.8 mega joules (MJ) of energy is used to produce a kilogram of agricultural machinery. Consequently, on average, it takes 9.6 kg of CO_2-e to produce a kilogram of agricultural machinery [56,57]. It is worth noting that there could be differences in farm machinery and manufacturing technologies between countries. However, due to data constraints, this study uses the values from Pimentel [56] and Maraseni et al. [57].

Water-energy-carbon tradeoffs were analyzed using indicators as follows:

(a) Total energy inputs per hectare of irrigated land;
(b) Non-renewable fuel resources depleted;
(c) Total CO_2 emissions per hectare of irrigated land;
(d) Crops produced per kg of CO_2 emissions, that is, the ratio of the yield of grapes to total CO_2 emissions [61];

(e) Carbon dioxide emissions per MJ of input, that is, the ratio of total CO_2 emissions to the energy input;

(f) Water productivity [61], calculated as follows:

$$WP = \frac{Y}{ET} \tag{4}$$

where WP = water productivity (kg/m^3), Y = yield of grapes (kg/ha), and ET = crop evapotranspiration (m^3/ha);

(g) Energy efficiency (Ee), estimated using the formula:

$$EE = \frac{E_{out}}{E_{in}} \tag{5}$$

where E_{out} = energy output (MJ/ha), and E_{in} = energy input (MJ/ha),

(h) Energy productivity, calculated as follows:

$$EP = \frac{Y}{P} \tag{6}$$

where EP = energy productivity (kg/kWh), and P is the total energy input for producing grapes (kWh/ha).

3. Results

3.1. Farm-Level Analysis of Water, Energy, and Carbon Tradeoffs

Irrigation water-associated energy inputs and carbon emissions:

Farm 1 and Farm 2 use different irrigation strategies. Farmers practicing gravity irrigation applied eight irrigations varying from 1201 m^3/ha early spring to 985–1123 m^3/ha, each during the summer season at Farm 1. Intervals between irrigation were prolonged, especially in the summer season, causing a mismatch between water supply and crop water requirements. The farmer, employing groundwater irrigation, provided fifteen low-rate high-frequency irrigations varying from 389 to 685 m^3/ha, each at Farm 2. Intervals between irrigations varied from one month in spring to one week in July and the first half of August; such frequent irrigation allowed for maintaining soil moisture content at the optimal level. Water supplied for irrigation is spent almost entirely for crop transpiration thanks to covering the entire area by grape vines at the height of 2 m and low-rate high-frequency irrigation by short furrows.

Table 3 summarizes water-associated energy inputs reflecting the differences in irrigation strategies. Water-related energy inputs are low under gravity irrigation and significantly increase for groundwater irrigation, causing high carbon emissions. Since water is free at Farm 1, the farmers have insufficient incentives to adopt water-saving technologies. In opposite, at Farm 2, the farmer is induced to reduce irrigation applications and use water more efficiently due to the high cost of electricity to pump water. The electricity consumption to operate the pump causes high carbon emissions.

Water balance studies found crop evapotranspiration at 5740 m^3/ha at Farm 1 and 7496 m^3/ha at Farm 2. Despite the minor difference between the irrigation applications at Farm 1 and Farm 2, there was a high difference in water productivity. This was because (1) according to coarse estimates using the crop cover change, over 83% of the water applied at Farm 2 and only 47% of the water applied at Farm 1 are depleted productively for crop transpiration; (2) timely irrigation according to crop water requirements at Farm 2, which were difficult to follow at Farm 1 acquiring water from the unregulated river, and; (3) intensive farming practices at Farm 2, including better management of soil nutrients, better use of labor and fertilizers, resulted in optimal crop canopy and high efficiency in harvesting solar energy.

Table 3. Farm-level water-associated energy inputs and carbon emissions.

Farming Inputs	**Farm 1 (Gravity Irrigation)**		**Farm 2 (Groundwater Irrigation)**	
	Energy MJ/ha	**Emissions kg CO_2-e/ha**	**Energy MJ/ha**	**Emissions kg CO_2-e/ha**
Labor use	314		235	
Irrigation water delivery, m^3/ha	8588	0	7891	0
Water depleted, m^3/ha	5740		7496	
Water energy	5855	0	7646	0
Electricity to pump water	0	0	14,349 *	4003
Total water related energy	5855	0	21,995	4003

* Energy consumption to generate electricity is at off-farm level, that is why, further, electricity inputs to pump water were cut from the farm level and moved to the system level.

The data presented in Table 3 shows that irrigation water supply becomes very energy and carbon emission intensive under groundwater irrigation, which puts farmers under pressure to apply comprehensive farming practices to produce high yields of grapes to recover made investments in water. The intensive farming technology at Farm 2 resulted in the fast growth of grapes bushes, which required manual labor to cut a large number of leaves and branches; moreover, the grape harvest was labor-intensive. There were hidden electricity savings to pump water thanks to the highly efficient irrigation technology allowing the farmer to save energy against high water losses under gravity irrigation. GHG emissions due to groundwater pumping amounted to 0.51 kg CO_2-e/m^3.

Agricultural inputs energy and carbon emissions: Table 4 summarizes agricultural inputs, energy, and carbon emissions.

Table 4. Farm-level agricultural energy inputs and carbon emissions.

Farming Inputs	**Farm 1 (Gravity Irrigation)**		**Farm 2 (Groundwater Irrigation)**	
	Energy MJ/ha	**Emissions kg CO_2-e/ha**	**Energy MJ/ha**	**Emissions kg CO_2-e/ha**
Labor use	413		2483	
Diesel	3153	235	3379	252
Agrochemicals	1979	142	9643	797
Agricultural machinery	719	82	1184	136
Total	6264	459	16,689	1185

Notes: Energy inputs are given for field-level only; the energy of applied agrochemicals is higher at Farm 2 mainly due to the increased application rate of ammonium nitrate given in Table 1.

Data presented in Table 4 showed that Farm 2 employing groundwater irrigation practices more labor inputs and agrochemicals, which required short-term investment. Farmers were ready to install deep wells, securing water for irrigation. However, small-scale farming and lack of capital did not allow them to invest in access to groundwater and agricultural machinery. Timely irrigation, intensive labor use, and agrochemicals permitted farmers to make farming practices comprehensive. However, it increased energy inputs and associated carbon emissions.

High grapes yield vs. high energy inputs and carbon emissions: Table 5 presents estimated farm-level environmental indicators of grape production under gravity and groundwater irrigation.

Table 5. Estimated farm-level environmental indicators of grape production under gravity and groundwater irrigation.

Sources of Emissions by Farming Inputs	Farm 1 (Gravity Irrigation) Energy MJ/ha	Farm 1 (Gravity Irrigation) Emissions kg CO_2-e/ha	Farm 2 * (Groundwater Irrigation) Energy MJ/ha	Farm 2 * (Groundwater Irrigation) Emissions kg CO_2-e/ha
Energy inputs				
Water inputs, depleted (m^3/ha)	5740		7496	
Water associated energy inputs	5855	0	7646	0
Agricultural energy inputs	6264	459	16,689	1185
Total energy inputs	12,119	459	24,335	1185
Outputs				
Yield (kg/ha)	6740		18,600	
Energy output	79,534		219,480	
Environmental indicators				
Water productivity (kg/m^3) **	1.17		2.48	
Energy productivity (kg/MJ)	0.56		0.24	
Energy efficiency (MJ/MJ)	6.56		2.85	
Crop yield per kg of CO_2-e emissions (kg of crop yield/kg of CO_2-e)		14.7		15.7
Kg of CO_2-e/MJ of energy input		0.04		0.05

* 944 grapes bushes at Farm 1 and 714 at Farm 2, ** Water productivity is given per m^3 of water depleted. Notes: Energy consumed is given for field-level only; the energy of the agrochemicals used on Farm 2 is higher than on Farm 1, mainly due to the increased application rate of ammonium nitrate.

Table 5 also shows tradeoffs between higher yields and higher environmental impacts. The shift from gravity to groundwater irrigation and improved farming practices increased water-use efficiency. Despite similar application rates, groundwater irrigation allowed timely and efficient water application. Farmers receiving desired water applied intensive farming practices and invested more inputs, such as fertilizers, resulting in a three-time-higher grape yield at Farm 2, 18,600 kg/ha, compared to 6740 kg/ha on Farm 1. Introducing intensive farming and timely groundwater irrigation at low rates and high frequencies tripled the yield and water productivity. It also increased energy efficiency and energy productivity by 8% each. This was because the grapevines cover the entire area at the height of 2 m increased solar energy harvest. At the same time, plant roots occupying the inter-row space up to a depth of 50 cm allowed plants to use water and nutrients effectively.

The major disadvantage of the intervention was the significant increase in the energy inputs and CO_2 emissions per hectare of cropland and per m^3 of groundwater applied. The current 2.75 times increase in crop production is traded for future issues associated with 2.6 times more accumulation of GHGs in the atmosphere.

On-farm level estimates showed that farm-level interventions dealing with the water-energy-carbon nexus were insufficient to produce mutual gains and disclose potential tradeoffs. Increasing food crop production and improving water productivity was balanced by growing energy inputs and CO_2 emissions, indicating a need for a wider, system-level consideration of the water-energy-carbon tradeoffs.

3.2. System-Level Analyses of Water-Energy-Carbon Nexus

There are different, case-specific, potential cases to improve the sustainability of agricultural production [62,63]. This study considers several alternative cases of grape production. These alternative scenarios are as follows.

Case 1: Gravity irrigation and conventional farming practices.
Case 2: Pump irrigation using groundwater and conventional farming practices: a TPP is a source of electricity to pump groundwater.
Case 3: Pump irrigation using groundwater, intensive farming practices, and water-saving irrigation: a TPP is a source of electricity to pump groundwater.
Case 4: Using energy-efficient pumps to lift groundwater, intensive farming practices, and water-saving irrigation: a TPP is a source of electricity.
Case 5: Case 4 plus supplying energy to pump groundwater from the upstream HPP.

Case 6: Case 4 plus supplying energy to pump water from the midstream HPPs.
Case 7: Case 4 plus supplying energy to pump water from the HPPs, located downstream of the main river.
Case 8: Using a solar pump, intensive farming practices, and water-saving irrigation.

System-level analyses in this study include on-farm crop production and relevant water management and power generation and delivery system. System-level options assume that the impact of farm-level decisions on the system level and the opposite, system-level choices on the field level have to be considered to improve resources, water, energy, and productivity as well as reduce carbon dioxide emissions. For example, a transition to intensive farming practices, energy-efficient pumps, or water-efficient irrigation technologies, which is often farmer-driven, should consider a system-level impact, as this is where the decision would be made to switch from fossil fuels to renewable energy sources or improve the efficiency of electricity generation and distribution. For example, cases 3 and 8 may have similar results at the on-farm level. However, there is still a difference at the system level on CO_2 emissions. Alternatively, some cases may contribute to better resource productivity at the on-farm level. However, they may increase fossil non-renewable resources depletion at the off-farm level and increase carbon dioxide emissions. It is essential to clarify at the system level whether there are high productivities of water and energy, fossil resources still remain, and carbon dioxide emissions minimized. That is why linking on-farm alternatives with the system-level options is essential in one case. Analyzing such cases contributes to formulating future visions for developing agriculture, water, and energy sectors.

The first case represents Farm 1 producing grapes using conventional farming and gravity irrigation. The second case analyzes the shift from gravity to groundwater irrigation using thermal power-based electricity but no changes in farming practices. The third case represents Farm 2, producing grapes using groundwater, intensive farming practices, and water-saving furrow irrigation. The fourth case evaluates the adoption of energy-efficient pumps and improves power generation efficiency. The fifth to seventh cases consider shifting powering pumps from TPP to HPP. The eighth case considers shifting to solar energy. Cases 5, 6, and 7 analyze the gains and shortcomings of obtaining electricity from HPPs located upstream, midstream, and downstream of the rivers, respectively. They differ based on the relationship between electricity generation and evaporation losses from relevant reservoirs; evaporation losses were estimated using data available for HPPs located in the Syrdarya and Amudarya River basins, while CO_2 emissions from appropriate reservoirs were calculated using the relations given by IHA [64]. The emission rate for CO_2 was 48 gCO_2-eq/kWh for solar PV (utility) [64].

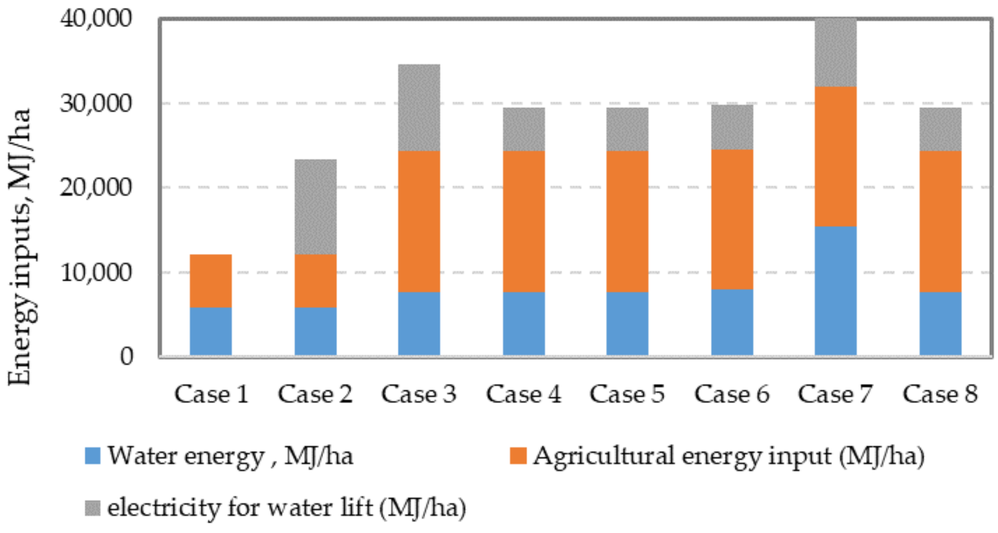
The assessment of introducing drip irrigation to grape production at Farm 2 showed that replacing low-rate high-frequency furrow irrigation with drip irrigation may produce only minor water savings. This is due to the combination of intensive vineyard cultivation technology with furrow irrigation when: (a) plant roots cover the entire soil space between the vineyard rows up to 0.5 m below the ground surface, causing no significant water deep percolation losses; and (b) the vineyard leaves cover the entire surface area at the height of 2 m, resulting in irrigation water depletion mainly in the form of transpiration. The irrigation water losses from surface runoff, on average 10%–15% of the total water applied, are collected by the tailwater recovery system and directed to an adjacent field for irrigation use [40]. These estimates show that the farmer used the available water efficiently. For this reason, drip irrigation was excluded from further analysis.

The comparison of the cases included estimating the environmental indicators at the farm and system levels, including on-farm and off-farm. For example, in the case of the HPP energy supply, the on-farm level estimates include irrigation water and other farming inputs. In contrast, at the system level, additional water depletions have evaporation losses from a relevant reservoir and water delivery losses if losses form depletions. In the case of TPP energy supply, on-farm level estimates include energy inputs related to water and other farming inputs. In contrast, at the system level, additional energy inputs include the depletion of fossil fuel resources. The system-level inputs considered include on-farm- and off-farm-level water and energy inputs to pump groundwater; off-farm energy depletions associated with other farming inputs were beyond the scope of this study.

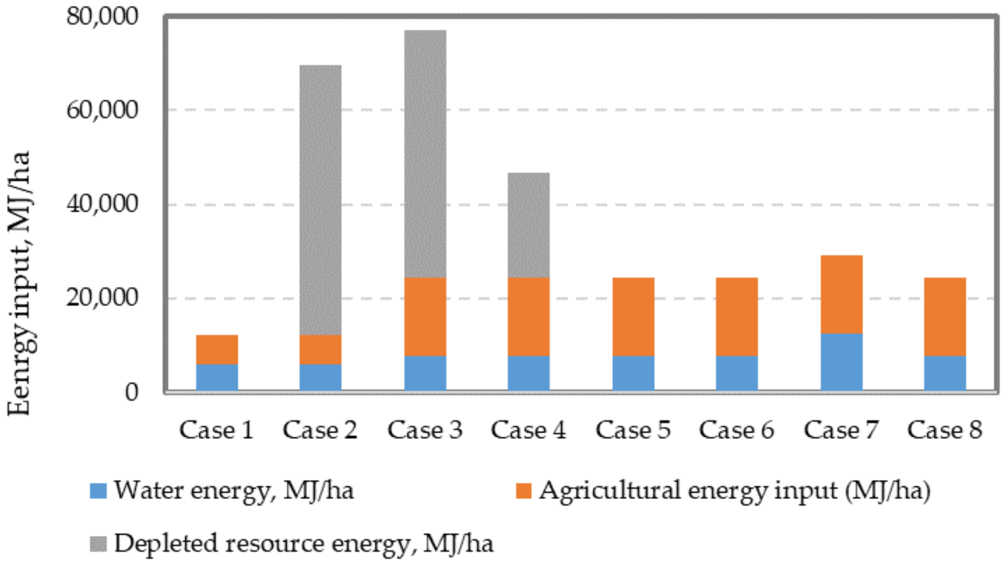
The comparison of the cases was undertaken using resource productivity and GHG emissions; however, there may be other case-specific factors and conditions beyond this study's scope.

3.3. Energy Inputs as Affected by Alternative Cases

Figure 3 shows the difference between the energy input estimates for alternative cases at the on-farm and system levels.



(**a**)



(**b**)

Figure 3. Energy inputs at (**a**) on-farm level and (**b**) system level for alternative cases of water and energy use. Depleted energy includes fossil fuel resources for TPP; renewable energy includes water evaporation losses for HPP and water for cooling solar panels. On-farm level estimates include the energy of water, farming inputs, and electricity to pump water. System-level estimates include energy for pumping water, system-level water consumption and fossil fuel resource depletion, and on-farm-level energy of farming inputs.

The analysis at the farm level showed minor differences between the cases with pumping water (Figure 3a). While case 1, with gravity irrigation and conventional farming practices, indicates the lowest energy consumption per area, the shift to groundwater irrigation in case 2 and the introduction of intensive farming practices in case 3 increased energy inputs to a maximum. Other cases show similar energy inputs per ha, indicating no significant differences, except case 7, which uses hydropower downstream to pump groundwater.

The picture is different in Figure 3b. The system-level analysis considers fossil fuel consumption for electricity generation, its transportation and distribution, and the energy loss associated with water evaporation from reservoirs. The research shows high variations between cases with different energy sources for pumping water. In cases with TPP power supply, even in case 4 with improved water and energy efficiency, energy consumption is 1.5–1.9 times higher than those with HPP or solar power supply. In the cases with HPP power supply, the energy consumption in cases 5 and 6 is almost similar, while the energy consumption increases significantly in case 7. This is because of the excessive energy depletion associated with water delivery losses, recharging saline brackish water aquifers, and extra evaporation losses from the relevant reservoirs. Based on the system-level analysis, energy inputs are minimal for cases 5, 6, and 8, characterized by groundwater irrigation, improved water, and energy use, and renewable energy from the upstream (case 5) or midstream (case 6) HPPs or solar energy. System-level estimates show significant differences in energy inputs for crop production using thermal power and renewable power supply for groundwater irrigation.

Figure 4 compares the total energy inputs, considering farm-level inputs against energy inputs at the system level. Figure 4 clearly shows that the worst cases characterized by high energy inputs occur when electricity is generated at TPPs for water pumping at farms using conventional (case 2) or intensified farming practices, including water-saving irrigation (case 3). The same crop production can be obtained with much lower energy inputs if electricity is produced using renewable energy, hydropower, or solar power (cases 5, 6, and 8, respectively).

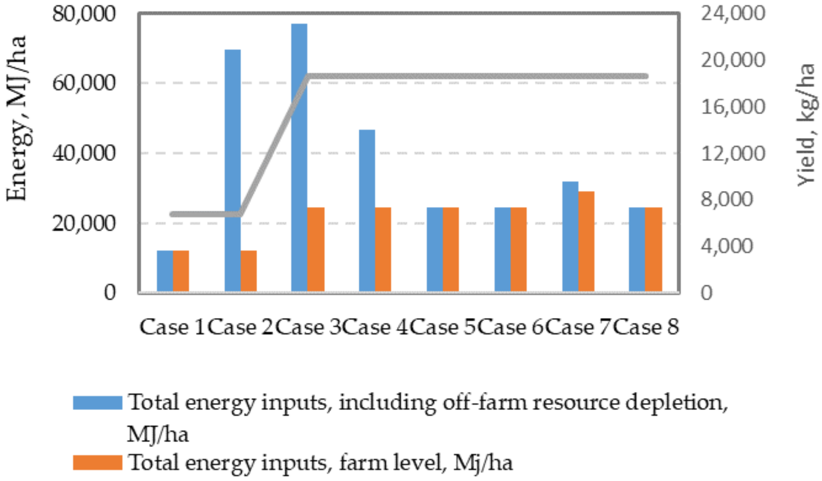
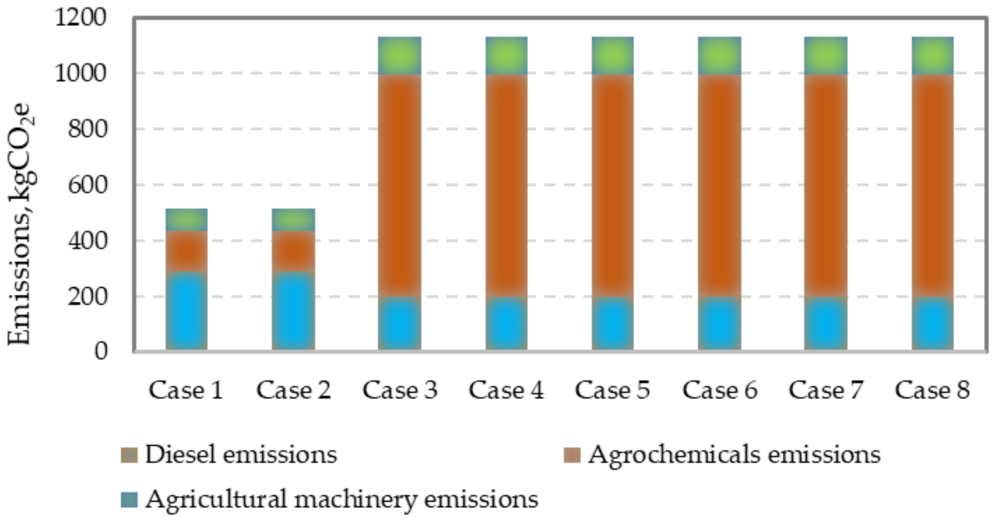


Figure 4. Total energy inputs for crop production under different water and energy cases (MJ/ha).

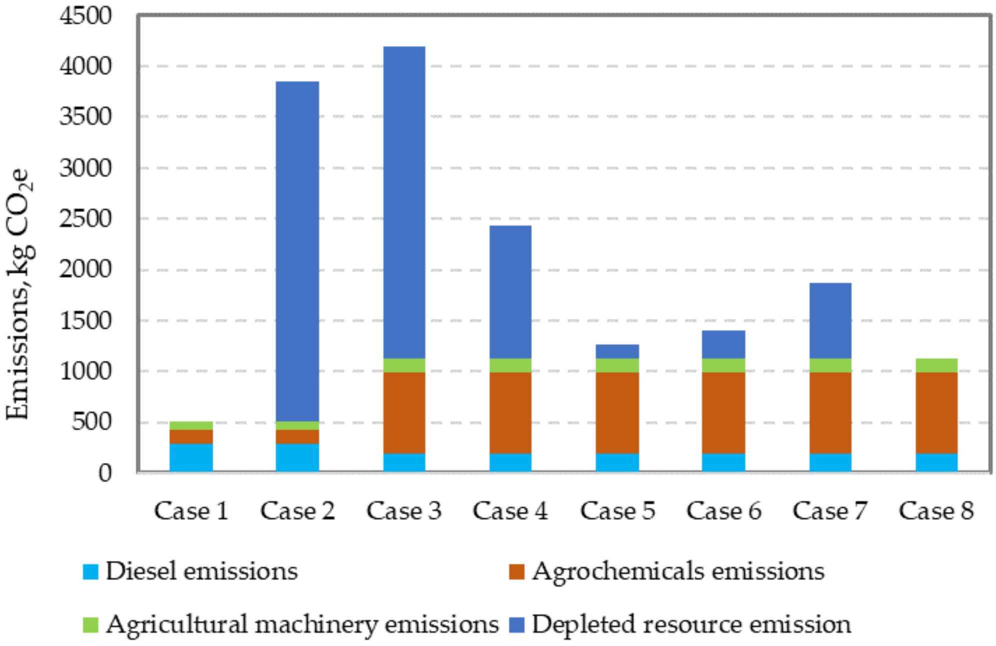
Using power supply from the upstream HPP (case 5), the midstream HPP (case 6), or solar energy (case 8) reduces the energy intensity by 65%, and from the downstream HPP (case 7) by 53%, as compared to using thermal power (case 2). These data indicate no justification for replacing gravity irrigation with groundwater irrigation if electricity is supplied by thermal power.

3.4. Carbon Dioxide Emissions as Affected by Alternative Cases

Figure 5 shows carbon dioxide emissions associated with crop production under different water and energy inputs cases.



(**a**)



(**b**)

Figure 5. Estimated (**a**) on-farm and (**b**) system-level carbon dioxide emissions, as affected by different water and energy input cases.

On-farm level estimates show that introducing intensive farming practices doubled CO_2 emissions; however, there are no differences between the cases with groundwater irrigation using different sources of power supply (Figure 5a). The on-farm level assessments were insufficient to disclose water, energy, and carbon tradeoffs in the studied cases.

The system-level estimates of CO_2 emissions clearly show the differences between the cases (Figure 5b). In the cases with TPP power supply for pumping water, conventional farming practices (case 2) resulted in 8.2 times higher CO_2 emissions than under gravity irrigation. Intensifying farming and improving irrigation practices (case 3) increased CO_2 emissions by 11%. Improving pumping efficiency and power generation efficiency (case 4) reduces CO_2 emissions by 36% compared to case 2. Advancing TPP energy generation (case 4) reduced the emission rate; however, the case remains uncompetitive against cases with renewable energy supply (cases 5–8).

The shift from thermal energy to hydropower energy reduced CO_2-e. The energy supply of groundwater irrigation from the upstream HPPs (case 5) and midstream HPPs (case 6) had the lowest CO_2 emissions at 1173 and 1225 kg of CO_2-e/ha, respectively. These rates are comparable to emissions when solar power was applied (1200 kg of CO_2-e/ha) while using the downstream HPP power supply, CO_2 emission rates were 1655 kg of CO_2-e/ha. The system-level assessments disclosed the benefits of applying renewable energy to the low-carbon transformation of food production on irrigated land. Table 6 shows the main environmental indicators of the studied cases.

The data presented in Table 6 indicate that increasing crop production and obtaining gains in water, energy, and carbon, including the highest crop production per carbon dioxide emissions, are found for cases 5, 6, and 8. No case with a TPP power supply was suitable for groundwater irrigation, even using water- and energy-saving technologies. These cases have high water productivity, but increased CO_2 emissions characterize low energy efficiency and productivity. The water productivity indicator alone was not enough to conclude on the sustainability of the crop production because the WP value did show no differences between the cases with non-renewable and renewable energy sources characterized by significantly different carbon emissions. In contrast, the crop yield ratio to the carbon emissions directly reflected the impact of the case on the use of energy sources, carbon emissions, and crop yields. The energy efficiency and the energy productivity indicators indirectly reflected differences in carbon emissions. The energy efficiency indicator did not consider the changes in crops yields. The worst-case for crop production development was the case of groundwater irrigation using conventional irrigation and farming practices; the second-worst case was the shift to groundwater irrigation using intensive farming practices with no improvements in irrigation practices. Case 4, using TPP-based electricity, had higher water productivity than conventional farming with gravity irrigation (case 1). However, the depletion of non-renewable resources and relatively high carbon emissions make these cases not applicable for the future.

Groundwater irrigation using downstream HPP (Case 7) is characterized by lower water and energy productivity and crop yields per kg of CO_2 emissions than the other HPP cases due to increased evaporation losses and CO_2 emissions from the relevant reservoir off-farm water losses to saline groundwater. Case 8, with groundwater irrigation using a solar pump, showed the highest water and energy productivity and the crop yield per kg of CO_2 emissions.

From an environmental viewpoint, the current strategy of gravity irrigation (case 1) showed many advantages. There are no fossil fuel inputs for power generation to lift water, and the energy inputs and CO_2 emissions are low. However, practicing gravity irrigation depends on the availability of water according to crop water requirements; conventional farming practices often applied along with gravity irrigation produce low crop yields and are characterized by low water and energy productivity. The case of replacing gravity irrigation with a low-head micro-irrigation system, which requires power to pump water into the system, was beyond the scope of this study.

Table 6. Environmental indicators of different cases of water and energy inputs.

Resource Use	Case 1: Current Practice	Case 2: GW Irrigation	Case 3: GW Irrigation and Intensive Farming	Case 4: GW Irrigation, Intensive Farming, and Improved *EE* *	Case 5: HPP Upstream	Case 6: HPP Midstream	Case 7: HPP Downstream	Case 8: Solar Energy for Water Pumping
Total water inputs, depleted (m^3/ha)	5740	5745	7500	7499	7540	7752	15,055	7513
Total energy inputs, system level (MJ/ha)	12,119	69,585	77,131	46,731	24,380	24,596	32,045	24,364
Natural gas depletion (m^3/ha)	0	1199	1102	661	0	0	0	0
Yield (kg/ha)	6740	6740	18,600	18,600	18,600	18,600	18,600	18,600
Energy output (MJ/ha)	79,534	79,534	219,480	219,480	219,480	219,480	219,480	219,480
Total emissions (kg of CO_2-e/ha)	459	3797	4198	2432	1173	1225	1655	1200
Crop yield per kg of CO_2-e emissions (kg of grapes/kg of CO_2-e)	14.68	1.78	4.43	7.65	15.86	15.18	11.24	15.50
Water productivity (kg/m^3)	1.17	1.17	2.48	2.48	2.48	2.48	1.53	2.48
Energy efficiency (MJ output/MJ input)	6.56	1.14	2.85	4.70	9.00	8.92	6.85	9.01
Energy productivity (kg/MJ input)	0.56	0.10	0.24	0.40	0.76	0.76	0.58	0.76

* Energy efficiency.

4. Discussion

Water productivity is considered one of the main indicators of basin sustainability [65,66]. Brauman et al. [65] highlighted that improved crop water productivity increases water sustainability. Cai et al. [66] gave different examples, including when increasing a basin's water productivity was at the expense of agricultural sustainability. This study results suggest that in the environment, when carbon emissions become the main factor of environmental and agricultural unsustainability, WP indicator is not enough alone to decide whether the crop production is sustainable because, despite it being an important indicator of crop return on consumed water, it does not reflect differences of alternative cases in carbon emissions. From this point of view, the crop yield response to kg of carbon emissions indicator can be applied along with water productivity to compare alternative cases of agricultural production using pumped irrigation. To obtain a complete picture of environmental sustainability, it is also essential to consider the third indicator—the depletion of non-renewable fuel resources. The scale of analyses of the indicators is vital.

Analyzing the water-energy-carbon tradeoff only at the farm level [22,23] may mask the gains and shortcomings of interventions to improve water and energy use and hidden environmental impacts. On-farm level analyses show the effect of farm-level inputs and measures to improve their efficiencies on crop yield and the increasing energy inputs and corresponding CO_2 emissions. The energy source—hydro, solar, or thermal—makes no difference from a farm perspective. However, the energy source makes a big difference at the system level. A system-level analysis, including on-farm crop production and linked off-farm water and energy sources depletions, is necessary to find possible solutions that may produce gains in crop production, resource reduction, including water and energy, improved water, and energy productivity, and reduced CO_2 emissions.

The system-level analysis indicates that the energy consumption for crop production is high when the electricity supply for water pumping comes from a TPP. Fossil fuel resources become the main component of energy inputs, making thermal power less compatible with renewable energy resources. The results of this study suggest that it is not sustainable to expand thermal power because of the high depletion rate of fossil fuel resources, while improving and advancing existing thermal power plants may reduce CO_2 emissions and contribute to reducing the depletion of fossil resources. Besides introducing intensive farming practices and water and energy-saving technologies, improving pumping and energy generation efficiencies may bring about resource reduction and environmental benefits [27]. However, pumped irrigation using thermal power cannot deal with water-energy-carbon tradeoffs. It reduces energy efficiency and productivity, accelerates fossil fuel resource depletion, and increases CO_2 emissions. Under conditions of increasing long-term temperature, due to climate change and depleting fossil fuel resources, the gradual shift to environmentally friendly renewable energy resources is a better solution than meeting the growing needs by expanding all available resources, including thermal resources.

For assessing the sustainability of water management, a basin's level is an appropriate scale [67–69]. Analyzing trade-offs for water, energy, and carbon may require linking basin water management to corresponding power generation alternatives located outside the basin. For example, inter-basin water transfers from the Amudarya River basin are critical for sustainable water supply in the lower reaches of the Zerafshan River and the Kashkadarya River. However, the reliable operation of pumping stations that pump water depends on power plants located outside of their basins. In such cases, trade-off analysis requires linking the basin water management analysis with energy supply alternatives.

The estimates show that hydropower-based pumped irrigation has advantages over thermal-power-based irrigation: fewer energy inputs in crop production and less carbon intensity at the system level. These gains can be achieved by accessing upstream and mid-stream hydropower resources. Many studies consider the practice of obtaining hydropower electricity in summer and trading for fossil natural gas in winter as a benefit-sharing approach for transboundary river basins with upstream hydropower and downstream agriculture [32]. This study indicates that the joint development and use of upstream hydropower may reduce the depletion of fossil fuel resources and lead to more sustainable agriculture based on pumped irrigation. The upstream hydropower development should consider water for food, energy, and the environment. This case can be pioneered in the case of the Zerafshan River upstream of Tajikistan and downstream to Uzbekistan—there is an agreement for two HPPs to be installed by the downstream country in the river's upstream.

Similar advantages are inherent in the development of midstream hydropower. This approach means developing small midstream hydropower in the Fergana Valley, Tashkent, Surkhandarya, and Kashkadarya regions in Uzbekistan or the northern part of Tajikistan. This proposal coincides with the ongoing construction of new small HPPs on small rivers and canals in many regions of Uzbekistan and Kazakhstan. Small HPP installation does not require extra water depletion because the downstream reservoirs can capture hydropower releases; there are minor power transportation and distribution losses and CO_2 emissions. HPPs on small rivers and widespread canals can produce energy from upstream hydropower releases and supply power for developing groundwater and wide adoption of micro-irrigation.

The study showed the shortcomings of installing hydropower downstream, which may cause high water losses due to evaporation in the hotter desert zone.

There are also environmental and social considerations in prioritizing hydropower while infringing the needs of other uses, such as the environment and agriculture [70–73]. Therefore, hydropower development must ensure environmental flows, with high importance for river ecosystem services. In the case of hydropower releases from reservoirs in winter, agriculture may have irrigation water shortages in summer. This is where further tradeoff analysis is required to minimize system-level losses. Mitigation measures may include the development of sufficient capacities for re-regulating upstream hydropower releases in the midstream, focusing on preserving river ecosystem services downstream, shifting from canal irrigation to groundwater, and using a managed aquifer recharge technique. Hydropower development must contribute to diversifying benefits from water rather than prioritizing a single water use. This requires close cooperation of riparian states in energy production and water management to enhance food production.

Solar power was confirmed as the best option for water-energy-carbon tradeoffs. Groundwater development using solar power requires minimum resources, water, energy, inputs, high resource efficiency, and productivity. It produces minimum CO_2 emissions—the emissions were 51% less than water pumping using electricity from TPPs. This is higher than the emission reduction value found by De Vlugt [74] for groundwater pumping for irrigation in India.

Developing solar power could be an essential contribution to sustaining the growing demand for energy supply and ensuring win-win outcomes. While there are plans to install six 100 MW solar power plants by 2030 in Uzbekistan and similar developments in neighboring countries, they can be further expanded to cover the growing energy demand.

5. Conclusions

Amid the growing demand for food and increasing pressure on limited, vulnerable river flow, the shift to pumped irrigation using groundwater has addressed water scarcity in agriculture. This adaptation strategy creates a base for increasing crop production by introducing intensive farming practices, water-saving irrigation, and energy-saving technologies. However, in this case, improved yields of crops and water productivity may be traded for high carbon inputs and CO_2 emissions. This study results suggest that in the environment, when carbon emissions become the main factor of environmental and agricultural unsustainability, WP indicator is not enough alone to decide on the sustainability of crop production because, despite it being an important indicator of crop return on consumed water, it does not reflect differences of alternative cases in carbon emissions. Under climate change induced by anthropogenic carbon emissions, a combination of three indicators, including crop yields per kg of carbon emissions, water productivity, and depletion of non-renewable fuel resources, can be used to clarify whether crop production using groundwater irrigation is environmentally sustainable.

The study revealed that only a farm-level analysis of water-energy-carbon tradeoffs might mask the gains and shortcomings of interventions to improve water and energy use and hidden environmental impacts. Instead, a system-level that includes a combination of farm-level and off-farm-level analysis of the tradeoffs is necessary to find crop production cases, which are environmentally sustainable.

The study found that, in Fergana Valley, the shift to groundwater irrigation using thermal power supply makes crop production unsustainable—groundwater supply is based on rapidly depleting fossil energy resources, with crop yields per kg of CO_2 emissions two times less than when electricity for groundwater pumping comes from the upstream or the midstream hydropower. The worst cases, characterized by high carbon emissions, occur when electricity is generated at thermal plants that pump water to farms using conventional or intensified farming practices.

The study shows that hydropower-based pumped irrigation has advantages over thermal-power-based irrigation. Hydropower can ensure timely irrigation and increase resource efficiency and productivity simultaneously by improving power availability, producing much lower CO_2 emissions. With the same water productivity, grape yields (kg/ha) per kg of CO_2-e/ha were 15.2–15.9 using electricity from hydropower against 7.7 kilograms of grapes/kg of CO_2-e using thermal plants. Many previous studies have considered the practice of obtaining hydropower electricity in summer traded for fossil natural gas in winter as a benefit-sharing approach for transboundary river basins with upstream hydropower and downstream agriculture. However, the present study suggests that this approach does not sustain power generation in the basin while continuously utilizing fossil carbon reserves. Instead, joining the development and use of upstream hydropower by riparian states reduces the depletion of fossil fuel resources, making agriculture more sustainable based on pumped irrigation. Hydropower development must ensure environmental flows and consider food, energy, social, and environmental tradeoffs to bring basin-scale benefits. This requires close cooperation between riparian states on water management and energy generation to enhance food production.

Midstream hydropower can serve to re-regulate upstream hydropower releases. The installation of small HPPs does not require extra water depletion because the downstream reservoirs can capture hydropower releases; there are minor power transportation and distribution losses and CO_2 emissions. Installing power stations on small rivers and widespread canals can form a basis for developing groundwater and wide adoption of micro-irrigation. Thus, hydropower development must contribute to diversifying benefits from water rather than prioritizing a single water use. The study indicates that downstream hydropower is less attractive because it causes extra water depletion and CO_2 emissions from the related reservoirs.

The results of the study highlight that solar power is the best case to deal with water-energy-carbon tradeoffs. Pumped irrigation using solar power showed similar to hydropower grape yields per kg of carbon emissions, water, and energy productivities; In contrast, hydropower may reallocate water from food production and increase water shortages for agriculture solar power requiring minimum water resources, which has no environmental impacts.

The three pillars for addressing water, energy, and carbon tradeoffs for sustainable food production are system-level interventions for water and energy saving, use of renewable energy to pump water for irrigation, and river basin scale cooperation. These pillars can lead to low carbon transformation of pumped irrigation-based food production in Central Asia and elsewhere. Further studies are required to analyze other cases, link cropping systems, water saving irrigation strategies, and alternative energy sources, and make future projections to achieve environmental sustainability in agricultural production. A special focus in future studies is to be given to a scale of water management sustainability analyses under the water, energy, and carbon tradeoffs at different levels—field, system, and basin.

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