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DECARBONIZING IRRIGATION SYSTEMS: INNOVATIVE TECHNOLOGIES FOR ENERGY EFFICIENCY AND SUSTAINABLE WATER RESOURCE MANAGEMENT

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Abstract

Decarbonizing irrigation systems plays a pivotal role in mitigating climate change and promoting sustainable agricultural practices. This paper explores advanced technological solutions to enhance the energy efficiency and sustainability of water resource management in irrigation systems. By leveraging innovations such as floating photovoltaic panels, smart irrigation controls, and the integration of renewable energy sources, this research aims to reduce dependency on fossil fuels and optimize water usage. The analysis encompasses the socio-economic and environmental impacts of these technologies, highlighting significant benefits including reduced greenhouse gas emissions, improved water conservation, and local economic development.

***Key words**: decarbonization, renewable energy, sustainability, water management, environmental impact.*

INTRODUCTION

Irrigation systems are essential for maintaining agricultural productivity, especially in regions with limited rainfall or facing the increasing threat of drought due to climate change (Aspe et al., 2016). However, conventional irrigation practices often rely heavily on fossil fuels for pumping and distribution, contributing to greenhouse gas emissions and exacerbating climate change (Borza & Coste, 2003). Additionally, inefficient water management in these systems can lead to overwatering, water scarcity, and environmental degradation (Baradei & Sadeq, 2020).

The need for decarbonizing irrigation systems has never been more critical. The Food and Agriculture Organization (FAO) projects that by 2050, the world population will reach 9.1 billion, requiring a 70% increase in global food production. Achieving this without further stressing our finite land and water resources demands innovative and sustainable approaches (FAO, 2022).

Ecological farming practices, innovative agricultural techniques that adjust to shifting weather patterns, minimized application of pesticides, new soil management approaches focused on maintaining soil health and carbon retention through crop cultivation and harnessing atmospheric nitrogen will all contribute to a sustainable agricultural sector that supports the Green Economy principles and delivers healthy food to the population. This aligns with the EU Green Deal's objective for a carbon-neutral Europe by 2050 (Ionitescu, 2023).

In this context, advanced technological solutions such as floating photovoltaic (FPV) panels, smart irrigation controls, and the integration of renewable energy sources emerge as viable strategies to enhance the energy efficiency and sustainability of water resource management in irrigation systems.

To address these challenges, there is a growing need for innovative technologies that can decarbonize irrigation systems and promote sustainable water resource management. This paper explores several promising solutions, including floating photovoltaic (FPV) panels, smart irrigation controls, and the integration of renewable energy sources. These technologies offer the potential to reduce energy consumption, optimize water usage, and mitigate the environmental impact of irrigation systems (McKuin et al., 2020).

State of the Art in Floating Photovoltaic (FPV)

Floating photovoltaic (FPV) systems represent a future solution in renewable energy, leveraging water bodies to enhance solar energy while conserving the land surface. Notably, FPV systems on irrigation channels offer several advantages, including land conservation, increasing energy efficiency also due to the cooling effect of water, and conserve water resource by reducing evaporation. These systems are particularly beneficial in regions with agriculture where the need for clean energy and food industries are competing for land use. Research employing MATLAB tools has demonstrated that FPV systems on irrigation reservoirs can significantly enhance power generation efficiency. The study highlighted the impact of temperature variations and solar irradiance on the performance of PV panels, emphasizing the improved efficiency of FPV systems over traditional land-based systems (Anbarasu et al., 2024).

Various countries are pioneering the development of floating photovoltaic (FPV) projects and advanced analytical tools to enhance the generation of green and clean energy.

The Fraunhofer Institute for Solar Energy Systems (ISE) has been a leader in FPV research, particularly on artificial water surfaces like pit lakes. Their research demonstrates that FPV systems can outperform land-based systems due to the cooling effects of water, significantly reducing the levelized cost of energy (LCOE) despite higher initial investments (FRAUNHOFER ISE, 2024).

In USA, significant advancements include the development of a global inventory map for FPV systems using satellite imagery. This tool aids environmental assessments and policy management by providing detailed data on FPV installations worldwide. Additionally, technological innovations focus on improving the stability and efficiency of FPV systems in diverse environmental settings, such as pontoon-type structures designed for harsh offshore conditions (Bellini, 2023).

Japan has made significant strides with its Tokyo Bay Offshore Floating Solar Project. This initiative integrates solar energy with electric mobility infrastructure, providing renewable energy for electric vehicles and boats, demonstrating Japan’s commitment to local renewable energy generation and sustainability (Oceannews, 2024; Garanovic, 2022).

India has explored the feasibility and benefits of FPV systems in regions like Gujarat and Tamil Nadu. These projects demonstrate significant energy generation and environmental benefits, particularly in areas with limited land availability (Nagababu, 2024).

Brazil’s notable FPV projects include the Araucária floating photovoltaic plant and Iberdrola’s installation on Fernando de Noronha Island, a site that is declared by UNESCO as a World Natural Heritage Site, part of Brazilian National Marine Park and Environmental Protected Area. These projects aim to develop business models that contribute to decarbonization and sustainable development on an isolated ecosystem (Neves, 2023; Iberdrola, 2024).

In the Netherlands, large-scale FPV parks like the 41.1 MWp Sellingen and 29.8 MWp Uivermeertjes parks have been implemented. These projects generate significant renewable energy while integrating into the local landscape with minimal ecological impact. Researchers from the Netherlands analyzed the effects of floating PV in different climate zones, finding that FPV systems can increase annual energy yield by up to 6% due to the cooling effect of water (Weetch, 2021; Dörenkämper et al., 2021).

Spain's FPV advancements include the Sierra Brava Floating PV Plant, in the reservoir in Cáceres, which covers 12,000 m² and features 3,000 floating solar panels with a total capacity of 1.375 MWp. The project explores various solar module technologies and configurations. supported by new government regulations to boost FPV deployment and includes advanced technologies like hydro-elastic membranes and environmental measures to protect local wildlife (Acciona, 2024).

Romania has initiated significant FPV projects, such as the country's first large-scale floating

PV system by TMK Hydroenergy Power. This 1 MW system, located on a pond in Caras Severin county, is integrated with a hydropower plant, generating power for internal consumption. Additionally, Renera Energy is developing the largest floating photovoltaic park in Romania, with a 50 MW capacity on 37 hectares in Brăila County (Economedia, 2024; Renera, 2024).

The diverse geographical locations, climate challenges, geomorphological and hydrogeological conditions, and opportunities for circular economy practices highlight the necessity for tailored FPV projects. Each project must be thorough designed to address the specific context of its implementation area. This requires a comprehensive assessment tool that can accurately evaluate project efficiency by taking into account all relevant factors. Essential documentation, including Do No Significant Harm assessments (DNSH), Cost-Benefit Analyses (CBA), Environmental Impact Assessments (EIA), climate change and immunization studies, social analyses, economic feasibility studies, and technical evaluations, must be integrated into a multi-composite analysis. This holistic approach ensures that all potential limitations and opportunities specific to the implementation area are thoroughly considered. By adopting this method, it becomes possible to declare a project both efficient and financeable, ensuring that all necessary documentation and studies are part of a cohesive and robust evaluation process. This comprehensive strategy is critical for maximizing the project's success and sustainability, particularly in unique and variable environmental contexts.

Giurgiu-Răzmirești case study

The Giurgiu-Răzmirești irrigation system in Romania serves as a compelling case study for the implementation of innovative technologies to decarbonize irrigation and enhance water resource management. This approach represents the key for Romania to achieve the carbon net zero emission in the water-related infrastructure projects (Sandu et al., 2023). This system, covering 19 administrative territorial units (ATUs) across Giurgiu and Teleorman counties, faces challenges related to old infrastructure, inefficient water use, and high energy consumption.

The proposed project aims to address these challenges by installing floating photovoltaic panels on the existing irrigation canals. This dual-use approach not only generates clean electricity to power the irrigation system, but also reduces water evaporation, contributing to water conservation. The project also includes the rehabilitation of existing canals and the implementation of a modern water management system to optimize water distribution and minimize losses (Kleps & Tusa, 1992).

The Giurgiu-Răzmirești project is expected to generate approximately 151.8 GWh of renewable energy annually, significantly reducing the system's reliance on fossil fuels and lowering greenhouse gas emissions. The project's innovative approach aligns with the European Union's RePowerEU plan, which aims to decarbonize industries and increase the use of renewable energy sources (Directive EU, 2018/2001). An environmental impact assessment (EIA) was conducted to evaluate the potential environmental effects of the Giurgiu-Răzmirești project. The assessment considered various factors, including land use change, greenhouse gas emissions, water quality, and biodiversity (Nicolae et al., 2021).

Biodiversity field monitoring and studies are essential activities to ensure the durability and sustainability of infrastructure projects. Given that most infrastructure projects occupy large land areas, alter landscapes, or utilize land within or adjacent to environmentally protected areas, which can serve as habitats for protected species, it is crucial for future projects to consider their interactions with biodiversity parameters. This is particularly important for maintaining ecological balance and complying with environmental regulations. Figure 1 illustrates these relationships and the importance of integrating biodiversity considerations into project planning.

The biodiversity criteria to analyse in these projects is mandatory, as infrastructure projects are proven to be a source of multiple environmental impacts, such as roadkill, habitat loss, and habitat fragmentation (Nicolae & Stefan, 2022).

The installation of FPV panels on existing canals eliminates the need for additional land acquisition, thereby minimizing the project's impact on land use. However, the

Environmental Impact Assessment (EIA) estimated that the project would result in the emission of 18,239 tons of CO_2 due to the disturbance of biomass and soil during construction. To offset these emissions, the project proposes afforestation of 9,600 hectares of degraded land or the establishment of windbreaks on 480,000 hectares of agricultural land.

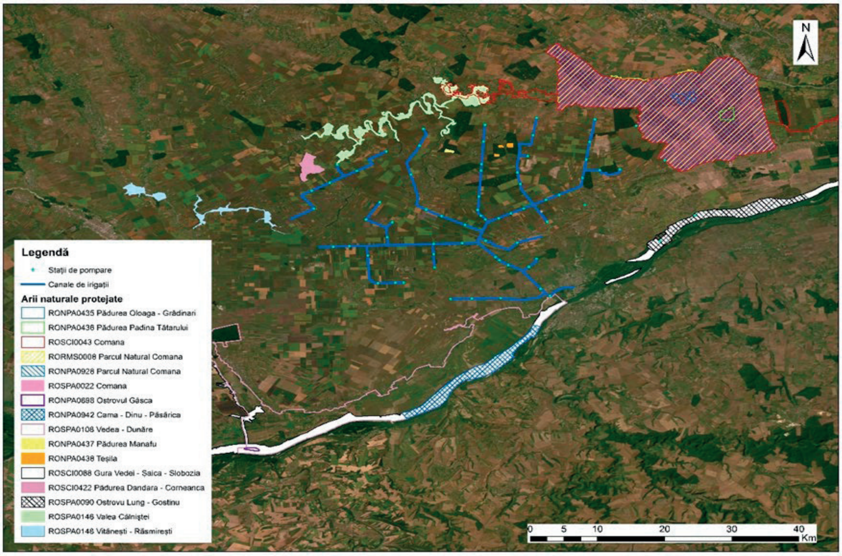

Figure 1. Map of the irrigation project in relation to nearby protected natural areas (GEOSTUD, 2022)

CO_2 Emissions from Biomass Conversion

A comprehensive analysis based on IPCC 2006 guidelines illustrates the significant CO_2 emissions associated with converting different types of land to infrastructure as seen in Tables 1, 2 and 3.

Table 1. Conversion from Pasture to Infrastructure (GEOSTUD, 2022)

Equation 2.15 & 2.16 IPCC 2006	**Explanations/IPCC Default Values**	**Pasture land**	**Total**
ΔAto_others (ha)	Area in conversion	19.5	19.5
BAFTER (tDM/ha)	Biomass associated with future use, i.e., biomass stock in the first year after conversion, immediately after conversion	0	-
BBEFORE (tDM/ha)	Biomass associated with previous use, i.e., before conversion	6.1	-
CF	Carbon fraction in dry biomass/IPCC value	0.47	-
ΔCG (tC/yr)	Increase in stock in the year in question	0	-
ΔCL (tC/yr)	Carbon loss in the year in question	0	-
Total C stock change, tC		-55.9065	-
Total emissions ("+")/removals ("-"), tCO_2		204.9905	204.9905

The conversion of 19.5 hectares of pastureland to infrastructure results in approximately 205 tonnes of CO_2 emissions due to the loss of biomass that previously acted as a carbon sink.

Table 2. Conversion from Orchard to Infrastructure (GEOSTUD, 2022)

Equation 2.15 & 2.16 IPCC 2006	**Explanations/IPCC Default Values**	**Orchard**	**Total**
ΔAto_others (ha)	Area in conversion	6.5	6.5
BAFTER (tDM/ha)	Biomass associated with future use, i.e., biomass stock in the first year after conversion, immediately after conversion	0	-
BBEFORE (tDM/ha)	Biomass associated with previous use, i.e., before conversion	Calculated	-
CF	Carbon fraction in dry biomass/IPCC value	Generic	-
ΔCG (tC/yr)	Increase in stock in the year in question	0	-
ΔCL (tC/yr)	Carbon loss in the year in question	0	-
Total C stock change, tC		-30.55	-
Total emissions ("+")/removals ("-"), tCO_2		112.0167	112.0167

The conversion of 6.5 hectares of orchard to infrastructure results in approximately 112 tonnes of CO_2 emissions due to the removal of biomass stocks that sequester carbon.

Table 3. Conversion from Arable Land to Infrastructure (GEOSTUD, 2022)

Equation 2.15 & 2.16 IPCC 2006	**Explanations/IPCC Default Values**	**Arable Land**	**Total**
ΔAto_others (ha)	Area in conversion	104	104
BAFTER (tDM/ha)	Biomass associated with future use, i.e., biomass stock in the first year after conversion, immediately after conversion	0	0
BBEFORE (tDM/ha)	Biomass associated with previous use, i.e., before conversion	10	10
CF	Carbon fraction in dry biomass/IPCC value	0.47	0.47
ΔCG (tC/yr)	Increase in stock in the year in question	0	0
ΔCL (tC/yr)	Carbon loss in the year in question	0	0
Total C stock change, tC		-488.8	-
Total emissions ("+")/removals ("-"), tCO_2		1792.267	1792.267

The conversion of 104 hectares of arable land to infrastructure results in approximately 1792 tonnes of CO_2 emissions, reflecting a significant release due to the loss of carbon-sequestering biomass.

These substantial CO_2 emissions highlight the environmental impact of converting various types of land to infrastructure. Arable lands, in particular, sequester substantial amounts of carbon, and their conversion results in significant greenhouse gas emissions, exacerbating climate change. This underscores the critical need for sustainable land-use practices and policies that mitigate carbon emissions by preserving high-biomass areas and promoting green infrastructure.

By understanding and addressing both the emissions from biomass disturbance during construction and the long-term implications of land-use changes, the project can implement more effective strategies to minimize its environmental footprint (Figure 2).

This comprehensive approach ensures that while the immediate CO_2 emissions are accounted for and mitigated through measures such as afforestation and windbreaks, the broader implications of land-use changes are also considered in the planning and execution of sustainable projects.

The project is also expected to have a positive impact on water quality by reducing evaporation and preventing algal blooms. The rehabilitation of canals will further improve water management and minimize losses due to seepage and infiltration (Kumar et al., 2018).

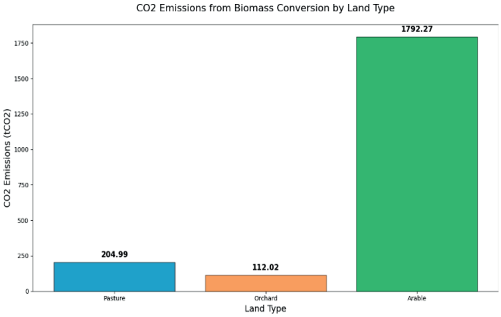

Figure 2. Project's CO_2 emissions from biomass conversion. Adaptation after (GEOSTUD, 2022)

In order to complete the efficiency analysis, a DNSH (*Do No Significant Harm*) study was elaborated according to the European requirements for national funded projects (EC, 2021).

A socio-economic impact assessment (SEIA) was conducted to evaluate the potential social and economic benefits of the project. The assessment considered factors such as job creation, local economic development, and agricultural productivity.

Climate change vulnerability

Data from national meteorological stations indicate that the average annual temperature in 2020 was approximately 13°C. Projecting current trends in temperature increase, we estimate that by 2050, the annual temperature could rise to approximately 22°C. This significant increase underscores the urgent need for optimized water management and conservation of water resources. Moreover, the project must be designed to withstand the impacts of rising temperatures, necessitating the incorporation of more durable and sustainable components. Additionally, it is imperative to address the challenge of diminishing the use water resources, ensuring that the project can adapt to these future climatic conditions (Figures 3 and 4).

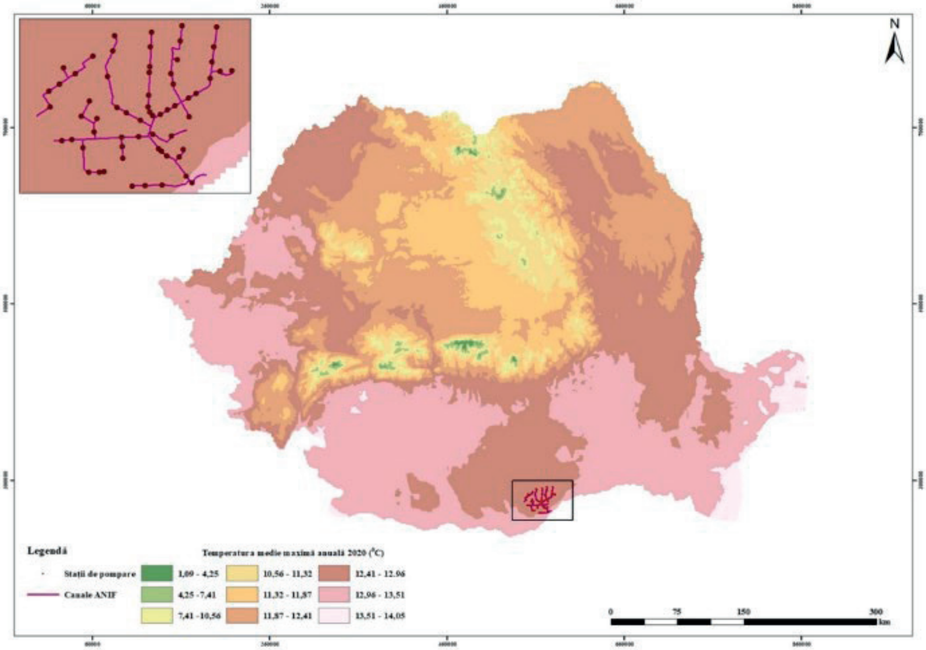

Figure 3. Annual average temperature for the year 2020 - actual situation (GEOSTUD, 2022)

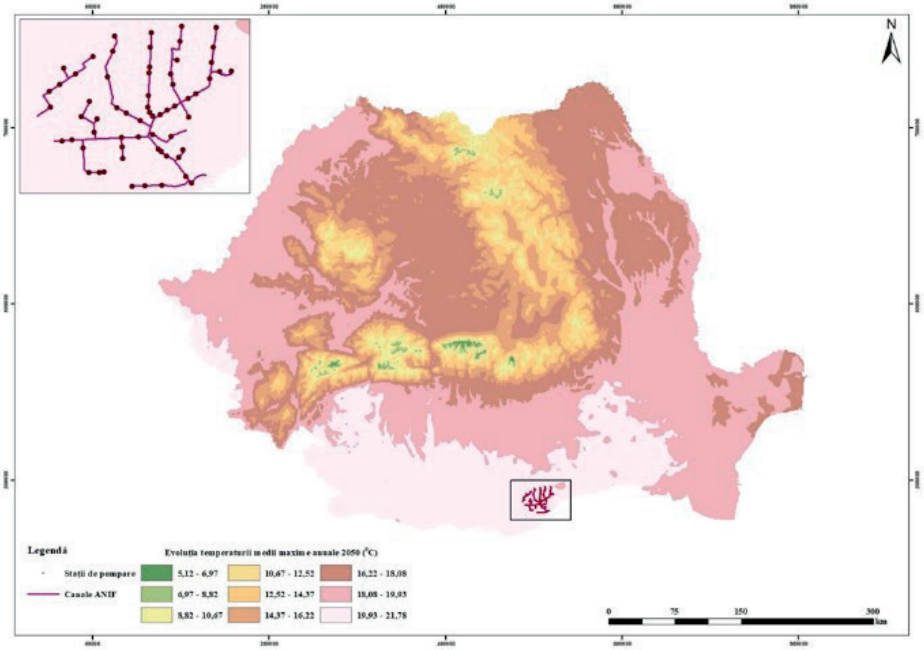

Figure 4. Annual average temperature for the year 2050 - estimated situation (GEOSTUD, 2022)

The project is expected to create new jobs during the construction and operation phases, contributing to local economic development. The improved irrigation efficiency and increased agricultural productivity resulting from the project are also expected to have positive socio-economic impacts on the local communities (Table 4).

Table 4. Estimated socio-economic benefits of the Giurgiu-Răzmirești project

Impact category	Estimated benefit
Job creation (construction phase)	500 direct jobs, 1,000 indirect jobs
Job creation (operation phase)	50 direct jobs, 100 indirect jobs
Increased agricultural productivity	10-15% increase in crop yields
Reduced water costs for farmers	15-20% reduction in irrigation costs
Increased income for farmers	10-15% increase in farm income

A financial analysis was conducted to assess the economic viability of the Giurgiu-Răzmirești project. The analysis considered the investment costs, operating costs, and revenue generation from electricity sales and water fees. The project's initial investment cost is estimated to be €50 million, with an additional €2 million per year for operation and maintenance. The revenue from electricity sales is projected to be €8 million per year, while the revenue from water fees is estimated to be €4 million per year. Based on these figures, the project is expected to have a payback period of fewer than 10 years and a positive net present value, indicating its economic viability. Table 5 presents the estimated financial performance of the Giurgiu-Răzmirești project over a 20-year period, showcasing its strong economic viability and profitability.

The project generates significant value from energy production, starting at €12,144,000 in the first year and gradually decreasing to €10,260,466 in the twentieth year. Despite this decline, the project consistently produces a high total value. The energy consumed by the project remains constant at €4,100,800 annually, indicating stable operational costs. The surplus energy distributed to the grid, which begins at €8,043,200 and decreases to €6,159,666 by the twentieth year, contributes additional revenue and supports the overall energy supply (Figure 5).

Economic efficiency means obtaining some useful economic effects, under the conditions of spending some resources in a rational and economical way (Zaman & Geamanu, 2006).

Table 5. Estimated profitability of the Giurgiu-Răzmirești project over a 20-year period

Year	Total value generated from energy production (EUR)	Value of energy consumed by the project (EUR)	Value of additional energy distributed to the grid (EUR)	Profitability
1	12144000	4100800	8043200	3942400
2	12044419	4100800	7943619	3842819
3	11946053	4100800	7845253	3744453
4	11846472	4100800	7745672	3644872
5	11746891	4100800	7646091	3545291
6	11648525	4100800	7547725	3446925
7	11548944	4100800	7448144	3347344
8	11449363	4100800	7348563	3247763
9	11350997	4100800	7250197	3149397
10	11251416	4100800	7150616	3049816
11	11153050	4100800	7052250	2951450
12	11053469	4100800	6952669	2851869
13	10953888	4100800	6853088	2752288
14	10855522	4100800	6754722	2653922
15	10755941	4100800	6655141	2554341
16	10656360	4100800	6555560	2454760
17	10557994	4100800	6457194	2356394
18	10458413	4100800	6357613	2256813
19	10358832	4100800	6258032	2157232
20	10260466	4100800	6159666	2058866
TOTAL	**224041013**	**82016000**	**142025013**	**60009013**

Profitability is a key highlight, starting at €3,942,400 in the first year and remaining positive throughout the 20-year period. This consistent profitability demonstrates that the project effectively covers its operational costs while generating substantial profit. The financial stability of the irrigation system, combined with its environmental and social benefits, underscores its potential as a model for sustainable irrigation and energy management, offering a blueprint for similar initiatives aimed at integrating renewable energy and enhancing resource efficiency.

A complete financial analysis can be performed only by taking in consideration the cost of execution and, the cost of operation and maintenance.

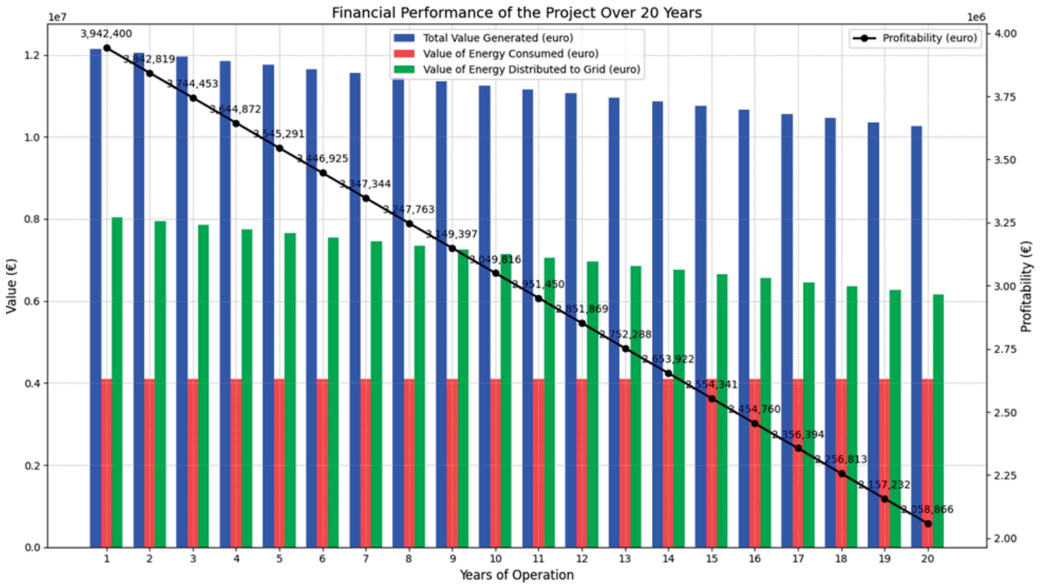

Figure 5. Graphic representation of the project's profitability. Adaptation after (GEOSTUD, 2022)

The analysed hydro-improvement project aims to enhance irrigation efficiency and integrate renewable energy solutions. Below is the summarized data comparing the current scenario without the project and the projected scenario with the project implementation in corelation with the operation cost (Table 6).

Table 6. Operation cost variation of the Giurgiu-Răzmirești project before and after implementation

Specification	**Unit**	**Without the project**	**With the project**
Water volume required at capture point for irrigation	thousand m³	307,027.69	250,294.32
Electric energy consumed for water pumping	GWh	95.60	58.20
Electric energy consumed for water pumping	kWh	95,600,000.00	58,200,000.00
Renewable electric energy produced by floating photovoltaic panels	GWh	-	138.00
Total operating costs	thousand lei	100,615.22	59,415.64

The volume of water required at the capture point for irrigating the entire area significantly reduces from 307,027.69 thousand m³ to 250,294.32 thousand m³ with the implementation of the project. This indicates a substantial improvement in water use efficiency.

The electric energy consumed for water pumping shows a remarkable reduction from 95.60 GWh (95,600,000 kWh) to 58.20 GWh (58,200,000 kWh). This reduction in energy consumption can be attributed to the enhanced efficiency of the irrigation system and possibly the use of more efficient pumps or techniques.

Additionally, the project introduces the generation of 138.00 GWh of renewable electric energy through floating photovoltaic panels, which not only offsets the energy required for pumping but also contributes to the grid.

The total operating costs are projected to decrease from 100,615.22 thousand lei to 59,415.64 thousand lei. This reduction in operating costs is likely due to the decrease in energy consumption and the integration of renewable energy sources, leading to lower energy costs and improved operational efficiency, as seen in Figure 6.

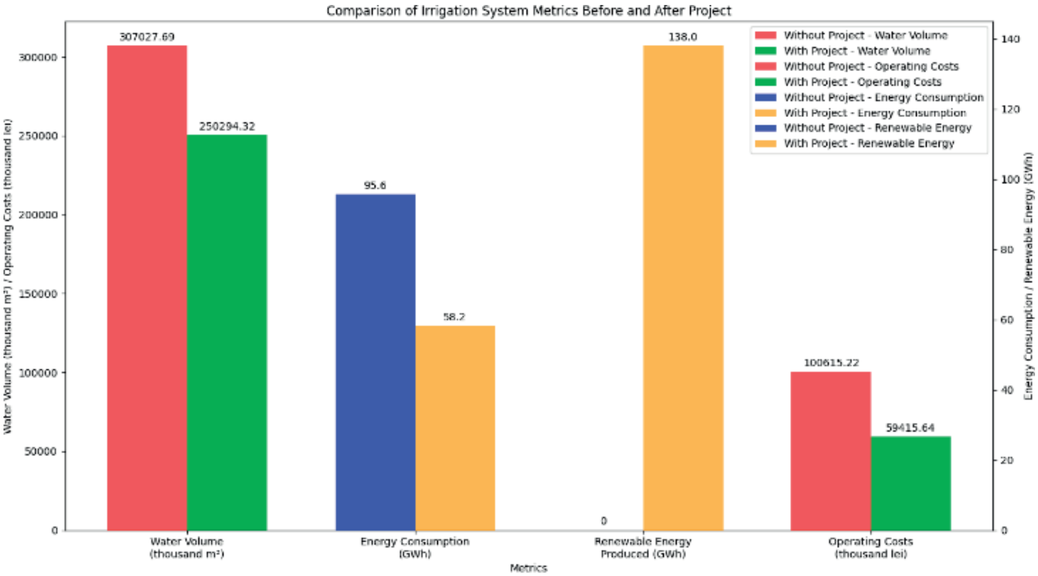

Figure 6. Operation cost with and without the project and the energy produced vs cost.
Adaptation after (GEOSTUD, 2022)

MATERIALS AND METHODS

This study employed a mixed-methods approach, combining literature review, data analysis, and field assessments to evaluate the effectiveness of innovative technologies in decarbonizing the Giurgiu-Răzmirești irrigation system and enhancing its water resource management.

A comprehensive literature review was conducted to examine existing research on FPV panels, smart irrigation controls, and renewable energy integration in the context of irrigation systems (Gallagher et al., 2017). This review provided a theoretical foundation for understanding the potential benefits and challenges associated with these technologies. It also helped identify relevant case studies and data sources for further analysis.

Data collection and analysis

Data on the Giurgiu-Răzmirești irrigation system were collected from the Romanian National Administration for Land Reclamation and Improvement (ANIF) and other relevant national and European sources. This data included information on the system's current energy consumption, water usage, infrastructure conditions, and agricultural productivity.

The collected data were analyzed using various statistical methods to assess the potential impact of the proposed technological interventions. Energy consumption and water usage were modelled under different scenarios, with and without the implementation of FPV panels, smart irrigation controls, and renewable energy integration. The results of these analyses were used to quantify the potential reductions in energy consumption, water usage, and greenhouse gas emissions.

Field assessments were also conducted to evaluate the current state of the Giurgiu-Răzmirești irrigation system and to identify potential sites for the installation of FPV panels. These assessments involved site visits, interviews with local stakeholders, and the collection of environmental data. The findings from the field assessments were used to inform the design and implementation of the proposed technological interventions.

Congruence factor methodology

To assess the overall sustainability of the project, a congruence factor methodology was developed. This methodology integrates economic, social, and environmental criteria into a single metric, providing a holistic assessment of the project's performance. The weights assigned to each criterion were determined through expert consultation and stakeholder engagement, ensuring that the assessment reflects the values and priorities of the local community.

The congruence factor formula is as follows:

Congruence Factor = (w_e * E) + (w_s * S) + (w_env * ENV),

where:

- w_e, w_s, and w_env are the weights assigned to economic, social, and environmental criteria, respectively.
- E, S, and ENV are the standardized scores for each criterion.

The standardized scores were calculated by dividing the raw value of each criterion by its maximum value, ensuring that all criteria were on the same scale.

The weights and standardized scores are as follows:

Weights:

- Economic: 0.3
- Social: 0.3
- Environmental: 0.2
- Water Conservation: 0.2

Standardized Scores:

- Economic: 0.95
- Social: 0.90
- Environmental: 0.92
- Water Conservation: 0.90

The Congruence Factor is calculated as follows:

Congruence Factor = (0.3×0.95) + (0.3×0.90) + (0.2×0.92) + (0.2×0.90) = 0.922

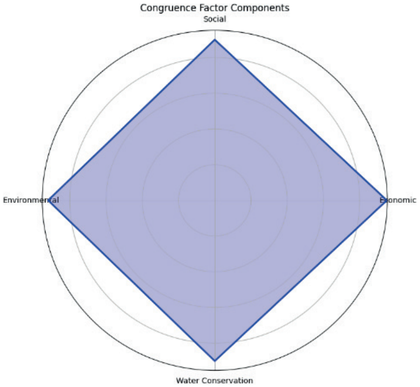

Figure 7. The congruence factor analysis of the Giurgiu-Răzmirești project

The graphical representation of the balanced congruence factor derived from the analysis is presented in Figure 7. This figure illustrates the integration of various environmental, social, and economic criteria to optimize infrastructure performance.

This score reflects a project with exceptionally high performance across all dimensions, indicating a well-balanced and highly efficient project

Evaluation of project efficiency

The efficiency of the Giurgiu-Răzmirești project was evaluated using a combination of quantitative and qualitative indicators. Quantitative indicators included energy savings, water savings, and greenhouse gas emission reductions. These indicators were calculated based on the data analysis and modelling results.

Qualitative indicators included social acceptance, environmental impact, and technological feasibility. These indicators were assessed through stakeholder interviews, field assessments, and expert consultations.

The overall efficiency of the project was determined by calculating the congruence factor, which integrated the quantitative and qualitative indicators into a single score. A higher congruence factor indicates a more sustainable and efficient project (Neaga, 2015).

RESULTS AND DISCUSSIONS

Floating photovoltaic (FPV) panels are a novel technology that involves installing solar panels on water bodies, such as reservoirs and irrigation ponds. This dual-use approach not only generates clean electricity, but also reduces water evaporation, making it an attractive option for decarbonizing irrigation systems.

The literature review and case studies revealed that FPV systems have the potential to significantly reduce greenhouse gas emissions associated with irrigation. FPV systems can help conserve water by reducing evaporation losses, which is particularly important in arid and semi-arid regions.

However, the implementation of FPV systems also poses some challenges, such as the need for specialized equipment and expertise for installation and maintenance. Additionally, there are concerns about the potential impact of

FPV panels on aquatic ecosystems, although research suggests that these impacts can be mitigated through careful design and management.

Smart irrigation controls utilize sensors, weather data, and advanced algorithms to optimize water delivery to crops. This technology can significantly reduce water waste and improve irrigation efficiency, leading to substantial water savings and reduced energy consumption.

The data analysis revealed that smart irrigation controls can reduce water consumption by up to 50% compared to conventional irrigation methods. This translates to significant energy savings, as pumping and distributing water accounts for a substantial portion of energy use in irrigation systems. Moreover, smart irrigation can improve crop yields by ensuring that plants receive the right amount of water at the right time, further contributing to sustainable agricultural practices.

However, the adoption of smart irrigation controls requires upfront investment in technology and training for farmers. Additionally, the effectiveness of this technology depends on the accuracy and reliability of weather data and sensors, which may be a challenge in some regions.

Integrating renewable energy sources, such as solar and wind power, into irrigation systems can significantly reduce reliance on fossil fuels and lower greenhouse gas emissions. This can be achieved through the use of solar-powered pumps, wind-powered turbines, and hybrid systems that combine multiple renewable energy sources.

The renewable solutions must secure a circular economy approach in order to prevent the inefficient future waste management (Gautam et al., 2021).

The circular solution implies developing a business model that generate a close-loop cycle that will ensure the project sustainability (Contreras-Lisperguer, 2021).

The literature review and case studies highlighted the significant potential of renewable energy integration for decarbonizing irrigation systems.

Additionally, renewable energy can provide a reliable and cost-effective source of power for irrigation, especially in remote areas where grid electricity may be unavailable or unreliable.

However, the initial investment costs for renewable energy systems can be a barrier for some farmers. Moreover, the intermittent nature of renewable energy sources requires careful planning and design to ensure a stable power supply for irrigation.

The analysis of the irrigation system revealed significant potential for improvement in energy efficiency and water resource management. The implementation of FPV panels is projected to generate a substantial amount of renewable energy, as shown in Table 7.

Table 7. Estimated financial performance of the Giurgiu-Răzmirești project over a 20-year period

Year of operation	Energy production (MWh)	Energy consumption (MWh)	Surplus energy (MWh)
1	151,800	51,260	100,540
2	150,555	51,260	99,295
3	149,326	51,260	98,066
4	148,113	51,260	96,853
5	146,915	51,260	95,655
6	145,733	51,260	94,473
7	144,567	51,260	93,307
8	143,416	51,260	92,156
9	142,281	51,260	91,021
10	141,161	51,260	89,901
11	140,057	51,260	88,797
12	138,968	51,260	87,708
13	137,894	51,260	86,634
14	136,835	51,260	85,575
15	135,792	51,260	84,532
16	134,763	51,260	83,503
17	133,749	51,260	82,489
18	132,750	51,260	81,490
19	131,767	51,260	80,507
20	130,800	51,260	79,540
Total	**2,817,242**	**1,025,200**	**1,792,042**

Figure 8 illustrates the energy dynamics of the analysed irrigation system over a 20-year period. The green line represents the energy production from floating photovoltaic panels, showing a gradual decrease from 151,800 MWh in the first year to 130,800 MWh by the twentieth year. The constant red line indicates the energy consumption of the irrigation system, fixed at 51,260 MWh annually. The blue line, depicting the surplus energy, highlights the difference between energy production and consumption, starting at 100,540 MWh in the first year and gradually decreasing to 79,540 MWh in the final year. This surplus energy is fed back into the grid, contributing to the overall energy efficiency and sustainability of the project. The consistent energy consumption contrasted with the decreasing energy production underscores the importance of maintaining high energy efficiency and optimizing renewable energy sources to sustain long-term surplus generation. The figure below illustrates the projected energy production, consumption, and surplus over the 20-year lifespan of the project.

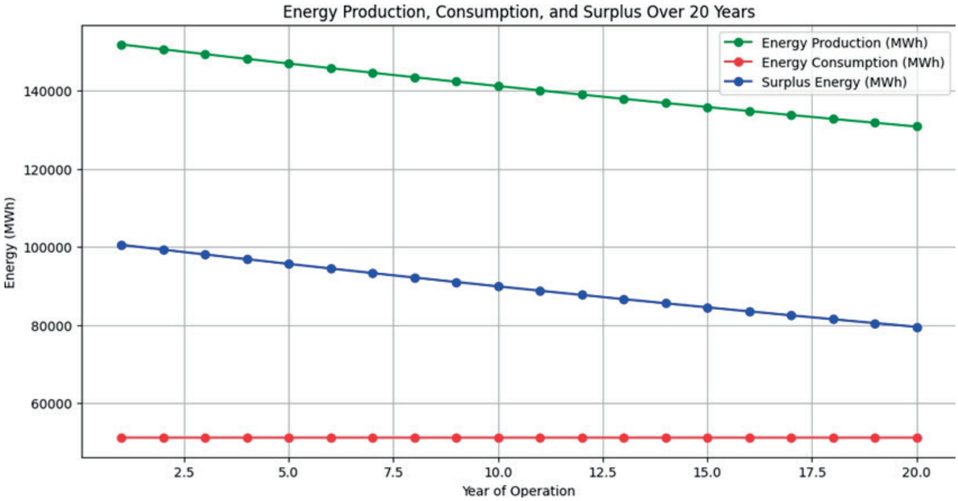

Figure 8. Financial performance of the project. Adaptation after (GEOSTUD, 2022)

The surplus energy generated by the FPV panels can be fed into the grid, providing additional revenue for the project and contributing to the decarbonization of the energy sector. The implementation of smart irrigation controls is expected to result in significant water savings, as shown in Table 8.

Table 8. Estimated water consumption of the Giurgiu-Răzmirești irrigation system with and without smart irrigation controls

Scenario	Water consumption (thousand m^3)	Cost (€)	Savings (€)
Without smart irrigation controls	337,730	23,641,100	-
With smart irrigation controls	275,324	19,272,680	4,368,420
Reduction	**62,406**	**4,368,420**	-

The average estimated cost for m^3 of irrigation water in Romania was €0.07/m^3. This reduction in water consumption not only conserves a valuable resource, but also reduces the energy required for pumping and distribution, further contributing to the project's overall efficiency. The annual cost savings from reduced water consumption would be €4,368,420, and the cumulative savings over 20 years would be €87,368,400.

The integration of renewable energy sources, such as solar and wind power, is expected to further reduce the project's reliance on fossil fuels and lower greenhouse gas emissions. The combination of FPV panels, smart irrigation controls, and renewable energy integration is projected to achieve a high congruence factor, indicating a balanced and sustainable approach to irrigation system management.

CONCLUSIONS

This study shows that the decarbonization of irrigation systems is possible through the use of innovative technologies such as floating photovoltaic systems, smart irrigation controllers and the integration of renewable energies. In the case of the Giurgiu-Răzmirești irrigation system, these technologies offer significant potential to reduce greenhouse gas emissions, save water and promote sustainable agricultural practices. The implementation of floating photovoltaic panels is expected to generate a significant amount of renewable energy that exceeds the energy consumption of the system and provides surplus energy to feed into the grid. This not only reduces the system's dependence on fossil fuels, but also generates additional revenue through the sale of electricity. The integration of smart irrigation controllers is expected to result in significant water savings, conserving this valuable resource and reducing the energy required for pumping and distribution. These combined benefits contribute to the overall efficiency and sustainability of the project.

However, the successful implementation of these technologies requires a holistic approach that considers the technical, economic, social, and environmental aspects of irrigation systems. Policymakers, researchers, and industry stakeholders need to collaborate to develop supportive policies, financial incentives, and capacity-building programs to encourage the widespread adoption of these technologies. Future research should focus on expanding the dataset to include a wider range of social and environmental indicators, as well as refining the weighting methodology for the congruence factor. Additionally, the application of the congruence factor to other sectors, such as energy and water infrastructure, could provide valuable insights for sustainable development planning in Romania.

The findings of this study have broader implications for climate change mitigation and adaptation efforts in the agricultural sector. By demonstrating the feasibility and benefits of decarbonizing irrigation systems, this research can serve as a model for other regions facing similar challenges. The integration of renewable energy and smart technologies in agriculture is not only essential for reducing greenhouse gas emissions but also for ensuring food security and resilience in the face of climate change.

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