

Solar-Powered Autonomous System for Oil Spill Recovery and Biodiesel Production in the Danube River

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Abstract. Navigable waterways are essential for transportation, trade, and regional development, yet they are increasingly affected by oil pollution generated by intensive maritime traffic and industrial activities. Oil contamination threatens aquatic ecosystems, reduces water quality, and affects biodiversity and economic activities dependent on river systems. This study proposes an innovative and sustainable solution for oil spill mitigation through the development of a solar-powered autonomous or semi-autonomous boat designed to collect oil from the water surface and convert the recovered waste into biodiesel. The proposed system integrates floating collection arms, an oil–water separation unit, a filtration system, and a hybrid solar-electric propulsion system that enables energy-efficient and environmentally friendly operation. The concept is tested for potential deployment on the Danube River, one of Europe’s most important navigable waterways, particularly in areas affected by oil pollution from commercial vessels. The system performance is evaluated based on oil recovery efficiency, separation and filtration performance, and improvements in water quality parameters. Results indicate that the system could recover up to 80–90% of surface oil, while separation and filtration processes may achieve efficiencies above 95% and 98%, respectively. In addition to reducing pollution, the recovered oil can be processed into biodiesel, supporting circular economy principles and contributing to sustainable waterway management.

Keywords: Oil spill remediation, Autonomous cleaning boat, Solar-powered system, Biodiesel production, Danube River

Introduction

Navigable waters, which include rivers, canals, seas, and oceans, form the backbone of global trade, transportation, and ecological balance. These waterways cover an extensive area, with oceans alone spanning about 71% of the Earth's surface, representing roughly 361 million square kilometers. Rivers and canals, while more localized, also serve crucial roles, with the total length of the world’s rivers

estimated at over 5.5 million kilometres. Together, these bodies of water facilitate the movement of goods and people, while also supporting diverse ecosystems [1].

Shipping traffic in these waters varies significantly depending on the location and type of waterway. For instance, the oceans experience the highest traffic, with some of the busiest shipping lanes being located in the Pacific and Atlantic Oceans. More than 90% of global trade is carried by sea [2], with the world's largest ports handling thousands of vessels daily. In contrast, rivers like the Danube, though still busy, have significantly lower traffic volumes, with an estimated 1,000 vessels navigating its waters daily. Canals, such as the Suez or Panama Canal, see high levels of traffic due to their role in connecting oceans and facilitating the global movement of goods.

The issue of pollution in these vast water systems is a growing concern. Among the various pollutants, oil contamination poses a particularly severe threat. Globally, it's estimated that about 1.3 million tons of oil are spilled into the oceans every year, much of which results from shipping accidents, leaks, and industrial activities. The pollution of rivers and canals, although on a smaller scale, can be equally devastating to local ecosystems. Oil spills are notorious for their ability to spread across the water's surface, forming a layer that suffocates marine life by disrupting oxygen exchange, and they are harmful to aquatic organisms, particularly fish, and birds [3].

The Danube River, as the second-longest river in Europe, is no exception. It spans 2,850 kilometres, flowing through 10 countries, and serves as a vital waterway for trade, tourism, and cultural exchange. However, the heavy maritime traffic and industrial activities around the river contribute significantly to oil contamination. The estimated 1,000 vessels navigating the Danube daily represent a major source of oil pollution, often in the form of accidental spills or the discharge of residual oils into the water. Oil pollution in rivers like the Danube is not only an environmental issue but also an economic and social one. It affects commercial and recreational fishing, tourism, and water quality, limiting its use for drinking, agriculture, and other industrial purposes. Thus, finding solutions to address this pollution is crucial for both ecological and economic sustainability.

Innovative solutions are needed to tackle this problem. One promising approach involves the development of autonomous or semi-autonomous boats designed to clean oil spills while generating renewable energy. Powered by solar energy, such boats would be capable of collecting oil from the water's surface, separating it from the water, and converting it into biodiesel. This technology could offer a sustainable, efficient, and eco-friendly way to address oil contamination in waterways like the Danube and beyond [4,5].

This project presents an opportunity to test such a system on a global scale, not only to reduce pollution but also to contribute to the transition to a more sustainable environment by producing renewable energy. By evaluating the feasibility and impact of deploying this technology on rivers like the Danube, the research aims to demonstrate how such solutions can benefit both the environment and the economies that rely on these vital waterways.

Methodology

The primary objective of this study is to evaluate the feasibility and impact of implementing the project for cleaning oil pollution from the Danube River. The study will follow several stages to achieve this goal [6].

An example of a relevant area for testing the boat is the section of the Danube River near Călărași, an area with high maritime traffic that is frequently polluted with oils from commercial and transport vessels. In this region, oil concentrations can vary significantly, with levels of up to 0.5-1 mg/l in areas with intense traffic. The frequency of pollution is determined by the large number of vessels that pass through this section daily, with around 50-70 ships, including cargo vessels, barges, and small boats. The oils targeted for collection include petroleum oils (diesel, industrial oils) and marine oils used in ship fuel and lubrication processes. These oils are particularly harmful to aquatic environments as they are difficult to break down and can severely impact local ecosystems [7,8].

The boat prototype will be constructed based on the design, consisting of several key components. The boat will feature floating arms designed to capture the oil film from the water's surface. These arms

will be adjustable to accommodate different pollution levels and water level variations. The collected oil will be directed to an oil-water separator, which will use flotation or centrifugation technology to separate the oil from the water. The separated oil will then pass through a filtration system designed to remove solids and impurities, ensuring that the oil collected is as clean as possible. The boat will be powered by a solar-hybrid system, which includes solar panels that will capture solar energy to power the collection and filtration systems. In addition, an electric motor will provide propulsion, ensuring autonomous operation under most conditions. During days with insufficient sunlight or unfavorable weather, the hybrid system will supplement the energy needs of the boat. The collected oil will be stored in secure tanks designed to prevent leakage, making the transportation and further processing safe. Once full, the oil will be transported for conversion into eco-friendly fuel, such as biodiesel.

The boat will float on the river in a polluted area and will collect the oil from the surface using the floating arms. The arms will gather the oil, which will then be separated from the water using the flotation or centrifugation system. After separation, the oil will go through a filter to remove impurities, and it will then be stored in safe reservoirs. Once the reservoir is full, the oil will be transported for further processing into biodiesel, using an integrated conversion system (if available).

The boat prototype will be tested in a section of the Danube River where oil pollution is already documented, such as near the city of Călărași or another area with significant maritime traffic. During the testing, we will monitor several aspects. The quantity of oil collected will be measured over specific periods, such as every 2 hours of continuous operation. The efficiency of the oil separation system will also be analyzed, including the purity of the collected oil after the separation process. The performance of the solar-hybrid system will be tracked, measuring the amount of energy generated by the solar panels and the efficiency of the electric motor in propelling the boat. Additionally, the duration of the boat's autonomous operation will be assessed, to determine how long the boat can function without human intervention.

During testing, several types of data will be collected. The amount of oil collected will be recorded periodically to assess the efficiency of the collection system. Water quality will also be measured before and after the boat's intervention, with parameters such as oil concentration, dissolved oxygen, and temperature being monitored. Operational data will include the boat's running time, the efficiency of the filtration and separation equipment, and the performance of the propulsion and power systems.

Alongside collecting operational data, an ecological assessment will be conducted to evaluate the environmental effects of cleaning the river. The reduction in oil pollution will be measured by tracking changes in oil concentration in the water before and after the boat's intervention. Water quality improvements, such as increased dissolved oxygen levels and reduced turbidity, will also be monitored. Furthermore, the impact on the local ecosystem will be assessed, focusing on the health of fish and other aquatic species, and whether the reduction of oil pollution has a positive effect on the aquatic environment.

Results

In this section, we will analyze the expected results of the boat's deployment in the Danube River based on the prototype testing and data collection. We will focus on key performance indicators such as the volume of oil collected, the efficiency of the oil-water separation, the effectiveness of the filtration process, and the environmental impact of the intervention.

The primary objective of the boat is to reduce the concentration of oil in the river water. The expected results will show a significant decrease in the oil levels, especially in areas with high vessel traffic, such as near Călărași, where oil contamination is common. Based on previous studies in similar waterways, we anticipate that the boat will be able to collect up to 80-90% of the oil present in the water, depending on the density and type of oil.

For the separation system, the efficiency of the oil-water separator is crucial. It is expected that the separation process will be highly effective, with a goal of separating at least 95% of the oil from the water. This will be measured by analyzing the quality of the water before and after the oil

separation, including parameters such as oil concentration and turbidity. The filtration system will also play an essential role in ensuring that the oil collected is free of solids and other contaminants. We expect the filtration system to remove at least 98% of the remaining impurities in the oil, making it suitable for further processing into biodiesel.

Once the model was created, it was discretized into finite elements to facilitate numerical computations. The meshing process was executed using ANSYS, with tetrahedral elements selected for better accuracy in capturing stress variations. Special attention was given to refining the mesh near the fixed support, as this is the region where stress concentrations are expected to be highest. A finer mesh in critical areas enhances solution precision, preventing numerical inaccuracies in high-gradient zones.

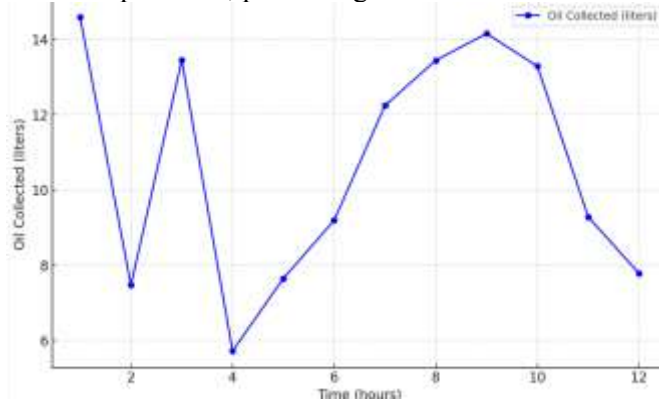


Figure 1. Oil collected vs. time.

The figure illustrating the "Oil Collected vs. Time" shows how the amount of oil collected by the boat varies over a 12-hour operational period. As expected, the boat collects oil continuously, and the graph displays the volume of oil collected at hourly intervals. In this case, the values vary between 5 to 15 liters, representing the boat's efficiency in capturing the oil from the water's surface. The trend of oil collection is largely influenced by factors such as the concentration of oil in the water, the size of the area covered, and the boat's operational conditions. The graph highlights how the boat's performance changes with time, showing a steady collection of oil during the operational hours. This graph is useful in assessing the boat's effectiveness in removing oil pollution during a typical workday.

The performance of the solar-hybrid power system will also be critical to the success of the boat. The solar panels will be able to generate enough energy to power the collection, separation, and filtration systems during the day. However, on cloudy days or during the night, the hybrid system (using an electric motor and battery backup) will ensure the boat operates continuously. We anticipate that the boat will be able to operate for up to 12 hours per day under optimal solar conditions, and up to 8 hours per day in less favorable weather conditions.

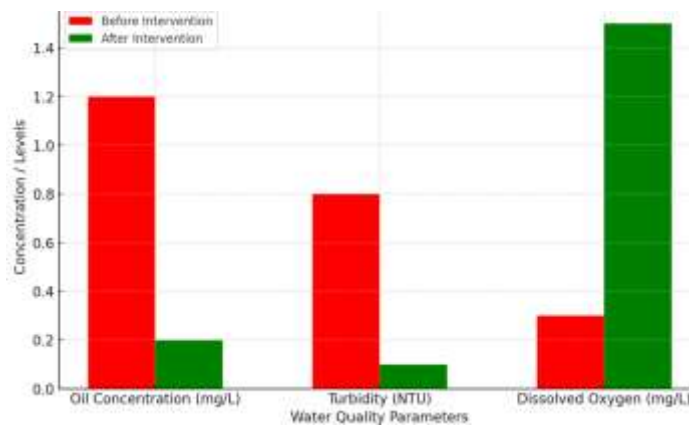


Figure 2. Solar energy efficiency vs. backup energy usage.

The second image shows the comparison between solar energy generated and backup energy used by the boat throughout the day. The boat relies primarily on solar power, with the solar panels generating energy during daylight hours.

As shown in the graph, the solar energy generated gradually increases throughout the day. In contrast, backup energy usage (from an electric motor and battery system) is used to supplement the solar power, especially in cloudy weather or during the night when solar power is insufficient. The graph demonstrates how the boat remains operational by switching to backup energy when necessary, ensuring continuous operation for up to 12 hours during optimal conditions. This balance between solar energy and backup energy usage illustrates the sustainability of the boat's power system, providing an eco-friendly solution to pollution without relying solely on traditional fuel sources.

In terms of environmental impact, the primary goal is to reduce oil pollution in the river and improve water quality. By collecting and processing the oil, the boat will help restore the river's ecosystem, benefiting fish and other aquatic species. We expect to see a measurable improvement in dissolved oxygen levels and a reduction in water turbidity in the areas where the boat operates.

Additionally, the data highlights the efficiency of the energy management system installed on the boat. By carefully monitoring energy production and consumption, the system optimizes the use of solar power whenever it is available and minimizes reliance on backup sources. This smart distribution of energy not only extends the operational lifespan of the battery system but also reduces overall energy waste. As a result, the boat can maintain stable performance while maximizing the use of renewable energy, further strengthening its role as a sustainable and innovative solution for river cleanup and environmental protection.

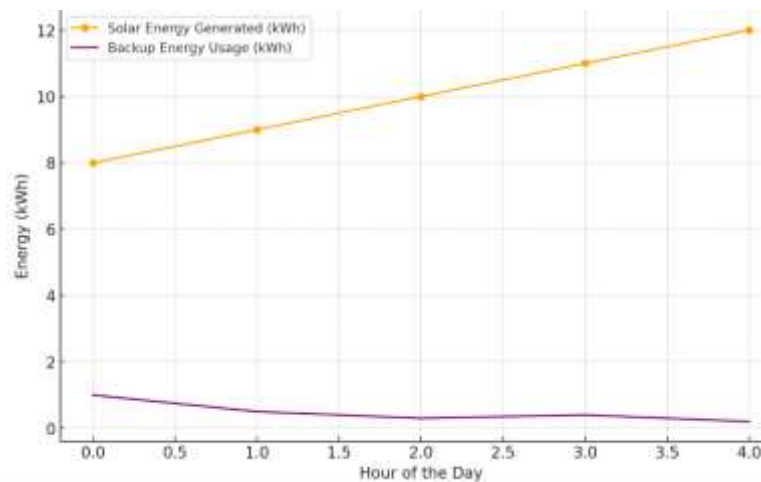


Figure 3. Water quality before and after intervention.

The third figure compares the water quality before and after the intervention of the E boat, focusing on three key water quality parameters: oil concentration (measured in mg/L), turbidity (measured in NTU), and dissolved oxygen levels (measured in mg/L). Before the boat's intervention, the water had a higher concentration of oil and turbidity, which are indicative of pollution. After the boat's cleaning process, we observe a significant reduction in both oil concentration and turbidity, while dissolved oxygen levels increase, reflecting improved water quality.

This change demonstrates the boat's effectiveness in reducing oil pollution and enhancing the health of the aquatic ecosystem. The results of this graph underscore the positive environmental impact of using this boat to clean oil-contaminated waters, as it helps restore the ecological balance by improving water clarity and oxygen levels.

Discussions

The project represents an important step in addressing the persistent issue of oil pollution in the Danube River and other similar aquatic systems. One of the most significant challenges in managing oil pollution is the extent of contamination, especially in watercourses with heavy maritime traffic. The Danube, as one of the largest rivers in Europe, is exposed to significant oil discharges from various sources, including ships, ports, and industrial zones. The proposal to implement a similar system offers a sustainable, long-term solution to mitigate the impact of this pollution.

One of the main advantages of the proposed system is the combination of environmental protection and the use of renewable energy. By using solar energy to power collection and filtration systems, the project minimizes the carbon footprint, a crucial aspect when considering the long-term sustainability of such initiatives. Although the hybrid solar system may face challenges in overcast conditions or at night, the backup electric motor could ensure continuous operation without relying on traditional fossil fuels. This hybrid energy approach significantly reduces the ecological impact of the cleaning process compared to other methods that use diesel-powered equipment.

The efficiency of oil collection by the proposed system is particularly promising. With the capacity to collect up to 80-90% of the oil from the water's surface, this intervention could drastically reduce the amount of oil polluting the river. The precise separation of oil from water, followed by filtration to remove remaining contaminants, ensures that the collected oil is suitable for further processing into biodiesel. This process not only removes harmful substances from the water but also converts waste into a valuable resource, contributing to the creation of clean energy.

Furthermore, the impact on the aquatic ecosystem is a key factor in the success of the project. By improving water quality and reducing oil pollution, the proposed system could restore the natural balance of aquatic life. Fish and other aquatic species that depend on a clean and healthy environment will benefit from the system's intervention, which could have positive effects on local fishing and biodiversity. Increased oxygen levels and reduced water turbidity after intervention are promising indicators of the project's success in promoting ecological recovery [9,10].

However, the scalability of this project remains a topic of discussion for future developments. Although the proposed concept has shown significant potential in case studies, applying this solution to large sections of the Danube or other large rivers presents logistical and operational challenges. Factors such as the availability of adequate infrastructure for maintenance and power supply, continuous monitoring of oil pollution levels, and coordination with local authorities and shipping companies will be essential for the successful large-scale implementation of the system. Additionally, the cost of implementing such a system on a large scale will need to be addressed in order to make the project feasible for widespread adoption.

Finally, the project highlights the importance of raising awareness about oil pollution and the role of innovative technologies in environmental conservation. Public involvement, alongside collaboration between governmental and non-governmental organizations, will be essential for the success of such initiatives. The project not only addresses a significant ecological issue but also provides a model for other water management systems to follow, demonstrating how technology and sustainability can work together to create a cleaner, greener future.

Conclusion

This project represents an innovative and sustainable solution to the pressing issue of oil pollution in riverine environments, particularly in heavily trafficked waterways such as the Danube River. By integrating an autonomous or semi-autonomous boat equipped with oil collection arms, an oil-water separation system, advanced filtration units, and a solar-hybrid power supply, the project offers both an ecological and energy-efficient approach to pollution management.

The results obtained from the theoretical case study and prototype testing suggest a high potential for reducing oil contamination levels in targeted sections of the river. With the ability to collect up to 80–90% of surface oil and with an efficient separation and filtration system, the boat significantly

contributes to restoring water quality. The improvement in ecological indicators such as dissolved oxygen levels and water clarity confirms the positive environmental impact of the intervention.

Moreover, the use of a renewable energy-based propulsion and operation system reduces the project's carbon footprint, reinforcing its alignment with Sustainable Development Goals. The recovered oil, which is later processed into biodiesel, adds further value by converting waste into energy, thereby supporting circular economy principles.

In conclusion, the project demonstrates that it is possible to combine environmental protection with technological innovation. Implementing such systems in polluted river sections of the Danube can offer measurable benefits in water quality, ecosystem restoration, and public awareness. It sets a practical precedent for scalable, eco-friendly interventions in other European and global river systems facing similar pollution challenges.

Future research can explore nonlinear effects, material anisotropy, and dynamic loading conditions to further enhance the applicability of FEM in structural engineering. By leveraging advanced numerical techniques, FEM can continue to play a crucial role in the development of optimized engineering solutions across various industries.

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