



Sustainability comparison of petrol and electric small boats on Lake Balaton: A life cycle and total cost analysis

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Abstract

Because Lake Balaton is shallow and ecologically fragile, the regulation of small-boat traffic on the lake currently rests mainly on propulsion type: recreational use of internal-combustion-powered small boats is effectively prohibited. In contrast, purely electric-powered boats may operate freely. This study examines the environmental and economic differences between petrol and electric-powered small boats over their full life cycle, and considers what these differences imply for further developing the regulatory framework. The analysis draws on data from one specific petrol-powered and one electric small-boat model. The life cycle assessment (LCA) compares CO₂ emissions across the manufacturing, operational, and end-of-life (EoL) phases over 15-year and 20-year horizons, while the total cost of ownership (TCO) analysis compares investment, operating, mooring, and maintenance costs over the same horizons. Results: manufacturing emissions for the electric boat are nearly five times those of the petrol boat, but this disadvantage is offset by lower operating emissions within roughly 5.7 years; over 15 years, the electric boat's total emissions are about half those of the petrol boat. The economic picture runs in the opposite direction: owing to its higher purchase price and the cost of battery replacement, the electric boat's total cost exceeds the petrol boat's over both examined time horizons. Since environmental and economic considerations do not align, sustainable boating cannot be reduced to a single criterion and instead calls for deliberate, multi-criteria evaluation. Regulation would benefit from accounting not only for propulsion type but also for the actual environmental burden a boat generates (speed, power, intensity of use).

Keywords

leisure boating, life cycle assessment, total cost of ownership, Lake Balaton, sustainability

1 Introduction

Sustainability plays an increasingly decisive role in the evolution of transport systems today, particularly in settings where environmental impact directly affects ecosystem health. Waterborne transport, specifically small-boat traffic, takes on particular significance when it occurs in a sensitive environment such as Lake Balaton. Balaton is Hungary's largest standing body of water, at once a national natural asset and a central pillar of domestic tourism, so its use requires a continuous balancing act between economic interests and environmental protection. Because the lake is shallow, with an average depth of just 3.3 meters (OVF, n.d.), and largely enclosed, the environmental pressures created by boat traffic – air pollution (Viana



et al., 2014), fuel and oil contamination (Depree, 2007; Jüttner et al., 1995), noise, wave generation, and sediment resuspension – take hold quickly and intensely (Carreño and Lloret, 2021; Mosisch and Arthington, 2004).

Accordingly, recreational use of internal-combustion-powered small boats on Lake Balaton is, as a general rule, prohibited, with only a narrow set of exceptions – for example, sailboats' auxiliary engines during calm winds, or vessels performing official or public-service duties (Government Decree 30/2003 (III. 18.); NFM Decree 57/2011 (XI. 22.)). Purely electric-powered boats, by contrast, may operate freely, since their use produces no local exhaust emissions, generates less noise, and carries no risk of fuel leakage. This regulatory logic essentially treats propulsion type as the main decision criterion, even though the full environmental impact of electric boats can only be understood by considering the entire life cycle: battery manufacturing, the composition of the electricity used to charge them, and end-of-life treatment.

Choosing a propulsion system is therefore a decision-theoretic problem as well: boat owners and regulators alike must weigh a combination of information – life-cycle emissions, total cost, and the regulatory framework – whose interpretation and integration constitute a cognitive task. This connects directly to the concept of cognitive sustainability, which draws on cognitive science to describe and model sustainability, linking its ecological, economic, and social dimensions within a single holistic framework (Zöldy et al., 2022). The economic dimension of this concept focuses on how individuals or organisations can make conscious, resource-allocation decisions that account for all relevant factors – precisely the problem the present study addresses by jointly applying life cycle assessment and total cost of ownership analysis. Waterborne transport also features within the cognitive mobility (CogMob) framework: the digitalisation of port infrastructure and data-driven support for propulsion-related decisions are increasingly linking human and machine cognitive capacities within mobility systems (Zöldy and Baranyi, 2023). Energy management in boating – whether estimating fuel consumption or designing battery-electric propulsion – offers a concrete example of how sustainability enters the decision matrix (Zalacko et al., 2020), while waste-based and alternative fuels, along with the circular economy, are gaining growing importance in the end-of-life treatment of vessels (Zsoldos et al., 2025).

The present study examines the environmental and economic differences between petrol- and electric-powered small boats and how these differences can be interpreted in the specific environmental and regulatory context of Lake Balaton. The analysis rests on two pillars: a life cycle assessment (LCA), evaluating CO₂ emissions generated over the boats' full life cycle, and a total cost of ownership (TCO) analysis, examining economic considerations over a longer time horizon. Our starting point is that environmental and economic considerations do not necessarily lead to the same conclusions. The aim is to show what trade-offs arise when these considerations are weighed together.

2 Data and methods

2.1 Regulation at Lake Balaton and internationally

Under NFM Decree 57/2011 (XI. 22.) on the rules of waterborne transport, a small boat is defined as any self-propelled, motorised vessel with a hull shorter than 20 meters and a maximum carrying capacity of 12 people. On Lake Balaton, recreational operation of such boats with internal combustion engines is prohibited – apart from the narrow exceptions set out in Government Decree 30/2003 (III. 18.) – while purely electric boats are permitted, subject to strict technical conditions that rule out hybrid or auxiliary-engine solutions. An international perspective nuances this either/or regulatory logic. At Lake Garda in Italy, speed limits (20 knots by day, 5 knots at night) serve as the main instrument. The lake's northern, more ecologically sensitive basin – largely within the province of Trento – has its own zone strictly restricting motorised boating (Boat Garda, n.d.). Water quality at Lake Garda is also studied intensively (Giardino et al., 2007), underscoring the need to combine regulation with monitoring for sensitive large lakes. At Lake Constance (Bodensee), one of Europe's most important sources of drinking water, regulation centres on engine-emissions compliance: boats fitted with engines meeting EU directives are exempt from individual testing, while power limits (59 kW for outboard motors, 150 kW for inboard motors) and near-shore speed restrictions complete the system (Boote-Magazin, 2016). Both examples show that, between outright prohibition and unrestricted access, a range of intermediate solutions based on speed, power, and zoning exists – solutions that could inform refinements to Balaton's regulatory framework. Adopting them unchanged would nonetheless be unwarranted, given that Balaton's shallowness, tourism role, and conservation significance together create a distinctive situation.

2.2 Life-cycle assessment methodology



Using the Life Cycle Assessment (LCA) method, this study compares the CO₂ emissions generated over the full life span of one petrol-powered and one electric small-boat model, split into three phases: manufacturing, operation, and end-of-life (EoL) treatment. In the manufacturing phase, the mass of each system (hull, propulsion, fuel system/battery) was combined with the specific manufacturing energy demand of the relevant materials (MJ/kg), which was then converted into CO₂ equivalents using the average emission intensity of the European Union's electricity mix (253 g CO₂/kWh, i.e. roughly 0.07 kg CO₂/MJ) (Ember, 2022). In the operational phase, the petrol boat's emissions were based on manufacturer-reported fuel-consumption figures (19.5 l/h at a 40 km/h cruising speed; 1.9 l/h at idle) together with an internationally used emission factor of 2 310 g CO₂/liter, while the electric boat's emissions relied on the specific emission intensity of the Hungarian electricity mix, 274.9 g CO₂/kWh (MVM Next, n.d.). In the end-of-life phase, each boat's final CO₂ balance was calculated from the emissions and savings associated with the recycling, incineration, and landfill shares assigned to each material fraction (metal, composite, lithium-ion battery). Calculations were carried out for 15- and 20-year service lives, complemented by a sensitivity analysis assuming an average speed of 50 km/h and a further analysis excluding the hull's life cycle. This methodology is consistent with LCA frameworks previously applied to compare propulsion systems in the maritime sector (Bordbar et al., 2025; Jeong et al., 2018), which likewise emphasise that battery manufacturing represents a substantial burden concentrated in the early stages of the overall life cycle (Ellingsen et al., 2014).

2.3 Total cost of ownership methodology

The total cost of ownership (TCO) analysis aggregates investment (purchase price), operating (fuel or electricity), mooring and storage, and maintenance costs over 15- and 20-year horizons. In the 20-year scenario, a one-off but substantial cost item – battery replacement – was also built into the model for the electric boat. The purpose of this methodology is to reveal how the various cost components jointly shape the economic assessment of the two boat types, and whether the operating-cost advantage can offset the initial gap in investment cost.

3 Results and discussion

3.1 Life cycle assessment

In the manufacturing phase, the electric boat's emissions (34,322 kg CO₂) are nearly five times those of the petrol boat (7,141 kg CO₂), owing mainly to the energy-intensive production of the aluminium hull and the 400 kg lithium-ion battery. In the operational phase, however, the picture reverses: over 15 years, the petrol boat emits 68,384 kg of CO₂, compared with just 12,370 kg for the electric boat, meaning that fossil-fuel consumption alone exceeds the electric boat's total life-cycle emissions (*Table 1*). The electric boat's advantage widens further in the end-of-life phase: thanks to the high recycling rate of aluminium and other metal components, it achieves a saving of 6,338 kg CO₂, compared with just 294 kg CO₂ for the petrol boat's composite hull.

Table 1. Total life cycle CO₂ emissions over 15- and 20-year horizons (kg CO₂)

Phase	Petrol (15 yr)	Electric (15 yr)	Petrol (20 yr)	Electric (20 yr)
Manufacturing	7 141	34 322	7 141	34 322
Operation	68 384	12 370	91 199	30 992
End-of-life (EoL)	-294	-6 338	-294	-6 338
Total	75 232	40 354	98 047	58 976

** please note negative signs mean CO₂ savings of end-life recycling*

Analysis of the cumulative emissions curves shows that the electric boat's initial manufacturing disadvantage is recouped within 5.66 years, after which its cumulative emissions remain below those of the petrol boat. In the sensitivity analysis, more intensive use (an average speed of 50 km/h) shortens the payback period to 5.11 years, since the petrol boat's fuel consumption rises disproportionately faster with speed than the electric boat's energy consumption does. Excluding the hull's life cycle from the system boundary – as the heaviest and most distorting element – shortens the payback period further, to 4.1 years, confirming that the drivetrain and battery alone compensate quickly for the initial excess in manufacturing emissions.



3.2 Economic results

The total cost of ownership analysis points in the opposite direction to the environmental results. The electric boat's purchase price (HUF 79,7 million) is nearly five times that of the petrol boat (HUF 16,2 million), a gap its lower operating cost cannot offset (HUF 10,1 million over 15 years, compared with HUF 16,7 million in fuel costs for the petrol boat). Mooring and storage fees are identical for both boat types and represent a substantial cost item. As a result, over a 15-year horizon, the petrol boat's total cost is HUF 62,6 million, compared with HUF 118,8 million for the electric boat. In the 20-year scenario, the roughly HUF 8 million cost of battery replacement for the electric boat widens the gap further, to HUF 78,1 million versus HUF 139,9 million (*Table 2*).

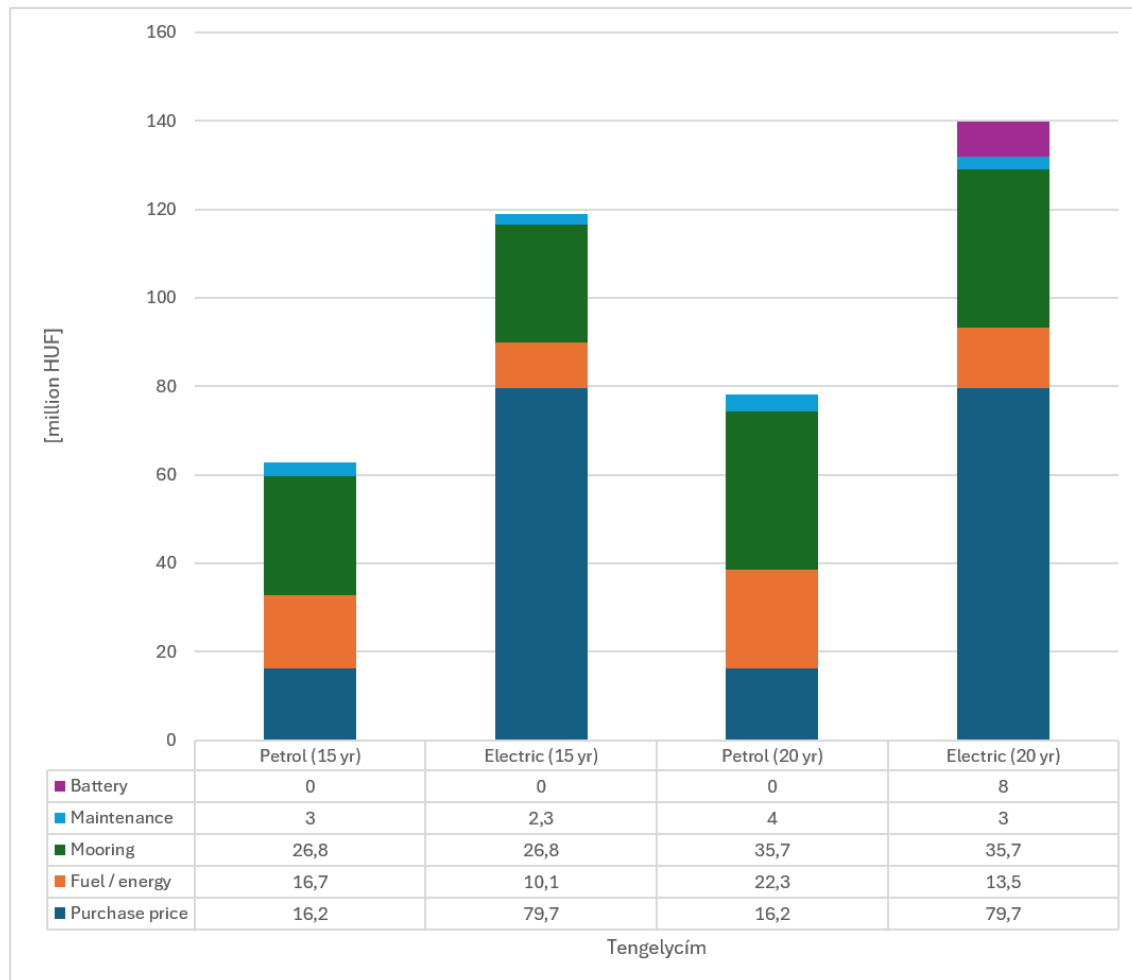


Fig. 2 Total costs over 15- and 20-year horizons (HUF million)

Source: own calculation

3.3 Interpreting environmental and economic considerations together

These results reinforce two, partly conflicting, conclusions. From an environmental standpoint, electric propulsion is clearly the more favourable option for Lake Balaton's sensitive ecosystem: the absence of local emissions, lower noise levels, and a favourable end-of-life balance all point in this direction and are consistent with other LCA studies of boating (Bordbar et al., 2025). Economically, however, the petrol boat remains the cheaper option under current conditions, since the burden of the electric boat's high purchase price and battery replacement outweighs the savings generated by lower operating costs. This discrepancy illustrates well that, in practice, sustainability decisions cannot be reduced to a single indicator. Boat owners and regulators alike need to weigh environmental and economic information together deliberately to



reach a well-founded decision. This kind of multi-criteria, data-driven evaluation lies at the very heart of the concept of cognitive sustainability (Zöldy et al., 2022).

The current Balaton regulation, which treats propulsion type as the main dividing line, is defensible on environmental grounds, yet it does not differentiate boats by their actual environmental burden. While an electric boat produces no local exhaust emissions, the physical burden created by wave action, speed, and power – sediment resuspension, disturbance of shoreline habitats – remains present regardless (Gabel et al., 2017; Kunc et al., 2016), particularly in a lake as shallow and eutrophication-prone as Balaton (Istvánovics et al., 2007; Csősz, 2021). Past fish-kill events at Balaton likewise show that the lake reacts sensitively to human-induced pressures (Takács et al., 2013). In light of this, the future direction of regulation may lie not in relaxing restrictions but in refining them: a differentiated approach based on speed and power, one that accounts for the differing sensitivities of specific areas of the lake, could play a larger role. Building such a system, grounded in actual burden rather than propulsion type alone – in line with the data-driven, digitalisation-oriented approach of cognitive mobility (Zöldy and Baranyi, 2023) – would require more precise data on the spatial and temporal patterns of boat traffic. In designing incentives to ease the economic constraints of switching technologies (e.g. targeted subsidies, fee discounts), it is also worth bearing in mind that not every electric boat delivers the same degree of environmental benefit, and that battery-related costs and emissions (Ellingsen et al., 2014; Zsoldos et al., 2025) are expected to become more favourable in the medium term as the technology continues to mature.

4 Conclusion

This study examined the environmental and economic dimensions of small-boat navigation on Lake Balaton, with particular attention to the roles of petrol and electric propulsion. According to the life cycle assessment, the electric boat's higher manufacturing emissions are offset within 5–6 years by its lower operating emissions and more favourable end-of-life balance, yielding substantial CO₂ savings over the longer term. The total cost of ownership analysis, by contrast, shows that under current conditions the petrol boat can be operated at a lower total cost, since its operating-cost savings cannot offset the burden of a higher investment cost and battery replacement. The tension between these two perspectives points to the fact that sustainable boating is not a simple matter of technology choice but a decision problem that is, in its own right, cognitively complex, requiring the joint weighing of environmental, economic, and regulatory factors.

Limitations of this study include its reliance on data from a single petrol- and a single electric-boat model, as well as the fact that battery costs and the emission intensity of the electricity mix are both parameters that shift over time. Future work should therefore refine the analysis by drawing on a broader fleet of boats, longer time series of price and emissions data, and actual boat-traffic data from Lake Balaton, and should examine the practical feasibility of introducing a differentiated regulatory model based on power and speed.

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