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Save water to generate savings for bus operators: Facts, figures, practice and policy implications

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ABSTRACT

This paper aims to examine the frequently neglected concern of water usage in bus fleet maintenance, especially within the transit sector, which has traditionally prioritized energy and emissions management. The study seeks to assess the prospective savings derived from advanced water management technologies, including rainwater harvesting (RHR) and waxing, as part of the EC-funded LIFEH2OBUS initiative. The study employs a cost-benefit analysis (CBA) to compare business-as-usual (BAU) scenarios with the deployment of these technologies, evaluating their feasibility and efficacy in diminishing water consumption and expenses. Key findings indicate that the use of these technologies may decrease water usage by almost 70 %, resulting in an annual save of nearly 18 million liters for a fleet of 500 buses. Furthermore, the economic assessment reveals that both RHR and waxing technologies offer significant cost-saving potential relative to conventional water management techniques. Waxing, derived from the aviation industry, diminishes the need for frequent washing while providing enduring protection advantages for automobiles. The research indicates that implementing new water management technology can markedly improve the sustainability of bus fleet operations. The results indicate that these technologies ought to be adopted more extensively to realize both ecological and financial advantages. The policy implications highlighted include enhancing societal awareness and safeguarding the environment, revising regulatory frameworks, and promoting a "water culture" among transit operators to facilitate the widespread adoption of sustainable water practices in the transportation sector.

1. Introduction

Water usage in transportation, particularly in managing urban transit fleets, is seldom discussed in scientific literature, resulting in a lack of available statistics. This contrasts with the predominant emphasis on reducing emissions and exploring alternative fuels. It is likely because researchers, decision-makers, and transportation operators typically regard water usage as a lower priority. However, solutions like electrification or cleaner engines for buses might result in higher costs and additional know-how and staff, which can be unaffordable in the case of inappropriate subsidies, especially for small operators [1]. At the same time, saving is imperative for transit operators, who must look elsewhere to pursue this goal. Water can represent a new avenue to explore, and not just because it is an essential element in numerous worldwide sustainability programs, such as the European Circular Economy Action Plan, the Water Directive's Regulation E.U. 2020/741 of the European Parliament, the United Nations' 2018 International Decade for Action, Water for Sustainable Development, and the U.N.'s Sixth Sustainable Development Goal. These initiatives prioritize water conservation, preventing excessive extraction, and utilizing rainfall for many purposes.

Some figures illustrate the crucial significance of water conservation in ensuring the sustainable functioning of bus fleets. The typical water use of an American household is approximately 380 liters per day [2], nearly equivalent to the 300 liters of freshwater needed for each bus wash, occurring three times per week [3]. This is effective for approximately 46,800 liters per bus each year. When taking into account the 684,285 buses comprising the European bus fleet [4], approximately 32 million cubic meters of freshwater are used each year solely for the purpose of washing. In the United States, there are 939,220 registered buses [5], resulting in a relative impact of 44 million cubic meters (corresponding to the typical rural reservoir size in Europe).

In conjunction with all the above, the European Commission funded the LIFEH2OBUS - *Best practices for* H_2O *management and savings for BUS*

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operators research project in late 2022 to promote sustainable water management and conservation among transit companies in bus washing operations and evaluate the economic benefits. The goal is to provide transit operators with concrete facts and figures on water conservation and environmental improvements by assessing advanced washing techniques.

The rationale of this paper moves from the two major LIFEH2OBUS advanced washing techniques: rainwater gathering with reclamation, and waxing (this adapted from the aviation sector), with the research goal to determine the feasibility of these solutions in terms of cost-efficiency and environmental impact, as well as to emphasize the financial benefits that transport operators might get from water conservation. The evaluation and comparison will be conducted between the regular cleaning operations and each other, which is unprecedented in this sector. By showcasing the potential advantages of these techniques, the additional goal is to make significant progress towards the objectives of increasing awareness about water usage, fostering a new water-conscious mindset among transit operators, engaging stakeholders and lawmakers, and ultimately facilitating the establishment of regulations, policies, and practices related to water management in this sector. Accordingly, the paper outlines typical washing operations in bus garages (Section 2) and introduces innovative washing technologies, with a focus on waxing due to its novelty for the bus sector (Section 3); the methodology and the case study to assess the financial benefits of the two LIFEH2OBUS washing techniques are then described (Section 4) and results elaborated (Section 5) and discussed to highlight implications in depot practice and transport policy in terms of societal awareness, environmental safeguard, and regulatory and standardization revisions (Section 6); to conclude, the LIFEH2OBUS work ahead is described and how the achieved results are going to be exploited (Section 7).

2. Water in bus garage operations

The scanty scientific literature on bus washing has been thoroughly analyzed elsewhere [6], highlighting:

- Greater interest in water treatment practices and technologies, including water recycling in urban areas [7] and industrial operations [8], although these are not always directly related to transit operations but to commercial carwash ones, instead [9].
- Research in the fields of chemical processes and environmental implications focusing more on carwash wastewater treatments (e.g. removal of metals [10], oil, grease, and total suspended solids [11], chemical and biochemical oxygen demand concentrations [12]) rather than on water management for transit, which remains underexplored despite being critical for mitigating climate change impacts [13], also in the light of the regulations on green procurement [14].
- Likewise, scientific literature addresses water consumption prevalently in car washing within a broader context, including chemical risks [15], pollution loads [16], and wastewater treatment techniques [17].
- A significant gap in policies on water management in transit operations, often overshadowed by studies on air quality and emissions and noise pollution [18].
- Few pioneering EU-funded projects exploring water optimization but not involving transit
- Few cases strictly on bus operations have been reported in the scientific literature, e.g. in Brazil [19] and Australia [20].
- Abundance of commercial literature on the Internet on washing products and systems for large-size vehicles and consolidated handbooks and manuals on conventional bus washing operations and facilities, e.g. [21].

Given the emphasis on carwashes, it is unsurprising to observe a distinct lack of national and supranational laws and recommendations regarding bus cleaning and washing processes, as seen from a statistical standpoint. Washing activities often adhere to established local garage routines, which align with the criteria outlined in public contract documents released by local government entities. In contrast, most European nations' private vehicle car wash business is subject to strict regulations, particularly regarding wastewater recycling, which is mandatory in some countries [22].

Moreover, due to the installation of automatic washing systems in bus garages prior to the prioritization of water conservation, these often consume excessive amounts of water that is not recirculated. In fact, most buses are washed at car wash depots, which include drive-through lanes equipped with automated brushes that spray water and chemicals [21]. Sludge wells are utilized to contain the oil and metal particles that are recovered from the effluent resulting from these treatments. This highly contaminated wastewater, if discharged into the sewage system without any further processing, can cause harm to the environment, as in the general case of run-off waters [23].

The washing process is also energy-demanding since, according to operators' reports [2], a single regular bus wash consumes 1.986 kWh of energy. Therefore, the total energy required to clean the entire fleet of buses on a European scale is around 212 GWh. The energy costs amount to around 28 million euros [24]. In the process of cleaning buses across Europe, approximately 55 million kilograms of carbon dioxide (CO_2) are generated [25]. These figures are much higher in the United States, reaching 291 gigawatt-hours and 121 million kilograms of carbon dioxide. The emission number is larger because of the larger fleet size and the higher average emission rate per kilowatt-hour in the U.S. [5,26].

2.1. *Introducing new washing technologies as saving resources*

Water is a significant cost factor, particularly in light of the recent energy crisis in Europe and the increasing expenses of water and sewerage services over the past decade [27]. Traditional "car wash depots" must be replaced with modern technologies and methods to achieve environmental sustainability and conserve resources. Although many advanced solutions are accessible (Table 1), their feasibility is contingent upon regional variables such as climate, water mineral composition, available area for installations, and the required investment costs.

Reclamation in RHR involves a multi-step filtering process, introducing filtered water into a recirculation segment equipped with a sand filter for additional filtration and disinfection (Fig. 1). The water is then preserved in a pristine reservoir for reuse in the washing process. Rainwater harvesting is employed to reduce water usage further. This method involves the collection of rainfall via a network of road gullies and pipelines. The collected rainwater is then piped into underground tanks for pre-treatment, enabling reuse. Buoys ensure a steady supply from the underground reservoir by continuously monitoring the water levels in the tanks. This process effectively limits the amount of water that is wasted and the negative environmental impacts [28].

The waxing technique, derived from the aviation sector, functions as a protective layer for vehicles. Applied by qualified personnel, this shield provides a non-abrasive and highly reflecting protection against the environment, particularly during severe weather conditions, such as winter, when the vehicle is subjected to salt, moisture, and other detrimental substances [29], and helps to extend the time between washes, thus significantly improving the water efficiency of vehicle cleaning operations [30]. Wax coating in aviation is applied for several reasons, all intuitive and well documented in the gray literature: to reduce aerodynamic drag (and then improve fuel efficiency); to safeguard aircraft exteriors from corrosion, oxidation, and other forms of damage commonly encountered during flight operations; and eventually to prolong the lifespan of aircraft exteriors, preserving their value and ensuring safe operation throughout their service life. Likewise, waxing can be exploited for transit vehicles and not just for beautification

Table 1
Novel washing methods.

Type of Method	Description
Partial and total water reclamation	Partial reclamation uses recycled water for washing and freshwater for final rinsing, reducing water requirements by 85 % on average; total reclamation may recycle up to 95 % of the water used by processing water as in a closed loop.
Rainwater harvesting	The use of naturally soft water to wash buses requires 25 % fewer chemicals than the same procedure using naturally hard waters, thanks to more efficient spray nozzles that reduce the amount of sprayed water.
Chemical and biological water reclamation	Recycling effluents and detergents helps to limit the amount of chemicals released into wastewater, resulting in significant savings in the number of detergents required for each washing operation.
Reverse Osmosis	During the final rinse, it removes mineral salts from the water, preventing streaks or stains on the vehicles.
Waxing	Waxing, which is widely used in the aviation industry, should keep the exterior of buses as clean as aircraft for longer than a regular wash. Never applied in the bus industry.
Nano or Ceramic Coatings	Coatings provide a durable layer of protection that chemically bonds with the vehicle's factory paint. Ceramic coatings rely on superior hydrophobic properties. Water and other fluids form droplets and easily slide off the surface, resulting in a self-cleaning action that readily eliminates dirt, dust, and grime. This decreases the likelihood of damage caused by caustic substances and mineral deposits. These coatings are especially advantageous in areas with high mineral content in the water, since their hydrophobic properties prevent the formation of water spots.

Fig. 1. The RHR at one of the LIFEH2OBUS test sites.

polishing, as for passenger cars. In fact, polishing and wax coating fulfill different functions in automotive finishing: the former just provides the final smoothness and shine effect on the vehicle's surface; the latter, acting as a shield, safeguards the clear coat over the paint from scratches, so further preserving the vehicle's surface against degradation caused by sunshine and dirt.

2.2. New washing technologies sustainability

Both RHR and waxing are environmentally conscious technologies. As said, within RHR, the filtration and disinfection of wastewater avoid releasing polluted run-off water into the local sewage system [6,23]. Purification is not just from residual dirt collected over the vehicle's surface but also from detergents used in the washing process itself, which contain Volatile Organic Components (VOCs), such as isopropanol and glycol ethers (both in general-purpose cleaners and the latter specifically also in glass cleaners), and butoxyethanol (in degreasers), that pose health risks if not managed properly. The same applies to acetone, which can be found in graffiti removers; although it evaporates quickly, this VOC can affect air quality, especially in closed environments like washing facilities. It must be stressed that if these chemicals enter drinking water systems or recreational water bodies, they can cause serious health issues, including skin irritation, respiratory problems, and long-term chronic conditions.

Contrary to popular assumption, the waxing production process is highly sustainable, too [31], although at a different level. The leaves of the Brazilian palm tree (*Copenicia Prunifera*) produce carnauba wax, which serves as the basis for this type of coating. Harvesting involves the collecting of palm leaves, which are subsequently sun-dried. A natural waxy coating forms on the leaves throughout the procedure. The coating is then eliminated, typically by striking the leaves, after which the wax is purified and processed, all without requiring the removal of trees. During the arid season, the crop flourishes, thereby functioning as an essential resource for local communities by offering work opportunities when rain is scarce and agricultural activities diminish. Carnauba wax is distinguished among natural waxes for its resilience and luster. Its natural origin imparts a unique luminescence that synthetic waxes cannot emulate, and it is considered safe for humans, even for consumption. By incorporating solvents and polymers, manufacturers improve the pliability of the product for application on vehicle surfaces. Then, the carnauba wax endures a solidification process onto the clear coat as these added ingredients evaporate, allowing for buffing to achieve a glossy finish. Nevertheless, although wax technology has the potential for environmental and operational advantages [32], there is a notable lack of study regarding the practicality and financial affordability of implementing waxing technology to decrease water usage in bus operations.

2.3. Advanced water management technologies for transit within the context of the smart city agenda

If the above mentioned water management technologies for bus fleets can innovate local garage routines by optimizing the management of a finite resource like water, they also align well with the concept of "smart city," which uses technology and data to improve urban sustainability and efficiency. More specifically, in a smart city context, water management can be seen as an integral part of the broader push for resource optimization, environmental protection, and sustainable mobility, also enhancing urban resilience to climate variability. Coherently, the smart city is a multifaceted concept, largely explored in the scientific literature on sustainable mobility and transportation, with the common goal to stress underpinning theories, directions, and practical solutions in urban processes that integrate technology, data, and policy frameworks all under the umbrella of the SDGs goals. In this context, key tools are ICTs like algorithms, smart grids, big data, Internet of Things (IoT), blockchain, and artificial intelligence (AI), all integrated into a robust infrastructure to enhance energy efficiency, water and food safety and waste management, thereby providing citizens with a clean, safe, inclusive, and diverse social environment [33]. The smart city context is, therefore, the natural background for the LIFEH2OBUS innovations at both the theoretical and practical levels, as further elaborated.

At the theoretical level, this context seeks to optimize the use of resources, improve urban functions, and foster sustainable development by applying visions, principles, and criteria mostly from urban metabolism [34] and circular urbanism [35], where cities are conceived as organisms that consume resources and produce waste, and circularity in water management implies reusing treated wastewater or collected rainwater rather than discharging it. Accordingly, bus garages can be retrofitted with facilities for RHR and reclamation and meet the requirements from the above-mentioned EU' Water Directive and Circular

Economy Action Plan; they can also help reduce freshwater dependence, thus fully aligning with principles of both resource efficiency and urban sustainability by closing the water loop. This example fits with the interpretation of water management as a "brokerage keyword," linking the concept of sustainability to both SDG policies and the smart city vision: research on water management in smart cities primarily emphasizes the design, development, and management of infrastructures that govern water resource deployment, while that on SDGs is mainly associated with sustainability challenges such as food security, sanitation, equity, poverty, and human rights [36]. Additional backing theories can be found in the Resilience Planning and Adaptive Management approach [37], especially in regions prone to droughts, where bus garages could prioritize rainwater storage and implement adaptive cleaning schedules that vary based on water availability, thus ensuring that bus washing operations can continue sustainably even during water scarcity.

This theoretical support is the actual background of a series of solutions to develop mobility within the smart city context, from the management of shared mobility and micromobility systems to those for the navigation of autonomous vehicles, traffic and parking governance, accident prevention, etc., with a detailed literature report in [38] and specific focuses either on AI [39] and IoT [40]. Case studies also abound, often stressing associated societal advances in terms of quality of life [41], care of vulnerable users [42], and behavioral changes [43].

At the practical level, for bus operators, a natural implementation of the smart city context and its ICT tool is represented by predictive maintenance, as an application of a Data-Driven Decision Making process (DDDM). It is intuitive that by collecting data on water usage, wash frequency, and weather patterns, transit operators can predict if, when, and how to wash vehicles, thus reducing water consumption. But within LIFEH2OBUS, this translates into the development of a specific dashboard function (further elaborated in Section 6.1), embedded in predictive maintenance software to forecast actual cleaning needs of bus fleets based on vehicle use, maintenance programs, weather, and accumulated dirt, with the multiple goals to reduce unnecessary washes, conserve water, save energy, and increase the overall garage operational efficiency. Once again, in this case, the application of the smart city concept goes beyond the introduction and use of digital technologies to improve efficiency, manage resources, and lower emissions [44]. It aims at rethinking the entire transport system also in terms of water management and wastewater disposal, aspects thus far overlooked but that are becoming of staggering importance to building resilience to and management of water crises, which range, depending on location and seasonality, from water scarcity to flooding. Moreover, being self-sufficient in terms of water and/or contributing to water savings allows bus garages not to burden communities when these are exposed to water crises or depend on water consumption for their activities (e.g., the agricultural ones). The synergy of introducing new technologies and sustainable practice for water saving contributes to fostering smart cities' sustainable development, a better quality of life for residents [45], and lessening the negative externalities on the environment [46].

3. Evaluating the water-management technologies via a cost benefit assessment

Based on all of the above, LIFEH2OBUS initially assesses the potential of both the RHR and waxing technologies through a case study to establish the potential effects on water management. This case study examines a typical bus depot in Europe, which includes a fleet of 500 buses powered by diesel fuel. These buses mainly operate suburban services in a metropolitan area, which experiences significant climate-related issues, such as prolonged periods of drought leading to water shortage, as well as heavy rainfall resulting in flooding. Additionally, the snowy winters contribute to alternating cycles of water abundance and scarcity. By attaining water self-sufficiency, reclaiming and collecting rainwater via the RHR technology enhances the ability of the local community to withstand and recover from challenges while also maximizing the efficiency of water utilization in bus washing activities. The current local practice of washing buses three times a week results in the wastage of about 23 million liters of water per year, which is equivalent to the capacity of nine Olympic-sized swimming pools. In turn, waxing is tested for its property to prolong the cleanliness of the bus exteriors. The frequency of waxing a bus varies based on manufacturer recommendations and operator preferences, but for cars, to maintain the protective benefit, the coating is recommended every 3–4 months [32].

3.1. *Cost-Benefit-Analysis*

The RHR and waxing technologies are essential for encouraging water conservation and can be readily adopted by different bus garages to improve sustainability and decrease water use.

Nevertheless, transit operators need concrete proof of both effectiveness and potential benefits to transition from traditional washing methods. In order to evaluate the technology used in the case study, a cost-benefit analysis (CBA) was conducted using the *Transport Innovation Deployment for Europe* - TIDE methodology [47]. CBA is highly recommended for assessing public transport projects funded by the European Union, where it has been extensively and effectively applied [48]. This is due to the tool's ability to express the different scenarios in economic terms, which is incredibly appealing in the case of limited budgets. The evaluation method monetizes the relevant data collected, allowing the selection of the most advantageous economic or sustainable solution [49]. Even data that do not have a market price, such as pollution, have value for individuals, businesses, or society, allowing them to be expressed in monetary terms [47]. That is achieved by employing methods to convert non-monetary effects, for example, establishing the citizens'/costumers' "willingness to pay" for a specific benefit [50,51]. The shortcoming of employing these methods is that they can be complex and time-consuming, which depends on the individual measure [52,53]. Therefore, pre-established standard values convert these data into monetary terms. However, typical values are only sometimes available, especially with the more unique or specific data that are not easily quantified and monetized [47]. This can be associated with the fact that the most considerable weakness in a CBA is that it requires an extensive amount of data to be considered accurate [54]. While TIDE has been employed in several transportation projects, it has yet to be utilized in water-related projects and their associated characteristics, thus adding complexity, especially for the input selection, as further elaborated. Despite the difficulties it may cause, monetization offers a significant advantage by expressing all the values in a currency of choice, permitting a straightforward comparison due to sharing the same unit [47].

Additional CBA's limitations are acknowledged in the scientific literature, among these: the underpinning assumptions of rationality [55], the challenges in predicting variables and preferences [56], the lack of experience in case of innovation [57], and eventually the major reliance on monetary valuation of all impacts, which might cast a shadow on important social or ethical considerations [58]. Thus, transitioning to the more flexible Multi-Criteria Analysis (MCA) provides a more holistic approach to decision-making that accommodates the complexities of real-world problems, ensuring that diverse factors are considered and leading to more equitable outcomes and socially responsible decisions within a multi-actor approach [59]. MCA can be integrated by advanced techniques and assessment tools such as, for example, Data Envelopment Analysis (DEA) [60], Order Performance by Similarity to Ideal Solution (TOPSIS) [61], Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) [62] nd the well-known Analytical Hierarchy Process [55]. The common trait of DEA, TOPSIS, PROMETHEE, and AHP in relation to MCA lies in their ability to evaluate alternatives based on multiple criteria, facilitating informed decision-making, with several applications in the field of transportation studies. All are designed to manage trade-offs between conflicting objectives and be adapted to various contexts and decision-making scenarios. Yet, a lack of consensus in the transportation sector concerning a preferable technique for integrating sustainability concepts has been observed [63].

Therefore, although acknowledging the high potential of the multi-criteria approach in providing very accurate results, the CBA tool has been preferred because of its: i) focus on economic efficiency [64] (as tangible evidence of the washing innovations), ii) structured framework that simplifies decision-making by presenting a single metric (the Net Present Value - NPV), which summarizes the overall impact of the LIFEH2OBUS novelty and easily informs the decision-making process [65], iii) standardized approach that enables the comparison of diverse solutions and alternatives within the same framework (with the comparability of the different washing options being particularly valuable for transit operators who will be willing to adopt them after the LIFEH2OBUS project, but in need to prioritize funding and resources), and iv) overall regulatory acceptance (as stressed above, not only CBA is the recommended tool for assessing EU-funded public transport projects, but also it is often favored in regulatory environments due to its historical use in policy analysis).

Accordingly, the LIFEH2OBUS CBA is developed within a scenario-building process comparing three alternatives:

- Business-As-Usual (BAU)
- RHR
- New Waxing Scenario (NWS)

This scenario is an advanced version of an inception one [6], focusing solely on the RHR compared to the typical BAU situation. Therefore, it did not assess the NWS performance relative to the other scenarios. Needless to say, including NWS not only implied a larger input dataset (Table 2) but also a full revision of the data provided in the inception scenario and the CBA assessment process. As a consequence, the analyses and input data have been updated due to the newness of some computations (in particular, the CO_2 emissions calculations have been updated for current European standards [25] instead of the North American EPA's [66], and the inflation rate has been updated to meet current standards [67]). Likewise, the societal effects have been fine-tuned according to the new field data from the case study garage and the above-mentioned revised parameters. Furthermore, this advanced scenario building gave rise to the policy implications, now first presented in Section 6.

The resulting metrics, particularly those related to water, seem to be low or moderate (for example, energy use directly impacts reducing CO_2, consolidating around 10 %).

Table 2
CBA input data.

Parameters	Values	Unit
Number of Vehicles	500	unit
Installation Costs	260,000	Euro
Added Maintenance Costs RHR	7500	Euro/year
Added Maintenance Costs NWS	200	Euro/year
Added Labor Costs NWS	19,200	Euro/year
Water Amount per Wash	300	liter/wash
Water Costs	0.47	Euro/wash
Water Reduction	92	%
Washes per Week	3	wash/week
Energy Consumption	1.986	kWh/wash
Electricity Costs	0.25	Euro/wash
Energy and CO2 Estimated Reduction	10	%
CO_2 eq Emission constant	0.258	kg CO_2eq / kWh
CO_2 costs (2024)	70	Euro/tCO_2eq
Passenger Awareness	71	%
Passenger Acceptance	67	%
Passenger Attractiveness	69	%
Passenger Travel Comfort	75	%
Staff Comfort	85	%
Staff Acceptance	85	%
Social Discount Rate	5	%
Inflation	2.23	%

Costs and benefits for both technologies are calculated according to the equations described in Table 3, coherently with the TIDE approach; more specifically, the present value (PV) for each scenario is determined in Equations 1 and 2, and the net present value (NPV), according to Equation 3, to analyze the economic efficiency. Standard evaluation criteria that influence operators' decisions regarding new technology installations were the primary focus of this CBA. These can be classified into two categories:

- Internal factors (including previously unaccounted-for expenditures for personnel, water, electricity, and the NWS's installation and maintenance),
- External factors include CO_2 emissions and societal effects.

Assessing the time-varying attributes and assigning a monetary value to external expenses are intricate endeavors. The inflation rate for this case study was determined to be 2.23 %, which is the average figure for a period of ten years [67]. External costs necessitated additional processing, typically for the responsibility for the pollution caused by bus garages, which falls on local communities rather than the garages themselves. To this end, the European Commission employed a pre-determined benchmark to assign a monetary value to CO_2 emissions, which was established at 70 Euros per metric ton of CO_2eq [68].

Likewise, for the societal effects, where prior studies on transportation sustainability have already offered valuable understanding, particularly regarding the response of operators to the introduction of new technologies for bus fleets [69], namely the EU-funded ELIPTIC project [70], which provided recommendations for measuring operational and economic parameters [70,71]. These facts helped to monetize revenues from various social factors, such as the opinions of drivers and passengers regarding the new technologies, according to surveys designed to assess levels of awareness, acceptance, attractiveness, and comfort. The social aspects were approximated to have accounted for around 19 % of the overall expenses and gains of the project, in terms of their relative financial contributions, and for the scenarios in hand, the societal benefits were coherently computed, according to Equation 4, in Table 3, and the input data from Table 2.

The last phase of a CBA involves a sensitivity analysis, with results reported in Section 4.1. In assessments like the CBA, there are multiple ways to introduce uncertainties, as previously mentioned, and the forecasting aspect of the CBA can also lead to uncertainties. For this reason, it is essential to evaluate the attainability and robustness of the findings by conducting a test on the values used to verify the degree of influence on the results attained [47]. The TIDE methodology suggests undertaking a sensitivity analysis, more specifically using a One-at-a-time assessment. This approach must be rerun by adjusting a few impact values (usually by around ±20 %), one at a time, and the result for each change must be recorded. This makes it easy to ascertain the impact of particular influences on the outcome. The assessment's

Table 3
Costs and benefits equations.

Equations	
$C_{PV} = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} (1)$	C_{PV}: present value of costs from year t to year T, $C_{t:}$ costs in year t, r: discount rate, at 5 % according to TIDE [33]
$B_{PV} = \sum_{t=0}^{T} \frac{B_t}{(1+r)^t} (2)$	B_{PV}: present value of benefits from year t to year T, $B_{t:}$ benefits in year t, r: discount rate, at 5 % according to TIDE [33]
$NPV = B_{PV} - C_{PV} (3)$	NPV: Net present value
$B_S = \sum_{t=0}^{T} \left(C_{Rt} - \frac{C_{Rt}}{(1-s)^t} \right) (4)$	$B_{S:}$ total benefits related to society from year t to year T, C_{Rt}: total running costs incurred in year t, S: proportionate monetary contribution, as in [33].

findings should make this ambiguity known if a certain consequence is significant and predicated on a dubious premise [47]. Due to the novelty of the research focus, the application of a sensitivity analysis was deemed appropriate.

4. Results: comparison and feasibility of the BAU, the RHR and the NWS

The CBA was established with a 15-year operational duration. In order to ensure clarity and uniformity, all expenses are denoted by negative numbers, while benefits are expressed as positive values. This approach guarantees a clear and unambiguous understanding of the program's financial effects.

The results, presented in Tables 4–6, reveal that when comparing the BAU, RHR, and NWS scenarios, the BAU option entails significant internal costs of - 576,429 Euros and external costs of −31,114 Euros, leading to an overall NPV of −607,543 Euros.

The RHR encounters internal costs amounting to −553,632 Euros but manages to generate lesser external savings of 47,442 Euros compared to the NWS. Overall, it attains an NPV of −506,189 Euros. The NWS has exceptional financial efficiency, with internal costs amounting to −263,752 Euros and significant external savings of 60,036 Euros, leading to an overall NPV of −203,716 Euros. Furthermore, it is important to acknowledge that both the RHR and the NWS have favorable impacts on society, leading to positive external costs. Nevertheless, the NWS exhibits superior control of external costs by having lower CO_2 expenses compared to both the RHR and the BAU. In addition, the NWS experiences reduced expenses for maintenance, water, and power, leading to higher internal cost efficiency when compared to both the BAU and the RHR.

Fig. 2 presents a comparative analysis of the cumulative cost over the 15-year period for the three distinct scenarios. The y-axis depicts the total accumulated expenditure, and the x-axis indicates the 15-year timespan. The three lines' trajectories depict each scenario's financial consequences as time progresses.

The BAU scenario exhibits a consistent and substantial rise in total costs over 15 years. Commencing with an initial cost in the first year, the expenditures steadily increase, exceeding the threshold of 600,000 Euros by the 15th year. The pronounced increasing trajectory demonstrates that persisting with existing methods without implementing strategic alterations results in the most substantial cost burden over an extended period.

On the other hand, the RHR scenario shows a rather modest rise in total expenses. Although it has an increasing trend comparable to the BAU scenario, the growth rate is comparatively slower. After 15 years, the total cost of implementing this plan amounts to a little over 500,000 Euros. Although the initial installation cost is expensive, by the 10th year, it will exceed the cost of the BAU alternative. This indicates that the RHR has the potential to alleviate certain financial consequences observed in the BAU strategy while the expenses remain substantial.

Table 4
CBA for 500 buses: BAU.

Cost and Benefits	Water (Euros)	Electricity (Euros)	CO_2 (Euros)	Yearly Total (Euros)
Year 1	−33,840	−18,000	−2798	−54,638
Year 2	−32,947	−17,525	−2724	−53,197
Year 3	−31,378	−16,691	−2595	−50,664
Year 4	−29,884	−15,896	−2471	−48,251
Year 5	−28,461	−15,139	−2353	−45,953
Year 6	−27,106	−14,418	−2241	−43,765
Year 7	−25,815	−13,731	−2135	−41,681
Year 8	−24,586	−13,078	−2033	−37,663
Year 9	−23,415	−12,455	−1936	−37,806
Year 10	−22,300	−11,862	−1844	−36,006
Year 11	−21,238	−11,297	−1756	−34,291
Year 12	−20,227	−10,759	−1673	−32,658
Year 13	−19,264	−10,247	−1593	−31,103
Year 14	−18,346	−9759	−1517	−29,622
Year 15	−17,473	−9294	−1445	−28,211
Total	−376,280	−200,149	−31,114	−605,510
NPV	**Internal −576,429 Euros**		**External −31,114 Euros**	**Overall −607,543 Euros**

The NWS scenario is the most economically efficient option out of the three. In this scenario, the cumulative costs increase at the slowest rate, remaining significantly lower than the costs associated with the BAU and the RHR scenarios. After 15 years, the total cost using the NWS technique is a little over 200,000 Euros, demonstrating significant long-term savings. These findings indicate that the adoption of inventive and effective water management can lead to the least long-term financial strain.

4.1. *Sensitivity analysis*

As stated previously in Section 3, the sensitivity analysis is the last phase of a CBA. There are several ways to incorporate uncertainty into evaluations, such as the CBA, as was already discussed, and the CBA's predicting component may also do so. Therefore, following TIDE's assessment approach, the One-at-a-time method was used to conduct the sensitivity analysis. The strategy involves changing ±20 % of each impact variable one at a time. Then, each change's outcome is recorded, as seen in Table 7.

As seen in Table 7, a few impact variables vary the results by relatively significant amounts. The most volatile are the Water Amount per Wash, and Washes per Week, which shows that the most influential aspect is the amount of water. The BAU was the scenario that experienced the most significant variance for the specific indicators that influenced it, as seen as the only scenario that experienced a change of ±20 % or more. The other two scenarios, notably the NWS, showed low change levels. The most influential impact variable for NWS was the added labor costs, which were almost ±10 % of the second and third most impactful variables for it (Society and Social Discount Rate).

Regarding the RHR scenario, only the installation costs breached the ±10 % mark. The influence of the high upfront cost from the installation also explains why the RHR has differing values of change for social discount rate and inflation, as those more directly affect running costs. It is important that despite the large fluctuations that some variables caused during the sensitivity analysis, none of the overall rankings between the scenarios changed even once. This is a critical remark since a fluctuation of ±20 % for a single value should not affect the final decision of the CBA.

Further evaluating the impact variables' effect of some multifactor linkage on the final CBA decision [72] is possible, but doing so would require switching from One-at-a-Time (such as the one TIDE recommends) to nonlinear models [73]. This typically entails typical multifaceted case studies developed within complex sensitivity analyses.

5. Discussing the potential: applicability of results

The BAU scenario yields the most substantial expenses, highlighting this scenario's lack of long-term viability. Conversely, the RHR scenario slightly reduces costs but still involves substantial expenditures. The NWS exhibits exceptional environmental sustainability by substantially decreasing CO_2 emissions and societal effects compared to the RHR. The favorable external savings of NWS highlight its efficacy in reducing wider environmental and societal expenses.

Fig. 2 unambiguously illustrates the financial benefits of using alternative water management measures compared to keeping the current practices. The NWS scenario offers the most efficient and economical approach, highlighting the possibility of significant monetary savings through the use of innovative water technologies. This analysis emphasizes the significance of strategic planning and investment in sustainable water management practices for the purpose of

Table 5
CBA for 500 buses: RHR.

Cost and Benefits	Installation (Euros)	Added Maintenance (Euros)	Water (Euros)	Electricity (Euros)	CO_2 (Euros)	Society (Euros)	Yearly Total (Euros)
Year 1	−260,000	−7500	−2707	−16,200	−2518	6785	−282,141
Year 2		−7302	−2636	−15,773	−2452	6606	−21,556
Year 3		−6954	−2510	−15,022	−2335	6291	−20,530
Year 4		−6623	−2391	−14,306	−2224	5992	−19,552
Year 5		−6308	−2277	−13,625	−2118	5707	−18,621
Year 6		−6007	−2168	−12,976	−2017	5435	−17,735
Year 7		−5721	−2065	−12,358	−1921	5176	−16,890
Year 8		−5449	−1967	−11,770	−1830	4930	−16,086
Year 9		−5189	−1873	−11,209	−1743	4695	−15,320
Year 10		−4942	−1784	−10,676	−1660	4471	−14,590
Year 11		−4707	−1699	−10,167	−1581	4258	−13,895
Year 12		−4483	−1618	−9683	−1505	4056	−13,234
Year 13		−4269	−1541	−9222	−1434	3862	−12,604
Year 14		−4066	−1468	−8783	−1365	3678	−12,003
Year 15		−3872	−1398	−8365	−1300	3503	−11,432
Total	−260,000	−83,395	−30,102	−180,134	−28,003	75,445	−506,189
NPV	**Internal −553,632 (Euros)**				**External 47,442 (Euros)**		**Overall −506,189 (Euros)**

Table 6
CBA for 500 buses: NWS.

Cost and Benefits	Added Maintenance (Euros)	Water (Euros)	Electricity (Euros)	Added Labor Cost (Euros)	CO_2 (Euros)	Society (Euros)	Yearly Total (Euros)
Year 1	−200	−2820	−1500	−19,200	−215	5614	−18,321
Year 2	−195	−2746	−1460	−18,693	−210	5466	−17,837
Year 3	−185	−2615	−1391	−17,803	−200	5206	−16,988
Year 4	−177	−2490	−1325	−16,956	−190	4958	−16,179
Year 5	−168	−2372	−1262	−16,148	−181	4722	−15,409
Year 6	−160	−2259	−1201	−15,379	−172	4497	−14,675
Year 7	−153	−2151	−1144	−14,647	−164	4283	−13,976
Year 8	−145	−2049	−1090	−13,949	−156	4079	−13,311
Year 9	−138	−1951	−1038	−13,285	−149	3885	−12,677
Year 10	−132	−1858	−988	−12,652	−142	3700	−12,073
Year 11	−126	−1770	−941	−12,050	−135	3524	−11,498
Year 12	−120	−1686	−897	−11,476	−129	3356	−10,951
Year 13	−114	−1605	−854	−10,930	−123	3196	−10,429
Year 14	−108	−1529	−813	−10,409	−117	3044	−9933
Year 15	−103	−1456	−774	−9914	−111	2899	−9460
Total	−2224	−31,357	−16,679	−213,492	−2393	62,429	−203,716
NPV	**Internal −263,752 Euros**				**External 60,036 Euros**		**Overall −203,716 Euros**

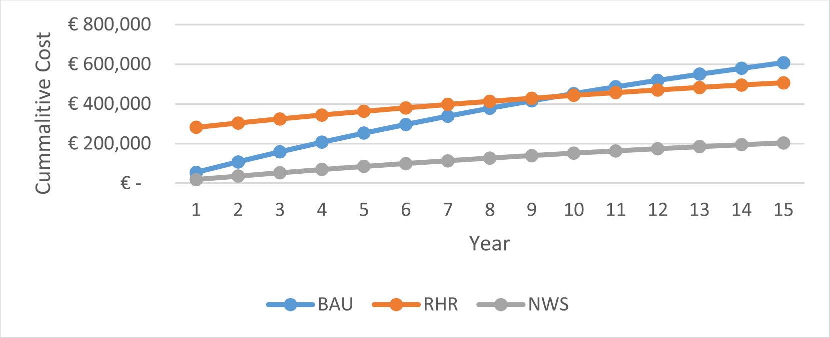

Fig. 2. Overall breakeven analysis.

decreasing long-term expenses and improving economic effectiveness.

After careful evaluation, the NWS stands out as the best method because of its superior financial performance, improved environmental outcomes, and overall sustainability advantages in water management. Future endeavors should use the NWS's strengths to achieve maximum worldwide impact and guarantee the implementation of resilient water management methods. Adopting sustainable methods is crucial for reducing the environmental effects of contemporary vehicle fleets. This analysis assesses the possible decreases in water usage, energy consumption, and emissions output across the three scenarios. The outcome is reported in Table 8.

In areas where water resources are scarce, water consumption is a critical environmental metric, which helps interpret the following consideration. According to the BAU scenario, each vehicle spends a total of 43,200 liters of water each year. This means that the entire fleet consumes a massive amount of 21.6 million liters of water. On the contrary, the RHR and NWS show substantial decreases. The RHR scenario significantly decreases water usage by around 92 %, with each

Table 7
Sensitivity analysis.

Input	Sensitivity	BAU	RHR	NWS	BAU Change	RHR Change	NWS Change
Installation Costs	−20 %	-€ 607,543	-€ 454,189	-€ 203,716	0.00 %	−10.27 %	0.00 %
	20 %	-€ 607,543	-€ 558,189	-€ 203,716	0.00 %	10.27 %	0.00 %
Added Maintenance Costs RHR	−20 %	-€ 607,543	-€ 493,423	-€ 203,716	0.00 %	−2.52 %	0.00 %
	20 %	-€ 607,543	-€ 518,956	-€ 203,716	0.00 %	2.52 %	0.00 %
Added Maintenance Costs NWS	−20 %	-€ 607,543	-€ 506,189	-€ 203,376	0.00 %	0.00 %	−0.17 %
	20 %	-€ 607,543	-€ 506,189	-€ 204,056	0.00 %	0.00 %	0.17 %
Added Labor Costs NWS	−20 %	-€ 607,543	-€ 506,189	-€ 171,033	0.00 %	0.00 %	−16.04 %
	20 %	-€ 607,543	-€ 506,189	-€ 236,399	0.00 %	0.00 %	16.04 %
Water Amount per Wash	−20 %	-€ 489,237	-€ 469,914	-€ 196,200	−19.47 %	−7.17 %	−3.69 %
	20 %	-€ 741,861	-€ 548,470	-€ 212,253	22.11 %	8.35 %	4.19 %
Water Costs	−20 %	-€ 532,287	-€ 501,581	-€ 198,916	−12.39 %	−0.91 %	−2.36 %
	20 %	-€ 682,799	-€ 510,798	-€ 208,516	12.39 %	0.91 %	2.36 %
Water Reduction	−20 %	-€ 607,543	-€ 510,798	-€ 203,716	0.00 %	0.91 %	0.00 %
	20 %	-€ 607,543	-€ 501,581	-€ 203,716	0.00 %	−0.91 %	0.00 %
Washes per Week	−20 %	-€ 486,034	-€ 469,718	-€ 203,716	−20.00 %	−7.21 %	0.00 %
	20 %	-€ 729,052	-€ 542,661	-€ 203,716	20.00 %	7.21 %	0.00 %
Energy Consumption	−20 %	-€ 561,290	-€ 474,326	-€ 200,796	−7.61 %	−6.29 %	−1.43 %
	20 %	-€ 661,802	-€ 543,568	-€ 207,146	8.93 %	7.38 %	1.68 %
Electricity Costs	−20 %	-€ 567,513	-€ 478,613	-€ 201,163	−6.59 %	−5.45 %	−1.25 %
	20 %	-€ 647,573	-€ 533,765	-€ 206,269	6.59 %	5.45 %	1.25 %
Energy and CO_2 Estimated Reduction	−20 %	-€ 607,543	-€ 509,730	-€ 203,716	0.00 %	0.70 %	0.00 %
	20 %	-€ 607,543	-€ 502,649	-€ 203,716	0.00 %	−0.70 %	0.00 %
CO_2 eq Emission constant	−20 %	-€ 601,320	-€ 501,903	-€ 203,350	−1.02 %	−0.85 %	−0.18 %
	20 %	-€ 613,766	-€ 510,476	-€ 204,082	1.02 %	0.85 %	0.18 %
CO_2 costs (2024)	−20 %	-€ 601,320	-€ 501,903	-€ 203,350	−1.02 %	−0.85 %	−0.18 %
	20 %	-€ 613,766	-€ 510,476	-€ 204,082	1.02 %	0.85 %	0.18 %
Society	−20 %	-€ 607,543	-€ 521,278	-€ 216,202	0.00 %	2.98 %	6.13 %
	20 %	-€ 607,543	-€ 491,100	-€ 191,230	0.00 %	−2.98 %	−6.13 %
Social Discount Rate	−20 %	-€ 644,659	-€ 521,229	-€ 216,161	6.11 %	2.97 %	6.11 %
	20 %	-€ 573,825	-€ 492,526	-€ 192,410	−5.55 %	−2.70 %	−5.55 %
Inflation	−20 %	-€ 605,131	-€ 505,212	-€ 202,907	−0.40 %	−0.19 %	−0.40 %
	20 %	-€ 609,955	-€ 507,167	-€ 204,525	0.40 %	0.19 %	0.40 %

Table 8
Estimated environmental impact for the case study fleet (Annual Values).

Key Performance Indicators	BAU (vehicle)	BAU (fleet)	RHR (vehicle)	RHR (fleet)	NWS (vehicle)	NWS (fleet)
Water Consumption (liters)	43,200	21,600,000	3456	1728,000	3600	1800,000
Energy Consumption (kWh)	286	143,021	257	128,719	24	11,918
Emissions Generation (tCO_2eq)	0.1	40	0.1	36	0.01	3

vehicle consuming a total of 3456 liters per year, resulting in a combined consumption of 1.73 million liters for the entire fleet. In the same vein, the NWS scenario attains a decrease of 91.67 %, with each vehicle consuming 3600 liters per year, resulting in a total fleet consumption of 1.8 million liters. These findings emphasize the significant capacity for water conservation provided by both RHR and NWS solutions.

Energy consumption is a significant issue to consider when evaluating environmental impact because it is directly linked to the utilization of fossil fuels and the resulting emissions. Under the BAU scenario, each vehicle has an annual energy consumption of 286 kWh, resulting in a total energy consumption of 143,021 kWh for the entire fleet. The RHR scenario results in a slight decrease of approximately 10 %, with each car consuming 257 kWh and the entire fleet using 128,719 kWh. Conversely, the NWS scenario shows an impressive decrease of 91.61 % in energy usage per vehicle (24 kWh) and a 91.66 % decrease for the entire fleet (11,918 kWh). The significant energy conservation achieved in the NWS scenario highlights its efficacy in decreasing dependence on non-renewable energy sources.

Minimizing emissions is paramount in addressing climate change and enhancing air quality. The BAU scenario leads to annual emissions of 0.1 tCO_2eq per vehicle, resulting in 40 tCO_2eq for the entire fleet. The RHR scenario retains the same level of emissions per car, but it successfully reduces fleet emissions by 10 %, resulting in a decrease to 36 tCO_2eq. The NWS scenario demonstrates the most notable enhancement, with a reduction of 90 % in emissions per vehicle (0.01 tCO_2eq) and 92.5 % for the entire fleet (3 tCO_2eq). The reductions emphasize the potential of the NWS scenario to decrease greenhouse gas emissions significantly. Although the emissions from washing may only make up a small portion of the sector's overall impact, it is essential to recognize that even the use of a very inexpensive RHR system can significantly affect the sustainability of the bus industry. An electric bus costs approximately 650,000 Euros, although even the previous generation EURO-VI versions are priced at barely half of that amount [74].

Upon comparing the BAU, the RHR, and the NWS scenarios, it becomes evident that the NWS scenario provides the greatest environmental advantages in terms of all major performance measures. It effectively reduces water and energy usage and carbon output, making it a highly successful technique for sustainable fleet management. The RHR scenario demonstrates significant enhancements, particularly in terms of water consumption, along with moderate increases in energy efficiency and lower emissions.

5.1. Operational implication at a larger scale

By applying these findings to 50 % of the European bus fleet, which amounts to 342,143 buses, the influence of the technology becomes even more apparent (Table 9). The BAU scenario depicts the present condition in which the fleet consumes 14.78 billion liters of water yearly. In sharp contrast, the RHR scenario drastically decreases water consumption by 92 %, resulting in a reduction to 1.18 billion liters. In a similar manner, the NWS successfully attains a reduction of 91.67 %, resulting in a decrease in water use of 1.23 billion liters. The significant

Table 9

Estimated environmental impact of 50 % of the European fleet (Annual Values).

Key Performance Indicators	BAU	RHR	NWS
Water Consumption (liters)	14,780,577,600	1182,446,208	1231,714,800
Energy Consumption (kWh)	97,867,131	88,080,418	8155,594
Emissions Generation (tCO_2eq)	27,354	24,618	2104

decreases demonstrate the efficiency of the RHR and NWS approaches in preserving water resources on a considerable magnitude.

The BAU scenario estimates an annual energy usage of 97.87 million kilowatt-hours. The RHR scenario provides a conservative 10 % decrease, reducing energy usage to 88.08 million kWh. Nevertheless, the NWS successfully accomplishes a significant decrease, lowering energy consumption to 8.16 million kWh. This substantial decline highlights the capacity of the NWS to diminish dependence on non-renewable energy sources. The BAU scenario leads to the annual output of 27,354 t of tCO2eq emissions. The RHR scenario decreases emissions by 10 %, resulting in a reduction to 24,618 tCO_2eq. The NWS demonstrates the most notable enhancement, reducing emissions by around 92.31 %, leading to a yearly reduction of 2104 tCO_2eq. These reductions emphasize the NWS's capacity to decrease greenhouse gas emissions substantially.

Based on this assessment, the NWS provides the greatest environmental advantages, reducing water consumption, energy consumption, and emissions. However, to optimize sustainability, it is possible to use both the RHR and NWS solutions, as they are not mutually exclusive approaches.

As previously seen, these values tend to fluctuate based on various input criteria contingent on the region. Therefore, conducting more customized research would yield more precise estimations. However, the expected impact is substantial. The United States differs from Europe in some aspects, but the potential influence of water management could be even more significant, as stated in [5]. Given the frequency of severe weather events in areas like the U.S. [75] and more recently in Europe that impact water and air quality, it is likely that the growing adoption of reclamation technology in the country is a valid response to this trend.

5.2. *Waxing vs water harvesting: practical issues*

Although results reported in Section 4 stress the superiority of both technologies over the BAU situation, several practical differences exist between the RHR and NWS as water management solutions. The RHR represents an active water management strategy, directly influencing water supply and quality by collecting rainwater, treating wastewater, and reducing reliance on municipal water sources. In contrast, the NWS is a passive technique with no direct impact on the water itself; it may reduce overall water consumption, but it still relies heavily on municipal water supplies as its only water source with no way to renew it. Additionally, while RHR provides wastewater treatment, preventing environmental harm, the NWS may contribute to pollution if associated with hazardous chemicals in the coating preparation when released into wastewater.

Climate plays a critical role in the efficacy of RHR. In arid regions with low rainfall, the potential for water savings is limited, making the recycling aspect crucial. Conversely, harvesting alone can meet water demands in areas with abundant rainfall, alleviating pressure on local water resources. Furthermore, RHR offers added benefits such as assisting drainage and mitigating flooding. While climatic conditions also affect NWS [76], these impacts are less noticeable. For instance, cold and moisture can increase the risk of paint damage, making winter waxing essential to preserve the bus's exterior. High temperatures can cause uneven wax application, emphasizing the importance of detailed application to ensure protection. Unlike RHR, NWS is more consistent across different climates, as it does not rely on rainwater availability.

When transferring these technologies to different regions, RHR performance remains relatively stable under similar climatic conditions. However, NWS performance can vary based on the type of wax used [77]. Natural waxes like carnauba offer a high-quality sheen but provide less protection than synthetic alternatives such as silicon, ceramic, or graphene-based coatings. Though more durable, synthetic waxes have more significant environmental and health impacts due to the petrochemical processes involved in their production. These waxes are less biodegradable and can pose risks such as skin irritation or respiratory issues if safety precautions are not followed [78].

Another advantage waxing has over RHR is its ability to form a protective layer that extends the duration between washes and preserves the bus's paint and structural integrity. This protection reduces the need for frequent and costly repairs, ultimately extending the lifespan of the buses. However, a significant practical difference is that waxing requires additional time, unlike the seamless integration of RHR. Depending on the type of wax and application method, the waxing process can range from a quick spray-on application to a labor-intensive task requiring up to four hours for two staff members to wax a 12-meter bus completely [3]. This extended time can be a logistical challenge for depots with limited resources or tight schedules.

6. Policy implications

By showcasing the potential advantages of these techniques, significant progress can be made towards the objective of appropriate water usage. This will foster a new water-conscious mindset in the transportation sector, engage stakeholders and decision-makers, and ultimately facilitate the establishment of regulations, policies, and practices related to water management in the bus sector.

However, a comprehensive set of policies must be adopted to effectively tackle the environmental, societal, and regulatory challenges associated with water usage in this field. These measures should promote sustainability and engage society in a shared responsibility for conserving water. Additionally, robust regulations are required to safeguard the environment and public health, ensuring that transit systems operate efficiently without exacerbating water scarcity or introducing harmful pollutants into the ecosystem.

6.1. *Garage efficiency*

As anticipated in Section 2.3. LIFEH2OBUS aims to incorporate water management into a predictive maintenance system (PDM) software, already operational and initially designed to launch PDM-based operations at bus garages within EC-funded projects [79], and further developed to compute bus fleet emissions, also in case of obsolescing vehicles still operational [1]. This PDM new dashboard's innovative function (partially described in [80] at its initial stage and now under test at the LIFEH2OBUS case studies) is designed to assist garage managers in choosing the best water management solution by shifting from a preventive cleaning activity to a predictive one able to leverage a reduction in water consumption. The dashboard function can be supplied by two primary kinds of information derived from everyday operations/services (data from the software's Fleet Management System function) and maintenance activities (the software's Intelligent Garage System function). Information is incorporated into the software calendar planner, enabling maintenance managers to verify deadlines for any washing activities, whether scheduled or unplanned, and create the right cleaning strategy. This cutting-edge adaptive scheduling of fleet washing, tailored to actual cleaning requirements, not only optimizes operations and resources but also paves the way for potential benefit at the "garage-policy" level. Deriving from a DDDM approach by *using data and analyses instead of garage practice to "inform" wash decisions*, bus managers can observe consumption and saving trends, thus committing to a particular garage maintenance strategy, "reshaping" budgets or reinvesting accordingly [80]. Needless to say, this also facilitates the establishment of attainable targets, the efficient allocation of resources, and the alignment of this garage strategy with the bus operators' overarching goals.

6.2. Societal awareness

One of the key policy areas is certainly societal awareness. To create meaningful change, transit companies need to increase public visibility around water usage in their operations, and a fundamental step is requiring the *public disclosure of water consumption data.* This problem is well-known in the global industrial sector [81], with the transportation sector characterized by meager disclosure rates [82] and where companies' internal self-regulation influences water disclosure strategies and corporate proactive measures are implemented just to anticipate governmental regulations [82]. By making such data available, particularly regarding the water used in bus washing operations, the public can gain insight into the scale of water use in transit systems. This transparency is informative and can foster community engagement in water conservation efforts, prompting citizens to push for more sustainable transit practices. Consequently, when communities are aware of how much water is being consumed, they are more likely to support initiatives aimed at reducing water usage, which can lead to a potential increase in the attractiveness of the service. Public transport companies that exhibit environmental awareness will likely improve their reputation. This favorable perception may draw more passengers, resulting in heightened ridership and profitability. Customer studies corroborate this, indicating that consumers are 59 % more inclined to purchase goods and services from companies that prioritize innovation and sustainability [83]. Complementing this, *educational campaigns* must be launched to raise awareness about the importance of water conservation in public transit. These campaigns should involve local schools, community organizations, and digital platforms like social media to reach a wide audience. A critical element of these campaigns would be showcasing successful water-saving initiatives from other cities or regions, inspiring local communities to advocate for similar practices (as planned within LIFEH2OBUS activities). By demonstrating that water conservation is both achievable and beneficial, these campaigns can help to shift public attitudes towards more sustainable water use in transit, emulating successful results achieved in other sectors where water scarcity has been long addressed, typically agriculture [84] or public health and equity [85].

In addition to raising awareness, policies can be designed to *incentivize public participation* in water conservation efforts. Successful stories of water management in the field of citizen science abound [86,87], and crowdsourcing [88] paves the way for potential approaches, e.g. creating programs that reward citizens for reporting water wastage in transit systems or for participating in clean-up initiatives or for just increasing knowledge acquisition for water resource applications by adding facts coming from the travel experience. This fosters a sense of shared responsibility, where the community actively contributes to the sustainability of its transit supply.

6.3. Environmental safeguard

From an environmental safeguard perspective, *mandatory implementation of water recycling systems in bus depots and cleaning facilities* is crucial. This will align with the already mentioned enforced regulations on mandatory wastewater recycling systems at car wash businesses in several European countries [22] and could drastically reduce the overall water footprint of transit agencies, mitigating the strain on local water supplies. This practice would be even more critical in regions facing water scarcity, ensuring that water used in transit operations can be reused efficiently rather than discarded. Transit agencies should develop *emergency water management plans* to ensure the resilience of transit systems in these regions prone to drought. General Draught Management Plans (DMP) have been enforced in Europe [89] according to specific guidelines, ensuring that essential public health services are maintained during critical periods of water scarcity [90]. Central to the DMP measures is prioritizing human consumption and hygiene over industrial uses. These would include bus washing, with waxing ensuring that cleaning standards would be met.

Another crucial environmental safeguard is the *implementation of runoff control measures.* To prevent wastewater containing contaminants from entering stormwater systems and, eventually, local water bodies during washing operations, policies should mandate the installation of filtration systems or retention basins that treat wastewater before it is discharged. Thus, transit operations should fully align with broader environmental regulations aimed at preventing water pollution.

Imposing *water consumption caps* on transit agencies could further incentivize conservation. These caps would limit the amount of water that can be used based on the size of the bus fleet and the availability of local water resources. Agencies that exceed these caps would face penalties, while those that stay within the limits could be rewarded with financial incentives or other benefits.

6.4. Regulations and standards

The above-mentioned water consumption caps introduce a third area of focus, i.e., the *introduction of specific regulations and standards* in transit operations. The standards gap must be filled to reflect environmental priorities, technological advancements in water conservation, and to eventually switch from local practice to standardized management. Specifically, new standards should be established to set maximum allowable water use per bus wash, ensuring that transit agencies utilize the most efficient methods available. These standards should be aligned with the latest innovations in water recycling and cleaning technologies (which LIFEH2OBUS is pioneering), creating a framework for continuous improvement. Introducing regulations and standards on water usage is also consistent with the observation that EU countries are enacting directives related to environmental changes and taxonomy for non-financial reporting. Companies are mandated to provide high-quality data pertaining to Environmental, Social and Governance (ESG criteria), with specific environmental indicators to assess the impacts of energy consumption, water usage, waste, and CO_2 emissions [81]. Aligning with ESG requirements could imply the *integration of water conservation into transit certification processes.* Transit agencies that meet or exceed water efficiency standards could be awarded certifications or labels recognizing their commitment to sustainability, and such recognition could be used as a marketing tool, demonstrating the company's sustainability commitment to reducing its environmental impact. In the long run, all the above might enable the *adoption of national water efficiency benchmarks* to ensure consistency in water usage across operators. Eventually, a system of *penalties and incentives* should be implemented to enforce these regulations. Non-compliance with water efficiency standards could result in fines or restrictions on operations. At the same time, transit agencies that exceed conservation or environmental targets could receive grants or subsidies to help them further enhance their sustainability efforts. Thanks to this combination of regulations, penalties, and rewards, transit agencies can be held accountable to the same level of environmental responsibility and, above all, prioritize water conservation as part of their overall operational strategy.

6.5. Further potential: gamification

The previously mentioned LIFEH2OBUS predictive maintenance dashboard is anticipated to improve the washing operations. To further enhance the effectiveness of the software, it could be gamified, which would help improve the human factor part of the process. Gamification is the process of integrating game-like elements such as rewards, points, and leaderboards. Employees are encouraged to engage more actively with the system, promoting regular monitoring and *timely* interventions. This can improve adherence to maintenance schedules, reducing the risk of equipment breakdowns and inefficiencies [91]. Gamification can also enhance employee motivation, making routine tasks like system checks or reporting more engaging and improving overall system performance and longevity. Additionally, it can foster a collaborative and competitive environment where teams are motivated to optimize bus washing operations, reduce water consumption, and minimize downtime, ultimately contributing to cost savings and operational efficiency as part of the rewarding process described previously.

7. Conclusion

The CBA of the two analyzed LIFEH2OBUS technologies demonstrates that water management can be effectively implemented, indicating significant financial benefits if compared to the status quo. Thus, using pricier but effective technology such as RHR might be a reliable cost-saving strategy for bus operators. Likewise, waxing significantly reduces the need for freshwater and shows its high potential in water's sustainable management at bus garages.

Facts and figures provided (Tables 5 to 7) stress all of the above, and more specifically for what concerns the water savings, the adoption of RHR and NWS technologies can reduce water consumption by up to 92 %, saving just less than 20 million liters annually for a fleet of 500 buses compared to BAU operation. This implies a similar reduction in emissions and energy consumption, with NWS offering up to a 92.5 % reduction in CO_2 emissions, with total fleet emissions reduced to 3 tCO_2 annually, compared to 40 tCO_2 in BAU. Similarly, the energy savings are substantial, with NWS cutting energy usage by over 91 %, bringing the fleet consumption down to about 11,918 kWh. Scaling the RHR and NWS solutions to 50 % of Europe's bus fleet would save around 12 billion liters of water. The economic impact is also clear: for a 15-year evaluation period, the NWS scenario shows the lowest total cost, reaching approximately 200,000 Euros, compared to 607,543 Euros in the BAU scenario, whereas the RHR scenario also reduces costs to 506,189 Euros, all highlighting significant long-term savings and cost efficiency of sustainable water management technologies. While the CBA has confirmed the feasibility of both systems in water conservation, the future work of the LIFEH2OBUS project will involve implementing these solutions more extensively at bus garages to conduct a more comprehensive examination. In order to facilitate a comprehensive evaluation of performance, both inside and across various technologies, a simple reclamation system, which requires less infrastructure, will be implemented alongside RHR and waxing. During this testing phase, the CBA will undergo ongoing updates and enhancements, consolidating the results with additional data and mitigating the CBA's shortcomings. To this end, typical limitations of CBAs associated with the problem of applying monetary values to all considered impacts need to be acknowledged. This specifically applies whenever it is not easy to assign monetary values to given impacts (typically the societal ones, associated with the perception of a novelty) which end up being neglected by decision makers [92]. To mitigate this risk and to have all the impacts equally considered, it is advisable to add purely qualitative impact assessments or non-monetary metrics within the CBA and use tools like severity ratings (introducing severity scales for non-monetized environmental or societal impacts [93,94], like water scarcity or pollution risks), threshold indicators (e.g., water savings beyond a minimum threshold) to signal significant environmental impacts [95], and even visual maps [96] (like impact maps, which can help convey the potential societal or environmental consequences of each scenario without requiring a direct monetary figure). Within LIFEH2OBUS, this will become central when developing the planned benchmark analysis among the three case studies performance, in light of the transferability of the LIFEH2OBUS practice at the European scale, when feasibility thresholds will be specifically developed.

This study's final objective is to increase knowledge about water preservation and establish a systematic approach for accurately determining the water requirements of each type of bus fleet. In the long run, this can give rise to new policies involving innovative environmental, societal, and regulatory requirements generated by more sustainable water usage at bus garages. More specifically, despite the ongoing nature of the LIFEH2OBUS research, specific policy recommendations can already be formulated based on the project's current findings. *Raising awareness of water management* is certainly a key policy area [36]. LIFEH2OBUS and the CBA emphasized that while the advantages of more environmentally friendly energy sources are recognized in theory, they are challenging to implement since operators typically give priority to the financial aspect of maintenance management [69,97]. This necessitates, on the one hand, that operators evaluate the environmental impact when choosing to enhance maintenance operations [98], and on the other hand, that they become more cognizant of the consequences of externalities for all stakeholders [99].

An additional policy direction is to *integrate public transportation into local water management*: The choice to use water management technologies for vehicle washing should be part of the overall water management policy of the urban area that the transit system is expected to service [100]. This should also include a variety of complimentary water preservation techniques for washing vehicles. The goal should be to coordinate local policies pertaining to the environment, transportation, and water conservation [101].

None of the above can be done without *regular funding.* Funding is needed to raise awareness and put environmentally appropriate water policies into place at the local, nationwide, and international levels. If just one-time financing is available for public transportation, water conservation won't be seen as a top priority in service management, and no ongoing investments will be planned to enhance operations from an environmental perspective [102,103]. In addition, funding needs to be consistent and sufficient for the scope of the operations [97,103]. One-time funding leads to minor benefits, which are considerably smaller for larger public transportation firms that do not prioritize cleaning operations. Conversely, for smaller businesses, the same cash can be significant and spur investment in new activities and vehicles that may eventually become unmanageable or unsustainable [97].

Last but not least, to create practice it is important to *enforce uniform regulations to incentivize water management practices for transport operators*: as stated, there are no local, nationwide, or international regulations pertaining to water that would allow public transportation corporations to regulate water management. A mandatory evaluation of the local water management system's quality could assist public transportation agencies in developing more sustainable plans for their present and future water management practices, as it happens in other urban management fields [104].

As for any pioneering study, there can be many caveats. Consolidated data from the LIFEH2OBUS tests will certainly improve the quality of these findings; at the same time, this study, by proving the effectiveness of both the RHR and waxing options, can assist garage managers in making decisions that are most beneficial from an environmental point of view. However, the acceptance of these technologies could not be fully valued by bus managers, who are reluctant to invest in absolute novelties [58]. Initiating a novel "Water Culture" inside the transportation sector will fill this gap, reverse the current conservative vision, and start a new sustainability-focused approach by prioritizing water management, such as air quality or noise pollution, when deciding on new vehicle purchases, investments in technology, or both.

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CRediT authorship contribution statement

Maria Vittoria Corazza: Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Matthew Robinson:** Writing – review & editing, Writing – original draft, Resources, Formal analysis, Data curation. **Alvin Benjamin Owusu-Afriyie:** Resources, Formal analysis, Data curation.

Declaration of competing interest

None.

Data availability

The data that has been used is confidential.

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