© 2020 The Authors
781

Water Practice & Technology Vol 15 No 3
doi: 10.2166/wpt.2020.063

Environmental and health impacts of electric service vessels in the recreational boating industry

Colin Hemez[a,b,*], Joy Chiu[b], Emma C. Ryan[c], Jia Sun[d], Robert Dubrow[e,f] and Michael Pascucilla[e,g]

[a] Systems Biology Institute, Yale University, West Haven, CT 06516, USA

[b] Department of Molecular, Cellular, and Developmental Biology, Yale University, New Haven, CT 06520, USA

[c] Department of Public Health and Community Medicine, Tufts University, Boston, MA 02111, USA

[d] College for Public Health and Social Justice, Saint Louis University, Saint Louis, MO 63104, USA

[e] Department of Environmental Health Sciences, Yale School of Public Health, New Haven, CT 06520, USA

[f] Yale Center on Climate Change and Health, Yale School of Public Health, New Haven, CT 06520, USA

[g] East Shore District Health Department, State of Connecticut, Branford, CT 06405, USA

*Corresponding author. E-mail: colin.hemez@yale.edu

Abstract

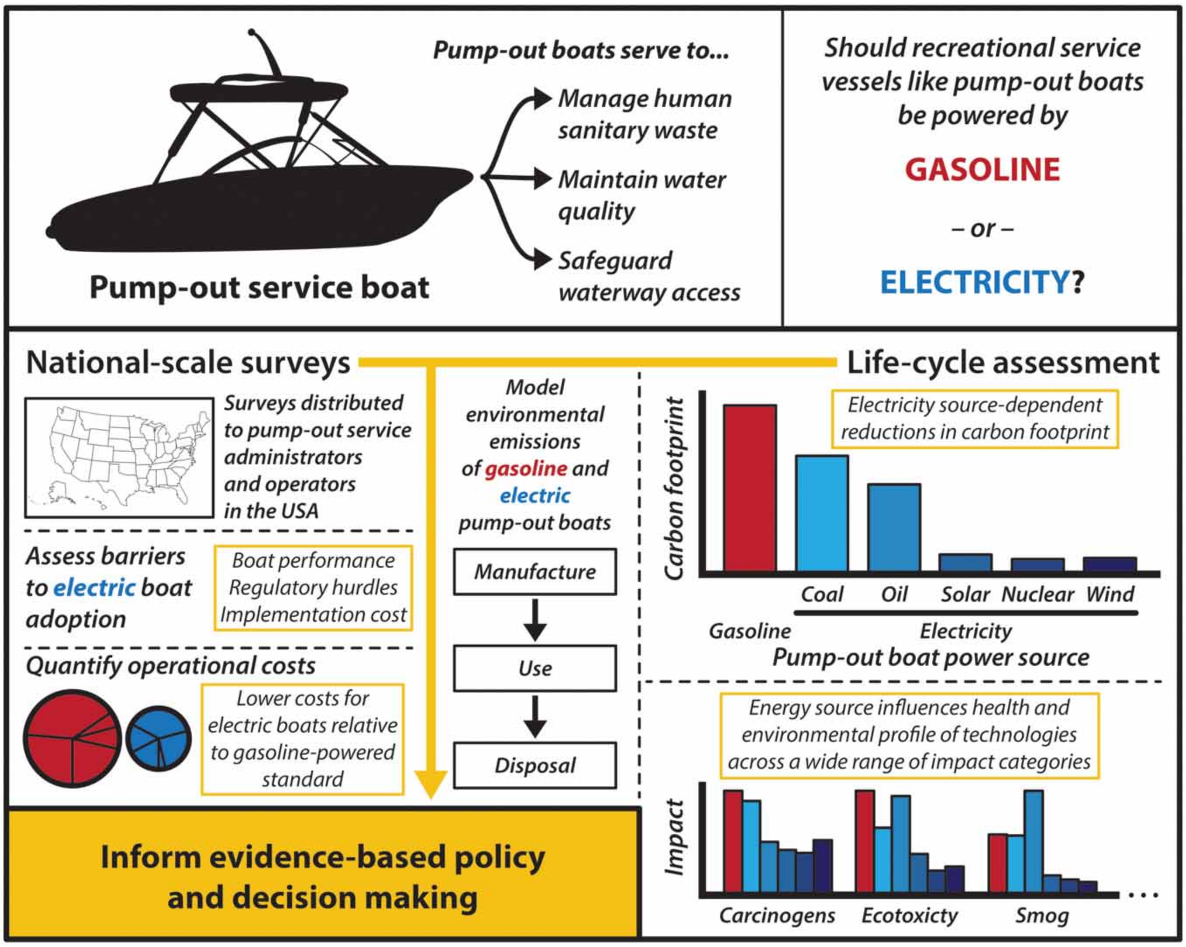
Recreational boating is increasing in popularity worldwide, prompting challenges concerning pollution management, aquatic ecosystem preservation, and waterway access. Electric boating technology may provide a sustainable alternative to gasoline-powered boats, helping to address these challenges. In this study, the environmental and health impacts associated with using electric service vessels in the recreational boating industry were assessed. The focus was on pump-out boats, which enable the sanitary management of human waste generated onboard recreational vessels, as a tractable model of the whole recreational boating service sector. To query stakeholder attitudes about changing to electric technology, surveys were distributed to a nationwide network of pump-out boat service providers. A wide range of attitudes exists among this group towards the adoption of electric technology, and financial concerns dominate the anticipated barriers to electric technology adoption. A life-cycle assessment of electric and gasoline-powered pump-out boats revealed that electric boats have lower lifetime greenhouse gas emissions than do gasoline-powered equivalents, especially when electric boats are charged using renewable resources. Our study demonstrates that already-existing electric technology is a sustainable alternative to gasoline combustion in the boating service sector, and identifies the key challenges remaining for the widespread adoption of electric service boats.

Key words: carbon emissions, climate change, electric boats, environmental policy, life cycle assessment (LCA), water quality

Highlights

- Electric pump-out boats have smaller carbon footprints than gasoline-powered equivalents.
- Electricity source strongly influences the carbon footprint of electric pump-out boats.
- Financial and performance concerns hinder the adoption of electric pump-out boats.
- Policymakers should consider lowering financial and regulatory barriers to entry for electric service boat technology.

Graphical Abstract



INTRODUCTION

The recreational boating industry in the United States has grown continuously since 2011, and participation in boating activities is also increasing among Americans (NMMA 2019). While exerting a positive effect on coastal economies (Stoll *et al.* 1988), the rise in popularity of recreational boating in the United States and worldwide presents numerous challenges in managing air and water pollution, preserving aquatic habitats, and safeguarding access to waterways. Underlying all of these is the need to control the release of untreated human sewage produced on recreational vessels. The uncontrolled release of human sanitary waste has numerous detrimental effects on aquatic ecosystems, including nutrient loading and eutrophication (Vargas-González *et al.* 2014; Lapointe *et al.* 2015), the formation of toxic algal blooms (Lapointe *et al.* 2015; van Beusekom 2018), and the dispersal of human hormones (often in the form of prescription drugs) that disrupt fish development and reproductive physiology (Hallgren *et al.* 2014; Adeel *et al.* 2017). Untreated sewage release can also have negative effects on human health by exposing swimmers and beachgoers to pathogens (Soller *et al.* 2014; Gregory *et al.* 2019) and inhibiting access to coastal resources (Betancourt *et al.* 2014).

Because of the damage that unregulated sewage discharge can cause to natural environments and human health, recreational and commercial vessels operating near United States coastlines are required by law to 'pump out' untreated sewage from their holding tanks into land-based sewage treatment infrastructure (33 USC 1322; 40 CFR 25). To do this, recreational boats may dock at shoreline-based stationary facilities. Alternatively, pump-out boats, which navigate within and between marinas to collect waste from other vessels, offer a versatile solution for managing the sewage generated from recreational boating activities. In the United States, federal funding for state- and locally-administered pump-out programs, allocated through the Clean Vessel Act (CVA) and managed by the United States Fish and Wildlife Service (USFWS), provides support for the operation and maintenance of pump-out boats (16 USC 777c).

Most pump-out boats are the size of a small- or medium-length recreational vessel, and virtually all are powered by gasoline engines. These engines contribute to air, water, and noise pollution around marinas; to greenhouse gas emissions and ozone depletion in the atmosphere; and to the detrimental burden of recreational boating on aquatic ecosystems (Lloret *et al.* 2008; Hansen *et al.* 2019). Electrically-powered pump-out and other service boats could provide a more sustainable alternative to gasoline-powered vessels. However, the environmental and health effects of operating electrically-powered recreational service vessels have never been quantified. Furthermore, because many service providers in the United States recreational boating sector are federally funded and publicly owned (including CVA-funded pump-out boat operators), the influence of policy and regulation on the adoption of low-impact boating technology needs to be explored.

In this study, the environmental, health, social, and policy impacts of converting to electric pump-out service vessels were assessed. Life-cycle assessments of electrically-powered and gasoline-powered pump-out boats were analyzed, and national surveys of pump-out boat operators and state-level CVA-funded pump-out boat program coordinators were conducted. The network of CVA coordinators served to gauge attitudes towards electric technology adoption for the recreational boating service sector as a whole. Boats that provide public services other than recreational pump-outs – such as those that monitor water quality, collect and control waterway pollution, and patrol high-use waterways – may experience similar barriers and benefits to adoption as do the pump-out vessels studied in this work. The multifaceted approach presented here enabled the identification of numerous challenges and opportunities that exist for widespread adoption of electric technology in the recreational boating service sector.

METHODS

Survey development and distribution

Two surveys were developed to assess the social and policy impacts of electric technology adoption for recreational service vessels. One was formulated for state-level coordinators of the CVA (50 CFR 85). The second was developed for operators of individual pump-out boat programs, and was designed to quantify the operating and management costs of pump-out boats. Both surveys included questions aimed at assessing attitudes and perceived barriers towards electric pump-out boats.

The state coordinator survey was distributed via email once weekly for three weeks to a list of CVA state coordinators maintained by the States' Organization for Boating Access (SOBA). Distribution of the CVA state coordinator survey began on February 21st, 2018, and respondents were only permitted to complete it once. In order to recruit respondents for the survey of individual program operators, respondents to the state coordinator survey were asked to provide contact information for program operators in their state. Individual survey requests were then sent to those program operators for whom contact information had been obtained. The first emails to individual program operators were sent out on February 28th, 2018. One follow-up request was sent to operators who did not respond to the initial recruitment email.

Life-cycle assessment

A life-cycle assessment (LCA) was conducted using the methodology outlined in protocol 14044 of the International Organization for Standardization (ISO) (Rebitzer *et al.* 2004; Curran 2013). It was hypothesized that the boat's propulsion method (i.e. internal combustion engine or electric motor using electricity generated from various power grid sources) and the heaviest boat components would dominate the environmental and health profile of recreational service vessels. The LCA's scope was therefore limited to investigating the influences of propulsion method and boat hull origin on the environmental and health impacts of a pump-out boat over its lifetime. Models of pump-out boats were constructed to isolate the effects of these variables (Table 1). The reference configuration for the LCA is an industry-standard pump-out boat with a recycled aluminum hull and a gasoline-powered engine. The modeled electric vessel derives 10% of its electric energy from onboard solar panels and obtains the remainder (90%) from power grid infrastructure. It was assumed that all boat configurations modeled are functionally equivalent; that is, all pump-out boats have the same lifespan and operating constraints, and perform the same number of pump-outs over the courses of their lifetimes.

Table 1 | Pump-out boat configurations modeled in the LCA

Configuration number	Energy source	Electricity source	Hull type
1	Gasoline	n/a	Primary aluminum
2[a]	Gasoline	n/a	Secondary (recycled) aluminum
3	Gasoline	n/a	Repurposed
4	Electric	Coal (90%), onboard solar panels (10%)	Secondary (recycled) aluminum
5	Electric	Oil (90%), onboard solar panels (10%)	Secondary (recycled) aluminum
6	Electric	Solar (90%), onboard solar panels (10%)	Secondary (recycled) aluminum
7	Electric	Nuclear (90%), onboard solar panels (10%)	Secondary (recycled) aluminum
8	Electric	Wind (90%), onboard solar panels (10%)	Secondary (recycled) aluminum

[a] Denotes the reference configuration.

In partnership with the Connecticut East Shore District Health Department (Branford, CT) and local stakeholders, Pilots Point Marina (Westbrook, CT) designed and constructed the first full-size (7.5 m length overall), fully electric pump-out boat in September 2018, to the Health Department's specifications. The specifications provided by the Marina (personal communication) enabled compilation of a system bill of materials (SBOM) for this vessel, which served as the prototype electric pump-out boat for this study. Using the manufacturers' estimated component lifetimes for the electric boat's propulsion system (onboard solar panels, batteries, and electric motors) enabled inclusion of replacement components in the SBOM for the electric boat. Specifically, it was estimated that half of the boat's 2 m^2 solar panels, two of its six batteries, and one of its two electric motors would need to be replaced during its ten-year service lifetime.

The electric boat's motor and battery sub-assemblies were modeled by scaling analogous electric automobile components to the final weights of those used in the boat constructed by the Marina (Burnham *et al.* 2006). A conventional gasoline-powered pump-out boat was modeled in the same manner, replacing electric-power-related sub-assemblies with components for an outboard internal combustion motor. The lifetime energy needs of the electric boat were modeled using operational parameters specified by the Marina, while the lifetime fuel needs of the gasoline-powered boat were estimated from the results of the pump-out boat operators' survey (see Survey development and distribution in the Methods section).

The Sustainable Minds software (http://www.sustainableminds.com/, Cambridge, MA) was used to evaluate the associated environmental discharges from all materials and processes identified in the SBOMs. Sustainable Minds collates data on the environmental discharges associated with the manufacture, use, and disposal of product configurations modeled by the user, and is compliant with ISO protocol 14044 (ISO14044 2016). The software then uses the United States Environmental Protection Agency's (USEPA) Tool for Reduction and Assessment of Chemicals and other Environmental Impacts, version 2.1 (TRACI 2.1) to normalize environmental discharges to a set of predefined impact categories (Gloria *et al.* 2007; USEPA 2015b). These environmental and health impacts were interpreted in the context of priorities voiced by pump-out service providers through the national surveys.

RESULTS

The CVA state coordinators' survey responses enabled the assessment of attitudes and concerns regarding the adoption of electric pump-out boats. It also enabled the recruitment of individual pump-out program operators for a second survey aimed at quantifying the operational and financial characteristics of pump-out boating across the United States. Many findings from the operator survey (including average days of use per annum of pump-out boats, average annual gasoline usage, and average engine replacement frequency) were incorporated into the LCA of gasoline-powered and electric boats.

There is a wide range of attitudes towards adopting electric vessels among pump-out boat service providers

During survey distribution (February to March 2018), 65 CVA state coordinators were registered with SOBA. Thirty-two completed surveys were collected from them, yielding a 49% response rate. Twenty-seven states were represented; two responses were received from Illinois, Kansas, Massachusetts, New Jersey, and North Carolina, respectively. Numerical responses from the two respondents in the same state were averaged, and non-numerical responses were counted as separate responses.

Of the 27 states that responded, 16 operated both pump-out boats and stationary pump-out stations (Table 2). The sizes of pump-out boat programs varied considerably, with the number of pump-out boats operated by each state ranging from 1 to 66 (mean: 15) (Figure 1). The number of CVA-funded pump-out programs in each state – including both pump-out boat programs and stationary services – ranged from 1 to 96 (mean: 11). CVA state coordinators leverage many different strategies to encourage recreational boaters to pump out their sewage rather than discharge it into waterways. When advertising their programs and distributing promotional materials, they often focus on the environmental and recreational benefits of vessel pump-outs by emphasizing the potentials for water quality improvements (52% of respondents), for swimming and beach-going (52%), and for recreational shellfishing (44%). Less emphasis is placed on commercial and economic benefits associated with vessel pump-outs (15%), although the presence of human waste in waterways can cause substantial economic losses in coastal regions by disrupting tourism and commercial fishing operations (Rabinovici *et al.* 2004; Soller *et al.* 2014).

CVA state coordinators most frequently identified lower carbon emissions (41% of respondents) and reduced air and water pollution (41%) as the primary benefits of converting pump-out boat fleets to electric power (Figure 2(a)). Financial and operating performance concerns dominated the anticipated barriers to adopting electric boat technology (Figure 2(b)). 41% of respondents cited the high implementation cost as a major barrier and 30% cited budget uncertainty, suggesting that year-to-year public funding fluctuations may make such service providers averse to adopting high-cost electric technologies. 30% of state coordinators indicated that using an electric vessel in open water (i.e. between service points at marinas along coastal regions) could

Table 2 | Responses from the CVA state coordinator and pump-out vessel operator surveys

Field	Value (range)
CVA State Coordinator Survey	
Number of respondents (n)	32 (n/a)
Response rate (%)	49 (n/a)
States represented (n)	27 (n/a)
States with pump-out boat programs (n)	16 (n/a)
Percentage of responding states with pump-out boat programs (%)	59 (n/a)
Mean number of pump-out boats per state (n)	15 (1–66)
Mean number of CVA-funded pump-out programs per state (n)	11 (1–96)
States represented in the survey: Arkansas, California, Colorado, Connecticut, Georgia, Idaho, Illinois (duplicate responses), Indiana, Kansas (duplicate responses), Maine, Maryland, Massachusetts (duplicate responses), Michigan, Missouri, Montana, North Dakota, Nebraska, Nevada, New Hampshire, New Jersey (duplicate responses), New York, North Carolina (duplicate responses), Oregon, Pennsylvania, South Carolina, Utah, Vermont	
Pump-Out Boat Operator Survey	
Number of respondents (n)	14 (n/a)
Average number of months per year a pump-out vessel is in service (n)	7.6 (5–12)
Average number of days per week a pump-out vessel is in service (n)	5.3 (1–7)
Average number of hours per day a pump-out vessel is in service (n)	6.6 (2–11)
Average number of days per year a pump-out vessel is not in service due to engine problems (n)	9.4 (0–120)
Average number of days per year a pump-out vessel is not in service due to problems other than engine failure (n)	2.6 (0–5)
Average number of times, in the past ten years, that a pump-out vessel has needed an engine replacement (n)	1.1 (0–5)
Average cost per engine replacement (USD)	14,718 (5,000–50,000)
Average number, in the past ten years, of pump-out vessel replacements per program (n)	0.77 (0–4)
Average amount of money spent to replace a pump-out vessel (USD)	59,593 (10,000–98,500)
Average annual maintenance cost per pump-out boat (USD)	5,368 (800–16,000)
Of which is devoted to gasoline engine maintenance (USD)	4,001 (500–15,000)
Average annual cost for the winterization of a gasoline engine per pump-out vessel (USD)	704 (300–1,800)
Average annual gasoline usage per pump-out vessel (liters)	1,360 (190–2650)
States represented in the survey: Connecticut (7 responses), Maine (2), Massachusetts (1), North Carolina (2), South Carolina (1), Rhode Island (1)	

present an operational performance barrier, and 30% also cited concern over the boats' charge capacities. Public regulations also generated substantial concerns. 11% of respondents noted that regulatory hurdles could hinder the adoption of electric technology, and two additional state coordinators commented that they could not stipulate the propulsion method of their state-funded boats.

Attitudes towards adopting electric boat technology varied widely among CVA state coordinators (Figure 2(c)). Sixteen respondents answered an optional question asking them to gauge their state's receptiveness towards converting to electric pump-out vessels. Among these, 44% believed that their state would be neutral towards the adoption of this technology. The CVA state coordinator survey results suggest that pump-out boat program managers are aware of the environmental benefits associated with electric technology, but have wide-ranging concerns about the financial and operational performance aspects arising from adoption.

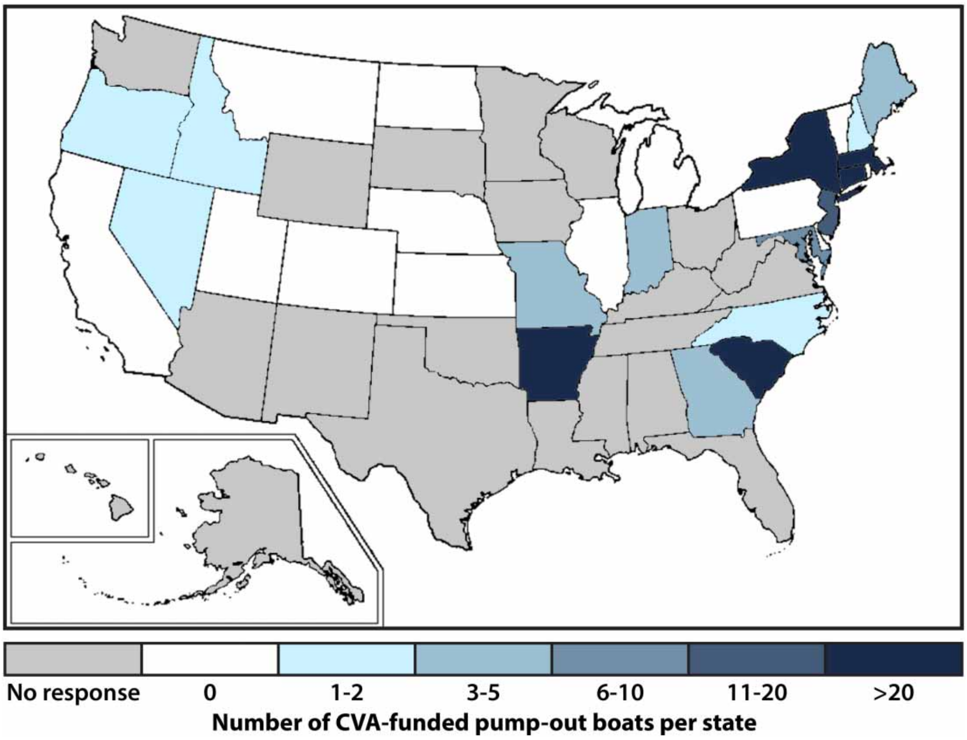


Figure 1 | The nationwide distribution of CVA-funded pump-out boat programs per state.

Electric vessels have lower anticipated operating costs than gasoline-powered vessels

A major concern among pump-out boat service providers is the cost of converting to electric technology. CVA state coordinators most frequently cited the cost of implementation as a barrier to adoption (Figure 2(b)). To assess the basis for this, the operating and maintenance costs of gasoline-powered and electric pump-out boats were compared using data from the national surveys. Currently, operators spend an average of US $5,370 annually per gasoline-powered pump-out boat (Figure 3). US $4,000 of this is devoted to maintenance items associated with using a gasoline engine. The remaining US $1,370 is spent on maintenance items that would also be incurred for an electric boat (including maintenance of the pump-out unit, the application of antifouling paint, and hull repairs). By contrast, the annual operating and maintenance costs of an electric boat with onboard solar panels for supplemental charge was estimated to be US $3,220 per boat per year, or 40% less than the gasoline-powered average. The majority of cost savings comes from the use of electricity (US $400 annually) instead of gasoline (US $1080 annually) as an energy source, as well as from the lower maintenance costs for an electric system (US $1,450 for an electric motor versus US $2,220 for a gasoline-powered engine).

Energy source dictates the lifetime greenhouse gas footprint of an electric pump-out boat

To test the hypothesis that propulsion method influences the lifetime health and environmental impacts of pump-out boats, LCA models of gasoline-powered and electric boats were constructed. The gasoline-powered boat uses an internal combustion engine, and responses from the pump-out boat operator survey indicated that a typical boat consumes an average of 1,360 liters of fuel annually. The electric boat is powered using electricity generated from coal, oil, solar, nuclear, or wind energy, and its annual energy requirements were estimated to be 2,100 kWh. The greenhouse gas emissions

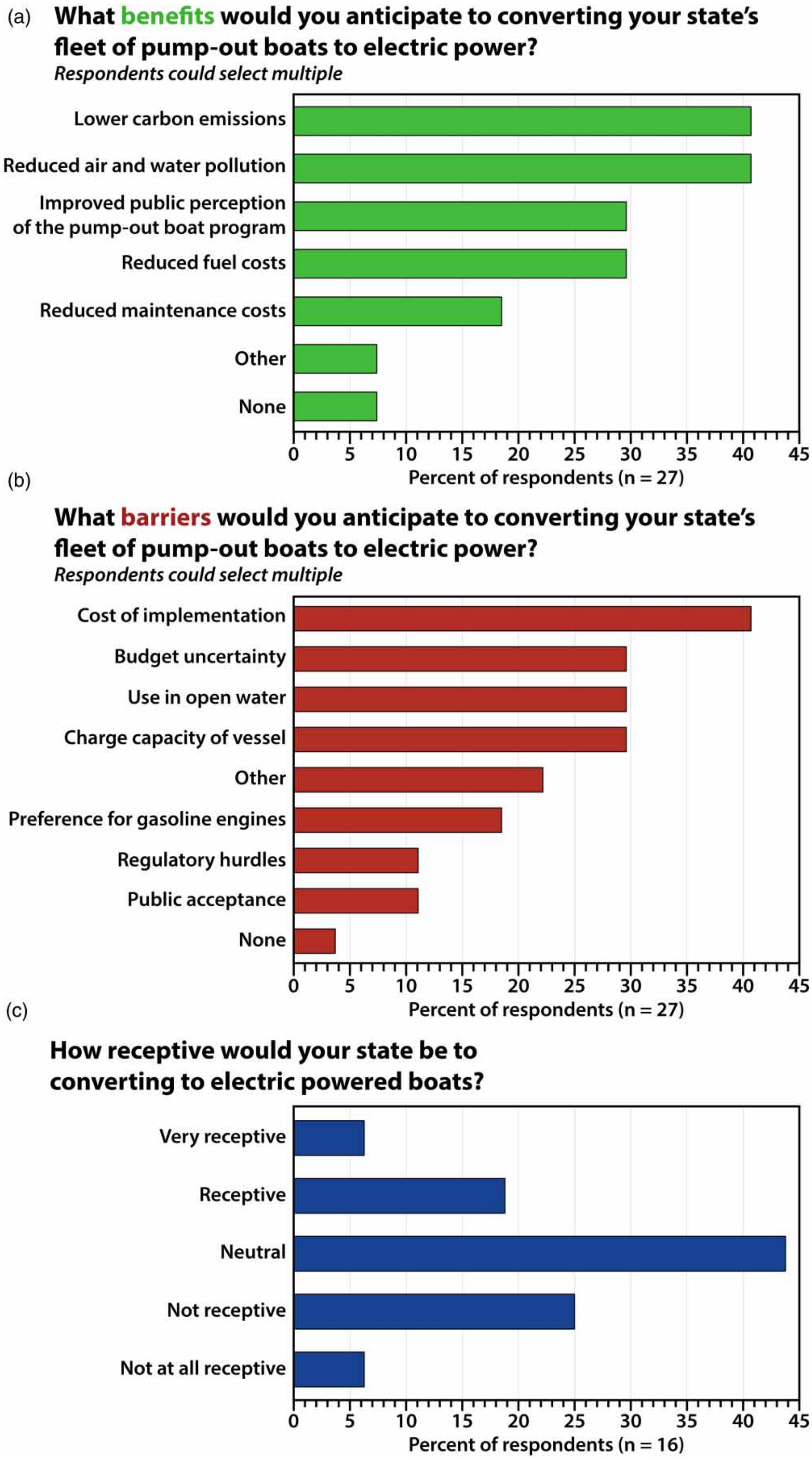


Figure 2 | Benefits, barriers, and potential receptiveness identified by CVA State Coordinators towards the adoption of electric service vessels.

per pump-out were assessed for each boat configuration, assuming that pump-out performance was identical for all models.

The LCA indicated that the gasoline-powered reference configuration generates 7.7 kilogram equivalents of CO_2 (kg CO_2-eq) per pump-out, amounting to 37,800 kg CO_2-eq over its ten-year service

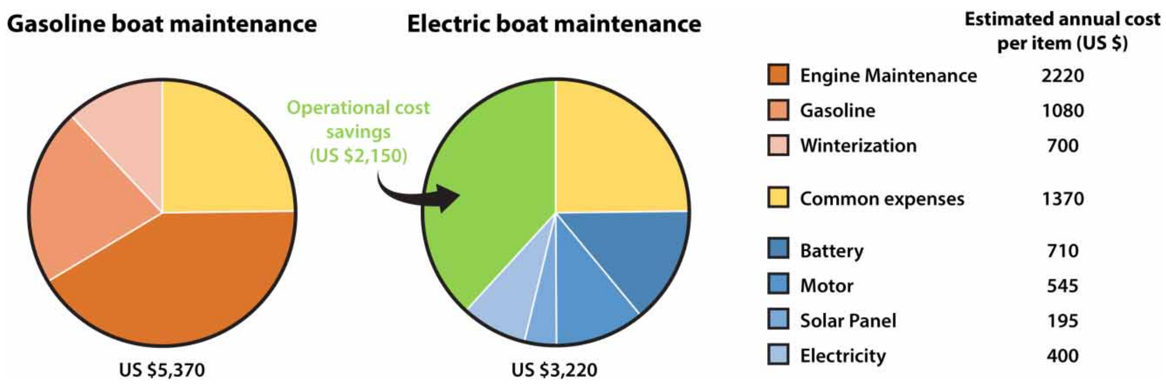


Figure 3 | Comparison of the yearly operation and maintenance costs for gasoline-powered and electric pump-out boats. Each pie represents a US $5,370 annual operation budget, all of which is spent for a gasoline-powered pump-out boat (left). Expenses common to both types of boat (totaling US $1,370 per year) are represented in yellow. The estimated operational cost savings for the electric pump-out boat (right), totaling US $2,150 per year, are denoted in green.

lifetime (Figure 4). Use-stage carbon emissions for the gasoline-powered boat account for 95% of all carbon emissions over its entire life cycle. Electric pump-out boats powered with non-renewable energy sources – coal and oil – have lower carbon footprints than does the gasoline-powered equivalent at 5.4 and 4.1 kg CO_2-eq per pump-out, respectively. Using renewable electricity, however, leads to dramatic reductions in the boat's use-stage carbon footprint. Electricity derived from infrastructural solar energy reduces carbon emissions to 0.90 kg CO_2-eq per pump-out, and nuclear- or wind-derived electricity leads to carbon emissions of 0.70 or 0.69 kg CO_2-eq per pump-out, respectively. For the wind-powered electric pump-out boat, use-stage carbon emissions account for 54% of lifetime carbon emissions.

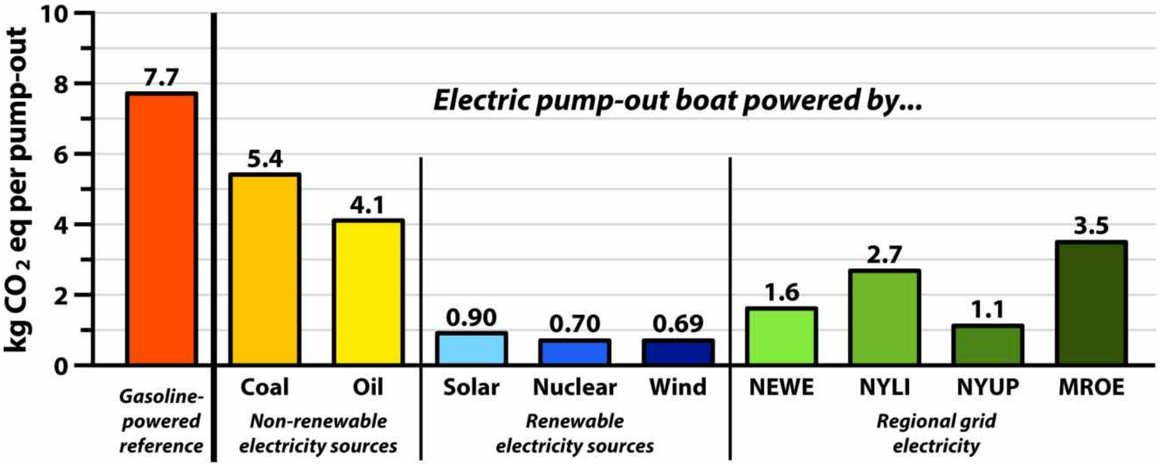


Figure 4 | Greenhouse gas emissions per pump-out for gasoline-powered and electric pump-out boats. One pump-out represents one functional unit for the pump-out vessel. All boat configurations shown in this figure are modeled with recycled (secondary) aluminum hulls. It is assumed that 10% of the electricity used to power electric boats is generated from onboard solar panels (NEWE: eGRID New England subregion; NYLI: eGRID New York Long Island subregion; NYUP: eGRID upstate New York subregion; MROE: eGRID eastern Wisconsin subregion).

These results highlight the profound impact that energy source has on the lifetime greenhouse gas footprints of pump-out boats. To study these effects in real-world settings, the actual per-pump-out carbon emissions of an electric vessel operating in the United States and drawing electricity from regional mixed resource grids were estimated. Using the 2016 version of the USEPA's Emissions & Generation Resource Integrated Database (eGRID) tool, it was estimated that a present-day electric pump-out boat in the northeast (NEWE) region would emit 1.6 kg CO_2-eq per pump-out (USEPA

2015a). 50% of the electricity produced in the NEWE region derives from natural gas (USEPA 2016), whose combustion emits some 50–70% less greenhouse gas per unit of electricity produced than coal combustion (Weisser 2007; Sovacool 2008). Another 3% of the region's electricity derives from non-renewable fossil fuels such as oil and coal, and the remaining 47% is generated from near carbon-neutral sources including nuclear energy, hydroelectric power, and biomass (USEPA 2016). A boat identical to that modeled in the LCA would emit 2.7 kg CO_2-eq per pump-out using electricity generated on New York's Long Island (NYLI) grid, only 30 km from the NEWE-based grid. Within the electricity grid with the lowest carbon footprint in the United States – that of upstate New York (NYUP) — the boat would emit as little as 1.1 kg CO_2-eq per pump-out. Within the country's worst performing electrical grid – the Wisconsin region along Lake Michigan (MROE) — the same vessel would emit 3.5 kg CO_2-eq per pump-out.

Environmental and health impacts of pump-out boats vary by energy source

The USEPA's TRACI 2.1 framework was used to compare boat configurations over eight environmental and health impact categories (Figure 5(a)) (Gloria *et al.* 2007; USEPA 2015b). TRACI-calculated impact scores were normalized to the total impact score for the reference configuration. Constructing a gasoline-powered pump-out boat by repurposing an existing hull led to modest impact reductions, while manufacturing a new hull from primary aluminum raised the boat's adverse environmental and health impact by 40%. This is primarily due to the release of carcinogenic compounds attributable to aluminum mining and refining (Wesdock & Arnold 2014). Regardless of electricity source, all electric pump-out boat configurations modeled had lower total impacts than a

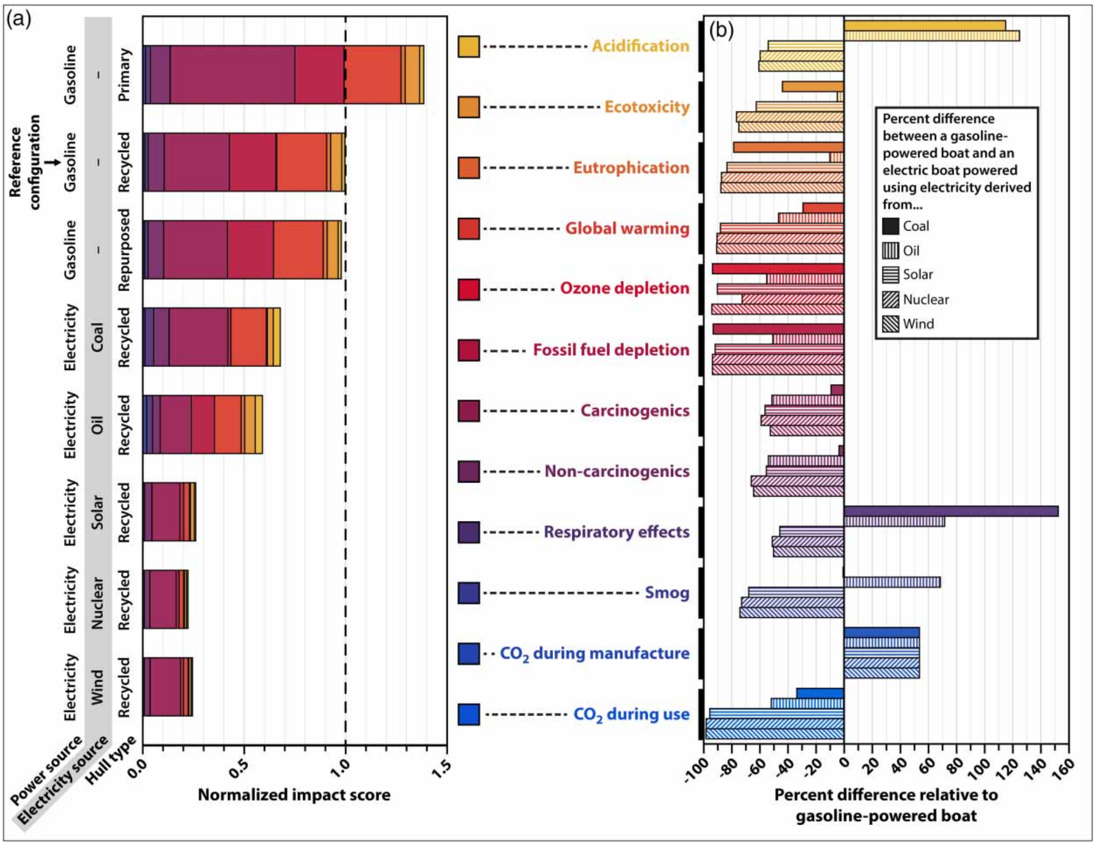


Figure 5 | Energy source dictates the lifetime environmental and health impacts of pump-out boats. (a) Normalized TRACI 2.1 impact scores for gasoline-powered and electric pump-out boats. (b) Percentage differences in TRACI 2.1 impact scores between the gasoline-powered reference configuration and an electric boat powered using various electricity sources.

comparable gasoline-powered vessel. Powering the boat using electricity generated from non-renewable fossil fuels led to smaller reductions in environmental and health impact than powering it using nuclear, wind, or solar electricity.

While all electric boat configurations had lower total impacts than gasoline-powered boats, they performed more poorly than the gasoline-powered counterpart with regard to particular environmental and health effects (Figure 5(b)). Electric pump-out boats powered with non-renewable electricity contributed equally or greater than gasoline-powered vessels to ocean acidification (sulfur dioxide release), respiratory health effects ($PM_{2.5}$ release), smog production (nitrous oxide and volatile organic compound release), and CO_2 release during manufacture. For electric boats powered using solar, nuclear, or wind electricity, the greatest impact reductions occurred with regard to ecotoxicity (measured via comparative toxic units for ecosystems), eutrophication (nitrogen release), global warming (lifetime CO_2 emissions), ozone depletion (chlorofluorocarbon release), fossil fuel depletion (surplus energy generated from non-renewable sources), smog, and CO_2 emissions during use. These findings confirm the role that energy sources play in determining the impacts of recreational service vessels on the environment and human health.

Rechargeable battery manufacture dominates the production-stage carbon footprint of electric pump-out boats

The LCA indicated that electric pump-out boat manufacture led to the emission of 55% more CO_2 into the atmosphere than gasoline-powered boat manufacture (Figure 5(b)). To understand the basis for this, the manufacturing-stage CO_2 emissions of electric and gasoline-powered pump-out boats with recycled aluminum hulls were analyzed (Figure 6). The electric boat's lithium-ion batteries played the largest role in increasing its carbon footprint during construction. Synthesizing organometallic compounds, including lithium hexafluorophosphate, for the batteries has a high carbon cost relative to other electric vessel manufacturing processes.

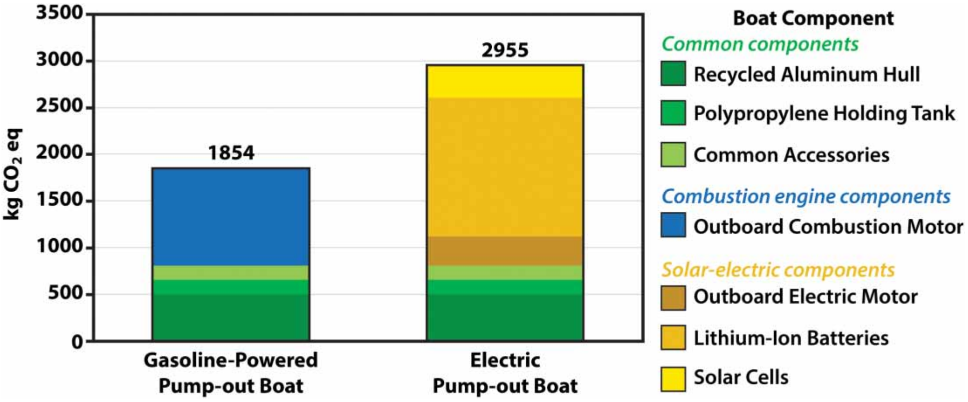


Figure 6 | Estimated greenhouse gas emissions involved in the manufacture of gasoline-powered and electric pump-out boats.

DISCUSSION

Electrically powered vessels represent a promising opportunity to reduce the adverse environmental and health effects of recreational boating services. However, the feasibility and impact of converting service vessels to electricity remain uncharacterized. In this study, national-scale surveys and LCAs of pump-out boats were conducted to shed light on the environmental, health, social, and policy factors affecting the conversion of service vessels to electric technology. The study was focused on pump-out boats because there exists an accessible national network of pump-out service providers, and models of gasoline-powered and electric pump-out vessels could be generated using available data. Narrowing the study's scope to pump-out boats enabled precise appraisal of the benefits, barriers, and consequences associated with adopting electric technology in the recreational boating service sector. A wide range of attitudes exists among pump-out boat service providers towards the conversion to electric technology in the United States. The LCA demonstrated that electricity-powered pump-out vessels have lower adverse environmental and health impacts than gasoline-powered boats, regardless of electricity source. The analysis also revealed that boats powered using non-renewable electricity sources show only modest reductions in lifetime greenhouse gas emissions relative to the gasoline-powered standard.

The CVA state coordinator survey (Figure 2) indicates that administrators in the recreational boating service sector are aware of the reduced environmental impacts of electric boat technology, a perception confirmed empirically with the LCA (Figures 4 and 5). CVA state coordinators identified implementation costs (coupled with budget uncertainty) as the greatest barrier to entry for electric pump-out boats. Costs notwithstanding, 31% of survey respondents also indicated that their states would be either 'not receptive' or 'not at all receptive' to adopting electric pump-out boats, suggesting that cultural and policy norms may hinder the transition to low-impact boating technology even if cost concerns are allayed. Motivating this transition may thus require initiatives extending beyond cost reduction or technology development and into policy action.

A national-scale pump-out boat operator survey enabled quantification of pump-out programs' operational characteristics, and estimation of the costs associated with operating and maintaining gasoline-powered pump-out boats in the United States. The operational cost analysis indicated that existing electric pump-out boat technology can address the financial concerns (and concerns associated with budget uncertainty) voiced by CVA state coordinators (US $3,220 per year for electric boats versus US $5,370 per year for gasoline-powered boats) (Figure 3).

The costs associated with decommissioning an existing gasoline-powered pump-out boat and replacing it with an electric vessel are likely too high for many pump-out programs – the electric boat upon which the LCA is based cost approximately US $200,000 to design and build (personal communication). The pump-out boat operator survey, by contrast, indicated that a conventional gasoline-powered pump-out boat costs US $59,600, on average, to replace (Table 2). This replacement cost may be an underestimate of the cost of an entirely new gasoline-powered pump-out boat, since many boat components – for example, navigation systems, safety equipment, and the pump-out unit – can be salvaged and reused. The electric pump-out boat on which the LCA was based, on the other hand, used all new components, and a significant share of its expense came from fixed costs for research and development. It is expected that reduced research and development costs, as well as economies of scale, will lower the price of electric pump-out boat construction in the future.

The LCA enabled identification of important design and operating issues for minimizing service vessels' detrimental impacts on the environment and human health. Holding all other design considerations constant, charging electric vessels using combinations of wind, solar, and/or nuclear electricity would lead to an order of magnitude reduction in the per-pump-out carbon footprint compared to the conventional gasoline-powered standard (Figure 4). This finding is similar to previously reported results on the effects of electricity source on the lifetime emissions for automobiles (Bauer *et al.* 2015; Onat *et al.* 2015; Elgowainy *et al.* 2016; Woo *et al.* 2017), and emphasizes the dominant role that energy sources play in determining total greenhouse gas emissions of personal-scale transportation. The electric pump-out vessel models were based on the assumption that onboard solar panels generate 10% of needed electricity, with the remaining electricity derived from infrastructural (i.e. grid) sources. Because of this, the use-stage carbon footprint of an electric pump-out boat with no onboard solar panels (i.e. entirely dependent on infrastructural power) is likely underestimated by approximately 10%. However, it should be noted that in the first year of operation of the prototype boat, the solar panels provided well over 10% of its electricity needs (personal communication).

Converting a pump-out boat to electric power leads to substantial reductions in a range of adverse environmental and health impacts, regardless of the electricity source used to charge the vessel (Figure 5(b)). The largest reductions result from the use of low-carbon electricity, including solar, nuclear, and wind power sources. However, conversion to electric power also shifts the balance of environmental and health effects relative to those of a gasoline-powered equivalent. The LCA results suggest that, for electric vessels charged using solar, nuclear, or wind power, the smallest reductions in TRACI-defined impact categories occur for emissions capable of causing ocean acidification, for carcinogens, and for particles that cause respiratory health issues. For low-carbon electricity-powered vessels, environmental and health effects (particularly carcinogen release) arise predominantly from the manufacture of batteries and electric motors, not from use-stage emissions associated with electricity generation. Even a pump-out boat using the current mix of renewable and non-renewable electricity available in the northeastern United States offers a substantial reduction in use-stage carbon emissions compared to that of a conventional gasoline-powered boat (Figure 4). As with electric automobiles, the remaining carbon and other emissions – along with their environmental and health effects – are non-local and occur primarily at electricity generation and electric motor construction sites (Tessum *et al.* 2014; Holland *et al.* 2016).

Pump-out boats provide a crucial service for recreational boaters by collecting the sewage generated on vessels that lack onboard waste treatment systems. The work presented here comprises a comprehensive study of pump-out boating practices in the United States. The range of attitudes expressed among pump-out boat administrators suggests that the widespread adoption of electric technology requires addressing the numerous environmental, social, financial, technological, and policy factors that govern decision making in the recreational boating service sector. This is similar to the constraints placed on the transition to electric-powered automobiles (Egbue & Long 2012; Bakker & Trip 2013).

The CVA program coordinator survey showed that awareness of electric technology's environmental benefits is high, but that aversion to its costs and doubts about budget stability hinder its adoption among pump-out boat service providers (Figure 2). Bringing the technology to scale is thus as much an issue of implementing suitable incentives through policy interventions as of further developing a technology that has demonstrated environmental and health advantages over the gasoline-powered standard. Encouraging the adoption of electric technology in the boating service sector – through financial subsidies at the federal (i.e. CVA) and/or state levels – could lead to immediate reductions in the sector's carbon footprint. Doing so would also lead to significant short- and long-term operational cost savings for service vessel operators.

This study demonstrates that sustainable change in the recreational boating service sector will require federal administrators, state CVA coordinators, and local stakeholders to design and demand initiatives that incentivize the adoption of existing electric technologies through partnerships with local boat builders, public relations campaigns, and realignments in federal funding structures. Electric boat technology can grow to become the preferred alternative for pump-out boats, other boating service sector vessels, and recreational vessels themselves. Operators of publicly owned fleets, state and local government administrators, and marina managers should all consider adoption of electric technology as an option to reduce the boating industry's carbon footprint, and its adverse environmental and health impacts, immediately.

AUTHOR CONTRIBUTIONS

MP and RD formulated the study. JC, ER, and JS developed the surveys. CH conducted the life-cycle analysis. CH, JC, and ER analyzed the data and generated figures. CH, MP, and RD wrote the manuscript. All authors reviewed the manuscript, provided feedback, and approved the manuscript for submission.

COMPETING INTERESTS

The Connecticut East Shore District Health Department, which MP directs, received a grant from the Connecticut Department of Energy and Environmental Protection, using funds received from the United States Fish and Wildlife Service, for the purpose of construction of an electric pump-out boat. This boat served as the prototype electric pump-out boat described in this study. A Provisional Patent Application for the prototype electric pump-out boat has been filed for a consortium of the East Shore District Health Department, the U.S. Fish and Wildlife Service, the Connecticut Department of Energy and Environmental Protection, and the Pilots Point Marina.

FUNDING

The Yale Climate Change and Health Initiative (New Haven, Connecticut) supported this work through a grant from the Overlook International Foundation. The United States Fish & Wildlife Service and the Connecticut Department of Energy and Environmental Protection (grant number 2017–190) also supported this work. The Connecticut East Shore District Health Department and its community partners provided additional funding.

ACKNOWLEDGEMENTS

We extend sincere thanks to Kate Hughes Brown of the Connecticut Department of Energy and Environmental Protection, and Lisa van Alstyne of the United States Fish and Wildlife Service for valuable input throughout this study and for assistance in distributing nationwide surveys to CVA program coordinators and pump-out boat operators. We also thank Jeremy Maxwell of Pilots Point Marina for providing information regarding the design and construction of an electric pump-out boat; Thomas Swarr of the Yale School of Forestry and Environmental Sciences for expertise on life-cycle assessments; Brianna Weller of the East Shore District Health Department for providing information on regional pump-out boat programs; and Libby Yranski of the States' Organization for Boating Access for assisting with survey distribution.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

16 USC 777c. *Division of annual appropriations* 1992, United States Code, title 16, section 777c, Cornell Legal Information Institute, Ithaca NY, USA.

33 USC 1322. *Marine sanitation devices; discharges incidental to the normal operation of vessels* 1996, United States Code, title 33, section 25, Cornell Legal Information Institute, Ithaca NY, USA.

40 CFR 25. *Marine sanitation device standard* 1976, United States Code of Federal Regulations, title 40, section 25, Government Publishing Office, Washington DC, USA.

50 CFR 85. *Clean vessel act grant program* 1992, United States Code of Federal Regulations, title 50, section 85, Government Publishing Office, Washington DC, USA.

Adeel, M., Song, X., Wang, Y., Francis, D. & Yang, Y. 2017 Environmental impact of estrogens on human, animal and plant life: a critical review. *Environment International* **99**, 107–119.

Bakker, S. & Trip, J. J. 2013 Policy options to support the adoption of electric vehicles in the urban environment. *Transportation Research Part D: Transport and Environment* **25**, 18–23.

Bauer, C., Hofer, J., Althaus, H.-J., Del Duce, A. & Simons, A. 2015 The environmental performance of current and future passenger vehicles: life cycle assessment based on a novel scenario analysis framework. *Applied Energy* **157**, 871–883.

Betancourt, W. Q., Duarte, D. C., Vásquez, R. C. & Gurian, P. L. 2014 Cryptosporidium and Giardia in tropical recreational marine waters contaminated with domestic sewage: estimation of bathing-associated disease risks. *Marine Pollution Bulletin* **85**(1), 268–273.

Burnham, A., Wang, M. & Wu, Y. 2006 *Development and Applications of GREET 2.7 – The Transportation Vehicle-Cycle Model*. Oak Ridge, Argonne National Laboratory, Argonne, IL, USA.

Curran, M. A. 2013 Life cycle assessment: a review of the methodology and its application to sustainability. *Current Opinion in Chemical Engineering* **2**(3), 273–277.

Egbue, O. & Long, S. 2012 Barriers to widespread adoption of electric vehicles: an analysis of consumer attitudes and perceptions. *Energy Policy* **48**, 717–729.

Elgowainy, A., Han, J., Ward, J., Joseck, F., Gohlke, D., Lindauer, A., Ramsden, T., Biddy, M., Alexander, M., Barnhart, S., Sutherland, I., Verduzco, L. & Wallington, T. 2016 *Cradle-To-Grave Lifecycle Analysis of U.S. Light-Duty Vehicle-Fuel Pathways: A Greenhouse Gas Emissions and Economic Assessment of Current (2015) and Future (2025–2030) Technologies*. Argonne National Laboratory, Argonne, IL, USA.

Gloria, T. P., Lippiatt, B. C. & Cooper, J. 2007 Life cycle impact assessment weights to support environmentally preferable purchasing in the United States. *Environmental Science & Technology* **41**(21), 7551–7557.

Gregory, L. F., Gitter, A., Muela, S. & Wagner, K. L. 2019 Should contact recreation water quality standards be consistent across hydrological extremes? *Journal of Contemporary Water Research & Education* **166**(1), 12–23.

Hallgren, P., Nicolle, A., Hansson, L.-A., Brönmark, C., Nikoleris, L., Hyder, M. & Persson, A. 2014 Synthetic estrogen directly affects fish biomass and may indirectly disrupt aquatic food webs. *Environmental Toxicology and Chemistry* **33**(4), 930–936.

Hansen, J. P., Sundblad, G., Bergström, U., Austin, Å. N., Donadi, S., Eriksson, B. K. & Eklöf, J. S. 2019 Recreational boating degrades vegetation important for fish recruitment. *Ambio* **48**(6), 539–551.

Holland, S. P., Mansur, E. T., Muller, N. Z. & Yates, A. J. 2016 Are there environmental benefits from driving electric vehicles? *The Importance of Local Factors. American Economic Review* **106**(12), 3700–3729.

ISO14044 2016 *Environmental Management – Life-Cycle Assessment – Requirements and Guidelines*. International Organization for Standardization, Geneva, Switzerland.

Lapointe, B. E., Herren, L. W., Debortoli, D. D. & Vogel, M. A. 2015 Evidence of sewage-driven eutrophication and harmful algal blooms in Florida's Indian River Lagoon. *Harmful Algae* **43**, 82–102.

Lloret, J., Zaragoza, N., Caballero, D. & Riera, V. 2008 Impacts of recreational boating on the marine environment of Cap de Creus (Mediterranean Sea). *Ocean & Coastal Management* **51**(11), 749–754.

NMMA 2019 *2018 Recreational Boating Statistical Abstract*. National Marine Manufacturers Association, Chicago, IL, USA.

Onat, N. C., Kucukvar, M. & Tatari, O. 2015 Conventional, hybrid, plug-in hybrid or electric vehicles? state-based comparative carbon and energy footprint analysis in the United States. *Applied Energy* **150**, 36–49.

Rabinovici, S. J. M., Bernknopf, R. L., Wein, A. M., Coursey, D. L. & Whitman, R. L. 2004 Economic and health risk trade-offs of swim closures at a Lake Michigan beach. *Environmental Science & Technology* **38**(10), 2737–2745.

Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.-P., Suh, S., Weidema, B. P. & Pennington, D. W. 2004 Life cycle assessment: part 1: framework, goal and scope definition, inventory analysis, and applications. *Environment International* **30**(5), 701–720.

Soller, J. A., Schoen, M. E., Varghese, A., Ichida, A. M., Boehm, A. B., Eftim, S., Ashbolt, N. J. & Ravenscroft, J. E. 2014 Human health risk implications of multiple sources of faecal indicator bacteria in a recreational waterbody. *Water Research* **66**, 254–264.

Sovacool, B. K. 2008 Valuing the greenhouse gas emissions from nuclear power: a critical survey. *Energy Policy* **36**(8), 2950–2963.

Stoll, J. R., Bergstrom, J. C. & Jones, L. L. 1988 Recreational boating and its economic impact in Texas. *Leisure Sciences* **10**(1), 51–67.

Tessum, C. W., Hill, J. D. & Marshall, J. D. 2014 Life cycle air quality impacts of conventional and alternative light-duty transportation in the United States. *Proceedings of the National Academy of Sciences of the United States of America* **111**(52), 18490–18495.

USEPA 2015a *Emissions & Generation Resource Integrated Database (eGRID)*. United States Environmental Protection Agency, Washington, DC, USA. Available from: https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid.

USEPA 2015b *Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI)*. United States Environmental Protection Agency, Washington, DC, USA. Available from: https://www.epa.gov/chemical-research/tool-reduction-and-assessment-chemicals-and-other-environmental-impacts-traci.

USEPA 2016 *eGRID Summary Tables*. United States Environmental Protection Agency, Washington, DC, USA. Available from: https://www.epa.gov/energy/egrid-summary-tables.

van Beusekom, J. 2018 Eutrophication. In: *Handbook on Marine Environment Protection*. Springer International, pp. 429–445. Available from: https://www.springerprofessional.de/en/eutrophication/15430710.

Vargas-González, H. H., Arreola-Lizárraga, J. A., Mendoza-Salgado, R. A., Méndez-Rodríguez, L. C., Lechuga-Deveze, C. H., Padilla-Arredondo, G. & Cordoba-Matson, M. 2014 Effects of sewage discharge on trophic state and water quality in a coastal ecosystem of the Gulf of California. *The Scientific World Journal* **2014**, 618054.

Weisser, D. 2007 A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies. *Energy* **32**(9), 1543–1559.

Wesdock, J. C. & Arnold, I. M. F. 2014 Occupational and environmental health in the aluminum industry. *Journal of Occupational and Environmental Medicine* **56**(5 Suppl), S5–S11.

Woo, J., Choi, H. & Ahn, J. 2017 Well-to-wheel analysis of greenhouse gas emissions for electric vehicles based on electricity generation mix: a global perspective. *Transportation Research Part D: Transport and Environment* **51**, 340–350.