REVIEW ARTICLE

Ecobuoys for Scalable Oceanography

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ABSTRACT

An approach to scalable surface-drifting buoys is needed to enable the high spatial and temporal resolution of oceanographic data that the science and meteorological communities are asking for. With the number of active buoys predicted to increase by a factor of 100 or more, the impact on the environment becomes even more important. Here, we present a pathway to a scalable and sustainable generation of buoys. We identify the main criteria to be used when developing such buoys to be low cost, with reliable data and neutral or even positive environmental impact. For each buoy subsystem—hull, electronics, energy generation and storage, sensors, and communication system—cutting-edge technological solutions are presented, many of them from emerging research in marine or other disciplines. We then assess the potential solutions against the design criteria and plot a path toward small, environmentally friendly, low-cost, and low-power buoys.
Keywords: low-cost buoy, environmental impact, buoy system, large-scale buoy network, scalable

Introduction

Anthropologically caused changes in the environment are affecting human health and habitat, and range from a changing climate to pollution in air, water, and soil. With oceans covering more than 70% of the planet, their state of health plays a key role in monitoring, predicting, and even mitigating changes affecting humans. For example, the global sea surface temperature is rising at a rate of 0.2°C/decade (Johnson et al., 2023) affecting a wide range of systems, from weather patterns and sea level rise, to fish populations. The oceans store over 90% of the greenhouse-induced warming in the climate system, acting like Earth's own heat sink, and are key for climate prediction (Årthun et al., 2017).

Knowing the state of the ocean enables researchers, coastal communities, and policymakers to iterate their behavior and understanding in real time, laying the foundation for a well-founded action plan to mitigate climate change and environmental pollution, and address issues ranging from climate modeling to sustainable fishing (Albaladejo et al., 2010; Baldock et al., 2014; Huang et al., 2021; Stark et al., 2007). As an example, the need for more data in the fast-changing polar regions is paired with costly and time-consuming access to these areas for deployment or direct measurements, making spatially resolved and long-term solutions using autonomous systems particularly attractive.

However, the impact of scaling oceanographic observations without changing their approach can easily be extrapolated based on National Oceanic and Atmospheric Administration's Global Drifter Program as an example; increasing the existing in situ population of ~1,500 drifters by a factor of 24 (see next section) would mean that ~36,000 surface-drifting buoys are in the ocean at the same time. If we imagine that technology advances can increase the average life-span from 12–18 months to 2 years, this means that 18,000 buoys at ~25 kg each would still need to be replaced annually, which translates to 450 metric tons of waste added to the ocean by this program alone.

These problems are starting to be addressed by the research community, and in this paper, we propose a path forward by leveraging technologies already found on the market and in research labs, often from other disciplines, and evaluate these solutions against the criteria described. Much like air pollution tools on land, in situ measurements will need to be paired with modeling data to inform a more complete picture and allow prediction. While we are organizing developing technology into actionable solutions for next generation ocean surface-drifting buoys, assessing the economic cycle at scale is too early for many of the solutions proposed and is beyond the scope of this paper.

Requirements for a Next Generation Ecobuoy

As we reimagine ocean surface-drifting buoys, we are guided by the many functions such an observing platform fulfills. The most important requirement from a user standpoint is reliable data. Any changes made to the density of the buoy network are intended to increase spatial and temporal resolution, but such changes need to take environmental and cost perspectives into account. As such, the requirements for Ecobuoys consist of the following three attributes:

1. *Data*: reliable and fast data transmission to shore, as well as extended deployment times. This means making the data stream redundant and communication protocols sufficiently fast, which will allow for longer missions and or fewer buoys deployed.
2. *Low environmental impact* from each buoy added to the ocean. This means making buoys small and either biodegradable or utilizing inert materials where this is not possible. Ultimately, a cradle-to-cradle assessment of impact on the environment will be needed.
3. *Low cost for each buoy* in order to allow for sufficient data resolution while keeping within budget. For example, with the oceans covering about 360 million km^2, we would need 36,000 buoys assuming a 100 km × 100 km grid. More likely, the distribution will be determined by need, for example, increasing the density for coastal areas or areas of rapid changing phenomena.

Table 1 shows ranges of key parameters for buoys currently deployed and compares these to our envisioned Ecobuoy. Smaller, lower power, lower cost buoys for which lifespan is not dictated by battery performance is a major goal here. At the end of life, these buoys would not add to the microplastics and toxins in the water, but biodegrade naturally, leaving behind only inert materials like ceramics and metals.

In the following section, these three criteria are leveraged to evaluate the next generation technology proposed for each subsystem of a buoy.

Buoy as a System

A typical ocean surface-drifting buoy is shown in Figure 1. All components within the buoy can be broken down into one of these five subsystems: communications, electronics, power generation and storage, hull, and sensors. In the following section, we introduce each of these five subsystems and assess recent technology advances that would allow an improvement toward the criteria outlined in the Requirements for a Next Generation Ecobuoy section, yielding a lower cost, networked buoy with minimal environmental impact.

Applying State-of-the-Art Technology to the Ecobuoy

In the following, we describe the current state-of-the-art technologies used for each of the buoy's subsystems shown in the Buoy as a System section, and offer methodologies and technologies that are evaluated for effective scalability against the criteria introduced in the Requirements for a Next Generation Ecobuoy section.

Hull

A buoy's hull serves two main functions: It protects the contents of the buoy such as electronics and sensors from water, as well as positioning the sensors in the desired location in the water by leveraging the center-of-mass and center-of-buoyancy force couple. Presently, most surface-drifting buoy hulls are made of plastics, often ending

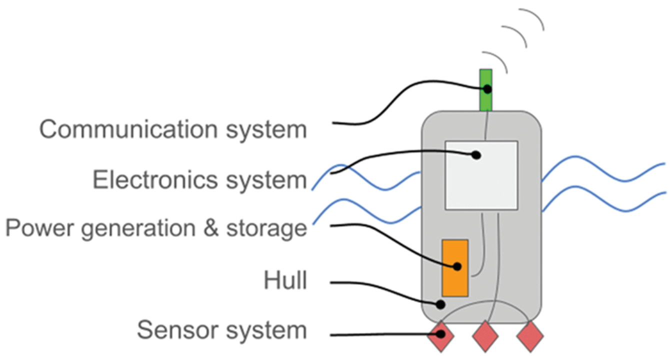
TABLE 1

Comparison between current oceanographic surface-drifting buoys and envisioned Ecobuoy parameters.

	Typical Oceanographic Buoy	Notional Ecobuoy
Size	~50 cm to several meters	< 30-cm diameter
Power demand	10 s of mW to W (average)	μW (average)
Cost	~$2,000 to $20,000+	< $500
Data transfer	Mostly satellite, Wi-Fi	node-to-node
Time in ocean	Months to ~5 years	years
Degradability	Plastic materials, toxins in electronics, sensors, and battery	Biodegradable or inert materials for most components, low toxicity options otherwise

FIGURE 1

Typical ocean surface-drifting buoy and its identified components.



up as waste, and degrading to microplastics after the buoy's lifetime. In the following, we describe a path toward environmentally friendly materials that allow easy scaling and assess less-common material options.

In the realm of sustainable polymers, the emerging and evolving terminology can often be complex and potentially misleading. Degradable materials refer to those that can be broken down biologically or chemically (Law & Narayan, 2022; Mohanty et al., 2022). The term "degradable" does not specify the time frame, the means for breakdown, or the nature of the byproducts, which might not be environmentally benign. Biodegradable materials, on the other hand, are specifically broken down by organisms such as bacteria and fungi into primarily H_2O, CO_2, or/and CH_4—that is, can be metabolized by microorganisms. It is also crucial to distinguish between physical and chemical degradation of plastics and complete biodegradation, which *removes* plastics from the environment. Even heavily weathered plastics break down to smaller pieces, which still retain high molecular weights, called microplastics, that hinder full microbial metabolization, resulting in limited biodegradation and the return of degraded particles to the environment. Compostable material is a further subset of biodegradable materials. These materials biodegrade in managed composting systems, which often utilize special heat and microorganism protocols to facilitate the process. In the context of this paper, we will be discussing degradation and biodegradation within a marine environment. Such biodegradation typically happens in three stages: biodeterioration, depolymerization, and assimilation (Kim et al., 2023).

Biobased plastics are made fully or partially from biological feedstocks rather than fossil fuel–derived resources (Campbell et al., 2023; Law & Narayan, 2022). However, these plastics are not necessarily biodegradable or compostable. It is essential to examine the full life cycle of biobased plastics to ensure they provide environmental benefits beyond just reducing the use of fossil resources. This examination includes considering changes in land use for feedstock production, in addition to energy consumption during manufacturing and waste streams. In terms of environmental persistence, most conventional plastics consist primarily of carbon–carbon bonds that make up their molecular backbone, which are highly resistant to degradation (Epps et al., 2021). This resistance has led to a significant accumulation of plastic waste in landfills and natural environments, contributing to ongoing ecological challenges. As we will discuss next, there are advances in the field of polymer science that enable both biobased sourcing and biodegradation as an end-of-life pathway.

Current Hull Materials Landscape

Conventional buoy hulls, both drifting and moored, are predominantly constructed from nonbiodegradable plastics, followed by metal alloys (Wilson, 1987). While these materials are durable and suitable for harsh marine conditions, their long-term environmental impact is significant. Nonbiodegradable plastics persist in marine environments, and if not removed, they contribute to pollution and the accumulation of micro and nanoplastics in maritime biomes. If such plastics can be recovered, depending on formulation, the material may be recycled or upcycled for future use. However, when factoring in transportation fuel and cost for an oceanic recovery, in addition to the energy imputed during a recycling process, the dilemma of trading (immediate) increased energy expenditure for reduced long term environmental impacts persists. Metal alloys, such as stainless steel or aluminum, have been used in an ocean environment in a range of capacities (Cocker et al., 2022; Timpe & Van de Voorde, 1995; Waterson et al., 2019). Although durable for buoys and generally considered to be environmentally inert, metals are heavy and consume high amounts of energy to manufacture and transport, posing their own environmental challenges. If recovered, metal hulls can be recycled and repurposed. In the aforementioned materials, to combat the inevitable biofouling and corrosion that occurs with extended water exposure, a layer of antifouling paint is essential for maintaining proper drag and buoyancy, and limiting any organically induced corrosion. Such specialty coatings have historically utilized toxic chemical compounds, but research is exploring natural, low-polluting, multi-functional coatings (Qiu et al., 2024) that may adhere well to future bioplastic hull materials too. Regardless, any coating comes with additional removal/breakdown processes when considering material recycling or breakdown.

Glass and ceramics are another category of materials that have been used as hull materials for maritime sensing equipment. They are favored in fully submerged applications for their impressive compressive strength and the ability to withstand extraordinary water pressures (Stachiw, 1965). Ceramics are typically only selected as a hull material for highly specialized devices to be deployed in deep sea or ocean-bottom environments (Asakawa et al., 2012; Bowen et al., 2008; Pausch et al., 2009; Pausch & Hardy, 2015; Qi et al., 2019; Stachiw, 1965; Stachiw et al., 2006). As a surface drifter, such material classes would need to be paired with protective shells to prevent brittle failure if impacted. Looking further back, natural materials such as wood were utilized given their buoyancy and availability. Wood has been used in ocean environments for hundreds of years, in the form of boats and piers. It can be found in buoy literature more recently as a potentially promising 100% degradable alternative to plastics, such as explored by Collecte Localization Satellite (Novelli et al., 2017), but it requires sealing to protect against water penetration and prevent uncontrollable swelling. Table 2 outlines the materials considered within this paper. Note that bioplastics, in principle, consist entirely or predominantly of fully biodegradable feedstocks. However, presently, there is little definitive proof or evidence pertaining to the nature of their degradation products.

Performance Needs and Environmental Impact

The dominant plastics in current buoy hulls range from flexible thermoplastics to rigid thermosets. Materials in use for hull manufacture include acrylonitrile butadiene styrene, polyethylene (high and low density, high-density polyethylene, and low density polyethylene), polypropylene, polymethyl methacrylate (PMMA, plexiglass), polycarbonate, and acrylate-based printable resins such as the ones available from Bluerobotics, Rolyanbuoys, Smartocean, or SofarOcean. These materials exhibit a wide range of mechanical properties, with strengths ranging from 1 to ~100 MPa and Young's moduli from 0.1 to ~10 GPa, all within a relatively narrow density range of 0.8–1.3 g/cm^3, that is, these are positively to neutrally buoyant. Such values set a benchmark and provide a broad range of properties for future hulls to match. The current material selection

TABLE 2

Summary of buoy materials currently used and under development.

Hull Material	Rate of Selection	Toxicity of Degradation Products	Comment
Polyethylene (PE)	Most common	Yes	Traditional buoy material
Poly(methyl methacrylate) (PMMA or acrylic/plexiglass)	Most common	Yes	Traditional buoy material
Polyurethane (PU)	Common	Yes	Traditional buoy material
Metal alloys (stainless steel, aluminum, copper-nickel)	Common	Inert	Less environmental impact, depending on manufacturing
Glass	Not common	Inert	High-pressure hull material, paired with protective shell
Ceramics	Not common	Inert	High-pressure hull material
Wood	Not common	None	Buoy material
PHAs	Not common	None	Recent buoy material
Bioplastics	Not common	None	Under development

approach often focuses on meeting these physical properties and overlooks end-of-life scenarios, a consideration that needs to be central to the development of scalable maritime materials (Boyer et al., 2022). Balancing the performance needs of buoy hulls with their environmental impact is not just about enhancing material properties but also about developing comprehensive testing and modeling frameworks that can predict their real-world behavior during and after service life. This holistic approach is crucial for transitioning to more sustainable and environmentally benign materials for marine applications.

Vision for Sustainable Solutions

The design challenge emerges from the pressing need to transition to environmentally benign materials for marine applications. With this, our vision for buoy hulls involves:

- using plastics that are biobased, sourced from renewable, non-fossil resources—preferably photosynthetic, fast-growing, and abundant biomass;
- adhering to green chemistry principles (Anastas & Eghbali, 2010), minimizing waste generation and solvent usage, and transparently reporting life cycle assessment metrics (which remains a major materials science challenge in itself) (Rosenboom et al., 2022);
- leveraging materials compatible with current plastics processing equipment, ideally being thermoplastic and processable through injection or compression molding.

Such materials would ensure that buoys remain intact during their service life and degrade into benign small molecules post-service. Biobased and biodegradable polymer solutions are thus a major target.

Along one avenue, polyhydroxyalkanoates (PHAs) are emerging as a promising family of biodegradable aliphatic polyesters (Kalia et al., 2021; Koller et al., 2017). Their versatile molecular backbone allows for tailored performance (Derippe et al., 2024; Pinto et al., 2016). The commercial market for PHAs is expected to reach significant volumes in the coming years (annual volumes of > 100,000 MT) (Mohanty et al., 2022). Unlike chemically synthesized polymers, PHAs are produced by bacteria, including *Pseudomonas* and *Ralstonia* strains, as well as microalgae (Costa et al., 2019). Microorganisms produce PHAs as energy storage purposes intracellularly, with storage levels varying up to 80% of the cell volume (Costa et al., 2018; Zytner et al., 2023). The PHA production process can utilize various carbon-rich feedstocks, including inexpensive food residues and liquefied plastic wastes, enhancing the overall circularity of this particular process. Circularity is a term used for processes where materials are reused or recycled within the production cycle, reducing waste and contributing to a more sustainable, closed-loop system. Thus, materials can be reused, recycled, or regenerated at the end of their life cycle, rather than being discarded as waste. This approach is part of the broader circular economy framework, which aims to minimize waste and make the most of resources. Although traditional extraction methods often involve halogenated organic solvents, multi-step processes that generate waste and can be expensive as well as unsustainable, more environmentally benign and solvent-free cell disruption methodologies are currently being developed.

Another promising approach involves the use of entire algal organisms (micro and macroalgae) to capitalize on their polymer composition (Campbell et al., 2023; Fredricks et al., 2021; Iyer et al., 2023). In this case, the entire organism is utilized as a material feedstock, sometimes termed “biomatter” (Iyer et al., 2023). The first examples of this new class of biomatter bioplastics (i.e., made from biomatter and demonstrating a thermoplastic behavior) showed a stiff and rigid performance as well as a thermoplastic behavior, with Young’s modulus between 0.1–5 GPa, strengths 1–50 MPa at a density range of 0.9–1.3 g/cm^3—within the region of the plastics used today in hulls. Optimizing the water sensitivity of these materials is crucial for maintaining the integrity of the buoy hull so the functionality of buoys are not compromised before the end of their designed service life. This is currently the most pressing engineering obstacle, as it impacts both performance loss and biodegradation. Other candidate materials, such as thermoplastic starch blends, face similar challenges (Mohammadi Nafchi et al., 2013).

Other solutions include polylactic acid (PLA), which although rapidly growing in use as a biobased and compostable plastic, requires specific composting conditions for end-of-life management, which are not feasible in marine environments. Polybutylene succinate (PBS) also presents challenges due to its complex synthesis processes and inconsistent biodegradability across different environments. Petroleum-based biodegradable plastics, such as polybutylene adipate terephthalate (PBAT) and polycaprolactone (PCL), do not support a transition to a circular economy due to their fossil-derived origins (Mohanty et al., 2022).

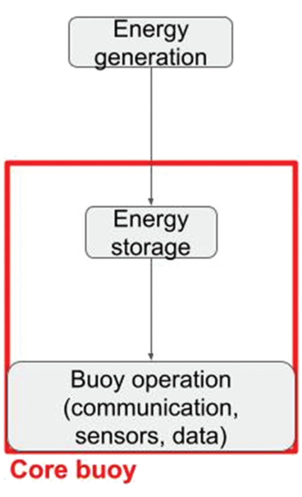
The future of sustainable bioplastics in marine science instrumentation hinges on their compatibility with existing systems and ensuring biodegradability. Advances in machine learning (Martin-Martinez, 2024; Zhu et al., 2021), additive manufacturing, and polymer science enable researchers to optimize material performance while minimizing environmental impact. By integrating data-driven design and sustainable materials, we can create marine technologies that promote healthier ecosystems and support the shift toward greener ocean practices.

Power Generation and Storage

The power generation and storage system is made up of all parts of the buoy that generate, store, or deliver power, as shown in Figure 2. Commonly, a buoy contains an energy storage—usually batteries—that feed any buoy operation on board, such as communication, sensors, or data management. This unit is referred to as the core buoy here. For a fixed amount of battery storage, the smaller the buoy, the larger the volumetric percentage the batteries make up. In addition, some buoys are able to harvest energy from their environment via solar, wind, or wave power, for example, recharging batteries and extending the lifetime of the buoy.

FIGURE 2

Block diagram of power generation, storage, and use on a buoy. The core buoy, where a battery feeds the buoy's operation only, is indicated.



The goal for small, networked Ecobuoys is to reduce the volume allocated to the power storage and generation unit; because we can also miniaturize electronics, this will effectively reduce the overall size of the buoy. Reducing size has many benefits including reducing environmental impact by reducing mass, reducing cost of materials, and making deployment easier. Within the power generation system, this can potentially be achieved by:

1. Optimizing power use by incorporating low power sensors and communication systems, thus decreasing the required battery volume for a given mission. Low power sensors are increasingly coming online for ocean applications (Nawaz, 2023), and reducing energy cost for communication is discussed in the Applying State-of-the-Art Technology to the Ecobuoy section of this paper;
2. Optimizing power use through a smart buoy approach, that is, finding ways to cut down on communication and transmission power needs through strategic prioritization, exploring trade-offs between energy costs of local signal processing to downsample/condense data (e.g., computing and transmitting the Fourier transform instead of transmitting a long-duration recording) versus transmitting raw data, using "sleep mode," and real-time decision on board the buoy,
3. Supplementing the battery power through strategic incorporation of low volume energy harvesting systems, reducing the overall volume of the combined power storage and harvesting unit. This aspect is discussed below in more detail.
4. Using higher density (energy storage per volume) storage systems. As battery and capacitor technology advances, these can be leveraged for buoys.

Energy Generation

Energy generation through harvesting of environmental energy could play a significant role in reducing the battery size and thus hull size and costs for small buoys. The mechanism of transferring energy from the environment to the buoy is described in the following. This is particularly important when comparing different energy harvesting systems, as currently no standard way of reporting exists.

The energy in the environment E_E is converted to energy available at the harvesting unit E_H with an efficiency of η_h. This efficiency loss describes how much of the environmental energy can be captured by a harvesting unit. The energy available at the buoy E_B can then be calculated with $E_B = \eta_c E_H$, where η_c is the conversion loss from harvesting unit to the buoy's energy storage. When comparing energy harvesting methods, it is thus important to compare the overall system efficiency and the energy available based on the same environmental conditions $E_B = \eta_h \eta_c E_E$. In the following, we list the energy harvesting methods of interest to small, low-power, and low-cost Ecobuoys.

1. Solar power is the most prevalent energy source used on buoys to date. Solar cells have an energy efficiency of ~20% under ideal conditions; thus, the power output can theoretically reach 200 W/m^2 on

bright sunny days. However, in reality, the output is closer to 30–70 W/m^2 due to weather and cloud conditions and the angle of the sun onto the photovoltaic cells. It is not suitable for areas with low light conditions (such as the Arctic in winter) or underwater buoys such as gliders and profiling floats, unless those platforms spend significant time at the surface to recharge.
2. Wind energy is sometimes used to supplement solar power on larger buoys. It can provide energy when wind speeds of 3–5 m/s are reached. However, wind turbines small enough for Ecobuoys would still need to be developed, as this technology is currently applied to larger buoys only.
3. Kinetic energy harvesting on buoys refers to the conversion of wave energy through a pendulum or moving mass and induction to a power output. A 220-g pendulum kinetic energy harvester buoy can produce power on the order of mW in waves with a frequency of 0.3 Hz and height of 1.42 m (Carandell et al., 2020). No external moving parts make this approach less prone to errors. Due to its potential off-the-shelf approach, we see this as a potentially promising path forward.
4. Triboelectric Energy Nano Generators (TENG)—TENG devices are an emerging technology that harvest energy from wave motion. They require a kinetic energy harvesting device such as a pendulum or moving mass but are effective at producing power even at low temperatures (Jung et al., 2023). They generate high-density power and can produce an average power on the order of 100 mW, depending on the wave state (Jung et al., 2025). Positioned inside the buoy hull, the TENG electricity generation device requires no moving parts outside the buoy and is protected from the harsh outside conditions.
5. Piezo Electric Nano Generators (PENG)—PENG devices are based on the deformation of a piezo crystal causing an electric voltage. Because of this, they are often installed in beams that are exposed to waves or flowing water. PENG devices also require the wave motion to be converted to mechanical motion, but the moving parts can be installed inside of the buoy and protected from the environment. A wide variety of piezoelectric energy harvesters have been invented, and they produce power on the order of µW to mW (Liu et al., 2023).
6. Thermoelectric or thermal gradient–based harvesting—Thermoelectric and thermal gradient–based devices harvest energy from environmental temperature differences such as between water layers or water and air. They have no moving parts and are therefore considered durable for marine applications. They are estimated to produce on the order of mW average power, depending on several factors including the thermal gradient. This method can be useful for gliders and profiling floats that frequently cross thermal gradients and where other energy sources are not necessarily available (Chao, 2016).
7. Other—other potentially interesting energy generation methods for small, low-cost buoys include Seawater batteries. These are commonly not recharged, but could be used as supplemental energy harvesting from the ocean. Recently, Kim et al. introduced a system < 20 cm in diameter that can be recharged (Kim et al., 2022). In addition, some technologies such as seawater-driven electricity nanogenerators (Su et al., 2023) should not be overlooked in the search for the ideal energy harvesting mechanism for Ecobuoys (Table 3).

Energy Storage

The most common way to store energy in oceanographic buoys is through the use of Li-Ion or Alkaline batteries, with Lead-Acid, Sodium Sulfate, and Seawater batteries being less utilized options (Wang et al., 2019). Energy storage in capacitors has been discussed due to the advantage of faster charge/discharge cycles, potentially smaller footprint, as well as a solution to combine with energy harvesting systems with low charging power, like the ones mentioned above in options 3–7 (Ho, 2024). At the cutting edge of development, enzyme-powered batteries have produced 380 µW (Zhu et al., 2022).

While there seem to be a spread of potential options, it is worth noting that the systems of energy harvesting, energy storage, and utilization of energy for operation are not standalone and are ideally developed together. Further, the type of buoy needs to be taken into account; some technologies will work well for surface-drifting buoys, but less well for profiling floats.

Electronics Subsystem

For the purpose of this paper, the electronics subsystem inside a buoy is responsible for converting power, supplying control signals to the sensors and communication system as needed, and managing the preanalysis and flow of data. As such, it

TABLE 3

Overview of main energy harvesting methods suitable for surface-drifting Ecobuoys, along with high-level advantages/disadvantages.

Method	Advantage	Disadvantage
Solar	Most commonly used, commercially available	No power at night or at high latitudes in winter, and limited by surface area
Wind	Good supplement to solar and a simple well-known technology for larger buoys	Intermittent, unpredictable, and not used on small buoys
Kinetic wave	No external moving parts	Not commercially available
TENG wave	Effective at low temperatures	New technology
PENG wave	No external moving parts	New technology
Thermoelectric	No external moving parts	Dependent on strong thermal gradients such as those in the Arctic

is distinct from other components such as communications and power generation. The electronic boards usually consist of a composite material made of woven fiberglass cloth and epoxy resin, combined with the electronic components like capacitors, resistors, and processors. These materials take geological time spans to break down in the ocean and are a source of toxins and microplastics in the water. The goal for Ecobuoys is to reduce the toxicity of the electronic components within a buoy significantly by utilizing biodegradable or inert materials where possible (Gabrys, 2013).

Currently, there are several efforts toward making e-waste more recyclable (Chakraborty et al., 2022), or changing the material of the printed circuit board to less toxic and biodegradable options (Soon et al., 2024; Zhang, Biswal, et al., 2024; Zhang, Parker, et al., 2024). Notably, there are several groups successfully working on bioresorbable circuit board materials and components meant to be attached to or even implanted into human bodies (Chiong et al., 2021; Hwang et al., 2013). Materials like biocompatible polymers, paper, or flax and biobased resin would reduce the environmental impact both in the ocean and on land are being developed as part of a circular economy (Ogunseitan et al., 2022). Today, some Printed Circuit Boards (PCB) manufacturers offer lower-toxin options, but only select alternate substrate materials are generally available (e.g., ceramic).

Our vision for Ecobuoys electronics components is to leverage materials already found to work on land, test their biodegradation in ocean environments, and build a path toward low-impact electronics for oceanography. It should be noted that today, most of the mass and volume in electronics comes from the plastic or ceramic packaging around silicon chips and large fiberglass PCBs. In the future, the use of chiplets and multichip assemblies will reduce this footprint by combining components like analog processing, computation, and storage within a single package. This trend toward integration will simplify electronics design, cut down on size, and enhance efficiency (Loh et al., 2021; Mounce et al., 2016).

Sensors

Sensors form the payload of a buoy, and as such, they need to be optimized to the buoy's mission. The data from these sensors are sampled at an interval appropriate to the use-case and then often pre-processed on board the buoy before they are transmitted to the user via the buoy's communication system. To enable scaling, the sensors additionally need to be small, low cost, and low power, and allow for networking within the buoy or across multiple buoys in a network.

Common physical sensors on a buoy measure ocean temperature, salinity, depth, wave motion, or turbidity, while biological sensors measure phytoplankton biomass via optics or DNA/RNA sensors. Chemical sensors measure quantities such as pH, dissolved oxygen, carbon dioxide, or nutrients. Typical sensors currently are on the order of 0.1 m × 0.5 m and larger, with prices ranging from $1–10k, depending on what is measured and what accuracy is required. Both size and cost currently do not lend themselves to scaling of oceanographic measurements.

Toward that goal, the interest in small, low-cost, and low-power sensors in oceanography has grown in recent years, along with the technological capability to manufacture such sensors and systems. Recent examples of this are OpenCTD (Thaler et al., 2024), SEA-CO2 (Scalable, Multiparameter Chip-Size Carbon Sensor), and

Salinity sensor (Nawaz et al., 2023), and more improvements to sensors and systems are coming online (Albaladejo et al., 2010; Lee et al., 2015; Whitt et al., 2020). Interest and funding for these sensor systems comes from government agencies like Defense Advanced Research Projects Agency (e.g., Ocean of Things [Ellen, 2022]), Advanced Research Projects Agency-Energy, National Oceanographic Partnership Program, as well as foundations like Schmidt Marine Technology Partners.

For the Ecobuoy, we envision sensors that cost less than (and hopefully much less than) $1k. Examples under development include salinity and other ion sensors based on electrochemistry, as well as dissolved oxygen and nutrient sensors (Marcelli et al., 2021; Nawaz et al., 2023). To further this development, the Ecobuoy design will leverage existing sensor technologies that are already produced at scale, such as those in the medical field, as well as knowledge gained in the Internet of Things, especially for electronics integration and data management.

Communication

The purpose of a buoy's wireless communication system is to provide measured data and system status to, and to receive instructions from, the land-based operator. Performance goals for a communication system in this context include prompt delivery of messages, appropriate bandwidth for the data type and application, and low power consumption. Poor communication performance can incur costs in time and materials far beyond the baseline costs of hardware. A comparison of the major types of wireless communication, several relevant attributes is given in Table 4. Examples for Satellite and Land based Cellular Communication are Iridium, Kuiper, Starlink, and LTE-NB, SigFox, LoRa, respectively. We focus on communication options that are commercially available as opposed to, for example, the ham radio Automatic Packet Reporting Service or custom-made radio frequency systems. To ensure valid comparisons, we are also staying focused on supporting applications requiring low bandwidth, such as Conductivity Temperature Depth sensor, versus high bandwidth applications such as those requiring continuous hydrophone recording.

The current state-of-the-art for buoy communication systems is to use satellite-based communications, in particular when sighting is too far from shore to allow communication with land-based receivers. Coastal systems can access terrestrial networks like LTE-NB, SigFox, LoRa, and traditional cellular networks with an order of magnitude lower energy costs, but they must be within tens of km from shore.

The options for satellite communications have recently increased and include Iridium as the most prevalent solution alongside new players like Kuiper, Starlink, and Astranis. When comparing these options, the energy consumption per data unit sent to the user is roughly the same. Kuiper and Starlink in particular are intended for high bandwidth communication (10 s to 100 s of MB per second), where typical Ecobuoys need only enough bandwidth for ocean environment measurements and system state-of-health, much less than 1 kB per second and as low as 1 kB per day depending on application.

For high data applications, a method increasing in popularity where a high-speed Wi-Fi link is established from a visiting ship. A Wi-Fi–equipped drone, instead of a visiting ship, would reduce the cost and increase the scale at which this concept could be used to service Ecobuoys. This approach would allow transfer of even large amounts of data for low energy costs, though it has several downsides: Data latency would be limited by the speed

TABLE 4

Comparison of popular classes of wireless communication for buoys.

	Communication Class		
Requirement	**Satellite**	**Land-Based Cellular**	**Multi-Hop Mesh to Land**
Latency	Depends on sea state; link can take several minutes	Low; connection is typically available	10 ms for one hop in ideal case, depends on distance from user
Range	Anywhere on Earth	Limited to cellular towers	Multi-hop mesh can span 100s of km from shore
Typical data rate	~1 packet per hour or less	Many megabits per second	~1–10 packets per second
Energy per message/packet	Very high; > 10 J	Moderate; ~1 J	Very low; < 1 mJ per hop

of the drone's travel, and it would be difficult to scale to the number of Ecobuoys we imagine. Nonetheless, short-range communication to a visiting drone remains a potential middle-ground option for high data generators. The Iridium link would provide the GPS position and buoy health data, and a drone or ship can pick up the oceanographic data.

Today, communication of data makes up most of the energy consumption in a small buoy. Ideally, most of a buoy's energy would be available for the main mission of gathering environmental data, while the overhead of processing and communications would be minimal in a highly efficient electronics system (Leon et al., 2023). We envision that high quantities of Ecobuoys can utilize a system that hops information from buoy-node to buoy-node, passing information to the user while needing less power, fewer batteries, and therefore smaller buoy housings. This system has already been demonstrated on land at 10-km node spacing (Rady et al., 2022). It requires a higher density network of buoys, with nodes spaced at a minimum of 1 per 10 km × 10 km square. As an example, in the Gulf of Mexico, this would require 15,000 buoys, or 400,000, to cover the North Atlantic. This density would provide unprecedented spatial resolution of oceanographic properties, but also underscores the need for optimizing the cost and minimizing the ecological impact of each buoy.

Hops between nodes under ideal conditions take 10 ms, but the transmission time depends on the location of the data source and the number of hops and connection retries it must make. A network of possible paths from source to the user builds in more redundancy and therefore makes this communication system more robust. If a given hop, or link, fails, the data are queued and sent through a backup link. Data rate through these links is subject to node count and how many links exist to the Internet or other infrastructure. As an example calculation, a single high-capability root node could use 10 channels in the 915-MHz band to handle data from 1,000,000 nodes that have been aggregated through the mesh network. If each packet occupies a 10-ms communication slot, this presents an opportunity for data from each of the 1,000,000 nodes to communicate new data every 1,000 s or approximately 16 min through the mesh network and out to the Internet via this root node. With retransmissions and network overhead packets included, a practical data rate should aim to be 5–10× slower. Each packet can contain up to 127 bytes of payload, approximately 25% of which is occupied by network protocol overhead. Compression and other careful efficient uses of transmitted data can increase the number of sensor samples per packet, increasing effective throughput. More root nodes connected to the Internet, and more redundant paths will proportionally increase the rate at which each node can send new data. With mass-produced custom chips to perform data processing and communication on the order of $0.10, and commercially available chips costing a few tens of dollars today, this form of communication can also be less expensive than using satellite technology. Moving forward, we can see this technology successfully implemented in areas where buoy densities of 10 km^2 are possible, such as coastlines or other areas with high spatial variability of interest. Node-hopping communication systems could also utilize a heterogeneous buoy network, where one large, high-power, high-capability node is placed in the open ocean with many small inexpensive low-power nodes gathering spatially resolved data around it.

Discussion

Mapping the improvement potential of each subsystem onto the criteria outlined in the Requirements for a Next Generation Ecobuoy section yields Table 5 shown below. Almost all subsystems can contribute to lowering the environmental impact of a buoy at the end of life; the only system potentially not able to change quickly in this respect is the power storage unit, since its replacement with fundamentally different technology like enzyme batteries is still a few years out. Two subsystems can radically improve the reliability of data transfer and the length of deployment—switching to a node-to-node system of communication and adding a power generation system that would extend the lifetime of the buoy, ideally removing the expiration date posed by the battery altogether. The two most costly components of a buoy are the sensors and the communication system. These would be lowered substantially by utilizing small, low-cost sensors that may not have the same accuracy as their high-end counterparts, but could provide the spatial resolution needed for scientific modeling and prediction, and utilizing node-to-node communication that is much cheaper to buy and maintain than satellite connection. In addition, energy harvesting extends the lifetime of the buoy, thus bringing down the cost of a buoy network per year. An

TABLE 5

Buoy subsystems mapped to the criteria for sustainable, large scale deployment

	Reliable fast data, extended length of deployment	Lower environmental impact	Lower cost
Communication system	yes	yes	yes
Power generation and storage	yes	possibly	yes
Hull	no	yes	possibly
Sensor	no	yes	yes
Electronics	no	yes	no

ideal design solution would include maximizing the service lifetime and locating and recovering all buoys when they go out of service. However, the realities of storm damage, random system failures, and the vast size of the ocean mean we must also design Ecobuoys to be ecologically inert if they remain in the ocean indefinitely.

Not all subsystems carry the same impact on one criteria. For example, a hull made out of bioplastics or wood has a higher impact on lowering toxins from the buoy than switching the communication system to a smaller form factor node-to-node option. Furthermore, it should be noted that there are issues beyond the scope of this work that the community will need to face as we move toward implementing larger buoy networks in general, and Ecobuoys in particular. For example, maintaining an even density of buoys over long periods of time is not possible in many locations due to currents. Simulations and measurements could help here, but communication and observations that depend on an even distribution will need to plan carefully around this. Another issue is how the large amount of buoys will be deployed in practice; experiments will show if airplane, ship, or drone deployments suffice, or new engineering solutions are needed to enable these large-scale deployments. Yet another question is assessing the costs of the end product for each potential technology and subsystem. These depend on a range of factors including the logistics of sourcing the materials needed, being able to leverage existing large-scale manufacturing plants, and the size of the markets that the solution can be sold at.

Many of the ideas discussed in this manuscript could also be applied to other ocean sensing platforms, such as moored buoys and autonomous profiling floats. Profiling floats are generally not recovered (like surface drifters) and thus could greatly benefit from advancement in the systems discussed here. This is particularly true as the Array for Real-time Geostrophic Oceanography profiling float network continues to expand.

Conclusion

If we want to enable the spatial and temporal resolution of oceanographic data that the science and meteorological communities are asking for, we cannot utilize today's buoys due to their size, cost, and high environmental impact. By listing design criteria and assessing each buoy subsystem with the technologies available today, we presented a vision for the path toward the small, low-cost, and environmentally low-impact buoys needed to succeed in this endeavor. While some technologies are available off the shelf today, many of them need to be vetted for oceanographic use. A network of high-density buoys could be used for assessing coastal areas where the gradient of data is steep and results often actionable. Other applications could include areas of interest such as the Arctic and Antarctic, or other areas of interest with respect to biodiversity, climate change, or as a warning system for coastal communities. Deployment modes of the Ecobuoys as envisioned could be either as drifters, moored, or gliders. Buoys could be in a network closer to shore or around a larger "traditional" high-accuracy buoy away from shore.

As buoy manufacturers scale up to meet the demands of scientific research, pollution monitoring, and climate prediction, we recommend adopting design criteria centered on reliable data collection, cost-efficiency, and minimal environmental impact. The approach presented here is a vision toward a design approach ensuring that oceanographic data-gathering aligns with sustainable practices that can simultaneously position ocean technology as a leader in the global shift toward circular and eco-friendly design principles.

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