# Development and Implementation of a Low-Cost Electrochemistry Lab Kit for Educational Outreach: Literature Review

Student: Christopher Hunt
Mentor: Dr. Kelsey Stoerzinger

Electrochemical research holds immense potential to address challenges in energy sustainability and environmental conservation. This field encompasses work on renewable energy generation, energy storage, carbon capture, and environmental remediation, among others (citation). A cornerstone for propelling advancements in these areas is educating the next generation of engineers and scientists. However, the significant costs associated with essential instrumentation, coupled with a lack of educational resources, present considerable hurdles.

At the heart of electrochemical research lies the potentiostat, an instrument fundamental to a variety of experimental methods. Commercial potentiostats often retail for over a thousand dollars, a price point that restricts educational opportunities and limits the pursuit of electrochemical innovation (citation).

An increasing number of researchers have leveraged the rising accessibility of affordable microcontrollers, like the Arduino Uno, to develop low-cost potentiostats (citation). While these economical devices may not yet match the capabilities of their commercial counterparts, they serve as invaluable educational tools. Still a gap exists between the research and the standardization of design for academic use. Literature explored in this review has shown designs all meeting benchmark testing, however, these projects remain difficult to implement in a high school or undergraduate setting (citation). By introducing electrochemical techniques to students and resource-constrained communities, these low-cost potentiostats facilitate learning and stimulate innovation, despite financial limitations.

This review encompasses four potentiostat designs. A design by Gabriel N. Meloni from the University of Sao Paulo, refered here as The Meloni design. Another by Aaron A. Rowe, et al. from the University of Santa Barbara called the CheapStat. Another by Allison V. Cordova-Huaman, et al. called the PaqariStat. And another designed by Adrian Butterworth, et al. named the SimpleStat. These designs will be evaluated against specific criteria that align with our ambition to enhance education and outreach in Electrochemical Engineering. These criteria include: design complexity, functional efficacy, educational accessibility.

## Design Complexity

Potentiostat design complexity is a critical factor that influences both the user experience and the device's functional range. Among the four studied designs, two design approaches are discernible: the Arduino-based designs (the Meloni design and Paqari Stat) and the IC-based designs (Cheapstat and Simplestat). Each design's complexity is influenced by the hardware architecture, software implementation, and information transparency.

### Hardware Architecture

The Meloni design and the Paqari Stat employ an Arduino Uno microcontroller as the backbone of their design. Their hardware architectures are modular, composed of three primary units: a Digital to Analog Converter (DAC)/signal converter, a control amplifier, and a transimpedance amplifier. This modular design approach can facilitate problem isolation, making it easier to diagnose and resolve hardware issues. However, there are slight differences between these two designs; while the Meloni design utilizes a counter electrode to measure output current, the Paqari Stat uses the working electrode for this purpose. This difference might impact the overall measurement accuracy, stability, and noise performance of the system.

On the other hand, Cheapstat and Simplestat are centered around a surface mount IC microcontroller, a more compact and integrated approach. This kind of architecture results in reduced size and possibly lower power consumption, making these designs more suitable for field applications. However, this integrated design approach could pose challenges in terms of self-assembly and troubleshooting.

### Software Implementation

The software for the Arduino-based designs (Meloni and Paqari Stat) is programmed within the Arduino code, a high-level, user-friendly language that provides good accessibility for non-specialists or beginners. Additionally, the Paqari Stat goes a step further by incorporating a smartphone-based app, improving user interaction and data visualization capabilities. However, it could introduce a learning curve for users unfamiliar with the app's operation.

In contrast, Cheapstat and Simplestat require assembly language coding for their software. Assembly language, a low-level language, allows direct hardware control and optimization but comes at the cost of complexity. Understanding and programming in assembly language can be a challenging task, especially for beginners or non-specialists. This could limit the accessibility and adaptability of these designs to specific experimental setups or novel applications.

### Information Transparency

Another factor influencing design complexity is the transparency of the information provided in the design documents. This includes the clarity of component values, assembly instructions, and system schematics. For the Meloni design, the component values are not clearly explained, which could lead to difficulties in replicating or modifying the design.

Similarly, for Cheapstat and Simplestat, the hardware design is not well-documented. This lack of clarity could pose significant challenges during self-assembly, especially for users with limited hardware experience. The Paqari Stat design documentation appears to be more comprehensive, providing clearer guidance on component selection and assembly.

In conclusion, design complexity varies significantly among the four potentiostat designs studied. The Arduino-based designs are characterized by a more modular hardware architecture, user-friendly software, but require clear component specifications for ease of replication. On the contrary, the IC-based designs have more integrated architectures, more complex software, and require more detailed assembly documentation. The choice between these design routes will largely depend on the user's technical skills, application requirements, and available resources.

## Functional Efficacy

The functional efficacy of a potentiostat design is defined by its ability to deliver accurate and reliable measurements under various experimental conditions. Each of the four potentiostat designs - the Meloni design, Cheapstat, Paqari Stat, and Simplestat - was evaluated for their efficacy based on their performance in Cyclic Voltammetry (CV) tests using a standard potassium ferricyanide experiment.

The Meloni design has demonstrated high functional efficacy as its performance closely matched the expected results from the literature. The design follows a three-stage architecture, utilizing an 8-bit Pulse Width Modulation (PWM) signal for control, which may influence the accuracy of the results. However, it should be noted that this design is limited to performing only Cyclic Voltammetry, limiting its applicability to a narrower range of electrochemical experiments. The effect of these design choices on the device's performance in a wider range of experimental conditions is an area that warrants further exploration.

The Paqari Stat demonstrated positive results, with the device's performance falling within acceptable margins when tested against lab-grade equipment. This is an encouraging indication of its functional efficacy. Like the Meloni design, it is based on an Arduino microcontroller and follows a similar three-stage hardware architecture. The Paqari Stat, however, uses the working electrode to measure output current, unlike the Meloni design, which uses a counter electrode. This difference in design choice might have an impact on the comparative functional efficacy of the two designs, though further investigation is required to confirm this.

Although Cheapstat claims to meet lab-grade standards in the CV test, there's a conspicuous lack of elaboration on its testing parameters and the specific correlation with expected results. This limitation makes it challenging to form a definitive conclusion about its overall functional efficacy. While the Cheapstat's compact and integrated design could offer advantages in terms of portability and field usability, the potential impact of these characteristics on measurement precision and stability is not discussed.

The Simplestat's performance was also tested against a potassium ferricyanide solution, yielding positive results. Like the Cheapstat, the Simplestat utilizes a surface mount IC microcontroller and is designed around a printed PCB. The Simplestat's design incorporates an 8-bit DAC and a 10-bit ADC, allowing for a CV range of -0.6v to 0.6v. These design choices might contribute to the observed efficacy but, as with the Cheapstat, a more detailed elaboration of the testing parameters and comparative performance would enhance understanding of the design's efficacy.

The functional efficacy of each potentiostat design appears promising based on the described CV testing. However, there are clear variations in the amount of detail provided about the testing process and the specific outcomes for each design, which impacts the certainty with which conclusions can be drawn about their comparative efficacy. Moreover, the efficacy of these designs across a broader range of electrochemical experiments beyond Cyclic Voltammetry, is largely unexplored. Therefore, further comprehensive testing and detailed documentation are necessary to fully ascertain and compare the functional efficacy of these potentiostat designs.

## Educational Accessibility

Educational accessibility is a key consideration when assessing potentiostat designs, particularly in terms of their suitability for teaching environments like undergraduate laboratories. This dimension encompasses the ease of understanding the device's operation, the clarity of its assembly instructions, and the feasibility of using it as a teaching tool to elucidate fundamental electrochemical principles.

The Meloni design, with its Arduino-based approach, offers a relatively straightforward design and software implementation. It relies on a commonly used Arduino Uno microcontroller, an 8-bit signal for control, and a three-stage hardware design, all of which are concepts that are relatively easy to grasp for undergraduate students. However, one significant drawback is the lack of clear explanation of the component values, which may render it less accessible for educational purposes. While the structure of the related article does not provide clear guidance for undergraduates, it provides a promising foundation that could be built upon with more detailed instruction.

Like the Meloni design, Paqari Stat utilizes an Arduino-based approach, making it comparatively more accessible for educational use. The addition of a smartphone app for controlling the potentiostat adds an intriguing modern element that could engage students familiar with mobile technology. However, this app could also potentially act as a 'black box', obscuring the underlying processes and impeding students from fully understanding the potentiostat's operation. While this design seems as promising as the Meloni design in terms of educational potential, the role of the smartphone app in an educational setting requires further exploration.

The Cheapstat, with its surface mount IC microcontroller and assembly language coding, presents a more challenging approach for undergraduate students. Assembly language, being a low-level language, provides deeper control over hardware but at the cost of complexity and a steep learning curve. Furthermore, the hardware design is not well-documented, which can cause further obstacles to understanding and replicating the design. While Cheapstat might be more appropriate for graduate students or practicing electrochemists who seek a cost-effective field potentiostat, its educational accessibility for undergraduate students seems limited.

Similar to Cheapstat, Simplestat employs a surface mount IC microcontroller and assembly language coding. This results in a higher level of opacity in both hardware and software design, which may present significant challenges for undergraduate students with limited programming and hardware experience. Consequently, it appears more suitable for advanced users such as graduate students or professional electrochemists.

In terms of educational accessibility, the Arduino-based potentiostats (Meloni and Paqari Stat) seem more approachable for undergraduate students due to their relative simplicity and familiar software implementation. The additional smartphone interface of the Paqari Stat could be a double-edged sword, simultaneously promoting engagement while potentially limiting understanding of underlying processes. In contrast, the IC-based designs (Cheapstat and Simplestat) present higher complexity, which might pose substantial challenges for students but offer potentially richer learning experiences for more advanced users. Further research, with a focus on user experience in a real educational setting, could provide valuable insights into the educational accessibility of these designs.