

Article

Directly coupled photovoltaic alkaline electrolysis with low-cost carbon and stainless-steel electrodes: an exploratory assessment of single-axis solar tracking at sub-watt scale

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ABSTRACT

Hydrogen produced by wiring a solar array directly to an electrolyzer, with no battery or power electronics in between, is cheap to build, but little data exists on how such systems behave at very small scales. We built a 1.6 W-rated photovoltaic (PV) array and coupled it directly to a two-electrode alkaline cell (3.6 M NaOH). Two inexpensive electrode materials were tried: carbon rods recovered from spent dry cells and grade 304 stainless steel. Each was run at a fixed tilt with an Arduino-controlled single-axis tracker on one clear and one overcast day in Chattogram, Bangladesh, yielding eight configurations. Current and voltage were read every 5 minutes for 60 minutes. Charge and energy were obtained by trapezoidal integration. Hydrogen is reported only as a charge-derived equivalent from Faraday's law, not as a measured volume. The cell received 1.8 to 24.7 mW, equivalent to 0.08 to 0.73 mL of hydrogen per hour. Mean cell voltages ranged from 7.9 to 16.1 V, indicating that ohmic and contact losses, not electrode kinetics, control the cell; voltage efficiency relative to the thermoneutral potential was only 9 to 19%. With carbon under a clear sky, tracking raised the energy delivered to the cell by 35%. However, the tracker used an estimated 180 to 720 J in the same hour, while the cell received at most 89 J, so tracking lost energy in every configuration we tested. A first-order break-even estimate puts the point where tracking starts to pay at about 0.9 to 2.0 W of delivered electrolysis power, some 35 to 80 times our load. Every configuration was run once, so the results are indicative only. The main finding is that active tracking is a net energy sink below about 1 W. We also identify the losses that limit the performance of directly coupled cells of this size.

Keywords: *Hydrogen production, Electrolyzer, Photovoltaic (PV), Electrode material*

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1. INTRODUCTION

Burning fossil fuels warm the climate, and their reserves are finite. Global greenhouse gas emissions reached 52 billion tons of CO₂ equivalent in 2022, underscoring the urgency of the shift to renewable sources [1]. Solar power is a strong alternative because sunlight is abundant and panels keep getting cheaper. Its weaknesses are intermittent output and modest conversion efficiency.

This is why so much work focuses on getting more energy from each panel through maximum power point tracking (MPPT) and mechanical solar tracking [2]. Hydrogen made by electrolyzing water with renewable electricity, usually called green hydrogen, is a candidate fuel for sectors that are difficult to electrify directly, such as heavy industry and long-distance transport [3]. The color labels describe the production route: green for renewable electrolysis, blue for fossil feedstock with carbon capture, and grey for fossil

feedstock without it [4]. Australia, China, France, Germany, the UK, and the US have all invested heavily in hydrogen technology. Fossil-based hydrogen currently costs about \$1 to \$3 per kilogram, and green hydrogen is still more expensive [5-11].

Abbreviations

SS	Stainless steel electrode
C	Carbon electrode
CS	Clear sky condition
DS	Cloudy sky condition
T	The solar tracking system is active.
NT	Non-tracking (fixed tilt) system
SS-CS-NT	Stainless steel, clear sky, non-tracking
SS-CS-T	Stainless steel, clear sky, tracking
SS-DS-NT	Stainless steel, cloudy sky, non-tracking
SS-DS-T	Stainless steel, cloudy sky, tracking
C-CS-NT	Carbon, clear sky, non-tracking
C-CS-T	Carbon, clear sky, tracking
C-DS-NT	Carbon, cloudy sky, non-tracking
C-DS-T	Carbon, cloudy sky, tracking
LDR	Light-Dependent Resistor
PLA	Polyactic acid
IDE	Integrated Development Environment
STP	Standard Temperature and Pressure
Q _A	Cumulative charge for SS-CS-NT (Stainless steel, clear sky, no tracking)
Q _B	Cumulative charge for SS-CS-T (Stainless steel, clear sky, tracking)
Q _C	Cumulative charge for C-CS-NT (Carbon, clear sky, no tracking)
Q _D	Cumulative charge for C-CS-T (Carbon, clear sky, tracking)
Q _E	Cumulative charge for SS-DS-NT (stainless steel, cloudy sky, no tracking)
Q _F	Cumulative charge for SS-DS-T (stainless steel, cloudy sky, tracking)
Q _G	Cumulative charge for C-DS-NT (carbon, cloudy sky, no tracking)
Q _H	Cumulative charge for C-DS-T (carbon, cloudy sky, tracking)
HA	Charge-equivalent hydrogen yield for SS-CS-NT
HB	Charge-equivalent hydrogen yield for SS-CS-T
HC	Charge-equivalent hydrogen yield for C-CS-NT
HD	Charge-equivalent hydrogen yield for C-CS-T
HE	Charge-equivalent hydrogen yield for SS-DS-NT
HF	Charge-equivalent hydrogen yield for SS-DS-T
HG	Charge-equivalent hydrogen yield for C-DS-NT
HH	Charge-equivalent hydrogen yield for C-DS-T

Low-cost carbon already has a place in solar energy hardware, mainly on the thermal side. Porous carbon nanoparticles improve flat-plate collector efficiency by increasing thermal conductivity and enhancing optical properties [12]; eco-friendly MWCNT/hBN hybrid nanofluids improve energy and exergy performance [13]; and green-synthesized graphene nanoplatelet/MWCNT hybrids slow mineral fouling [14]. All of this is heat-transfer work. We do not suggest that it carries over to the hydrogen evolution reaction. We cite it only to show that cheap carbon is an accepted functional material in solar systems.

A single-axis tracker keeps the panel pointed at the sun and can raise PV energy yield by 15 to 25% [15]. It is also simpler and cheaper than a dual-axis design [2]. Several groups have combined tracking or concentration with electrolysis. Parawan and Tayactac [16] powered an electrolyzer from parabolic-reflector concentrated solar power. Choi and Bhakta [17] sized grid-tied hybrid PV-hydrogen systems for vehicle charging. Gutierrez-Martin et

al. [18] modeled integrated PV-hydrogen systems but did not experimentally validate the model. Other related work is less direct. Kumba et al. [15] reviewed tracking technology without touching hydrogen; Ajeeb et al. [19] reviewed life cycle assessments of commercial electrolysis; Kabir et al. [35] combined membrane distillation with alkaline electrolysis using specialized materials; Roucham et al. [20] found in a bibliometric survey that experimental integration studies are still rare, and Arunachalam et al. [21] looked at the capital cost of renewable-powered desalination coupled to hydrogen production. The wider literature covers photoelectrochemical and thermochemical routes [22], PV emulator test rigs [23], maximum current point tracking [24], off-grid techno-economics [25], liquid organic hydrogen carriers [26-29], GIS-based siting [30], decentralized cooking [31], and microbial electrolysis cells [32]. Nearly all of it is at kilowatt scale or larger, or is simulation only. We found no report of a directly coupled cell in the milliwatt range, where the tracker's own power draw is about as large as the electrolysis load. Table 1 sets these studies beside ours.

Three gaps remain in the literature on directly coupled solar electrolysis. The first is electrode cost. Most experiments use noble metals, which work well but are too expensive for low-budget deployment, and the few studies with stainless steel or nickel did not test them under active tracking and real, changing irradiance. The second is buffering. Most solar-to-hydrogen systems place a battery, supercapacitor, or the grid between the panel and the cell, so little is known about a cell with no buffer. The third gap matters most for this paper: the system energy balance almost never includes the energy used by the tracking mechanism, even though at small scale it can exceed the energy reaching the electrolyzer. We address the third gap directly and add exploratory observations on the other two.

Our question is narrow. In a directly coupled PV-alkaline cell working at milliwatt level, how do current, voltage, charge, and energy differ between recovered carbon and stainless-steel electrodes, with and without single-axis tracking, under clear and overcast skies? And once the tracker's own consumption is counted, is there any net gain? The second part is what a designer needs to know. For a system of this size, the answer is no. The study is exploratory. Each configuration was run once, so we report no standard deviations, confidence intervals, or significance tests, and the differences between configurations are indications, not established effects. The electrode materials are widely used, and we claim nothing new about them.

We add an explicit energy account of the tracker at the sub-watt scale and note that ohmic loss is the main limit in a cell of this geometry. The work had four practical steps. We built an Arduino-based single-axis tracker on a 3D-printed frame. We built an alkaline electrolyzer with carbon and stainless-steel electrodes. We recorded current and voltage for each electrode material with and without tracking, under clear and cloudy skies. Finally, we compared charge, energy input, and charge-equivalent hydrogen yield across the eight configurations and set the tracker's consumption against the energy it gained.

Table 1. Overview of prior research and the research gap filled by this study

Focus	Material for Electrodes	Tracking	Buffering and Storage	Principal Restrictions	Study / Topic
CSP-driven electrolysis	Not specified	Yes (CSP)	Not disclosed	No low-cost material comparison	Parawan & Tayactac [16]
Grid-tied PV-H ₂ system	Commercial (PEM)	Yes	buffer for batteries	Costly electrodes and reliance on the grid	Choi & Bhakta [17]
Modeling PV-H ₂	Not experimental	No (model)	Storage is part of the model.	Absence of experimental confirmation	Gutiérrez Martín et al. [18]
Membrane distillation + AWE	Specialized membranes	No	None	No tracking, specialized materials	Kabir et al. [35]
LCA of electrolysis	Commercial	Not taken into account	Not taken into account	Absence of experimental data	Ajeeb et al. [19]
Carbon nanofluids for fouling mitigation	Carbon nanomaterials (thermal)	N/A	N/A	Thermal application – not electrochemical	Shaikh et al. [14]
Low-cost, direct solar-to-H ₂ electrodes	Carbon & SS	Yes/No comparison	No storage	Milliwatt-scale study; tracker parasitic load entered into the system energy balance; single unreplicated run per configuration	This study

Section 2 describes the apparatus, materials, and procedure. Section 3 presents the results for current, voltage, charge, hydrogen-equivalent, and energy. Section 4 interprets them, works out the tracker energy balance, and compares the study with earlier work. Section 5 presents the conclusions and the remaining work needed.

2. MATERIALS AND METHODS

2.1 Experimental setup overview

The apparatus (Figure 1) has four parts: a solar panel array, an Arduino-based single-axis tracker, an alkaline electrolyzer, and the measuring instruments. No energy storage exists between the panels and the cell. The array's DC output goes straight to the electrodes. Figure 1b shows the assembled rig, with the electrolysis cell wired to the tracked panel. An Arduino UNO (Figure 1a) reads two light-dependent resistors and drives a servo that turns the panel. A 3D-printed cell (Figure 1c) holds NaOH electrolyte, and we tested the two electrode materials separately. Figures. 1d and 1e show gas bubbles on the carbon rod and on the stainless-steel bolt, so the cathodic reaction runs on both. The bubbles look more evenly spread on the carbon, but we only saw this in single photographs. We do not treat it as evidence of a different reaction rate or active area.

2.2 Solar tracking system design and programming

The array consists of four polycrystalline mini epoxy panels in series (5 V and 80 mA each, 0.0094 m² active area, manufacturer-stated efficiency about 11.7%), for a nominal rating of 1.6 W. Clear-sky irradiance, measured with a handheld pyranometer, averaged about 1000 W/m² at solar noon. One point affects everything that follows.

The electrolyzer drew only 1.5 to 2 mA, while the array is rated at 80 mA, so the array was always far from its maximum power point. In every configuration, the cell was the limiting element, not the array. The tracker uses an Arduino UNO, two light-dependent resistors, an SG90 servo, and a PLA frame we designed in SOLIDWORKS and 3D-printed (Figure 2 and Figure 3). It uses a 3.7 V Li-ion battery. The servo draws 0.2 W while turning and 0.05 W when holding position, and the Arduino UNO adds another 0.25 to 0.5 W depending on regulator losses.

Over a 60-minute run, the servo therefore uses between about 180 J (idle the whole time) and 720 J (moving the whole time), before the controller is counted. This energy came from the battery, not from the array, so it is not part of the electrolyzer energy figures in Section 3.4. We account for it separately in Section 4.3, where it turns out to be larger than the energy delivered to the cell in every configuration. The tracking code uses a $\pm 10^\circ$ tolerance to prevent servo jitter. The full code is given in the supplementary material, Appendix 1. Servo travel is limited to 0-180°, and the panel starts at 90°, facing south at the optimum tilt of 25° [34]. With tracking switched off, the panel stays fixed at this tilt.

The frame was designed in SOLIDWORKS 2024. It has a flat base plate with filleted corners. The rotating shaft can be removed and adjusted to fit the servo's output shaft, and the servo support was made thicker to carry the motor's weight. We printed the parts in PLA (polylactic acid), which is biodegradable and convenient for prototyping. A metal frame would be the better choice for a permanent installation.

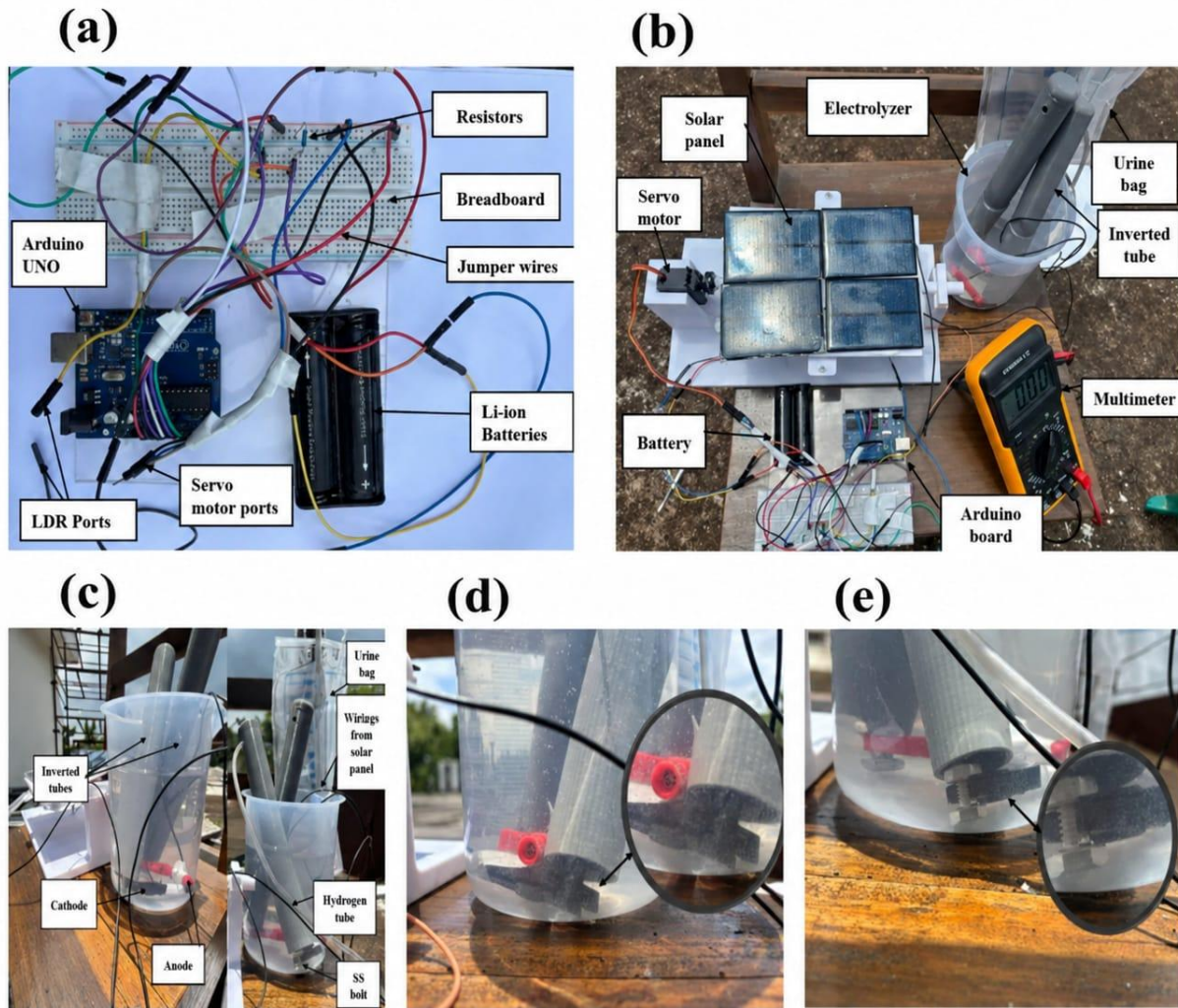


Figure 1. Overview of the experimental apparatus for hydrogen generation: (a) Arduino UNO-based circuit board controlling the tracking servo motor; (b) experimental setup; (c) hydrogen-generating electrolyzer; (d) hydrogen bubble formation at the cathode using a carbon electrode; (e) hydrogen bubble formation at the cathode using a stainless-steel electrode.

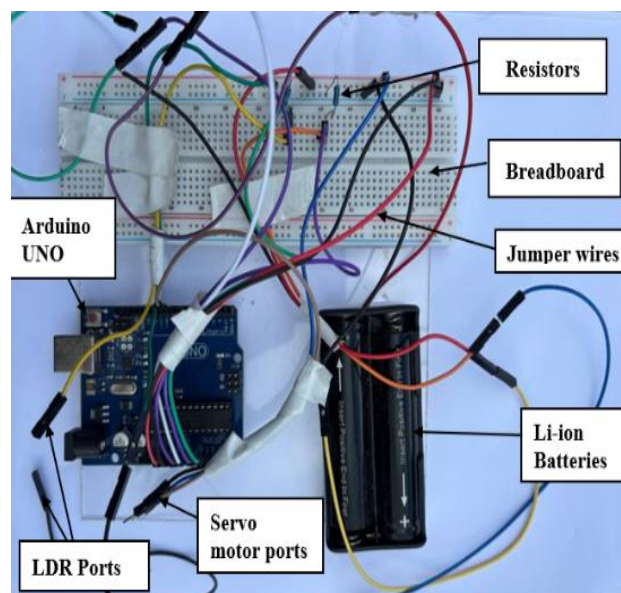


Figure 2. Electronics and programming of the single-axis solar tracker. (a) Breadboard assembly with Arduino UNO, LDR ports, servo motor connections, and Li-ion battery power supply

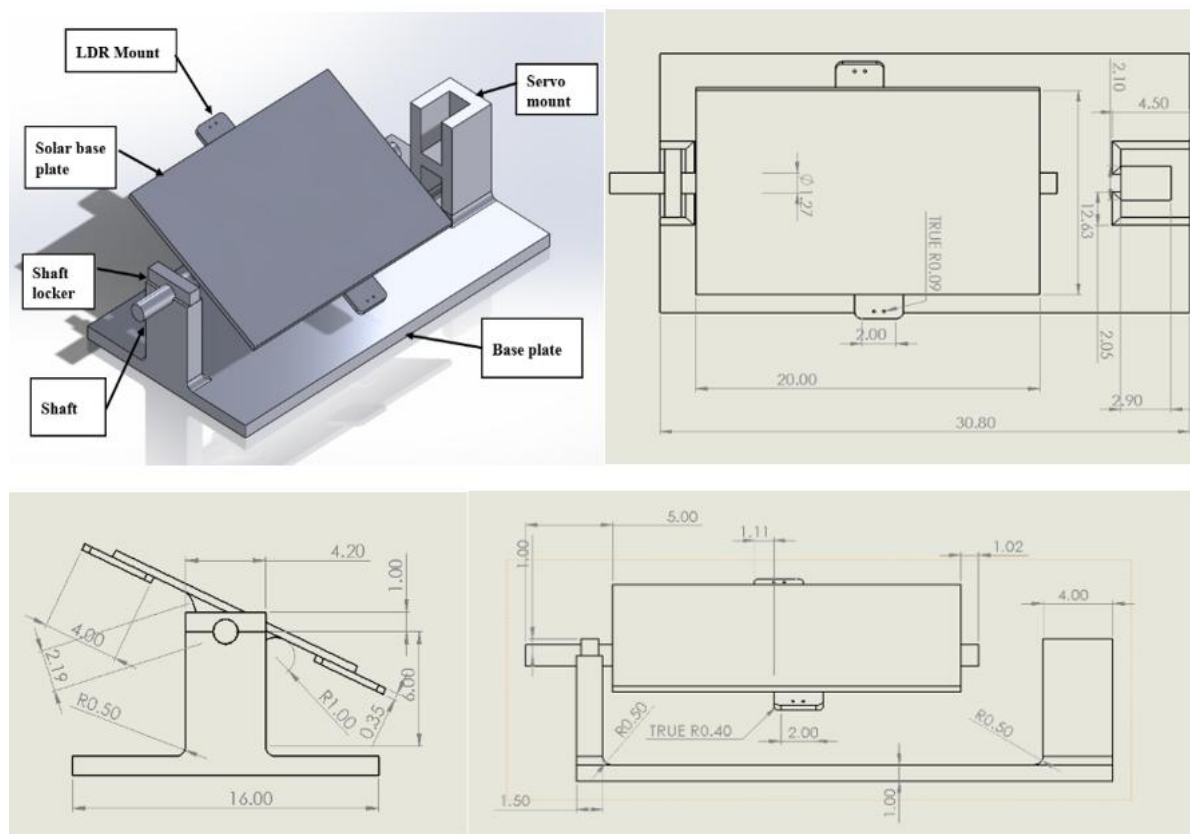


Figure 3. Computer-aided design (CAD) models of the solar tracking hardware. (a) Isometric view of the complete 3D-printed frame assembly showing the mounting positions for the LDRs, servo motor, and solar panel (top left corner). (b) Orthographic projections with critical dimensions (in cm) for manufacturing the PLA components (3 views of the mechanical drawings).

The series-connected panels are light, so we fixed them to the frame with double-sided epoxy. A clamp would have blocked heat transfer from the panels and reduced their efficiency. The epoxy does not interfere with the wiring or the output at any panel position. Figure 3 gives the dimensions needed to manufacture the frame.

2.3 Electrolyzer fabrication and electrode materials

The electrolyzer is a 3D-printed cylindrical cell (Figure 4) that holds 800 mL of electrolyte and has two electrode holders. It is a plain two-electrode arrangement: there is no reference electrode and no separator or membrane between the half-cells. Two electrode materials were tested, one at a time:

- Stainless steel bolts (Grade 304, 6 mm diameter)
- Carbon rods (extracted from used D-size dry cells, ~5 mm diameter)

The electrolyte was 3.6 M NaOH. We dissolved 115.49 g of NaOH pellets (98% purity) in 800 mL of distilled water and stirred until the solution was uniform. We chose this concentration because it is close to the conductivity maximum of aqueous NaOH at ambient temperature. It is stronger than the 1 to 2 M normally used in laboratory cells, making it more hazardous to handle and more corrosive; we count this as a limitation of the present set-up. The electrode reactions are:

Cathode: $4\text{H}_2\text{O}(\text{l}) + 4\text{e}^- = 2\text{H}_2(\text{g}) + 4\text{OH}^-(\text{aq})$ (Reduction reaction)

Anode: $4\text{OH}^-(\text{aq}) = \text{O}_2(\text{g}) + 2\text{H}_2\text{O}(\text{l}) + 4\text{e}^-$ (Oxidation reaction)

Net reaction: $2\text{H}_2\text{O} = 2\text{H}_2 + \text{O}_2$

Oxygen was vented to the air. The gas from the cathode went through silicone tubing to a collection bag. The bag graduations are much coarser than the volumes we produced, and we did not evacuate the tubing or the cell headspace before each run, so the bag readings cannot be used as quantitative data. For this reason, we report every hydrogen yield in the paper as a charge-derived equivalent, calculated from the measured charge using Faraday's law (Section 2.5.2). We report no directly measured gas volumes. This is a serious limitation, and we return to it in Section 4.7.

2.4 Experimental procedure

We conducted the runs on two days. Day 1 was clear (ambient temperature 35 °C, relative humidity 55%, wind speed <2 m/s) and Day 2 was overcast (31 °C, relative humidity 70%). Each run followed the same steps:

1) Set-up: for non-tracking runs, the array faced south at a fixed tilt of 25°, and for tracking runs, the Arduino tracker was switched on. The cell was filled with 800 mL of freshly prepared 3.6 M NaOH. The collection bag was attached to the cathode outlet tube and held upright. As explained in Section 2.3, the bag was not evacuated, and its graduations were too coarse for these volumes, so we did not use its readings quantitatively.

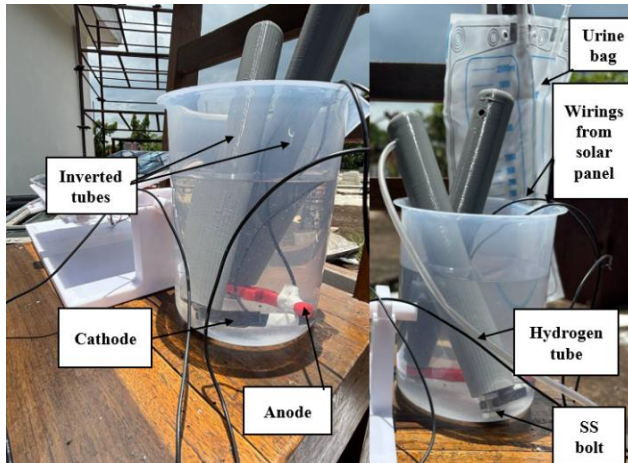


Figure 4. Experimental electrolysis setup. The cathode (SS bolt) generates hydrogen bubbles, which travel through the hydrogen tube to the inverted collection bag. The anode simultaneously produces oxygen gas. All components are labeled to show the complete gas collection pathway

- 2) The panel output was connected to the electrodes to close the circuit.
- 3) A stopwatch was started at the moment the circuit was closed, and each run lasted 60 minutes.
- 4) Every 5 minutes, we recorded current (mA) and voltage (V) with a digital multimeter (UNI-T UT139C; $\pm 0.5\%$ for voltage, $\pm 1\%$ for current). One meter was used for both, switched between series and parallel connections, so the two readings at each time point were taken one after the other and not together. The gap between them was about 10 to 15 s, and irradiance can change in that time.

On Day 2, when conditions were partly variable, this adds an error to the instantaneous power product that the instrument tolerance does not cover. We estimate it could reach 10 to 15% on individual points, although much of it should cancel over the 60-minute integration.

- 5) At the end of the 60 minutes, the volume in the collection bag was noted.

6) Each of the eight configurations was run exactly once, with no replicates. This is the study's main methodological weakness. Without replicates, we cannot calculate a standard deviation, confidence interval, or significance test, and we cannot separate differences between configurations from day-to-day and run-to-run variation. Each sky condition is also a single day, not a sample of days. Every comparison below should be read as exploratory.

Four configurations were tested on the clear day, each for 60 minutes:

SS-CS-NT: Stainless steel electrodes, clear sky (Day 1, $\sim 35^\circ\text{C}$), tracking off.

SS-CS-T: Stainless steel electrodes, clear sky, tracking active.

C-CS-NT: Carbon electrodes, clear sky, tracking off.

C-CS-T: Carbon electrodes, clear sky, tracking active.

The same sequence was repeated on the cloudy day (Day 2, $\sim 31^\circ\text{C}$) to give the four cloudy-sky configurations (SS-DS-NT, SS-DS-T, C-DS-NT, C-DS-T).

The raw current and voltage readings at every 5-minute point for all eight configurations are given in the supplementary tables in [Appendix 2](#).

2.5 Theoretical calculations

2.5.1 Charge accumulation

Faraday's laws state that the mass of product formed is proportional to the quantity of electricity passed [14]. We calculated the total charge Q passed through the electrolyzer from the current readings with the trapezoidal rule:

$$Q = \int_0^t I(t) dt \approx \frac{\Delta t}{2} [I_0 + 2I_1 + 2I_2 + \dots + 2I_{n-1} + I_n] \quad (1)$$

where $\Delta t = 300\text{s}$.

2.5.2 Hydrogen volume

From Faraday's law:

$$\text{Volume of } H_2 (\text{mL}) = \frac{Q}{nF} \times V_m \times 1000 \quad (2)$$

where $n=2$ (electrons per mole of H_2), $F=96485\text{ C/mol}$ [37], and V_m is the molar volume at experimental temperature and pressure (1atm). $V_m = RT/P$ with $R=0.082057\text{ L.atm/(mol.K)}$. For Day 1, $T=308\text{K}$, $V_m = 25.27\text{L/mol}$; for Day 2 ($T=304\text{K}$), $V_m = 24.95\text{L/mol}$. The factor 1000 converts liters to milliliters.

2.5.3 Energy input

The electrical energy supplied to the electrolyzer was found by integrating the product of voltage and current:

$$E = \int V(t) \times I(t) dt \approx \sum \frac{\Delta t}{2} [V_i I_i + V_{i+1} I_{i+1}] \quad (3)$$

2.6 Data analysis

All calculations were done in Microsoft Excel. Cumulative charge and energy were plotted against time for each configuration. With one run per configuration, there was nothing to test statistically, so no statistical tests are reported. Instrument precision tells us the resolution of a single reading; it does not replace replication. We describe the differences between configurations qualitatively and do not claim that any of them is statistically significant.

2.7 Assumptions

We made the following assumptions. (i) Hydrogen yield is calculated from the measured charge with Faraday's law at 100% Faradaic efficiency. This is an upper bound, not an estimate, because carbon oxidation, carbonate formation, and oxygen crossover would all lower the real figure. (ii) The molar volume of hydrogen is taken from the ideal gas law at 1 atm and ambient temperature (308 K or 304 K). (iii) NaOH concentration is constant during each 60-minute run. (iv) The tracker is powered by its battery, so its consumption is left out of the electrolyzer energy figures and treated separately in Section 4.3. (v) All comparisons rest on single runs and are exploratory.

3. RESULTS

3.1 Current-voltage characteristics

Current and voltage were read every 5 minutes, which shows how each configuration behaved under real sunlight. Figures 5 to 8 give the current and voltage traces over the 60-minute run for the four clear-sky configurations. [Figure 5](#) is the stainless-steel cell without tracking (SS-CS-NT). The current varies significantly during the run, from a minimum of 0.617 mA to a maximum of 1.512 mA. That is expected with a fixed panel, because the light falling on it changes as the sun moves. The voltage behaves similarly and stays between 11.26 V and 14.31 V. The power reaching the electrodes is therefore uneven throughout the run.

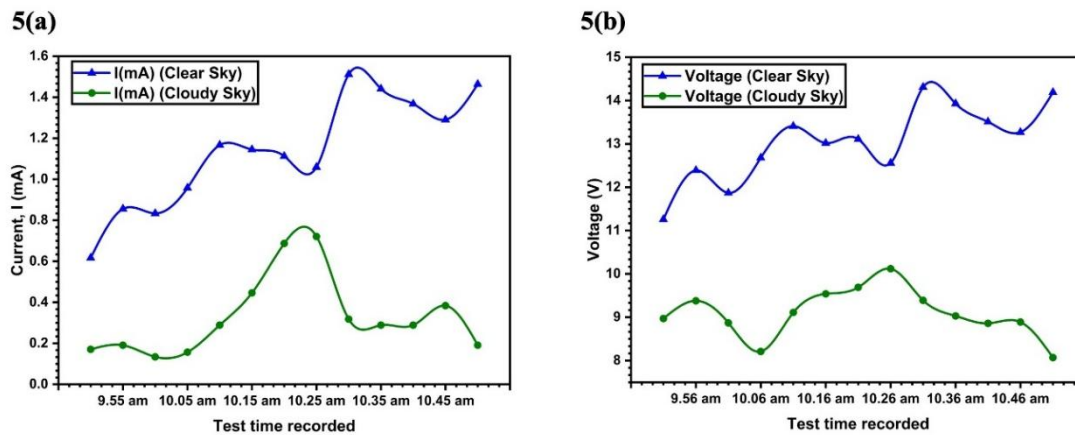


Figure 5. Stainless steel electrode without tracking system: (a) Current vs. time curve; (b) voltage vs. time curve

Figure 6 is stainless steel with the tracker running (SS-CS-T). The current ranged from 0.464 mA to 1.568 mA, and its swings were less abrupt. The voltage changed more clearly, staying high throughout the run, between 14.59 V and 17.88 V. The tracker was evidently keeping the panel better aligned with the sun. However, the current was not much higher than without tracking, suggesting the limit lies in the cell, not the supply.

Figure 7 is carbon without tracking (C-CS-NT). The current (1.012 mA to 1.589 mA) is higher than in either stainless steel run, even though the solar input varied. The voltage ranged from 14.13 V to 17.21 V, about the same as stainless steel with tracking. On this run, the carbon cell drew more current at a similar voltage. Whether that is a property of the material is examined in Sections 3.2 and 4.2.

Figure 8 is carbon with tracking (C-CS-T). It gave the highest current of all eight configurations, peaking at 1.94 mA, while the voltage stayed between 16.38 and 18.81 V. The high, fairly steady voltage fits a tracker that is holding the panel on the sun. The current also rose, but proportionally less than the voltage, as discussed in Section 4.1. On the cloudy day (supplementary tables in Appendix 2), current and voltage were much lower in every configuration. Carbon with tracking still gave the highest values among the four cloudy-sky runs.

Figure 9 puts the current traces of all eight configurations on one plot, with current from 0.0 to 2.0 mA and time from 0 to 4000 s. Each curve is one combination of electrode material, sky condition, and tracking state. Carbon with tracking under a clear sky (yellow) carries the highest current. It peaks near 1.94 mA at about 1200 s, and this run also has the highest total energy, 89.06 J. Carbon without tracking under a clear sky (cyan) peaks at 1.59 mA. The current in both carbon runs changes less abruptly than in the matching stainless-steel runs. With single runs, though, we cannot say whether that comes from the material or from different cloud passage during each run. Stainless steel with tracking under a clear sky (green) peaks at 1.57 mA and accumulates 4.457 C. That is slightly less charge than the same material without tracking (black, 1.51 mA peak, 4.550 C), although the tracked cell received 22% more energy.

Tracking raised the mean operating voltage for stainless steel from 12.0 V to 15.0 V, but the current did not increase proportionally. This is what we would expect if the extra potential is lost across solution and contact resistance and does not drive the electrode reaction.

Under an overcast sky, all the currents are much lower. Carbon with tracking (brown) is the highest of the four, with a 0.89 mA peak and 2.422 C accumulated; carbon without tracking (pink) peaks at 0.69 mA and accumulates 1.260 C. The proportional gap is larger than on the clear day. Tracking may help more when direct irradiance is scarce, but with one run per condition, we cannot separate this from differences in cloud cover between the two runs.

Stainless steel with tracking under an overcast sky (blue) is the lowest of the eight: a 0.29 mA peak and 0.637 C. Stainless steel without tracking (red) did better, with a 0.72 mA peak and 1.311 C. The tracker had its own battery, so it could not have drawn energy from the cell, ruling out tracker load as the cause. More likely, the cloud cover changed between the two consecutive runs, or the contact or surface condition differed between electrode mountings. We controlled neither, and with single runs we cannot take the observation further.

Taken together, the traces show carbon carrying more current than stainless steel when the tracker is running. At fixed tilt, the two materials are within 2% of each other in accumulated charge under a clear sky and within 4% under an overcast sky, where stainless steel is slightly ahead. The fixed-tilt data therefore show no advantage for carbon, and the apparent advantage under tracking rests on single runs. The multimeter tolerances of $\pm 0.5\%$ for voltage and $\pm 1\%$ for current describe reading resolution only.

3.2 Charge accumulation

Cumulative charge describes a whole run better than individual readings, and unlike the gas volumes, it comes directly from instrument measurements. Table 2 lists the charge accumulated after 60 minutes in each configuration, and Figure 10 shows how it built up.

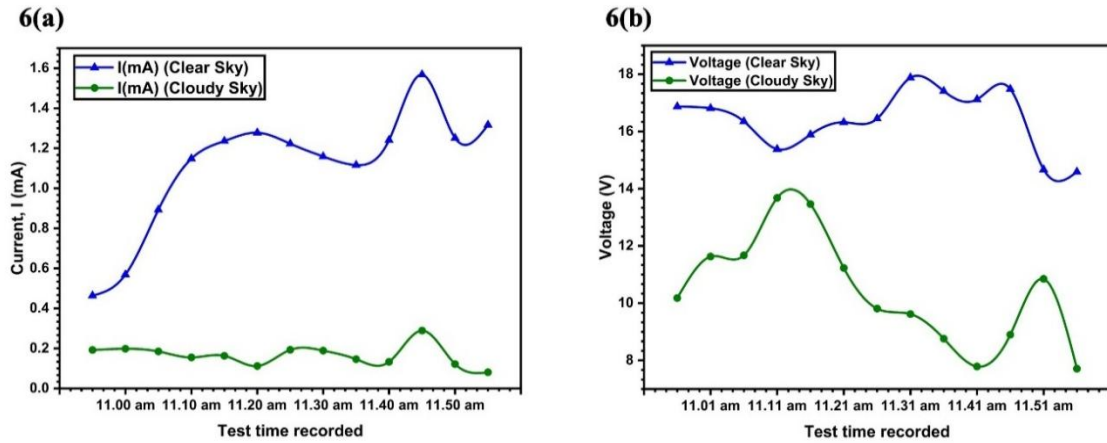


Figure 6. Stainless steel electrode with tracking system: (a) Current vs. time curve; (b) voltage vs. time curve

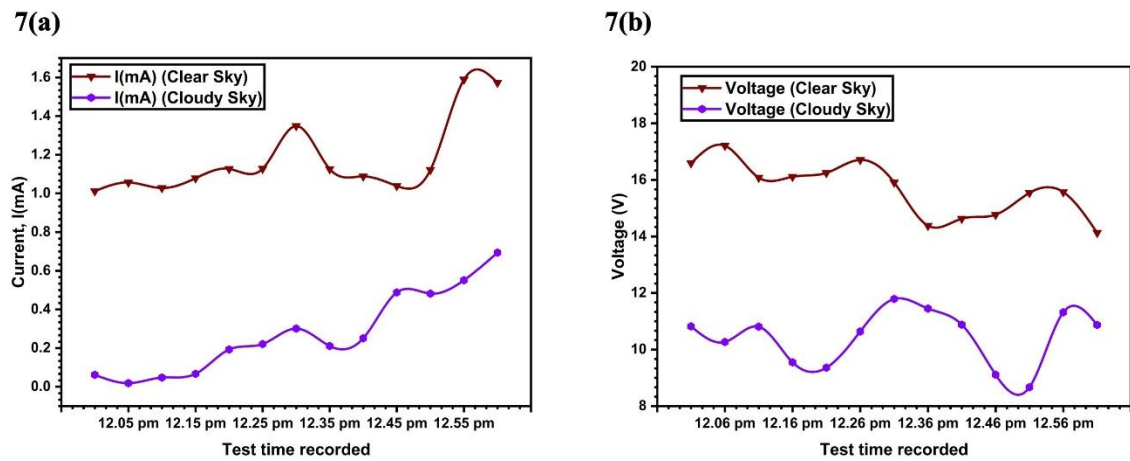


Figure 7. Carbon rod without tracking system: (a) Current vs. time; (b) voltage vs. time curve

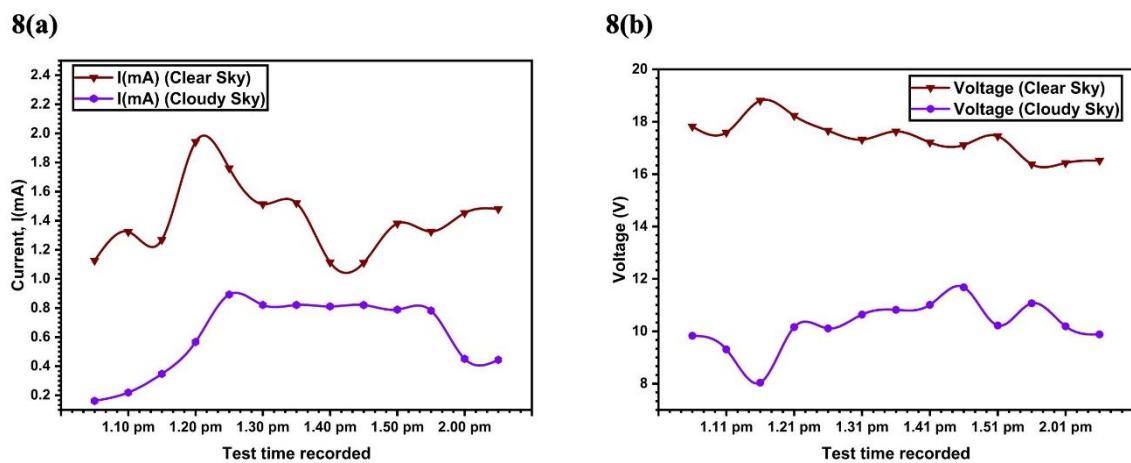
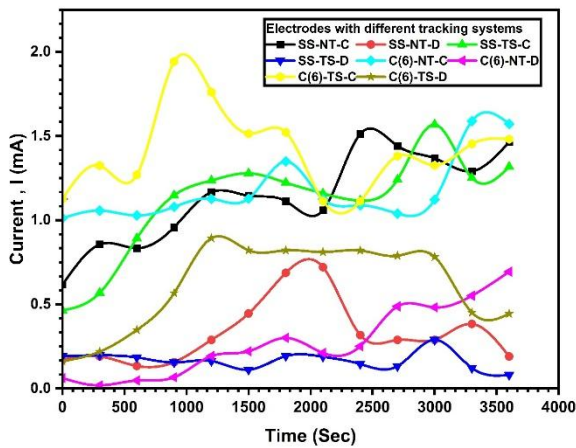
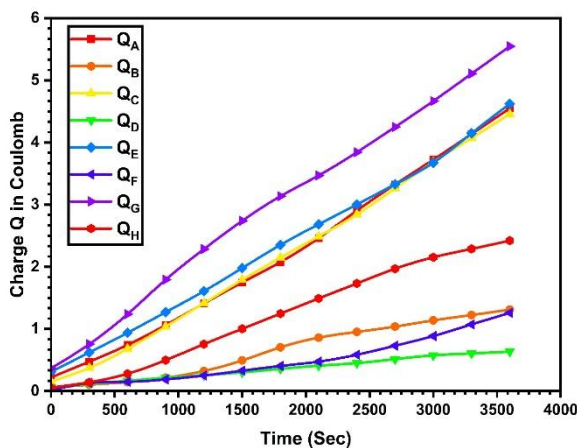


Figure 8. Carbon rod with tracking system: (a) Current vs. time; (b) Voltage vs. time

Table 2. Final cumulative charge (C) for all configurations

Configuration	Charge (C)
SS-CS-NT	4.550
SS-CS-T	4.457
C-CS-NT	4.623
C-CS-T	5.547
SS-DS-NT	1.311
SS-DS-T	0.637
C-DS-NT	1.260
C-DS-T	2.422

**Figure 9.** Current against time (s) for all eight configurations. SS denotes stainless steel and C(6) carbon (6 is the atomic number of carbon); NT is non-tracking, and TS is tracking; C is clear sky, and D is dark (cloudy) sky.**Figure 10.** Cumulative charge vs. time curve

In Figure 10, the slope of each curve at any point is the instantaneous current, so a steeper curve means a higher current. On the clear day, carbon with tracking (C-CS-T) accumulated the most charge (5.547 C), and its curve was steeper than the others throughout the run. Carbon without tracking (C-CS-NT) reached 4.623 C and stainless steel without tracking (SS-CS-NT) 4.550 C. That 1.6% difference

is well within the run-to-run variation expected in an unreplicated outdoor experiment. Stainless steel with tracking (SS-CS-T) reached 4.457 C, slightly less than without tracking, despite receiving 22% more energy. On the overcast day, charge fell sharply in every configuration. Carbon accumulated 2.422 C with tracking (C-DS-T) and 1.260 C without. Stainless steel accumulated 0.637 C with tracking and 1.311 C without. So, on this day the two materials responded to tracking in opposite directions. The tracker took no power from the array, so its load cannot explain the stainless-steel result. Unmeasured variation in cloud cover between consecutive runs is the more plausible cause, and single runs cannot settle it.

3.3 Charge-derived hydrogen equivalent and cell efficiency

Because the collection method could not quantify gas volumes (Section 2.3), we report hydrogen yield here as a charge-derived equivalent, calculated from the measured charge using Faraday's law. Table 3 lists the mean delivered power, mean cell voltage, and resulting voltage efficiency for the eight configurations.

3.3.1 Basis of the hydrogen figures

The hydrogen yields in this study were not measured. The collection arrangement in Section 2.3 cannot resolve volumes of 0.1 to 1 mL, and because the line and headspace were not purged, any reading would include an unknown volume of displaced air. The yields in Table 3 are calculated from the measured charge with the Faraday relation of Section 2.5.2. The result is an upper bound on hydrogen production because it assumes every transferred electron produces hydrogen. For an alkaline cell with recovered carbon electrodes, this is optimistic. Table 4 summarizes the system energy balance, including tracker parasitic consumption, over each 60-minute run.

Carbon can oxidize at the anode, dissolved CO_2 can form carbonate, and rods taken from dry cells may carry metallic residue; each can consume charge or release gas without net water splitting. Faradaic efficiency can only be found by analyzing the gas composition, which we did not do, and we claim no Faradaic efficiency anywhere in this paper. Deriving hydrogen from charge has one consequence worth noting: the specific yield in mL per watt-hour becomes a function of mean cell voltage alone. The voltage efficiencies in Table 3, 9.2 to 18.7%, are therefore the more useful numbers. They are low because the cell ran at 7.9 to 16.1 V across a single electrode pair, while the thermoneutral potential is 1.48 V. Between 85 and 91% of the applied potential went into solution resistance, contact resistance, and the wide gap between the electrodes, and not into the reaction. This loss, and not any difference between carbon and stainless steel, dominates the system.

Figure 11 shows the charge-equivalent hydrogen accumulation for all eight configurations, derived from the measured charge in Figure 10 using Faraday's law. Figure 11 has no error bars. The plotted quantity is derived from measured charge, and its main uncertainty is not the $\pm 1\%$ current tolerance. The main uncertainties are the lack of replication and the unverified Faradaic assumption, neither of which can be represented as an error bar on a single trace. The charge-equivalent hydrogen yields range from 0.08 to 0.73 mL/h.

Table 3. Delivered power, mean cell voltage, charge-equivalent hydrogen yield, and voltage efficiency for all eight configurations. Hydrogen values are upper bounds derived from measured charge, assuming 100% Faradaic efficiency, not measurements. Voltage efficiency is the thermoneutral potential (1.48 V) divided by the mean cell voltage.

Configuration	Mean delivered power (mW)	Mean cell voltage (V)	Charge-equivalent H ₂ (mL/h)	Voltage efficiency (%)
SS-CS-NT	15.19	12.02	0.60	12.3
SS-CS-T	18.59	15.02	0.58	9.9
C-CS-NT	18.32	14.27	0.61	10.4
C-CS-T	24.74	16.06	0.73	9.2
SS-DS-NT	3.19	8.75	0.17	16.9
SS-DS-T	1.77	10.00	0.08	14.8
C-DS-NT	2.76	7.90	0.16	18.7
C-DS-T	6.67	9.92	0.31	14.9

Table 4. System energy balance, including tracker parasitic consumption, over each 60-minute run. Tracker energy is bounded using the servo draw stated in Section 2.2 (0.05 W idle to 0.2 W active); the Arduino controller is additional and is not included in these bounds.

Configuration	Electrolyzer energy (J)	Tracker energy (J)	Net system energy (J)
SS-CS-NT	54.69	0	+54.69
SS-CS-T	66.93	180 to 720	-113 to -653
C-CS-NT	65.96	0	+65.96
C-CS-T	89.06	180 to 720	-91 to -631
SS-DS-NT	11.47	0	+11.47
SS-DS-T	6.37	180 to 720	-174 to -714
C-DS-NT	9.95	0	+9.95
C-DS-T	24.02	180 to 720	-156 to -696

The highest is carbon, tracked under a clear sky, and the lowest is stainless steel, tracked under an overcast sky. For context, these are three to four orders of magnitude below the output of a commercial alkaline electrolyzer stack of similar footprint. The reason is the milliwatt power level and the very low current density, not the electrode materials.

On the clear day, tracking raised the carbon yield from 0.61 to 0.73 mL/h, which corresponds to 20% more accumulated charge. For stainless steel, the same comparison gives a 2% decrease. On the overcast day, carbon yield rose by 92% with tracking, while stainless steel yield fell by 51%. These differences are between single runs, so we can't assign significance to them. The stainless-steel decrease, in particular, could plausibly be due to cloud variation between consecutive runs. The stainless-steel result under tracking is more interesting. Under a clear sky, tracking delivered 22% more energy to the cell but 2% less charge.

This is how a cell behaves when series resistance limits current rather than available power: a higher array voltage raises the cell voltage, and the extra potential is simply dissipated in the resistance. It might seem that the tracker's battery draw reduced the energy available to the electrolyzer, but that cannot be the explanation, because the tracker ran from a separate battery and took nothing from the array.

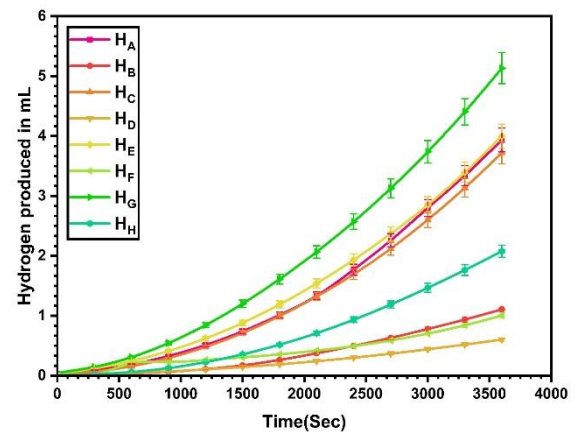


Figure 11. Charge-equivalent hydrogen accumulation for all eight configurations, derived from the measured charge of Fig. 10 via Faraday's law. These are computed upper bounds, not measured gas volumes.

On the overcast day, carbon with tracking gave the highest charge-equivalent yield of the four, 0.31 mL/h, and stainless steel with tracking the lowest, 0.08 mL/h. In proportional terms, the overcast configurations are more spread out than the clear-sky ones, but the absolute quantities are so small that this means little without replication.

3.4 Energy analysis

The energy delivered to the cell depends on what the array can supply and on how much current the cell can draw at the available voltage. Table 5 gives the cumulative energy after 60 minutes, and Figure 12 shows the same values as a bar chart.

Table 5. Final cumulative energy (J) for all configurations

Configuration	Energy (J)
SS-CS-NT	54.69
SS-CS-T	66.93
C-CS-NT	65.96
C-CS-T	89.06
SS-DS-NT	11.47
SS-DS-T	6.37
C-DS-NT	9.95
C-DS-T	24.02

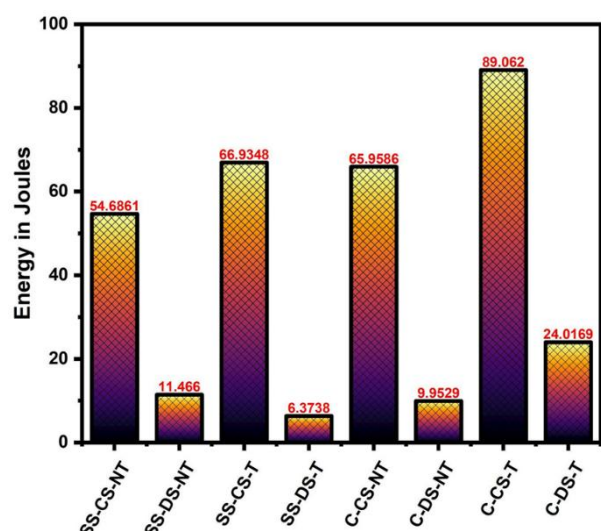


Figure 12. Cumulative electrical energy delivered to the cell over 60 minutes for each configuration. These values exclude the tracker's own consumption, which is accounted for separately in Table 4 and Section 3.3.

Figure 12 also has no error bars. The instrument tolerances ($\pm 0.5\%$ voltage, $\pm 1\%$ current) describe the resolution of individual readings and would overstate the confidence that unreplicated single runs can give. On the clear day, carbon with tracking received the most energy, 89.06 J. This is 35% more than carbon without tracking (65.96 J) and 33% more than stainless steel with tracking (66.93 J). As Section 3.3 showed, the extra energy did not produce a proportional gain in charge because the cell voltage rose and more was lost ohmically. The comparison

within each material makes the same point. For carbon under a clear sky, tracking gave 35% more energy (89.06 J against 65.96 J) but only 20% more charge. For stainless steel, it gave 22% more energy and 2% less charge. In both cases, much of the extra energy captured by tracking never reached the electrode reaction. On the overcast day, the energies are far smaller. Carbon received 24.02 J with tracking and 9.95 J without, an increase of 141%. Stainless steel received 6.37 J with tracking and 11.47 J without, a 44% decrease. As noted in Section 3.2, the tracker took no power from the array. The stainless steel decrease must therefore reflect lower irradiance capture during that run or a change in conditions between runs; it cannot be put down to tracker consumption.

Tables 3 and 5 can be combined. The carbon tracking configuration delivered 89.06 J for a charge-equivalent 0.73 mL, and the stainless-steel tracking configuration 66.93 J for 0.58 mL. That is 29.4 and 31.4 mL/W.h, respectively, so per unit of energy the carbon configuration is slightly less efficient, not more. Specific yield falls as mean cell voltage rises, and tracking raises cell voltage. The highest specific yields therefore belong to the overcast, fixed-tilt runs, which operated at the lowest voltages. In this system, maximizing hydrogen per unit captured energy and maximizing hydrogen in absolute terms pull in opposite directions.

4. DISCUSSION

4.1 Interpretation of current-voltage behavior

One feature of the current-voltage profiles (Figures 5 to 8) limits everything else we can say. The mean cell voltage was 7.9 to 16.1 V across a single electrode pair, whereas the thermoneutral potential is 1.48 V. Between 85 and 91% of the applied potential is therefore taken up by solution resistance, contact resistance and the gap between the electrodes. Under these conditions, the cell behaves much like a resistor. Current rises roughly in proportion to the applied voltage, not exponentially as it would in the kinetically limited Tafel region. The activation overpotentials of the two electrode materials differ by at most a few hundred millivolts, which is small compared with an ohmic drop of several volts. This agrees with the nearly equal charge accumulation we saw at fixed tilt.

4.2 Why the two materials perform similarly under fixed tilt

The literature reports a lower hydrogen evolution overpotential for carbon than for stainless steel in alkaline media, and porous carbon structures offer a larger electrochemically active area [38,39]. These results come from three-electrode cells at controlled potential and do not translate directly to a two-electrode cell running several volts above the reversible potential. In our data, at fixed tilt, the two materials differ by 1.6% in accumulated charge under a clear sky and by 3.9% in the other direction under an overcast sky. Single runs cannot resolve a material effect that small. The bubbles on the two electrodes looked different (Figure 1d, 1e), but bubble appearance is a qualitative observation and not evidence of a rate difference. To establish a material effect, we would need three-electrode measurements, electrochemical impedance spectroscopy, and replication. We did none of these.

4.3 Net Energy balance of the tracking system

Section 3.4 showed that tracking raised the delivered energy in three of the four comparisons. That gain has to be weighed against what the tracker used. From the servo figures in Section 2.2, a 60-minute run costs between 180 J (servo idle throughout) and 720 J (servo moving throughout). The Arduino controller is extra and would add roughly 900 to 1800 J. The largest energy gain from tracking in this study was 23.10 J. On the servo alone, then, the tracker used between 8 and 31 times the energy it gained. Table 4 shows a negative net balance for every tracking configuration. Tracking did not improve this system's energy performance. It made it considerably worse, and the apparent benefit in Section 3.4 exists only because the system boundary there is drawn around the electrolyzer alone.

4.4 Scale threshold for a net tracking benefit

This result comes from the system scale, not the tracker design. A tracker that draws constant power P is worth having only if the extra power it brings in exceeds P . If f is the fractional energy gain, the condition is that f multiplied by the delivered power exceeds P . Taking f as the 35% gain measured for carbon under a clear sky, and P as 0.05 to 0.2 W for the servo alone, break-even needs a delivered electrolysis power of about 0.14 to 0.57 W. With the Arduino controller included, the threshold rises to about 0.9 to 2.0 W. Our system delivered 24.7 mW at best, which is 35 to 80 times too low. In practice, this means that single-axis tracking of the kind used here cannot be justified for a directly coupled cell below about 1 W of delivered electrolysis power, and a fixed tilt is the better engineering choice at that scale. For example, cutting controller power by replacing the Arduino UNO with a microcontroller that sleeps between adjustments would lower the threshold but not remove it. The threshold is a first-order estimate from single-run data and should be checked with replicated measurements over a range of array sizes.

4.5 Comparison with previous studies

Table 6 places our results beside earlier experimental and modeling studies of solar-driven electrolysis. It would not be meaningful to compare the hydrogen production rates in Table 6 directly.

The cited studies operate at the kilowatt scale or in simulation, while ours delivered tens of milliwatts, a gap of four to five orders of magnitude. They also differ in electrode area, irradiance, electrolyte, and temperature. Rates in mL/h are not normalized for any of this, so we do not compare them numerically. The table is there to locate the present work by scale and method, not to rank it. It does show, however, that the milliwatt range is almost absent from this literature, and that is exactly the range where tracker parasitic load becomes dominant.

4.6 Component cost

The non-tracking apparatus cost about 24 USD in components: solar panels, electrodes, NaOH, tubing, and collection hardware. The servo, battery, LDRs with resistors, and PLA filament add 15 USD, for a total of about 39 USD. Supplementary Table 12 (Appendix 2) gives the itemized list. We have not calculated a payback period, a leveled cost, or a return on investment. That would need replicated yield data, electrode and component lifetimes, degradation rates, maintenance costs, and a scaling model, and a single-run study at this scale provides none of them. In any case, the energy balance in Section 4.3 shows that this scale tracks no net energy, so there is no payback period to calculate.

4.7 Limitations

This study has serious limitations, and we list them in full. (1) Each configuration was run once, on one clear day and one overcast day. There were no replicates, so no standard deviations or significance tests can be given, and none of the differences reported here should be treated as established. (2) Hydrogen yield was not measured. The collection arrangement could not resolve the volumes involved, and every hydrogen figure in the paper is an upper bound calculated from measured charge at complete Faradaic efficiency. (3) Gas composition was not analyzed. Without chromatography or a similar method, the Faradaic efficiency is unknown, and parasitic reactions such as carbon oxidation, carbonate formation, and oxygen crossover cannot be ruled out. Carbon rods recovered from dry cells may also carry metallic residues that release hydrogen chemically in strong alkali, regardless of the applied current.

Table 6. Positioning of the present work relative to prior solar-driven electrolysis studies by scale and method. Production rates are not compared numerically because the studies differ by four to five orders of magnitude in delivered power and are not normalized for electrode area, irradiance, electrolyte, or temperature.

Study	Electrodes	Tracking	Delivered electrical power	Basis of reported H ₂
Parawan & Tayactac (2024) [16]	Not specified	Yes (CSP, concentrating)	Not reported	Measured; method not stated
Choi & Bhakta (2025) [17]	PEM (commercial)	Yes	kW scale, grid-tied	Simulated (techno-economic)
Kabir et al. (2025) [35]	Specialised membranes	No	Not reported	Measured
Present work, C-CS-NT	Recovered carbon	No	18.3 mW	Charge-derived upper bound
Present work, C-CS-T	Recovered carbon	Yes	24.7 mW	Charge-derived upper bound

(4) The electrodes were not characterized. We have no surface area, morphology, composition, or impedance data, so we make no mechanistic claim about material performance. Recovered carbon rods also vary in composition and geometry from cell to cell, and we did not quantify this. (5) Current and voltage were read one after the other and not together, which adds an error in instantaneous power beyond the instrument tolerance. (6) The tracker's consumption is bounded from component ratings and was not measured. A direct measurement would tighten the bounds in Section 4.3 but would not change the sign of the result. (7) No durability or degradation tests were made, so the study says nothing about electrode or component lifetime. (8) The work was done at one site over two days and should not be generalized to other climates without further testing. (9) We did not assess the environmental side of disposing of 3.6 M NaOH or of sourcing carbon from spent dry cells.

5. CONCLUSION

We studied a directly coupled photovoltaic alkaline electrolysis cell working at milliwatt level. Recovered carbon and grade 304 stainless steel electrodes were compared at fixed tilt and with single-axis tracking, on one clear day and one overcast day. Each of the eight configurations was run once, so the findings below are indicative and not statistically supported. There are three main findings. First, the cell ran at mean voltages of 7.9 to 16.1 V, while the thermoneutral potential is 1.48 V, so the voltage efficiency was only 9 to 19%. At this geometry ohmic and contact losses dominate, not electrode kinetics. Second, at fixed tilt the two electrode materials differed by less than 4% in accumulated charge, and in opposite directions on the two days, so these data show no material advantage. Third, and most important, single-axis tracking raised the energy delivered to the cell by up to 35%, but the servo alone used between 8 and 31 times that gain. The net system energy balance was negative in every tracking configuration. A first-order break-even estimate puts the threshold for a net tracking benefit near 0.9 to 2.0 W of delivered electrolysis power once the controller is included. We delivered 24.7 mW. For directly coupled cells below about 1 W, a fixed tilt is the better engineering choice. It is better to lower cell resistance by narrowing the electrode gap and improving the contacts than to capture more irradiance. These results are exploratory and come from unreplicated single runs at one site. They do not establish a ranking of the materials, and we make no claim about practical hydrogen production. Before such a claim could be made, the following work is needed: replicated runs with irradiance and temperature logged at the same time; gas-phase composition analysis to establish Faradaic efficiency; a gas measurement method suited to these volumes, such as an inverted burette or a mass flow meter; three-electrode and impedance measurements to separate kinetic from ohmic contributions; direct measurement of tracker consumption; and tests over a range of array sizes to find the tracking break-even point experimentally.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically with regard to authorship (avoidance of guest authorship), dual submission,

manipulation of figures, competing interests, and compliance with policies on research ethics. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, more data will be available upon request from the corresponding author.

Conflict of interest

The authors declare no potential conflict of interest.

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Appendix 1

Arduino Code

```

1  #include <Servo.h>
2
3  const int ldrLeftPin = A0;   // LDR1 - Left
4  const int ldrRightPin = A1;  // LDR2 - Right
5  const int servoPin = 9;
6
7  Servo solarServo;
8  int pos = 90;                // Initial position at center
9  int tol = 30;                // Tolerance to prevent jitter
10
11 void setup() {
12     Serial.begin(9600);
13     solarServo.attach(servoPin);
14     solarServo.write(pos);
15 }
16
17 void loop() {
18     int leftLDR = analogRead(ldrLeftPin);
19     int rightLDR = analogRead(ldrRightPin);
20
21     int error = leftLDR - rightLDR;
22
23     if (abs(error) > tol) {
24         if (error > 0 && pos < 180) {
25             pos++;
26         } else if (error < 0 && pos > 0) {
27             pos--;
28         }
29         solarServo.write(pos);
30     }
31
32     Serial.print("Left: "); Serial.print(leftLDR);
33     Serial.print(" | Right: "); Serial.print(rightLDR);
34     Serial.print(" | Pos: "); Serial.println(pos);
35
36     delay(100); // Adjust delay for smoother motion
37 }
38

```

Appendix 2

Table 1. Experimental data for stainless steel for the non-tracking system (Current)

Time (min)	Current I (mA) for Day 1(Clear sky)	Current I (mA) for Day 2 (Cloudy sky)
9.50 am	0.617	0.171
9.55 am	0.856	0.191
10.00 am	0.834	0.134
10.05 am	0.958	0.157
10.10 am	1.167	0.289
10.15 am	1.145	0.446
10.20 am	1.113	0.687
10.25 am	1.059	0.721
10.30 am	1.512	0.318
10.35 am	1.441	0.289
10.40 am	1.368	0.289
10.45 am	1.291	0.384
10.50 am	1.464	0.191

Table 2. Experimental data for stainless steel for the non-tracking system (Voltage)

Time (min)	V (Volt) for Day 1(Clear sky)	V (Volt) for Day 2 (Cloudy sky)
9.51 am	11.26	8.97
9.56 am	12.39	9.38
10.01 am	11.87	8.87
10.06 am	12.68	8.21
10.11 am	13.41	9.11
10.16 am	13.02	9.54
10.21 am	13.11	9.69
10.26 am	12.56	10.12
10.31 am	14.31	9.39
10.36 am	13.93	9.03
10.41 am	13.51	8.86
10.46 am	13.27	8.89
10.51 am	14.19	8.07

Table 3. Experimental data for stainless steel for the tracking system (Current)

Time (min)	Current I (mA) for Day 1(Clear sky)	Current I (mA) for Day 2 (Cloudy sky)
10.55 am	0.464	0.192
11.00 am	0.569	0.198
11.05 am	0.893	0.185
11.10 am	1.148	0.155
11.15 am	1.236	0.163
11.20 am	1.278	0.112
11.25 am	1.223	0.193
11.30 am	1.159	0.189
11.35 am	1.116	0.146
11.40 am	1.241	0.133
11.45 am	1.568	0.289
11.50 am	1.251	0.122
11.55 am	1.317	0.081

Table 4. Experimental data for stainless steel for tracking system (Voltage)

Time (min)	V (Volt) for Day 1(Clear sky)	V (Volt) for Day 2 (Cloudy sky)
10.56 am	16.87	10.18
11.01 am	16.81	11.63
11.06 am	16.35	11.67
11.11 am	15.38	13.68
11.16 am	15.89	13.46
11.21 am	16.32	11.23
11.26 am	16.45	9.81
11.31 am	17.88	9.62
11.36 am	17.41	8.76
11.41 am	17.12	7.79
11.46 am	17.48	8.90
11.51 am	14.67	10.85
11.56 am	14.59	7.71

Table 5. Experimental data for carbon rod for non-tracking system (Current)

Time (min)	Current I (mA) for Day 1(Clear sky)	Current I (mA) for Day 2 (Cloudy sky)
12.00 pm	1.012	0.062
12.05 pm	1.057	0.019
12.10 pm	1.028	0.048
12.15 pm	1.079	0.067
12.20 pm	1.127	0.193
12.25 pm	1.128	0.221
12.30 pm	1.349	0.301
12.35 pm	1.126	0.211
12.40 pm	1.088	0.251
12.45 pm	1.039	0.488
12.50 pm	1.122	0.482
12.55 pm	1.589	0.551
1.00 pm	1.572	0.694

Table 6. Experimental data for carbon rod for non-tracking system (Voltage)

Time (min)	V (Volt) for Day 1(Clear sky)	V (Volt) for Day 2 (Cloudy sky)
12.01 pm	16.59	10.82
12.06 pm	17.21	10.27
12.11 pm	16.08	10.81
12.16 pm	16.11	9.55
12.21 pm	16.25	9.36
12.26 pm	16.71	10.64
12.31 pm	15.91	11.79
12.36 pm	14.38	11.45
12.41 pm	14.63	10.88
12.46 pm	14.77	9.11
12.51 pm	15.54	8.67
12.56 pm	15.57	11.32
1.01 pm	14.13	10.87

Table 7. Experimental data for carbon rod for tracking system (Current)

Time (min)	Current I (mA) for Day 1(Clear sky)	Current I (mA) for Day 2 (Cloudy sky)
1.05 pm	1.126	0.162
1.10 pm	1.324	0.219
1.15 pm	1.269	0.348
1.20 pm	1.942	0.567
1.25 pm	1.761	0.893
1.30 pm	1.514	0.821
1.35 pm	1.522	0.821
1.40 pm	1.114	0.811
1.45 pm	1.112	0.820
1.50 pm	1.381	0.789
1.55 pm	1.326	0.782
2.00 pm	1.453	0.451
2.05 pm	1.481	0.444

Table 8. Experimental data for carbon rods for the tracking system (Voltage)

Time (min)	V (Volt) for Day 1(Clear sky)	V (Volt) for Day 2 (Cloudy sky)
1.06 pm	17.82	9.83
1.11 pm	17.59	9.31
1.16 pm	18.81	8.04
1.21 pm	18.23	10.16
1.26 pm	17.66	10.11
1.31 pm	17.32	10.64
1.36 pm	17.63	10.82
1.41 pm	17.21	11.01
1.46 pm	17.11	11.68
1.51 pm	17.45	10.22
1.56 pm	16.38	11.07
2.01 pm	16.43	10.19
2.06 pm	16.52	9.88

Table 9. Cumulative charge for each time interval in the experiment

Time (Second)	Q _A (C)	Q _B (C)	Q _C (C)	Q _D (C)	Q _E (C)	Q _F (C)	Q _G (C)	Q _H (C)
0	0.221	0.0543	0.1550	0.0585	0.3104	0.0122	0.3675	0.0572
300	0.475	0.1031	0.3743	0.1159	0.6232	0.1321	0.7565	0.1423
600	0.744	0.1458	0.6805	0.1669	0.9393	0.1494	1.2382	0.2796
900	1.063	0.2138	1.0381	0.2146	1.2702	0.1884	1.7937	0.4986
1200	1.410	0.3241	1.4152	0.2559	1.6085	0.2505	2.2849	0.7557
1500	1.749	0.4941	1.7904	0.3017	1.9801	0.3288	2.7403	1.002
1800	2.075	0.7053	2.1477	0.3590	2.3514	0.4056	3.1357	1.2468
2100	2.461	0.8612	2.4889	0.4093	2.6835	0.4749	3.4696	1.4915
2400	2.904	0.9523	2.8425	0.4512	3.0026	0.5858	3.8436	1.7329
2700	3.325	1.039	3.2639	0.5145	3.3268	0.7313	4.2497	1.9686
3000	3.724	1.139	3.6868	0.5762	3.6747	0.8863	4.6666	2.1536
3300	4.137	1.225	4.072	0.6067	4.1489	1.0731	5.1067	2.2879
3600	4.550	1.3113	4.4572	0.6372	4.6231	1.2599	5.5469	2.4222

Table 10. Cumulative hydrogen generation for each interval of time in experiment

Time (S)	H _A (mL)	H _B (mL)	H _C (mL)	H _D (mL)	H _E (mL)	H _F (mL)	H _G (mL)	H _H (mL)
0	0.02894	0.007021	0.0203	0.007564	0.04065	0.00158	0.0481	0.00739
300	0.09114	0.02035	0.06932	0.02255	0.1223	0.01865	0.1472	0.0257
600	0.1886	0.0392	0.1584	0.0441	0.2453	0.2058	0.3093	0.0619
900	0.3278	0.0668	0.2943	0.07185	0.4116	0.2302	0.5442	0.1264
1200	0.5124	0.1087	0.4796	0.1049	0.6222	0.2626	0.8434	0.2273
1500	0.7414	0.1726	0.7141	0.1439	0.8815	0.3051	1.2023	0.3569
1800	1.0131	0.2638	0.9953	0.1903	1.1894	0.3575	1.6129	0.5181
2100	1.3354	0.3752	1.3212	0.2432	1.5408	0.4189	2.0673	0.7109
2400	1.771	0.4983	1.6934	0.3015	1.934	0.4946	2.5706	0.9349
2700	2.2587	0.6326	2.1208	0.3680	2.3697	0.5892	3.1271	1.1894
3000	2.8005	0.7798	2.6036	0.4425	2.8509	0.7038	3.7382	1.4678
3300	3.341	0.9382	3.1368	0.5209	3.3942	0.8425	4.407	1.7636
3600	3.9368	1.1077	3.7205	0.6033	3.9996	1.0054	5.1333	2.0767

Table 11. Cumulative energy table for each scenario

Time (Sec)	E _A	E _B	E _C	E _D	E _E	E _F	E _G	E _H
0	0	0	0	0	0	0	0	0
300	2.6328	0.4988	2.6089	0.6386	5.247	0.1299	6.5032	0.5447
600	5.7087	0.9458	6.2337	1.3079	10.4552	0.2370	13.5771	1.2702
900	9.0161	1.3174	11.072	1.9498	15.5421	0.4108	22.468	2.5539
1200	13.1852	1.9057	16.666	2.5969	20.8966	0.7777	32.4433	4.7722
1500	17.7691	2.9388	22.7406	3.1147	26.471	1.4014	41.0416	7.4368
1800	22.1944	4.5756	28.8871	3.5874	32.5177	2.2864	48.9999	10.0796
2100	26.3782	6.6686	35.0132	4.1441	38.1659	3.1811	55.9010	12.7514
2400	31.6183	8.2109	41.0361	4.6087	42.9823	3.9531	61.6308	15.5274
2700	37.8751	9.0503	47.1374	4.9559	47.6718	5.0296	68.0995	18.1736
3000	43.6584	9.8258	54.4356	5.4971	52.5891	6.3233	74.9722	20.6816
3300	49.0001	10.723	61.2997	6.0815	58.9156	7.8857	81.8111	22.6695
3600	54.6861	11.466	66.9348	6.3738	65.9586	9.9529	89.0620	24.0169

Table 12. Cumulative hydrogen generation for each interval of time in experiment

Component	Cost (USD)
Solar panels (4 × 5 V, 0.4 W each)	20
Arduino UNO microcontroller	10
Servo motor (SG90)	2
LDR sensors with resistors	1
PLA filament (3D-printed tracker)	2
Electrodes (carbon rods or SS bolts)	1
NaOH pellets (115 g)	2
Tubing and urine collection bag	1
Tracking configuration total	39
Non-tracking configuration total	24