

Analyzing Energy Use in 2D & 3D Imaging Systems and Workflows

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Abstract

This study examines energy consumption in cultural heritage imaging systems and workflows, addressing a gap in sustainability research that has to date focused primarily on data storage infrastructure estimations. Using Home Assistant edge computing and Z-Wave smart plugs, seven distinct imaging systems were monitored over 203 hours, capturing 55,211 images, and rendering 2,448 objects. Results show an average energy requirement of 11.1 Wh per object, with an annual total of 747 kWh for digitization activities. Findings highlight opportunities to reduce energy demand and improve efficiency, such as automating continuous light shutoff and optimizing postprocessing routines that support institutional sustainability goals and provide a transparent, reproducible model for other labs and studios.

Introduction

Institutional sustainability goals and emerging regulations increasingly require defensible resource accounting. Yet within cultural heritage digitization, energy analysis has largely centered on storage and data center infrastructure estimations, leaving the initial capture and postprocessing operational phases of imaging poorly understood [1][2][3].

This study aims to close that gap by measuring real-world practice in a production lab and by reporting methods, metrics, and results that are transparent and reproducible. Additionally, without rigorous, device-level measurements, it is difficult for programs to benchmark or optimize workflows, nor can they credibly communicate their energy footprint to stakeholders.

This study therefore asks: *How much energy is required to capture an object?* And *how much energy is required to postprocess and render it?* These, in turn, naturally elicit their own question of whether defensible methods to objectively gather energy use data of applied digitization practice can be fashioned.

Methods

Instrumentation and Design

When considering such an energy analysis, it is important to be mindful of some of digital imaging's particular characteristics. These include its multi-stage (e.g. capture, processing, rendering) and multi-device (e.g. cameras, lights, workstations, motor controllers) nature as well as how the power loads of such integrated systems can often be bursty and irregular. As a result, methods that will best sample power data around these known variables need to be devised.

For this study's measurement infrastructure, local, granular energy monitoring was implemented using a Home Assistant Green hub paired with a Z-Wave LR controller (Figure 1) and a network of Shelly Z-Wave smart plugs (Figure 2) in the University of Connecticut Library's Digital Imaging Lab. This data collection design, though unique in its greater measurement resolution, builds

upon prior energy monitoring research using Home Assistant edge computing conducted within IoT and biochemistry research lab settings [4][5].

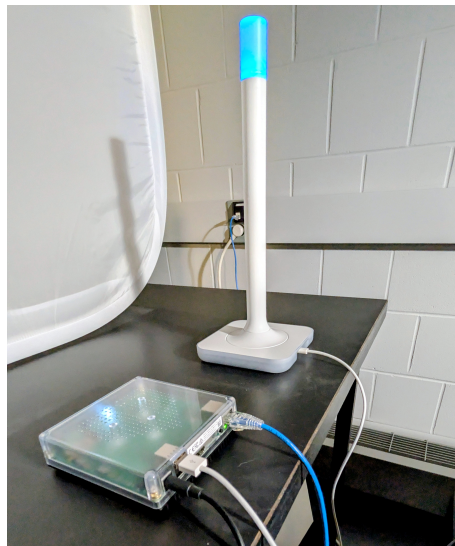


Figure 1. Home Assistant hub & Z-Wave antenna/controller

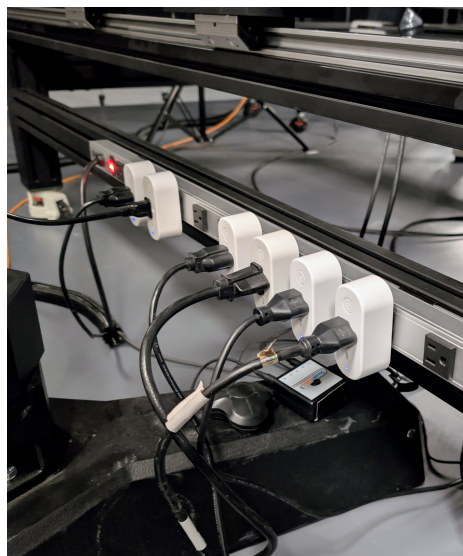


Figure 2. Shelly Z-Wave Plus LR smart plugs

Each imaging system component was individually metered using the smart plugs and event-driven, rate-limited Z-Wave

reporting settings in Home Assistant tuned to balance bursty device behavior with network capacity. Reporting thresholds and minimum report intervals were empirically adjusted to preserve stable Z-Wave network operation at scale while retaining sufficient temporal resolution to detect meaningful power changes during both capture and postprocessing workflows. This balance is important in energy studies, since precision often depends upon temporal resolution, not just aggregate totals. Detailed Z-Wave reporting profile definitions and per-class parameter settings are provided in the accompanying dataset [6].

Instantaneous power samples (W) were converted into cumulative Wh and kWh energy totals using Home Assistant's built-in Integral helper. Each helper integrated readings from its corresponding device-level watt sensor over time using a Riemann sum with trapezoidal integration and hours as the time base. This approach yielded a Wh running total that reflected variation in both steady and transient loads. Capture and postprocessing start/stop events were subsequently recorded by technicians through a custom Home Assistant task-tracking form, allowing session timestamps to be linked with smart-plug telemetry (Figure 3). Session-level energy consumption was then calculated as the difference between cumulative Wh values at the recorded start and stop timestamps. Overall, this instrumentation approach cost substantially less than industrial power meters, required no rewiring, and enabled monitored devices to remain in normal operational use, which is essential for characterizing real-world energy behavior.

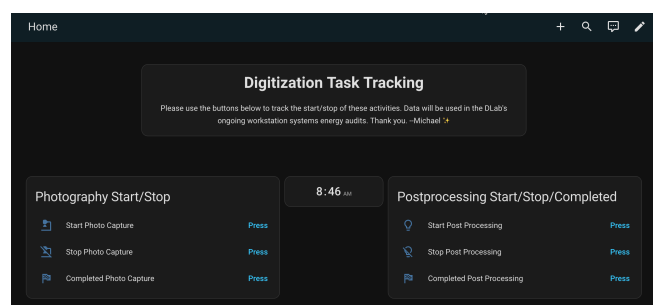


Figure 3. Custom Home Assistant task tracking web form

Seven distinct imaging systems—2D copy stand, BC100 bound-book capture, small and large automated turntables (3D photogrammetry), large automated XY table (2D stitching and orthomosaicing), and a drone-based photogrammetry pipeline—were tracked between August 2025 and February 2026 (Figure 4). Within this framework, device-level power/energy reports were collected and then analyzed per component or aggregated by imaging system and workflow phase (capture vs. postprocessing).

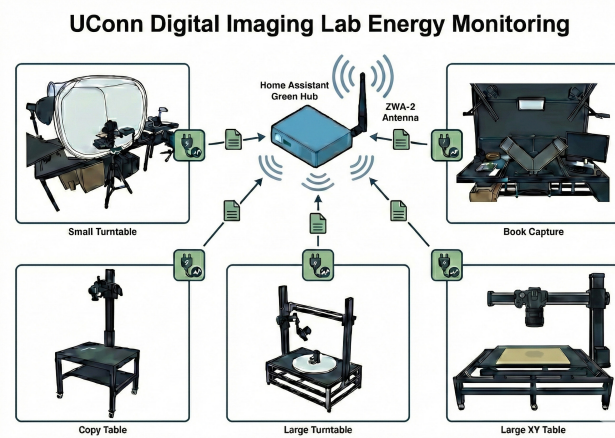


Figure 4. Energy monitoring design

Z-Wave is a low frequency wireless communication protocol in the 800-900 MHz range that has long distance signal transmission capabilities and can also travel through complex building structures much better than traditional 2.4 or 5 GHz Wi-Fi bands. The Home Assistant Green is a low power, SBC design edge computer that runs the open Home Assistant operating system, a stripped-down Linux offshoot. As Shelly describes power/energy measurement but does not specify a metering accuracy tolerance for their plugs, instantaneous W and cumulative Wh measurements were spot-checked against a P3 International P4460.01 Kill A Watt (true-RMS) reference meter across representative low-load and high-load conditions (~10–20 W and ~800–1500 W) in order to assess metering validity [7,8]. The Shelly readings were found to be operationally accurate with a roughly 5% plus/minus agreement with the reference. Once connected, the plugs were set up to act as repeaters, which allowed them to form a strong local wireless mesh network that easily covered the 2,500 ft² lab space.

Figure 5 depicts one student technician's partial shift in the lab. 182 images of archival company records were shot over 58 minutes followed by postprocessing routines that went on until the end of the shift. In the bottom graph, power spikes can be seen as flash pairs on either side of the copy table fired during the capture phase. This is followed by the elevated workstation power spikes in purple during postprocessing image editing. Again, power mainly describes instantaneous use, here expressed in Watts. Above the spiky power graph, the upward sloping, cumulative Wh energy graph represents a running sum of the energy of all a given photography station's hardware components during a given shooting and/or postprocessing session. So, in this way, both power and energy consumption were monitored for each capture system in the lab.



Figure 5. Power and energy graphs of one partial lab shift

In the case of Wh energy consumption values, these can be factored with either the number of objects shot or rendered to calculate overall digitization energy requirements by object. From there, better informed monthly or yearly energy use estimates can be made for a given lab or studio that are based upon actual use scenarios that fit a given unit's shooting style and computational postprocessing methods.

Aerial photography is also part of one of the University of Connecticut lab's alternative pipelines. Its most recent focus has been on a campus building survey that employs photogrammetry to create single, high resolution 3D renders of signature campus structures from thousands of aerial 2D images captured during programmed drone flight. Within the spectrum of the lab's integrations, this imaging system is unique in that its power draw comes from batteries used in the field, instead of plug-in outlets like the in-lab systems utilize. In turn, energy expenditure during aerial missions was derived from flight log telemetry (Figure 6). The total consumed energy was calculated by multiplying the proportional decrease in battery state-of-charge (SOC) by the battery's nominal capacity (Ah) and the time-averaged pack voltage over the flight duration [6].

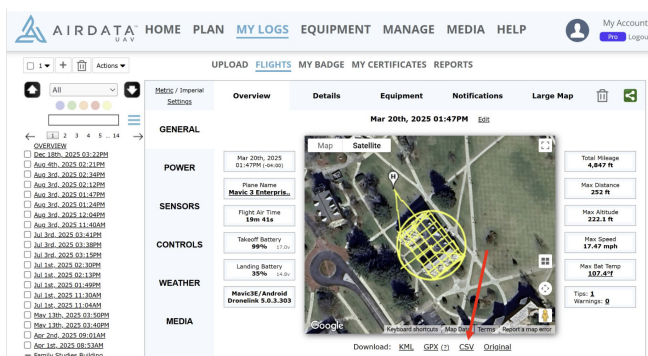


Figure 6. Logged telemetry data from drone flight missions

Results

In total, seven different imaging systems were analyzed as part of the study. These fell into two main groups. First there were the single image, single object, one-to-one, 2D systems, which included the lab's copy stand, and BC100 bound item capture systems. Then there were the many-to-one, multi-shot systems that capture anywhere from two to thousands of images per single rendered 2D or 3D object. These setups included both of the lab's two automated turntables, its large automated XY table system, and the drone-based aerial system.

The copy table and BC100 book capture workflows had the lowest overall Wh/object energy requirements, while the small turntable and drone-based workflows had the highest (Figure 7). However, notable trends emerge if these systems are broken down and more closely examined by their individual capture and postprocessing components.

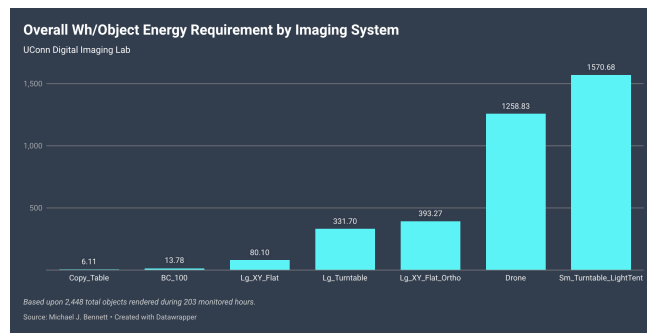


Figure 7. Energy requirement by imaging system

For the one-to-one, image to object systems, capture consumed more energy per object than postprocessing (Figure 8). This shared characteristic can be partially attributed to the fact that in each case, the postprocessing work is mostly batch scripted and carried out through efficient command line tools. What is perhaps more interesting here is the higher energy use that the BC100 book capture system uses during shooting in relation to postprocessing compared to the copy table's breakdown. This is mainly due to the fact that even though it can quickly photograph two images at a time, the book capture system utilizes continuous lighting, and employs foot pedals and attached pneumatic rig with air compressor to assist the photographer in repetitively raising and lowering the system's book platen that helps flatten pages to be imaged. In comparison, though it is only capable of shooting one object at a time, the copy table system uses extremely short duration flash units and no compressor.

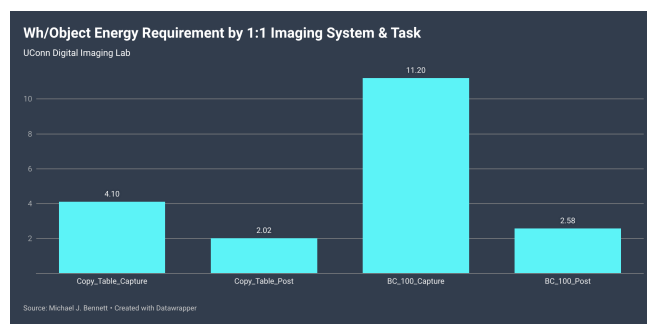


Figure 8. Energy requirement by 1:1 imaging system and task

In the many-to-one imaging systems (Figure 9), for the small turntable, capture requires more energy than postprocessing, while the opposite is true for the drone system. This is interesting since both systems employ photogrammetry techniques based upon similarly large source image sets to produce high resolution 3D objects. What could be causing this marked difference?

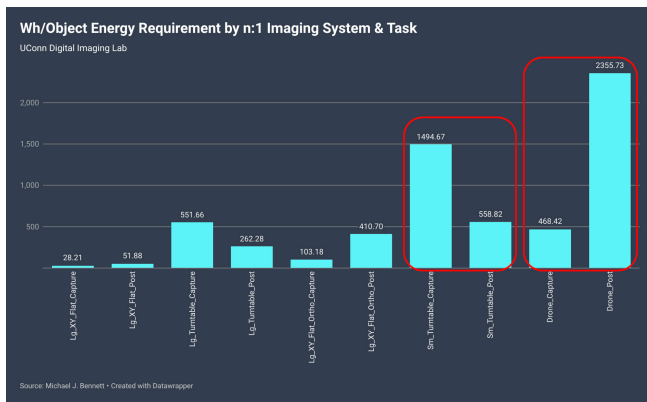


Figure 9. Energy requirement by n:1 imaging system and task

In the case of the small turntable (Figure 10), these large source image sets get sequentially distilled first through focus stacking in Helicon Focus. This reduces each large source folder's worth of images down to 36 images. These are then further fine-tuned through batch subject selection and masking in Photoshop. By the time the images are finally ingested into Metashape for photogrammetric 3D rendering, they are well prepared for efficient computation and final output.

This is important to consider when thinking about postprocessing energy consumption, as Metashape delegates much of its heaviest computational needs to the GPU, which can be a significant energy user with its own thermal control fans, etc. Prepping image sets in advance of their ingest into Metashape using sophisticated yet relatively lightweight handoffs and lower energy software processes, allows the photogrammetry program to run faster and more efficiently. It should also be remembered that the final polygon counts for objects going through the turntable workflow are normally much smaller than the drone pipeline, since the physical size of what the turntable process is rendering is also much smaller. So, this also influences overall energy use.

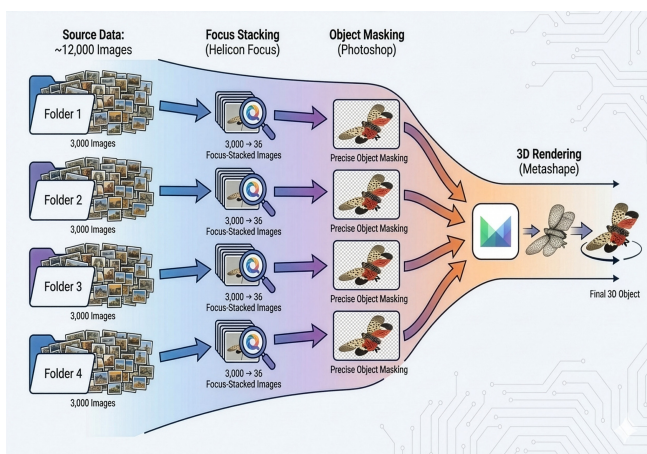


Figure 10. Small automated turntable workflow outline

In comparison, within the drone workflow (Figure 11), large image sets are ingested straight into Metashape which is then tasked with doing all the substantial 3D computational lifting on its own. Aerial building façade and roof images do not lend themselves to coherent masking, as the scenes are often much more complicated than an isolated object captured on a turntable in a lab environment. So, for rendering building structures, Metashape must make do with

more and noisier source data, which in turn require more compute cycles, more time, and more energy to process.

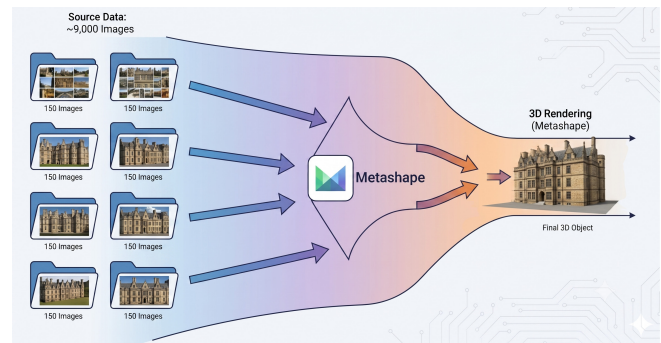


Figure 11. Drone-based photogrammetry workflow outline

Using weighted percentages based on total objects produced and measured energy requirements by imaging system, the lab's average energy intensity was calculated at 11.1 Wh/object. This weighted value reflects the dominance of low-energy workflows (copy table and BC100 bound book system), which together accounted for approximately 99% of objects rendered. Applied to an average annual production volume of roughly 67,000 objects, the measured capture and postprocessing workflows consume approximately 747 kWh per year. This figure represents the lab's annual operational energy footprint for digitization across its monitored imaging systems.

Applying 2024 EPA emission factors, this energy use equates to 172 kg CO₂e under the New England grid mix (NEWE) and 277 kg CO₂e under the U.S. National Weighted Average for electricity consumption (Figure 12). When expressed in equivalency terms, the annual emissions correspond to 428 miles driven (NEWE) or 687 miles driven (U.S. avg) by a typical passenger vehicle or approximately 19-31 gallons of gasoline burned. Such comparisons provide a tangible context for understanding the environmental impact of digitization and underscore the relatively minor carbon footprint of these workflows [9,10,11,12].

The weighted energy intensity per object (11.1 Wh/object) offers a normalized metric for cross-system comparison, particularly relevant for multi-shot capture systems, where raw image counts would otherwise distort efficiency assessments. Higher energy systems such as large-format XY rigs and turntable-based 3D capture contributed approximately 1% of total objects per year, minimizing their influence on the overall weighted energy rate. This finding suggests that future scaling of these workflows could significantly alter the aggregate footprint.

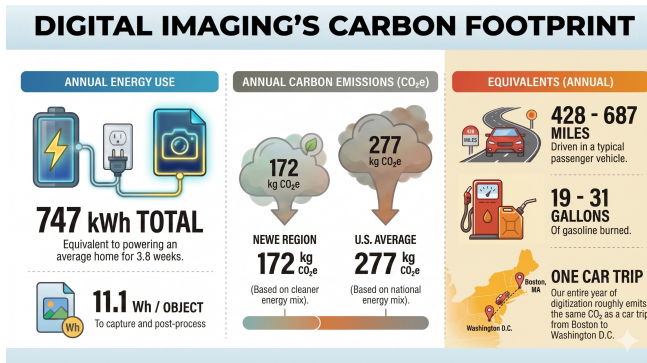


Figure 12. Digital imaging's annual carbon footprint equivalences

For a broader context, high-end range energy use estimations for HDD/NVMe hybrid storage for one year's worth of data production coming out of the lab were also added (Figure 13). These conservative calculations were based upon a 16 TB system made up of a 12 TB archival HDD (modeled at 0.3 W/TB) plus one 4 TB NVMe SSD for access (10 W/device), scaled by PUE = 1.58. Even when factoring in storage to the kWh total, albeit a one-year bounding scenario, digitization practice remains a relatively low energy endeavor [3,14,15,16,17].

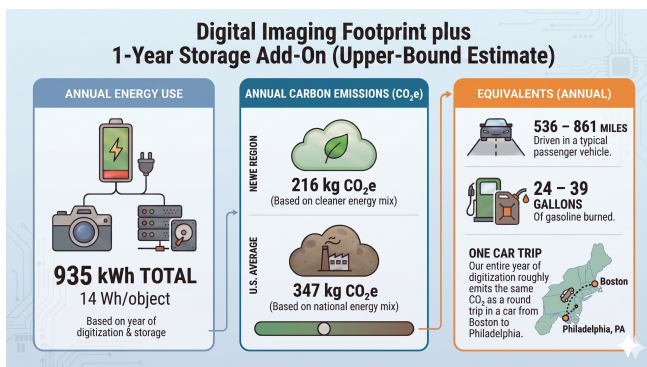


Figure 13. Digital imaging & storage's annual carbon footprint equivalences

Energy studies on digital preservation and access often compare carbon use values with zero, when a fairer contrast may be with complementary analog service models (Figure 14). For example, the University of Connecticut Archives has a large and unique collection of Latin American periodicals and newspapers that are of interest to researchers from locations such as South America who have in the past made the trip to Connecticut to view these items. Though it cannot replace the value of working in-person with collection specialists and physical originals, digital access, in this situation, can lower travel barriers and distribute its marginal energy requirements across global use.

Compare this to the concentrated resources used in long-haul flights for a single visit, which are often multiple orders of magnitude greater than analogous digital access. Quantifying such assessments with empirical data can be illuminating. It is an area that deserves continued research as it more equitably and holistically distributes assumptions on energy use across multiple service pathways and considers the effects of possible "avoided emissions" in clearer terms. Such reflections can also shift the fundamental framing of, "what is the carbon cost of collection digitization?" to "what is the carbon cost of *not* digitizing collections?"

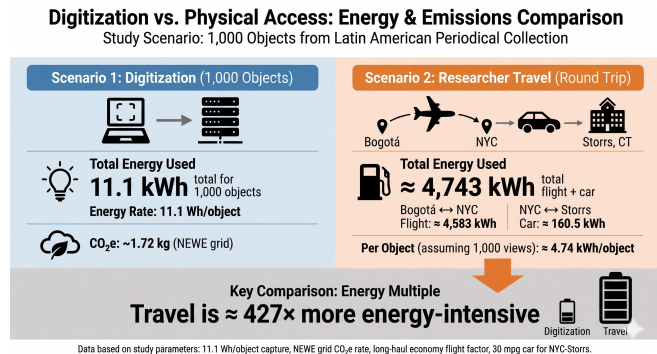


Figure 14. Digitization vs. physical access of collection objects

Summary

Digitization, even at production scale, is a relatively low-energy activity compared to other institutional operations. Nevertheless, measurable efficiency gains are achievable by focusing on aspects of the top two tiers of the Energy Hierarchy which include *Change behavior to reduce energy demand* and *Use technology to reduce waste and improve energy efficiency* [18,19].

For example, based upon the proportional energy use among the components of the BC100 book capture system (Figure 15), the imaging lab is currently looking for ways to either dim or turn off continuous photography lighting after shooting and during postprocessing within this setup. And on the small turntable rig, the Shelly smart plugs have now been programmed in Home Assistant to automatically turn off this system's constant lights and attached devices after the end of lengthy, programmed capture sessions that can often run unattended into the night. Meanwhile, applets like the lab's internally designed Lightroom plugins continue to be optimized and used at scale to help partially automate and in turn lower the energy needs of repeatable and traditionally time-consuming postprocessing tasks [20].

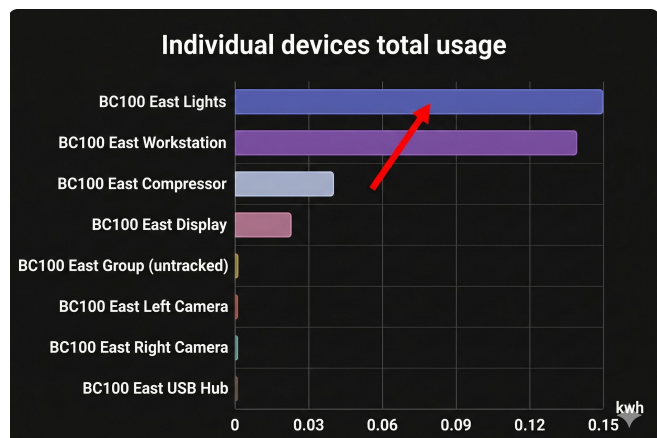


Figure 15. Book capture system's proportional energy use during capture and postprocessing of 516 ledger page images

In summary, the method developed for this study scales well (Figure 16) for the following reasons. First, it uses commodity hardware and an open platform for centralized data storage and edge computing that can be run as a local network. So, beyond an affordable initial investment in hardware, researchers can own and control their own data's interrogation and access. Second, because of this open and flexible architecture, it is imaging system agnostic, 2D and 3D compatible, and is built with components that can be

readily replaced or upgraded. Finally, the study's methods are replicable and allow for meaningful comparison.

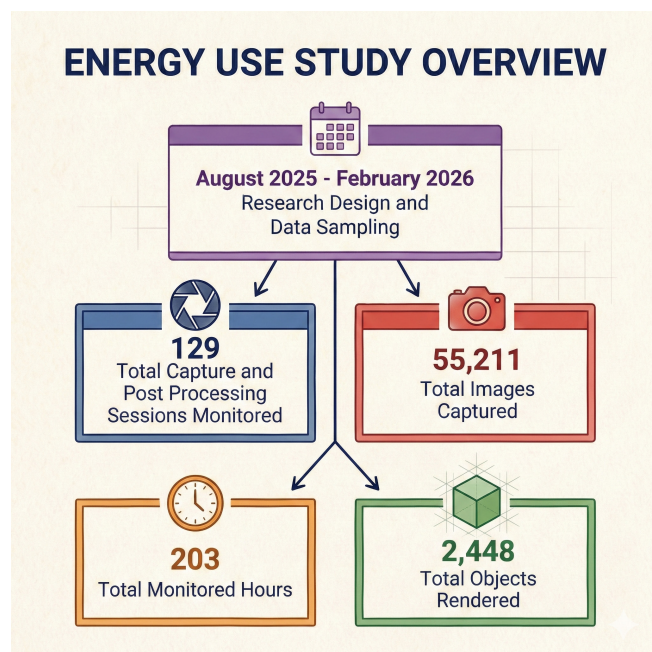


Figure 16. Study overview

Through transparent design and reported results, the Digital Imaging Lab strives to more tangibly align with sustainability frameworks and goals and to better demonstrate its role in accurate resource accounting. By sharing its findings, it highlights the relatively small environmental impact of digitization and the lab's ongoing efforts to measure and plan to further reduce its carbon footprint in the future.

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