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Connecting Power and Play: Investigating Interactive Energy Harvesting in Battery-Free Gaming

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Figure 1: The battery-free TURNER console in action. Turning the crank enables weapon firing in the game DOOM, whilst at the same time generating energy to charge TURNER's energy storage capacitor. The charging state of the capacitor is displayed by a small indicator at the top right hand side of the Liquid Crystal Display (LCD) panel. TURNER integrates solar energy harvesting sources, follows the form-factor of a modern handheld games console, and has the typical "ABXY" button configuration of a game controller. As implemented, TURNER weighs 509 g, its casing dimensions are 24 cm x 14 cm x 3 cm, and crank dimensions are 2 cm x 6.5 cm x 2 cm.

Abstract

Battery-free computer gaming offers a vision of sustainable interaction in which games run on hardware that does not require a battery, yet this approach introduces uncertainty due to frequent power failures. Rather than viewing these failures as limitations, this work examines how integrating energy harvesting with application design can encourage users to reimagine and work with such failures, thus shaping behaviour and supporting device use. We present TURNER, a state-of-the-art modular battery-free games console powered by a hand crank and solar cells, created as a research probe to study how energy harvesting mediates the relationship between power and interaction. In a mixed-methods study (N = 60), we explored the influence of energy harvesting on gameplay. Findings show significant variations in harvesting strategies, with interviews surfacing strategies for creating applications that respond to and build on the patterns of system power failure, the ergonomics of energy harvesting, and the value of embedding energy generation into play. Our work offers insights for interactive, sustainable battery-free computers.

CCS Concepts

• **Human-centered computing** → **Human computer interaction (HCI)**; **Interaction design**; **Ubiquitous and mobile computing**.

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battery-free interaction, sustainable computing, mobile gaming

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1 Introduction

As the number of mobile computing devices we interact with continues to grow, so too does our dependence on electric batteries and the inherent limitations of this energy-storage method. Batteries pose significant challenges for system design, environmental sustainability, and human health. Their size, weight, and thermal constraints restrict design possibilities, whilst their production often relies on finite critical materials, with sourcing and disposal carrying significant environmental consequences [15, 47]. These impacts extend across the entire battery lifecycle from material extraction to end-of-life. Serious labour abuses, including documented cases of child labour in cobalt mining supplying global battery chains [5], and improper processing of spent batteries posing significant human-health risks due to the toxicity of materials used [44], further underscore the need to reconsider how energy is harvested and stored in everyday technologies. These issues also align with broader societal movements, such as the 2000 Watt Society [26], which call for reducing overall energy use and encouraging more environmentally sustainable daily interactions. Together, these perspectives highlight the growing need to rethink energy in personal computing, considering both the necessity of the application and the devices tasked with carrying it out.

The gaming industry, as a rapidly expanding sector with rising energy demands [39, 40] and a reliance on batteries in handheld systems, makes a clear contribution to concerns about sustainability. At the same time though, the sector also offers opportunities to reimagine battery dependence by exploring new relationships between hardware, interaction, and energy. An estimated three billion people worldwide engage with digital gaming in some form [24]. Given this scale of participation and the associated environmental costs, there is a pressing need to investigate how alternative power strategies and interaction paradigms can support sustainability whilst preserving player engagement and quality of experience.

To address the growing challenges posed by batteries, the field of battery-free computing has emerged [2], envisioning low-power systems that harvest ambient energy and use it almost instantaneously for computation, without the need for a battery. By removing the weight and volume of batteries, this new computing approach opens possibilities for reimagined system form factors. Early applications have included Wireless Sensor Networks (WSN) [62] and wearable health monitoring [60], with more recent work exploring direct human interaction. Notably, de Winkel et al. [14] and Zhu et al. [63] introduced battery-free mobile gaming devices, demonstrating the potential for interactive systems without traditional energy storage methods. Despite these technical advances, both developed gaming systems are constrained by limited energy-harvesting capacity, low application complexity, and largely unexplored usability challenges.[1] Their defining feature, the absence of a battery, makes them reliant on fluctuating environmental energy and susceptible to sudden power loss, which can interrupt programme execution and produce non-classical system behaviours. Although significant prior work has developed recovery mechanisms for intermittently powered systems as detailed in the work of Lucia et al. [33], these approaches aim to efficiently restore computation, adhering to the assumption that devices should mimic battery-powered behaviour.

We believe that enabling battery-free gaming, and battery-free computing at large, is not only a challenge of efficiently restoring computation; it represents a distinct interactional paradigm in which energy harvesting shapes how and when play can occur. Responsiveness and flow are central to the experience of gaming, raising questions about how realistic it is to transition players to a state of reduced power reliability without considering novel interaction design.

Addressing these challenges requires understanding how people experience, adapt to, and engage with intermittent power, and how interaction design, integrated with core game features, can support this adaptation. Rather than viewing intermittence solely as a limitation, there is value in exploring how it might be mitigated, or even inspire new forms of play. Our work takes this approach, using the design and evaluation of a state-of-the-art battery-free gaming system, TURNER, as a probe to examine how energy harvesting shapes gameplay, whether intermittent power diminishes the gaming experience compared to battery-powered play, and how interaction design choices can sustain enjoyable play under real-world, intermittently powered conditions.

Contributions. To address the problem we present the following contributions:

- *TURNER, A state-of-the-art modular, crank- and solar-powered handheld games console with integrated interaction logging.* The crank functions both as an energy source and a gameplay input, coupling physical effort with interaction. Its modular design supports long-term use and maintenance, while its flexible architecture allows researchers to modify components, prototype new interaction techniques, and log detailed user behaviour—capabilities not offered by previous battery-free gaming systems. This new system acts as a research probe to explore novel interaction paradigms in battery-free computing.
- *Insights and design guidelines from the first user study on a battery-free, intermittently powered games console.* Through a user study employing a mixed factorial design ($N = 60$), we examine how linking energy harvesting with in-game input affects user interaction, perceived workload, and behavioural intention to use the system. The study reveals significant variations in user cranking behaviour and how participants interpreted and adapted to power-linked interactions from

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[1] Both consoles produced only low levels of harvested energy, as they relied on mechanical press or Quasi-Static Toggling (QST) harvesters. As a result, only simple games were feasible, and neither study conducted a substantial user evaluation.

which we propose a series of design strategies for interactive battery-free gaming including flexible input remapping, increasing power failure awareness, and exploring dynamic context-aware application integration.

Results Replication. The design files of TURNER, along with collected questionnaires, raw interaction logs, and data analysis files are available via [55], enabling researchers to build upon our work.

Paper Structure. In Section 2 we review related work. Section 3 presents an overview of the TURNER system, with Section 4 introducing the user study of TURNER, and study results detailed in Section 5. We then discuss our results in Section 6, propose strategies for interactive battery-free gaming in Section 7, outline study and system limitations in Section 8, and conclude in Section 9.

2 Related Work

In this section we explore existing examples of interactive battery-free computing, the relationship between human power and application design, and failure as a material for design.

2.1 Interactive Battery-Free Computing

2.1.1 Battery-Free Game Consoles. Most relevant to this research is the work of de Winkel et al. [14], who present a battery-free Game Boy emulator powered by solar panels and button pressing. The device enables intermittent gameplay and sets an early precedent for the battery-free gaming community, achieving play sessions of around ten seconds followed by roughly one second of downtime under ideal daylight conditions. Building on this, Zhu et al. [63] introduced a handheld console powered by a mechanical harvester mounted on the back of the device. While both systems demonstrate the feasibility of sustainable play, they remain limited in interaction: gameplay is largely confined to conventional button input, with little exploration of how energy harvesting itself might shape the play experience. Whilst these works mark important technical milestones, they give limited attention to interaction as a design space, particularly the potential to couple energy collection and gameplay.

Beyond consoles, Radio Frequency Identification (RFID)-based battery-free interaction has also been explored in game controllers. Maselli et al. [36] demonstrate a wireless, battery-free joystick, Mehmood et al. [37] present interfaces embedded in clothing and everyday objects as novel control modalities, and Katsuragawa et al. [28] showcase RFID's potential for gesture-based input. Together, these examples begin to move beyond button presses but have not been, as yet, integrated into a functional battery-free video gaming console.

2.1.2 Battery-Free Mobile Computing. Talla et al. [54] present a battery-free cellphone capable of maintaining connectivity when sufficient power is harvested from Radio Frequency (RF) signals of a local base station or from ambient light. A similar concept is explored by Adam et al. [1], who demonstrate a battery-free Long-Term Evolution Machine Type Communication (LTE-M) smartphone powered by an on-board solar panel or an optional portable hand-crank. These works illustrate the feasibility of sustaining core mobile functions without batteries, primarily by focusing on connectivity and energy harvesting hardware, including the use of a hand-crank in the latter work. Yet, how user interaction can work with application design remains largely unexplored due to the strong systems focus of the work.

2.2 Human Power and Energy Harvesting in Computer Design

2.2.1 Designing Computers with Energy Harvesting. Energy-driven computing has emerged as a way to develop systems that adapt functionality based on available power. Merrett and Al-Hashimi [38] and Sliper et al. [52] map how computing systems are *energy-neutral* or *transient*, creating a framework for situating new energy-driven systems. Building on this perspective, we can also consider the role of users in driving energy availability. Energy harvesting and user input are not mutually exclusive after all, in battery-free gaming de Winkel et al. [14] and Zhu et al. [63] harvest energy via console buttons or rear-mounted input. Mamish et al. [35] introduce a hardware toolkit offering both power harvesting and input, demonstrating speculative designs such as a *battery-free bop-it* and electronic *Etch-a-sketch*. Ryokai et al. [50] contribute with *EnergyBugs*, wearables for children that frame harvested energy as a tangible, manipulable object, while Villar and Hodges [57] present a device where turning a knob generates energy and serves as an input. Pierce and Paulos [48] explore the design space of Human-Powered Microgeneration, identifying opportunities and challenges in reshaping how people relate to energy through interactive devices. When combined, these works illustrate the growing potential to treat energy harvesting as a power source and an input modality for interaction.

2.2.2 Crank Based Computer Interactions. Crank-powered electronics have a significant history, first appearing in industrial mechanical systems and later in consumer devices such as emergency radios, flashlights, and novelty gadgets. These designs framed cranking as a practical way to ensure reliability in low-resource contexts, while also highlighting its potential to generate significant power levels [25] relative to typical mobile system consumption. More recently, Lundström and Fernaeus [34] presented battery-free crank-powered interaction designs, including a hand-cranked quote reader and a human-powered generative art machine. Crank-powered, battery-free operation has also been explored by Alghisi et al. [3] through a non-contact temperature measurement system, with Song et al. [53] examining how crank-driven input can challenge our relationship with social media. A notable commercial example is the Playdate console [46], which uses a crank as direct input for gameplay without energy harvesting. Crank-based computing has not always succeeded, however, with the crank-powered prototype of the One Laptop Per Child (OLPC) programme [49] ultimately being abandoned due to concerns over robustness and the physical demand of cranking. Collectively, these examples show that while cranking poses ergonomic and interaction challenges, its comparatively high energy yield makes it a compelling candidate for enabling richer battery-free applications and novel interaction design.

2.3 Embracing and Using Failure in Design

2.3.1 Reimagining System Failure as a Design Opportunity. System failure, which, in classical computation has typically been regarded as an undesirable system-level breakdown that affects the expected application, such as connectivity loss, software glitches, or complete power outage, can be reinterpreted as more than just something to be mitigated. In ubiquitous computing, *seamful design* [9, 12] seeks to embrace system limitations as design opportunities, rather than striving for seamlessness. Chalmers et al. [12] developed a mobile app that uses fading wireless coverage as a feature, while Bell et al. [9] introduced *Feeding Yoshi*, a game that exploits WiFi range limitations to drive play. Nilsson et al. [42] extended this with *Ghost Detector*, an educational museum game using Bluetooth signal fluctuations.

Beyond mobile applications, failure has also been used to foster creativity—Hazzard et al. [21] explore how musical performance failures can enable new creative possibilities, by enabling a different path through the music compared to the initial route, showing that failure can facilitate novelty. In the context of battery-free systems, failure can arise from a number of sources, not least software bugs and hardware failure due to the prototype nature of most existing systems, however these are largely controllable through improved testing. *Most interesting to our case is failure that arises from energy depletion rather than malfunction.* Power loss due to insufficient harvested energy is an inherent characteristic of intermittent energy harvesting. Thus, whilst *failure* carries a negative connotation, here it describes a predictable state change caused by insufficient energy, not a software or hardware fault.

Beyond these examples, work in human–robot interaction has begun to examine failure as a relational phenomenon that can be intentionally shaped. The work of Sætra [51] highlights that robot failure involves both an objective component, such as a lack of success in accomplishing a task, and a subjective component, in which behaviour is judged as failing to meet users' expectations or standards. This distinction shows how perceived failure can be intentionally shaped to calibrate trust rather than simply avoided. Similarly, the work of Kraus et al. [29] demonstrates that the manner in which a robot responds to an error (through apologies, technical explanations, or anthropomorphic justifications) can directly influence users' trust in the systems.

2.3.2 Failure in Gaming. Failure, as an intended experience of the application itself rather than an unintended behaviour of the system is a common aspect of gaming, a paradox explored by Juul [27] in how players both seek and avoid it. Games often tie failure to user action, but system-level behaviours, like power generation, are seldom directly integrated into gameplay. Iacovides et al. [22] examine *breakdowns* and *breakthroughs* in gaming, finding that breakdowns can sustain engagement if they lead to breakthroughs, but may also cause disengagement. This highlights how temporary disruption can meaningfully contribute to an experience when players can interpret or act upon it. Similarly, Aytemiz and Smith [7] propose a taxonomy that distinguishes between *in-loop failures*, which contribute to gameplay (e.g., missing a precise in-game jump), and *out-of-loop failures*, which disrupt it through misaligned expectations or unintended behaviours, such as confusing controls or unexpected system crashes. Battery-free systems blur this distinction, as failure can stem not only from in-game error but also from fluctuating energy availability due to the user, raising the question of whether energy depletion is an in-loop challenge or an out-of-loop disruption. Framing failure as playful and meaningful within games provides a useful lens for reimagining power loss as part of gameplay, while underscoring the need to keep such failure *in-loop* rather than disruptive.

2.4 Research Gap Summary

Growing awareness of the environmental and human costs of battery production and use provides an important societal motivation to explore alternatives to conventional battery-based mobile computing. Prior work on battery-free computing has demonstrated the technical feasibility of gaming and mobile interaction, while research in seamful design has shown how system limitations can be transformed into creative opportunities. Yet these domains remain largely disconnected: battery-free systems typically aim to conceal or overcome power loss rather than embrace it, with concern remaining around their acceptance compared to battery-powered systems. This leaves an important gap around understanding power failure as a design opportunity in battery-free computing. Gaming, where failure is already integral to the play experience, offers a natural testbed for reimagining power loss not as disruption but as part of interaction design. In this work we explore this gap by asking: *to what extent do variations in energy storage hardware, and the connection of energy-harvesting mechanics to gameplay, shape user behaviour, perceptions, and intention to use novel battery-free gaming systems?*

3 TURNER: A New Battery-Free Intermittently-Powered Mobile Gaming Platform

In this section we outline the design rationale behind TURNER and provide a high-level overview of its implementation and functionality. The complete hardware and software design files of TURNER are available via [55], enabling researchers to build upon this work.

3.1 TURNER Design Rationale

The battery-free gaming platforms of de Winkel et al. [14] and Zhu et al. [63] pose the following design limitations:

- **Limited design exploration in integrating gameplay with energy generation:** The work of de Winkel et al. [14] employs button pressing both to power the device and to interact with the game. However, neither of the consoles incorporate sophisticated integrations between their energy mechanics and in-game actions, leaving open the space for greater design exploration of energy-application coupling.
- **Lack of logging of user interaction with the console:** Neither current state-of-the-art platforms have the ability to collect data on interactions relating to powering the device, i.e. the amount of toggling of the device backplate (in Zhu et al. [63]) or button presses (in de Winkel et al. [14]) while playing. Other relevant performance statistics such as the number of *power off* events or the duration of *power on* cycles are also impossible to collect. This limits the ability of these platforms to be used for more complex quantitative user studies.

Table 1: Descriptive feature comparison of TURNER against state of the art.

	de Winkel et al. [14] (2020)	**Zhu et al.** [63] (2022)	**TURNER [this work]**
System modularity	No	No	Yes
Energy harvesting	Button Press, Solar	Backplate Toggling	Solar, Crank Turning
Memory checkpointing	Yes	Yes	Yes
Data logging	No	No	Yes
Settings menu	No	No	Yes
Games played	Nintendo GameBoy Color	Sokoban	Nintendo GameBoy Color, DOOM
Form factor	Nintendo GameBoy	Rectangular shape	Steam Deck [56] style
Display type	LCD	e-ink	LCD
Display size	1.28 inch diagonal (square)	1.54 inch diagonal (square)	5 inch diagonal (square)
Sound generation	No	No	No

- **Lack of system modularity and reconfigurability:** Existing systems have a fixed design that limits the ability to upgrade specific components without requiring a full system redesign or remanufacture. This limits sustainable development and further design iterations.
- **Low-levels of harvested energy from mechanical interactions and small console display:** Both mechanical press harvesters [14] and Quasi-Static Toggling (QST) harvesters [63] generate small amounts of energy to support gaming. Other, more efficient forms of energy harvesting are needed to support more complex computational tasks and bring battery-free devices closer in capability to their battery-powered counterparts. Existing systems also feature significantly smaller displays compared to modern handheld consoles, limiting the richness of user experience.

The outlined design constraints necessitated a new approach to building the TURNER console. In response, we developed a modular, reconfigurable system that collects data on user behaviour while integrating high-capacity energy harvesting directly into gameplay, thus setting a new standard for the battery-free gaming community.

3.2 System Implementation

This section summarises the hardware, kernel, and application architecture of TURNER. The entire implementation, both hardware and software, was developed in-house by the authors, with no reliance on external suppliers, developers, or designers.

3.2.1 TURNER Hardware Architecture. To support longevity and adaptability across studies, TURNER adopts a modular hardware design as seen in Figures 2 and 3. The system consists of four types of detachable module: (1) a *motherboard* that coordinates all components; (2) a *CPU module* responsible for processing and computation; (3) *power harvesting modules* which supply energy and interface with the CPU to monitor charging and interaction status; and (4) a *logging module* which records system data for later analysis. This modularity enables researchers to replace or upgrade individual parts over time, tailoring the console to different contexts without rebuilding the entire system. The core hardware of TURNER, i.e., the overall Printed Circuit Board (PCB) design enabling TURNER's modular architecture, casing, custom crank harvester, and logging module, was developed in-house. Off-the-shelf individual electronic components such as the main Microcontroller Unit (MCU), LCD, and solar cells, were used to fabricate a complete device (as seen in Fig. 3),[2] but the system as a whole was conceived and built by us.

3.2.2 TURNER Kernel Architecture. To ensure reliability under intermittent power and to simplify application development, TURNER runs on a lightweight custom-developed kernel with modular Application Layer Interfaces (APIs) that abstracts hardware complexity.

The kernel API is split into five different parts: input, screen, settings, checkpointing, and logging. Each of these parts should be enabled or disabled at compilation time, effectively changing the memory footprint of the kernel. Each one of those APIs allows hardware-agnostic access to the inputs and outputs of TURNER. It also provides a power-failure-resilient flash file system for game data, handles the User Interface (UI), renders menus, and supports a download mode for file transfer. On startup, the kernel initialises the hardware, restores the last checkpoint, and hands control to the application. Implemented in C, the kernel itself is not checkpointed since its initialisation takes only 2.25 ms—an insignificant time compared with the 127 ms required for hardware initialisation after power failure. Our kernel design ensures that applications remain responsive. The kernel is non-preemptive, i.e., the applications decide to return control back to the kernel. The kernel uses the API calls that the application calls at the end of each frame to do the required tasks like checkpointing, drawing capacitor charge level indicators and other interface objects on top of each application, and recover quickly from failures.

The kernel exposes four hardware-independent drivers. (1) Graphics driver, which handles frame rendering and vertical synchronisation to avoid screen tearing[3]. Double buffering improves performance but is memory-intensive (about 5 Mbit for two 320×240, 32-bit frames), so memory-constrained systems may rely on single buffering or direct drawing. (2) Screen driver, which maps graphics-driver commands (e.g., brightness, contrast, rotation) to hardware capabilities, with unavailable functions resolved automatically at compile time. (3) Crank driver, whose dedicated MCU performs

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[2] The interested reader is referred to the TURNER repository [55] and to [13] for the specifications of all electronic components used in fabricating TURNER.

[3] A visual artefact caused when fragments of multiple frames are shown simultaneously.

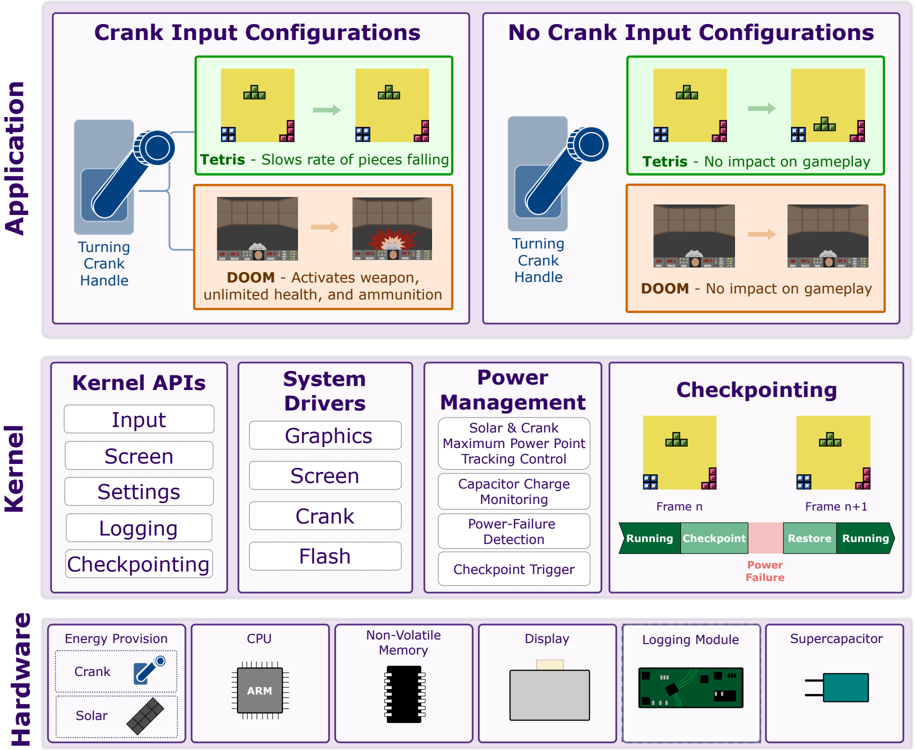

Figure 2: TURNER architecture illustrating application behaviour with and without crank input, alongside the supporting kernel, and hardware components.

maximum-power-point tracking of the crank motor at 10 kHz. (4) Flash driver, comprising internal and external modules: the internal driver provides fast, persistent, byte-addressable storage without alignment constraints, while the external driver extends this abstraction to off-chip Flash by mapping it for standard CPU read/write access.

3.2.3 TURNER Application Architecture. To support experimentation and reduce developer overhead, TURNER organises applications as modular, self-contained *apps*. Each app runs independently and can only exchange data through the storage subsystem, ensuring predictable behaviour, reliable operation, and reproducibility across devices and studies. Only one app can reside in memory at a time, though each may freely use its allocated heap and storage. Non-volatile memory is available on request, managed by the storage subsystem. The input subsystem supports up to eight buttons, two joystick axes, and three additional interaction inputs. This architecture simplifies development while allowing researchers to prototype diverse applications that deploy reliably in field settings.

To examine the interaction capabilities of TURNER, we ported two distinct interactive tasks for our user study. The first was *DOOM* [58], the iconic 1993 first-person shooter originally developed by id Software [23]. We selected *DOOM* for both its cultural resonance and its open-sourced engine, which facilitated straightforward modification and the integration of new mechanics. Our *DOOM* port builds on the nrf53840Doom project [59], with sound and networking removed to meet energy constraints. In one iteration, the crank of TURNER was mapped to the minigun, where continuous cranking fired the weapon, with temporary invincibility assigned to offset the added multitasking load. The second set of tasks was implemented using Gaembuoy, a Game Boy and Game Boy Color emulator [18] that replicates key features of the original hardware. Unlike DOOM, the emulator does not provide access to game source code or internal state, limiting the detection of in-game states and constraining the design of advanced interactions. As with DOOM, sound and networking were removed, and optimisations were applied to sustain 60 frames per second for most titles. Without direct access to game logic, crank rotation speed was instead coupled to emulator speed, for example slowing the descent of pieces in a falling-blocks task.

3.3 System Configurations of TURNER Developed for User Study

To investigate how different energy and input paradigms affect play, we created three variants of TURNER, detailed in Table 2. Two variants are fully battery-free, allowing us to observe the constraints and opportunities of direct energy harvesting, whilst one variant provides a battery-powered baseline. The first battery-free variant, BF/CI, couples the crank to both energy harvesting and gameplay, directly linking effort to interaction. The second, BF/NCI, uses the crank solely for harvesting, separating energy production from

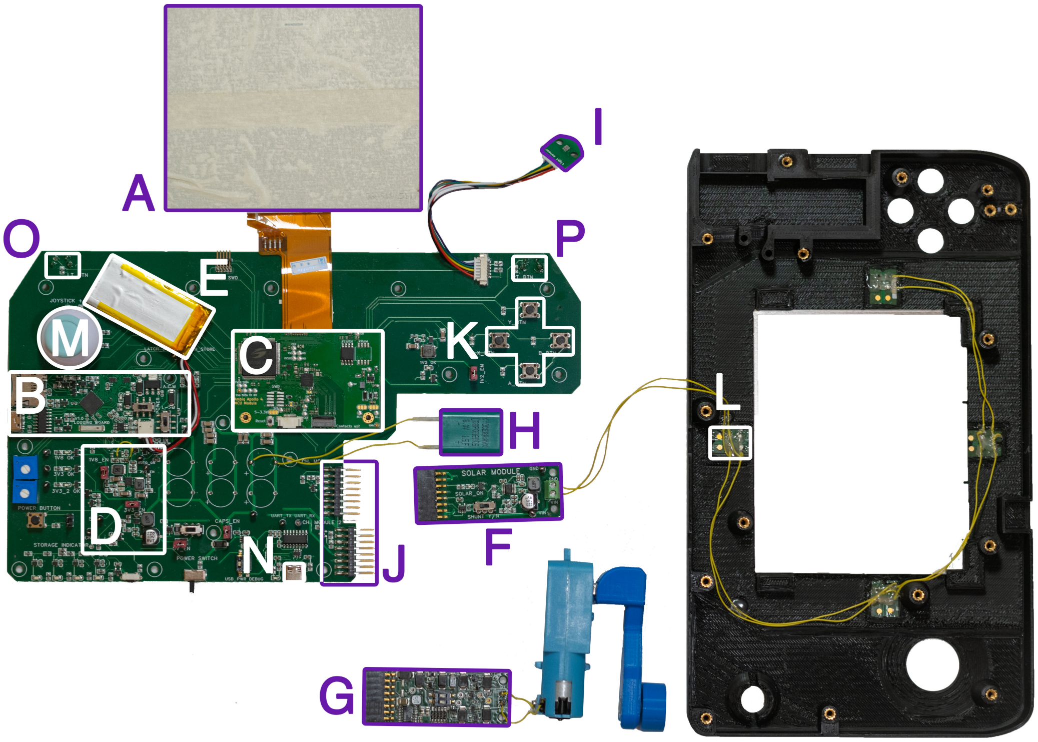

Figure 3: TURNER system implementation: (A) the back of the COM50H5M81XLC transflective LCD screen [45], (B) logging module using an Espressif Systems' ESP32 PICO Series microcontroller [16] (C) Central Processing Unit (CPU) module using an Ambiq Apollo 4 MCU [4], (D) power management, (E) logging module battery, (F) solar module implemented around the Analog Devices LTC3129 Maximum Power Point Tracking (MPPT) energy harvester buck-boost converter [6], (G) crank module, (H) 6V 1.5F Kyocera AVX-SCM super-capacitor [SCMR22H155PSBB0] [30], (I) ambient light sensor, (J) energy module connection points (K) 'ABXY' buttons (L) solar panel connection on front of system casing. Eight ExCellLight EXL10-4V170 high-performance solar cells [31] (50 mm x 20 mm each) deployed (M) joystick (N) Universal Serial Bus (USB) port, (O) left trigger button, (P) right trigger button. We emphasise that the battery is used *only* to power the logging module and in the battery-powered console configuration experimental condition.

play. The baseline, BP/CI, connects the crank handle to gameplay input in the same way as the BF/CI case, and participants were instructed to use the crank as an active gameplay control, however the system also used a rechargeable battery to support the crank and solar power inputs. This ensured that the BP/CI condition never suffered power failure, whilst still enabling a gameplay-interactive crank experience and isolating the effects of the crank from energy depletion. Participants were informed about the system's energy configuration prior to engaging with it. These variants enabled us to compare play across battery-free and battery-supported designs, assessing how coupling input with energy harvesting influences interaction behaviour, perceived workload, and intention to use the system.

4 User Study

We now detail our use of TURNER as a research probe to explore the variation between battery-free and battery-powered conditions, and the influence of connecting energy harvesting with application input.

4.1 Research Questions

- **RQ 1:** To what extent does linking the crank energy-harvesting mechanic of a battery-free games console to gameplay influence user behaviour, including the frequency of power failures and the time spent harvesting energy?
- **RQ 2:** How do user perceptions (workload and intention to use the system) vary among users interacting with three novel games console configurations: (i) a battery-free console with gameplay-integrated energy harvesting, (ii) a battery-free console without gameplay-integrated energy harvesting, and (iii) a battery-powered console with gameplay-integrated energy harvesting—across different game difficulties and genres?

Table 2: Variants of the console used in the user study, contrasting battery-free and battery-supported designs, and whether the crank input is coupled to gameplay.

Console Variant	Battery-Free	Energy Source	Crank Connected to Gameplay
Battery-Free/Crank Input (BF/CI)	Yes	Crank and Solar	Yes
Battery-Free/No Crank Input (BF/NCI)	Yes	Crank and Solar	No
Battery-Powered/Crank Input (BP/CI)	No	Battery, Crank, and Solar	Yes

4.2 Hypotheses

Hypotheses were preregistered at Open Science Framework (OSF) prior to data collection [11]. Exact wording has been slightly revised and the number of analysed instruments reduced in this paper to improve clarity and conciseness, whilst preserving the original intent of the preregistered hypotheses.

4.2.1 Hypotheses Derived from RQ1. We proposed that connecting the crank as an input modality to gaming would encourage its use beyond only powering the system, as explored in prior work [34, 57]. When the crank is connected, users will have a greater incentive to interact with it, such as performing specific in-game actions. We expected that this increased interaction would lead to longer durations of engagement and a reduced likelihood of system power failures.

- $\mathbf{H_{1a}}$**:** Users interact longer with the crank handle of a battery-free games console when it is directly linked to in-game mechanics, in DOOM and Tetris, compared to when it is not.
- $\mathbf{H_{1b}}$**:** Users experience fewer system power failures on a battery-free games console when its crank handle is connected as a console input and energy harvester, when playing DOOM and Tetris, compared to when it is only used for energy harvesting.

4.2.2 Hypotheses Derived from RQ2. We anticipated that greater integration between the crank and game mechanics would enhance engagement. This engagement could increase adoption intention and reduce perceived workload through immersion. However, higher difficulty or complex interactions could raise workload. Comparing the power-supplemented and battery-free versions, added battery power may improve gameplay consistency but reduce user investment by removing the necessity of manual input. While gameplay consistency might boost adoption and lower workload, reduced engagement could offset these benefits.

- $\mathbf{H_{2a}}$**:** Connecting the crank handle of a battery-free games console to in-game mechanics results in increased behavioural intention to use the device and lower perceived workload compared to a battery-free variant in which the crank handle is only used for energy harvesting.
- $\mathbf{H_{2b}}$**:** Users playing on a battery-free games console with the energy harvesting crank handle input connected to in-game mechanics have a different behavioural intention to use the device and level of perceived workload compared to users that play on a version of the console that has the same use of the crank as an input method for gameplay but is supplemented by battery power.
- $\mathbf{H_{2c}}$**:** Users will experience lower perceived workload when playing Tetris compared to DOOM on a battery-free games console, and increasing DOOM's difficulty increases the perceived workload of users.

4.3 Study Design

The user study of TURNER employed a mixed-methods approach, combining console log data, questionnaire responses, and post-study interviews.

4.3.1 Key Modifications Following the Pilot Study. Following the pilot, $N = 9$, we made two key changes: adding a tutorial level for participant familiarisation and obtaining Human Research Ethics Committee (HREC) approval to record and expand interviews for richer user insights.

4.3.2 Study Environment. All sessions took place in a quiet meeting space on the university campus of the main author, with five separate meeting locations used throughout the study, due to booking restrictions and user convenience. Studies were conducted over an eight month period. The average recorded environmental illuminance of the study environments was 267 lx (SD = 371), which is roughly equivalent to average indoor home lighting levels. Caution was taken to avoid excessive glare on the console screen from environmental lights. All rooms were furnished with a comfortable chair for the participant to sit on and a table to rest the device on and complete the questionnaire between gaming sessions. One researcher was present in each session and helped to direct the participant between activities.

4.3.3 Experimental Conditions. Our study used a split-plot design. Participants were randomly assigned, between-groups, to one of three console conditions, BF/CI, BF/NCI, or BP/CI, without being informed of their assignment, and within-groups when playing Tetris and both levels of DOOM, such that all participants played all games.

4.3.4 Independent Variables. The primary independent variables were the game played (*DOOM Level A*, *DOOM Level B*, and *Tetris*, see Section 4.4.4), which varied in difficulty and mechanics, and the console variant (BF/CI, BF/NCI, and BP/CI), each with different energy harvesting behaviours and crank input connections (as detailed in Table 2).

4.3.5 Dependent Variables. Multiple dependent variables were measured to assess participants' experience and engagement with the

Table 3: Validated questionnaires used, their construct components, and the number of items per component in brackets.

Questionnaire	Components
NASA-TLX [20]	Mental Demand (1), Physical Demand (1), Temporal Demand (1), Performance (1), Effort (1), Frustration (1)
HMSAM [32]	Joy (6), Control (6), Focused Immersion (4), Temporal Dissociation (3), Curiosity (3), Perceived Ease-of-Use (8), Perceived Usefulness (5), Behavioural Intention to Use (3)

games console.[4] Perceived workload was measured after each session using the NASA Task Load Index (NASA-TLX) scale [20], which assesses six dimensions on 21-point bipolar scales (see Table 3). Widely used in mobile computing and gaming [19], NASA-TLX was selected for its reliability and sensitivity to workload variation during interactive gameplay. Sample items include *"How mentally demanding was the task?"*, rated from *"Very Low"* to *"Very High"*. No items were modified or excluded. The weighted variant of the NASA–TLX multiplies each subscale by a participant-specific weight, scored 0–5 from 15 pairwise comparisons of the factors, and computes a weighted average. Behavioural intention to use the console, along with the hedonic–motivation constructs that precede it, were measured using the Hedonic-Motivation System Adoption Model (HMSAM) [32]. This was selected for its strong theoretical grounding in hedonic technology adoption and validated structure. Sample items include *"I found playing the game to be enjoyable"*, rated on a seven-point Likert scale from *"Strongly Disagree"* to *"Strongly Agree"*. All items were retained, with only *game* changed to *game console* for clarity. Additional questionnaire measures captured participants' game preferences and pausing behaviour. Console logs recorded ambient light, power generated via solar and crank input, and system power failures.

4.3.6 Participants. We recruited $N = 60$ participants for the main study and $N = 9$ for a pilot, using posters and flyers around the lead author's university campus, snowball sampling, and convenience sampling. During selection, particular attention was taken to avoid recruiting participants that were (a) in a position of subordination to the authors of the study due to teaching activities and (b) had detailed knowledge of the study, its design, or the console. Participants were able to withdraw at any time during the study, and their data was pseudonymised in accordance with our approved data management plan. Reimbursement in the form of a gift card was given to participants after completing the study. The sample size of $N = 60$ was chosen as a pragmatic balance between resource constraints, the time to recruit and test across three conditions, financial limitations, and the availability of functional consoles, and the study's inferential goals. A power analysis using G*Power software [17] shows that an effect size (Cohen's d) of $d = 0.8$ would be possible given an equal distribution of participants across three conditions for a statistical power of 0.80 and an alpha level of 0.05. We acknowledge that this sample size did not allow for the detection of medium to smaller effects, however, it was sufficiently powered to detect larger effects, and given the resource constraints of the study, we believe this sample size represents an appropriate compromise. Prior to participating, all participants completed an informed consent form, which had been approved, along with the study design, by the HREC of the university of the leading author. HMSAM and NASA-TLX responses were complete for all $N = 60$ participants. However, full system logs, defined as covering all three gameplay sessions, were only successfully extracted from $N = 47$ participants due to occasional data corruption or incomplete logging.[5] Among these, $N = 18$ were in the BP/CI condition, $N = 14$ in the BF/CI condition, and $N = 15$ in the BF/NCI condition.

4.4 Procedure

4.4.1 Background Questions. After providing consent, participants completed a brief questionnaire about their background with gaming and energy harvesting electronic devices. An overview of the study procedure is presented in Fig. 4.

4.4.2 Introduction to Console and Instructions. The initial interaction with the console began with an introduction and a set of instructions, where the energy harvesting behaviour and game input of the crank of their specific console variant was explained. Participants were given the opportunity to ask any questions regarding the console or its operation during this time.

4.4.3 Tutorial Level. To familiarise participants with the console's behaviour and input mechanics they played a three to five minute tutorial level of *Super Mario Land*. During this session, those in the BF/CI and BF/NCI conditions experienced at least one power failure, helping them understand the console's energy harvesting and power restoration behaviour. Following the tutorial, all participants completed a weighting questionnaire later used for workload assessment.

4.4.4 Main Gaming Activities. To mitigate learning and fatigue effects, game order was counterbalanced so participants were equally likely to start with either *Tetris* or the easy *DOOM* level. *DOOM* levels were then played sequentially to preserve a natural sense of progression and to maintain the coherence of the gameplay experience, which would have been disrupted by counterbalancing their order. In the BF/CI and BP/CI variants of *DOOM*, cranking both generated power and activated a Gatling gun-style weapon with unlimited ammo. In *Tetris*, connected cranking generated power and slowed the falling pieces. After each session, participants completed a workload questionnaire from Hart and Staveland [20]. The following game sessions were used:

- **DOOM Level A Task (5 minutes).** A low-complexity level selected for accessibility and low enemy count. The task was to reach the marked exit.
- **DOOM Level B Task (5 minutes).** A high complexity level with a higher enemy count but the same task objective. This represented an increase in difficulty compared to DOOM A.

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[4] A full report of the questionnaire instruments used in the study can be found in our preregistration [11].

[5] All log files were visualised and checked independently by at least two authors. Incomplete logs were excluded from analysis.

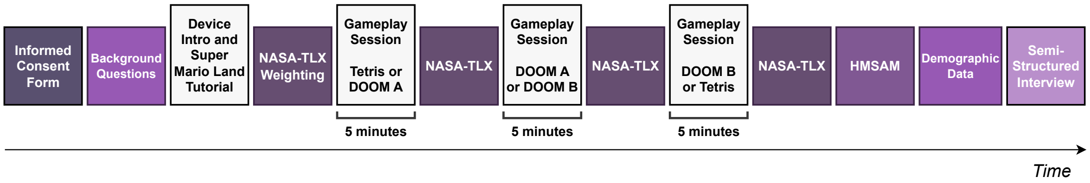

Figure 4: Study procedure. Questionnaire and interview data collection is denoted by the smaller boxes whilst participant interactions with the console are shown in the larger white boxes.

- **Tetris Task (5 minutes).** A falling-blocks task at an introductory difficulty level, with participants aiming to maximise score. Restarts were permitted if the grid filled.

4.4.5 Overall Perception of Console and Demographic Questions. Following their final gameplay session, users were asked to complete a questionnaire to explore the factors described in Lowry et al. [32]. Additional demographic information was also collected.

4.4.6 Post-Study Interview. Semi-structured post-study interviews were conducted with participants and lasted around 5-10 minutes per interview. During this time participants were prompted to discuss their experience with the device, any connected interaction between the crank handle and application features, and the impact of intermittency. Interviews were recorded and transcribed.

4.5 Data Analysis

4.5.1 Quantitative Analysis. A range of statistical tests were used to assess the significance of effects in our log and questionnaire data. Parametric tests were applied when assumptions of normality, from Shapiro-Wilk, and homoscedasticity, from Levene's tests, were met. For brevity, assumption tests are not reported. To analyse differences among more than two groups, we used Analysis of Variance (ANOVA) for between-subjects designs and repeated-measures ANOVA for within-subjects designs when parametric assumptions held, and Kruskal–Wallis or Friedman tests when non-parametric, respectively. Significant results were followed by post-hoc pairwise comparisons using Tukey's HSD (parametric) or Dunn's test with Bonferroni correction (non-parametric). For comparisons between two groups, we used independent samples t-tests or Mann-Whitney U tests, as appropriate.

4.5.2 Qualitative Analysis. We analysed post-study interviews using inductive thematic analysis, following the six-phase guidance proposed by Braun and Clarke [10]. The interview protocol was co-developed by the first and last authors and reviewed by the fourth author to ensure alignment with the study goals. Interviews were conducted by the first and last authors, and transcripts were produced and analysed by the first author.

Coding was inductive, with initial descriptive and in vivo codes generated through repeated engagement with participants' responses. Codes were iteratively refined and grouped into broader patterns through multiple rounds of analysis, with discussions between the first and fourth authors to clarify code meanings and assess coherence and distinction between themes.

To support interpretability and practical use of our results in systems-oriented design contexts, we made deliberate choices in how themes are presented. The presentation emphasises key distinctions across configurations by reporting the number of participants contributing to particular patterns to make the distribution of experiences across conditions explicit, and by including participants' design-oriented reflections and speculative suggestions as analytic material. As a result, themes are more compact than the extended narrative presentations often associated with reflexive thematic analysis, but remain interpretive and grounded in recurring user experiences, highlighting how participants reasoned about TURNER's behaviour, constraints, and trade-offs in a style oriented toward clarity and design use.

4.5.3 Statement of Positionality. We acknowledge that our positionality shaped the design and analysis of this study. Our research team includes researchers in Human-Computer Interaction (HCI) and Embedded Systems with a focus on battery-free technologies. As designers and advocates of such systems, our professional interests and experiences informed how we approached the research and interpreted participants' accounts.

Rather than seeking to eliminate this influence, we engaged in ongoing discussion throughout the research process to critically examine how our assumptions shaped analytic decisions. This included collaborative discussions between the first and fourth authors to question emerging interpretations and ensure that analytic claims remain grounded in participants' accounts while recognising our active interpretive role.

5 User Study Results

We proceed with the results of the user study. In this section we present our confirmatory pre-registered hypothesis testing and a series of exploratory analyses, which were not pre-registered, to understand the engagement of users with the console. Note that adjustment methods, such as the Bonferroni correction, have been applied where required in the post-hoc analysis to address the problem of multiple comparisons. Comprehensive descriptive statistics for our dataset are provided in Table 5, located in Section B.[6] Frequently observed crank interactions are demonstrated in

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[6] ChatGPT4o was used to assist with improving the quality of Python scripts written by the first author for data presentation. All scripts were reviewed for accuracy following modification. No collected data was passed through ChatGPT4o, in accordance with our data management plan.

(a) Intense cranking with a tight grip on the body of the console

(b) Light cranking with possibility of joystick interaction

(c) Classic gameplay interaction with the crank unused

Figure 5: Example frequent console interactions during gameplay sessions. We observed that console-chassis holding techniques varied according to the intended user interaction, which itself was shaped by the energy and game input configuration of TURNER.

Fig. 5, with example raw console log data is presented in Fig. 6 for reference.

5.1 Descriptive Statistics of Participants

Of our 60 participants, 22 identified as female, 37 as male, and 1 as non-binary. The average age was 30 (SD = 8.49), with ages ranging from 20 to 60. A total of 88% held at least a Bachelor's degree. 78.3% were right-handed, 13.3% left-handed, and 8.3% reported mixed handedness depending on the task. Awareness of battery-free computing was relatively high, 47% had heard of it, likely influenced by ongoing research at the primary author's university. Gaming frequency varied, 16.6% played daily, 30% weekly, 21.6% monthly, 16.6% yearly, and 15% never. Most, 85%, had previously played a first-person shooter, 40% had played *DOOM*, and 93.3% had played *Tetris*. 93.3% had used a handheld device powered by harvested energy, most commonly solar calculators, 56.6%, and hand-crank flashlights/torches, 55%. Participants' preferences for the games experienced in the study and their in-game pausing behaviour are given in Fig. 8.

5.2 Investigating User Interaction Through On-Board Console Logging Data

5.2.1 *Hypothesis Testing Relating to RQ1. Testing Variation in Crank Interaction Duration (H_{1a}) and System Power Failure Frequency (H_{1b}).*

Total cranking time for battery-free conditions. To test H_{1a} we compared the total cranking time of users between the BF/CI and BF/NCI conditions. Participants in the BF/CI condition had a higher mean crank interaction time than those in the BF/NCI case, however this difference was not significant ($t(27) = 1.61$, $p = .06$, $d = 0.59$). This can be seen in Fig. 7a. Although the moderate effect size suggests that linking the crank directly to gameplay may encourage greater crank interaction, our sample did not provide sufficient evidence to support this hypothesis.

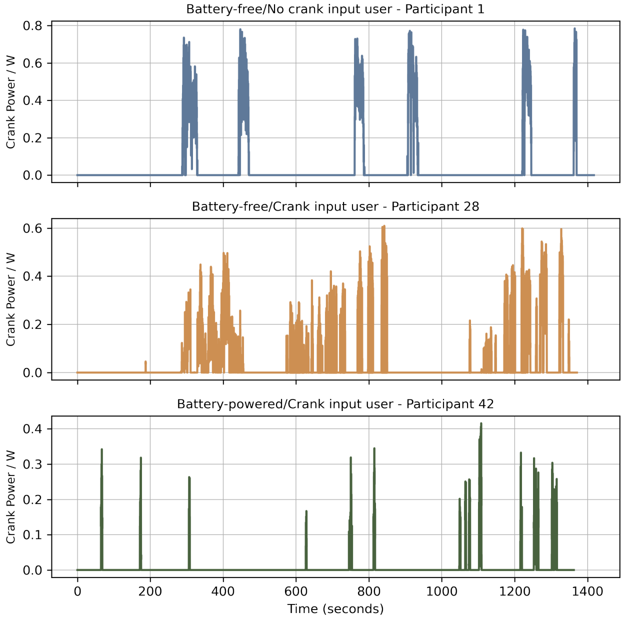


Figure 6: Representative raw crank power harvesting profiles for each console condition. Participants were selected due to their recordings demonstrating characteristic crank-power patterns for their respective condition, based on experimenter assessment and alignment with condition-level average values. We observed characteristic patterns of intense bursts of cranking for the BF/NCI case, lower-power but more frequent/distributed cranking in the BF/CI case, and sporadic short engagements in the BP/CI condition.

(a) Total crank time across all gaming sessions.

(b) Mean crank power across all gaming sessions.

(c) Total number of active cranking periods across all gaming sessions. Extreme outliers omitted for visual clarity but included in analysis.

(d) Mean cranking duration per active cranking period across all gaming sessions.

Figure 7: Results of exploratory analysis of log data. Comparison of total crank time, mean crank power, the total number of active cranking periods, and the mean cranking time per active period of cranking across all gaming sessions.

Total number of system power failures for battery-free conditions. In testing H_{1b} we found no significant difference in the total number of power failures between the *BF/CI* and *BF/NCI* conditions ($t(38) = 1.08$, $p > .1$, $d = 0.40$), so we were not able to find sufficient evidence to support H_{1b} in our sample.

5.2.2 *Exploratory Analysis. Further Understanding User Interaction with the Hand Crank.*

Total cranking time for all conditions. Returning to the total cranking time, we explored variations between all console configurations, including the battery-powered system. As visualised in Fig. 7a, we observed a significant difference in the median total crank time between at least two of the groups ($H(2) = 31.94$, $p < .001$, $\epsilon^2 = 0.68$). Given this, we then conducted post-hoc pairwise comparison using Dunn's test, which showed that participants in the *BP/CI* configuration had a significantly lower total cranking time than both the *BF/CI* ($p < 0.001$, $r = 0.72$) and *BF/NCI* ($p < 0.001$, $r = 0.60$) groups.

Mean crank power generated for all conditions. Comparing the mean crank power when the crank was active (above 0 W), as seen in Fig. 7b, demonstrated a significant difference between console configurations ($F(2, 57) = 62.74$, $p < 0.001$, $\eta_p^2 = 0.74$). Post-hoc pairwise comparison using Tukey's HSD test revealed significant differences between all groups: *BF/NCI* was higher than *BF/CI* (mean difference *[BF/NCI - BF/CI]* = 0.10 W, $p < 0.001$, $d = 1.50$) and also higher than *BP/CI* (mean difference *[BF/NCI - BP/CI]* = 0.24 W, $p < 0.001$, $d = 4.02$), with *BF/CI* also higher than *BP/CI* (mean difference *[BF/CI - BP/CI]* = 0.14 W, $p < 0.001$, $d = 2.30$). These results indicate that both the *connection of the crank to application features (crank input versus no crank input)* and the *power source (battery-free versus battery-powered)* have significant effects on the mean crank power when active.

Total number of active cranking periods for all conditions. Focusing on the total number of active cranking periods across the three console configurations, visualised in Fig. 7c, we observed a significant difference between at least two conditions ($H(2) = 18.83$, $p < .001$, $\epsilon^2 = .38$). Post-hoc pairwise comparisons using Dunn's test showed that participants in the *BF/CI* condition produced significantly more active periods of cranking (median = 57.5) than both the *BF/NCI* condition (median = 27.0, $p = .006$, $r = .51$) and the *BP/CI* condition (median = 20.0, $p < .001$, $r = .56$). No significant difference was observed between the *BF/NCI* and *BP/CI* conditions ($p = .895$, $r = .20$).

Mean cranking duration per cranking period for all conditions. Examining the mean duration of each active cranking period, as visualised in Fig. 7d, revealed a significant effect of console configuration on cranking duration ($H(2) = 27.16$, $p < .001$, $\epsilon^2 = .57$). Dunn's post-hoc tests indicated that the *BF/NCI* condition resulted in significantly longer cranking periods (median = 6.52 s) than both the *BF/CI* condition (median = 3.25 s, $p = .027$, $r = .46$) and the *BP/CI* condition (median = 1.86 s, $p < .001$, $r = .69$). The difference between the *BF/CI* and *BP/CI* conditions did not reach significance ($p = .051$, $r = .42$).

5.3 Investigating User Perceptions of the Gaming Experience Through Questionnaire Responses

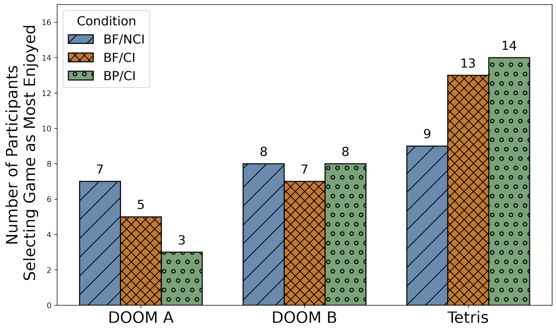
5.3.1 Exploring Users Intention to Use the System. **Hypothesis testing of H_{2a} and H_{2b} using HMSAM data.** The HMSAM questionnaire provided information on a number of construct factors relating to the *behavioural intention to use the system*, which was used to test elements of H_{2a} and H_{2b}. As can be seen in Table 4, we explored variations in these construct factors between all console configurations. The results showed no significant differences in the intention to use the system, or any of the composite factors. Thus, we were not able to find evidence to support H_{2a} or H_{2b} from analysis of the HMSAM data.

Table 4: Results for HMSAM factors tested between all console configurations. K-W denotes the Kruskal-Wallis test.

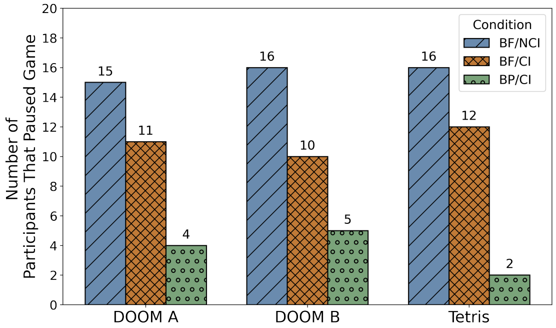
Factor	Test	Test Result
Behavioural Intention to Use	K-W	$H(2) = 1.08, p > 0.1, \epsilon^2 = 0.00$
Joy	ANOVA	$F(2,57) = 0.01, p > 0.1, \eta^2 0.0004$
Control	ANOVA	$F(2,57) = 0.01, p > 0.1, \eta^2 = 0.0003$
Focused Immersion	K-W	$H(2) = 1.61, p > 0.1, \epsilon^2 = 0.00$
Temporal Dissociation	K-W	$H(2) = 3.28, p > 0.1, \epsilon^2 = 0.02$
Curiosity	K-W	$H(2) = 3.42, p > 0.1, \epsilon^2 = 0.03$
Perceived Ease of Use	K-W	$H(2) = 3.80, p > 0.1, \epsilon^2 = 0.03$
Perceived Usefulness	ANOVA	$F(2,57) = 0.79, p > 0.1, \eta^2 = 0.03$

Exploratory analysis of HMSAM data. To assess whether the battery-free variants were practically equivalent to the battery-powered variant in terms of behavioural intention to use, we conducted Two One-Sided Tests (TOST) using equivalence margins of ±0.5 on the 7-point HMSAM scale. For both comparisons (BP/CI vs. BF/NCI and BP/CI vs. BF/CI), the TOST procedure was not significant (all p-values $> .05$), indicating that we could not demonstrate equivalence of intention to use the console between conditions.

5.3.2 Investigating User Perception of Workload. **Hypothesis testing of H_{2a} and H_{2b} using NASA-TLX data.** The total weighted perceived workload scores per console configuration for each game session are presented in Fig. 9. H_{2a} and H_{2b} were tested by checking for variations in total weighted NASA-TLX scores between console conditions during each game. For the *Tetris* case, there was no observed significant difference ($F(2,57) = 3.05$, $p = 0.055$, $\eta_p^2 = 0.10$). No significant difference was also seen in the case of *DOOM A* ($F(2,57) = 2.78$, $p = 0.071$, $\eta_p^2 = 0.09$). Although not statistically significant, the lower average perceived workload for the BP/CI condition in both *Tetris* and *DOOM A* hints at possible small-to-moderate effects that a more highly powered study could clarify. The results for *DOOM B*, which typically has a much more demanding interaction than *DOOM A*, across the three console configurations also shows no significant difference ($F(2,57) = 2.19$, $p > 0.1$, $\eta_p^2 = 0.07$). Thus, there was no significant difference in the weighted perceived workload between console variants, including between battery-powered and battery-free configurations, so evidence to support H_{2a} and H_{2b} was not found.



(a) Most enjoyed gaming experience for each console condition. Note, participants were able to select more than one game as *most enjoyed* if their experiences were equivalent.



(b) Number of participants that paused gameplay at least once per game.

Figure 8: Comparison of the most enjoyed games and the number of participants who paused each game at least once across the three console conditions.

Hypothesis testing of H_{2c} using NASA-TLX data. We tested H_{2c} by comparing the NASA-TLX scores across gaming levels for both battery-free console configurations. For the *BF/NCI* configuration across all three gaming sessions, there was no significant difference observed in the weighted TLX ($F(2,38) = 3.05$, $p = 0.059$, $\eta_p^2 = 0.14$). The *BF/CI* configuration also showed no significant difference between gaming sessions for the overall weighted results ($F(2,38) = 1.88$, $p = 0.167$, $\eta_p^2 = 0.09$).

Exploratory analysis of individual workload components between games. To deepen our understanding of H_{2c}, we examined the individual components of the workload data. For the *BF/NCI* configuration, significant differences between games emerged for *Physical Demand*, *Effort*, and *Frustration*. Physical Demand showed the clearest effect, with *Tetris* rated significantly lower than both *DOOM A* and *DOOM B* ($F(2,38) = 8.97$, $p = 0.001$, $\eta_p^2 = 0.321$). Frustration also differed across games, with *DOOM B* eliciting significantly higher ratings than *DOOM A* ($F(2,38) = 3.87$, $p = 0.030$, $\eta_p^2 = 0.169$). Although Effort showed a significant overall effect ($F(2,38) = 3.50$, $p = 0.040$, $\eta_p^2 = 0.156$), no pairwise contrast survived Bonferroni correction, indicating only a general tendency for *DOOM B* to be perceived as more effortful.

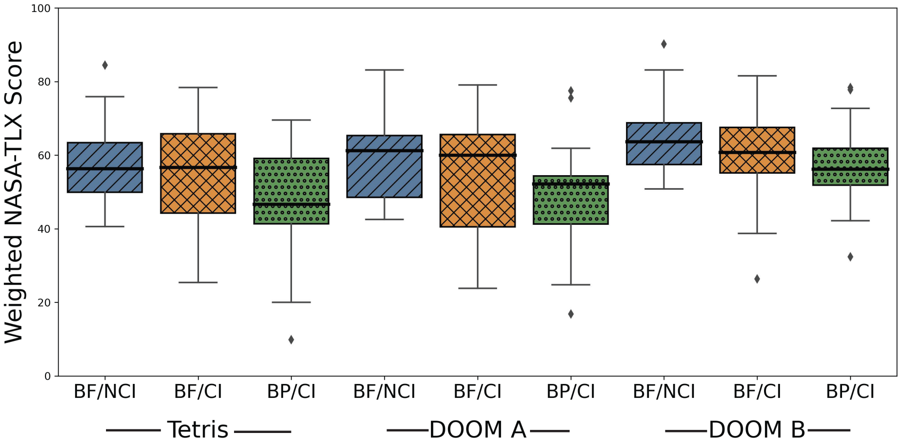


Figure 9: Box plot of the weighted NASA-TLX scores for each console condition across all three gaming sessions.

For the *BF/CI* configuration, significant overall effects were observed for *Temporal Demand* ($H(2) = 7.32$, $p = 0.026$, $\varepsilon^2 = 0.28$), *Performance* ($H(2) = 7.62$, $p = 0.022$, $\varepsilon^2 = 0.30$), and *Effort* ($H(2) = 9.23$, $p = 0.010$, $\varepsilon^2 = 0.38$). However, none of the associated post-hoc comparisons remained significant after Bonferroni adjustment, suggesting that although workload varied across games in aggregate, no specific game-to-game contrast exhibited a statistically reliable difference under crank input in the battery-free condition.

5.4 Qualitative Findings

All participants joined a semi-structured post-study interview, lasting around five to ten minutes. In this section, we consider data from users that played a battery-free variant of the console ($N = 40$).

5.4.1 ***Theme 1: Familiar Experiences as Anchors and Barriers in Responding to Power Failure.*** Participants tended to **draw on prior experiences to interpret power failure**. Just over half of participants (21/40) referred to a *"battery"*, despite an introduction and tutorial about the battery-free design. Using existing experience also manifested as users **returning to familiar modes of play**. For example, one participant stated, *"at first when I started playing, I just went back to what I know"* (P2:BF/CI), here referring to their existing experiences of mobile gaming. Others described how they became so *"[...] immersed in the game that I was forgetting about the [...] need to recharge it"* (P34:BF/CI), whilst others described surprise when power failure occurred unexpectedly: *"I would not keep track of the time, so every time for me it was a surprise that I was not anticipating"* (P14:BF/NCI). These findings suggest that familiarity acted as both a cognitive aid and a barrier; whilst it helped participants initially adapt to the console by allowing them to relate to existing experience, reliance on prior knowledge caused misinterpretations when users applied assumptions from other devices.

5.4.2 ***Theme 2: Users Learning to Live with, Reimagine the Inclusion of, and Value Failure.*** Confirming our belief that reliance on existing modes of play would diminish over time, some participants **adapted to failure as an inherent part of the experience** (10/40) by showing learning throughout gameplay sessions *"At the beginning I was quite annoyed [...] when the battery died [sic] [...] But like after a few times I began to kind of enjoy it. Like I knew it was coming, I knew that I could anticipate it."* (P1:BF/NCI). This progression highlights how initial frustrations transformed into acceptance and even appreciation, as participants integrated failure into their gameplay strategies. Participants found **playful sub-challenges within the failure experience** (11/40). *"There was kind of like a second game going, which is trying to keep the console alive as well"* (P50:BF/NCI), and the challenge of keeping the console powered *"[...] should be kind of like a mini game within the game"* (P25:BF/CI). These responses suggest that failure, rather than being seen purely as a limitation, became an opportunity for creativity and engagement, enhancing the overall gameplay experience.

Participants (7/40), particularly those that experienced the BF/NCI configuration, also reflected on the value of **failure as a way to break up periods of technology use**. One participant noted how failure acted as a natural interruption, encouraging healthier technology use: *"I'm getting a little bit too addicted to my phone, to Instagram and stuff. But with this thing, it's like when it dies [...] I just cannot continue."* (P1:BF/NCI) and that by facilitating periods away from direct immersion in gameplay the console *"[...] may be a good alternative for people who don't want to spend most of the time with phone."* (P4:BF/NCI). One participant remarked that: *"To me, this was a very relaxing experience and a normal game is always very frustrating. So therefore I prefer this because it requires you to take some break"* (P39:BF/CI). These responses point to the potential of failure as a design feature that encourages reflection, balance, and mindful gameplay.

When discussing strategies to manage failure, participants frequently suggested **nudging techniques using subtle cues to guide behaviour during failure recovery** (16/40). Imagined strategies included *"a low power beep"* (P29:BF/CI), *"the screen becoming darker"*(P14:BF/NC), or *"some sort of vibration"* (P44:BF/NCI). Participants also suggested providing clearer feedback on remaining play time, such as *"below 10% like [it] pauses automatically"* (P45:BF/NCI), or displaying remaining play time as more intuitive value since *"the percentages they were not telling me much in terms of the game experience. I would rather say like 10 seconds, 15 seconds and then you need to power up so that you know how much play time you actually have."* (P34:BF/CI), and mentioning failures as *"part of the statistics of the game itself"* (P14:BF/NCI). These desired strategies suggest that participants valued intuitive and actionable feedback from the console, however qualifying their ideas, one participant mentioned that power warnings could be *"super evident and warning but then it becomes a bit annoying"* (P14:BF/NC). This tension between the evident and distracting highlights the importance of subtle feedback that facilitate users' understanding of the device's behaviour.

5.4.3 *Theme 3: The Connected Crank as an Vector for Novel Interactions and Public Faux Pas.*

A majority (18/20) of users that played with the BF/CI configuration **valued the crank for its novelty and engaging interaction**. They mentioned that it was *"quite fun to use"* (P18:BF/CI), and that they *"[...] like that the crank was incorporated into the game mechanics when I figured it out how to use it."* (P2:BF/CI). **The crank mechanic in DOOM was perceived as creatively integrated and engaging** and noted by participants (10/20) as being *"[...] really cool I guess, very kind of tactile"* (P25:BF/CI). Others found that its integration into gameplay added depth and enjoyment, as one participant commented *"[...] connecting it to a weapon in the DOOM levels made it a bit more interesting and more of an enhancement"* (P18:BF/CI). By connecting the crank one participant remarked that *"I really liked it, actually using it as a weapon. Also because I just needed to do that to keep playing"* (P2:BF/CI).

The perceived value of the crank integration was not consistent across gaming condition however, with a number of participants (7/20) feeling that the **crank integration into Tetris was perceived as less aligned with the game's mechanics**, *"For me it felt kind of counter-intuitive that if I was cranking it really hard that it slowed down the pieces instead of making them go faster"* (P2:BF/CI). These comments suggest a mismatch between the physical requirements of the crank and the slowing effects of the game modification. This narrative was counteracted by a small number of users (3/20) that found the integration to be enjoyable, seemingly for the opposite reason *"[...] you can slow it down a bit with the crank and that for me is perfect because then I can think a little longer and see things a little better."* (P39:BF/CI). The variation in user responses between *DOOM* and *Tetris* highlights how the crank's value depended on its alignment with gameplay mechanics and player expectations, implying that novel input mechanisms are not universally engaging, but must be contextually integrated to create meaningful experiences.

Concerns about the sustainability of the crank's novelty were raised by some participants, who questioned whether its appeal would last over time. One participant remarked that integrating the crank was *"[...] a fun feature, but [...] in the end I felt myself going back to normal shooting"* (P51:BF/CI) suggesting that novelty alone may not be enough to sustain engagement with the crank, participants need deeper and varied ways to integrate the mechanism into gameplay.

Additionally, **social and practical challenges of using the crank in public** were highlighted, such as the sound produced and physicality of cranking. One participant remarked: *"in the train, if you're in the silent coach next to someone and you're like all of a sudden, hold on, I got to charge"* (P47:BF/CI), which reflects the tension between immersive physical interaction and the practicalities of using the system in public places. Despite these concerns, participants (10/40) offered **speculations on creative possibilities for integrating the crank into future game mechanics** that included new environmental interactions such as *"Repair when you've been damaged by a mistake, building something, changing something in the environment"* (P41:BF/CI) and the motion of characters and vehicles in the game *"like if you were on a boat or something or in a car and you needed to turn right or left. You could then use the crank to turn left or right."* (P47:BF/CI), or tasks involving vertical motion: *"places going up and down [...] elevate, or go down [...] with the help of this crank"* (P56:BF/NCI), and *"you can use the crank to do some character movement and to make your character move more fast or move slower"* (P49:BF/NCI).

5.4.4 *Theme 4: The Strain of Play. Ergonomic Tensions of Energy-Harvesting Design.*

Ergonomic issues were frequently mentioned (30/40). Some participants (7/40), particularly in the BF/CI category, had **difficulty coordinating gameplay and cranking simultaneously**, *"I really wanted to play and crank it up at the same time, which is very awkward to do"* (P2:BF/CI), which could lead to physical discomfort *"my left hand kind of cramped"* (P2:BF/CI). These highlight how the dual demands of interaction and power generation created physical strain, reflecting the tension between the novelty of the crank and its practical usability. Several users (8/40) had **issues gripping the console due to its form**, particularly whilst cranking *"you're not able to maintain proper grip to crank it at the appropriate speed"* (P43:BF/CI). A further (8/40) felt that the **console was too large or heavy to handle**, including those that felt the design was too physically demanding to hold *"[...] for me the the biggest problem I had with operating the device was actually the amount of physical strength I needed to hold it"* (P34:BF/CI) and that *"I think it's a bit too big for my hands to have, like good feeling"* (P8:BF/NCI). This was slightly counteracted by a minority of users that found the console proportions to fit well *"the dimension and the proportion are quite good"* (P50:BF/NCI). These contrasting experiences highlight the difficulty of designing a device that caters to diverse physical preferences, but reflect a system that was likely larger than the average preference.

The quality of the screen also emerged in discussion (15/40). The **screen was seen as insufficiently bright** by several participants (8/40), however this was most common in relation to DOOM rather than Tetris, *"the screen brightness was sometimes a bit difficult for me, but on Tetris for example it was fine so I guess that's just variable"* (P18:BF/CI) likely due to the brighter range of colours used in Tetris. The **colour display and size were appreciated**, *"first of all I was very impressed by the fact that it has a colour screen"* (P25:BF/CI), and *"the screen size is perfect"* (P10:BF/CI), however one participant did remark that they *"[...] would be fine with a smaller screen, if that allows for the battery [sic] to last longer"* (P3:BF/CI). There were **diverging perceptions of joystick sensitivity,** with some participants (3/40) explicitly finding it too sensitive and (2/40) finding it to their liking.

5.4.5 *Theme 5: The Tensions of Leveraging and Modifying Nostalgia.*

The console evoked a sense of familiarity through its use of retro games, with one participant remarking that *"I like retro games, I like Tetris, it's a nice game"* (P23:BF/CI). This was also grounded in some participants (4/40) directly referencing how the console made them **reminisce about childhood due to retro game use**, *"I really like the feeling of using it because it brings me back to when I was a kid"* (P50:BF/NCI). In contrast, leveraging classic video game titles was not universally accepted in the study though, with some participants finding **conflict in the act of modifying retro games with new interactions**, producing results that *"[...] seemed like cheating"* (P43:BF/CI). One participant noted that integration *"would be a bit jarring and a bit weird because people are just so used to playing the games how they used to play the games"* (P47:BF/CI). These responses suggest that whilst nostalgia was a useful tool to foster familiarity and connection, altering iconic gameplay experiences also risked disrupting participants' existing attachments to retro titles.

6 Discussion

6.1 Seeing the Connected Crank as a Distributed Energy Harvester and the Disconnected Crank as Mindful Intervention

Testing of H_{1a} and H_{1b} showed no statistically significant difference in the total cranking time or number of system power failures between the gameplay-connected (BF/CI) and disconnected (BF/NCI) battery-free conditions, yet exploratory analysis of system log data revealed a far more nuanced picture of participant behaviour. In BF/CI, participants had significantly more active cranking periods, yet produced lower mean crank power and maintained shorter durations of continuous cranking. These behavioural patterns suggest that gameplay connectivity did not reshape the total quantity of energy harvesting work performed, but rather the *texture* and *pacing* of that work, highlighting how **coupling game input with power harvesting can shape the feel and framing of interaction**.

In the BF/CI case, participants often kept cranking whilst playing, consistent with our design intentions, producing lower average power but a more evenly distributed energy-harvesting pattern. This interaction style echoes work that integrates energy harvesting directly into ongoing input [61], where physical effort becomes an unobtrusive, continuous contribution rather than a discrete, attention-demanding task. This behaviour also aligns with seamful and breakdown-oriented perspectives [22], in which small fluctuations or interruptions are absorbed into the flow of activity rather than experienced as disruptive. In this sense, BF/CI fostered a rhythm of play in which energy harvesting became a backgrounded yet frequent part of interaction, subtly shaping the tempo of engagement without demanding explicit attention. A further aspect of the BF/CI console worth noting is that any cranking pace produced the same application effect. This lack of differentiated in-game reward may have discouraged users from attempting more intense bursts. By flattening the relationship between effort and response, the design may have limited opportunities for players to develop more complex rhythms or strategies.

By contrast, the BF/NCI configuration encouraged more focused bursts of activity that were less frequent but longer in duration and produced a higher mean cranking power, with many participants cyclically pausing to crank intensely before resuming play; a pattern observed both in the system logs and in the number of participants pausing during the gameplay sessions. These rhythms echo prior accounts of breakdowns as interruptions that can disrupt flow yet also be incorporated into routines and foster new understandings [22], for example by helping users recognise when to pause, how to time cranking, and how to work with intermittent power. This reframing of cranking pauses less as obstacles and more as opportunities for reflection, as surfaced in Theme 2, gave users space to step back from the game and attend to the physicality of cranking. Echoing the intentions of Song et al. [53], some users described the barrier introduced by insecure power as an opportunity to cultivate deeper bodily awareness and temporary detachment from the application.

Testing of H_{2a} across the HMSAM and NASA-TLX data showed no significant variation in behavioural intention to use the system or perceived workload between battery-free configurations. Playing with the gameplay-connected crank was a fun and novel experience, as surfaced in Theme 3, yet the added complexity of the system's *encoding input* [7], serving simultaneously as a power source and a play mechanic, led to diverse views on its efficacy, to the point that no clear variation existed between it an the disconnected battery-free case for our user sample. This suggests that the crank's dual role at times created tension between the game input desired by users and the power input required by the console.

The BF/CI condition challenged our initial expectation that a tighter coupling between interaction and gameplay would reduce system failures, increase behavioural intention to use the system, and lower perceived workload compared to the BF/NCI case, as proposed in H_{1a}, H_{1b}, and H_{2a}. Despite this deeper integration, failures still occurred and perceptions were not significantly shifted. Yet the console logs and interviews reveal meaningful variations in how participants engaged with and made sense of the system. Rather than striving for ever-greater energy availability or minimal intermittency, as the battery-free community has typically pursued, our results suggest that the differing *textures* and *tempos* of harvesting elicited by coupling power and game input are the key to creating meaningful battery-free gaming experiences. Designers should work with these rhythms to imagine gameplay that adapts to, foregrounds, or even elicits such behavioural patterns. In this view, the absence of significant differences in total power harvested becomes less important than the distinct ways players generate that power. This points towards future game mechanics that respond to slow and steady cranking, to sudden intense bursts, or that dynamically shift pace in step with players' harvesting rhythms.

6.2 Divergent Interaction Patterns Despite Comparable Subjective Perceptions Between the Battery-Free and Battery-Powered Variants

Testing of H_{2b} across the HMSAM and NASA-TLX data showed no significant differences between the battery-free and battery-powered variants in behavioural intention to use the system or perceived workload. Despite this lack of perceptual variation, exploratory analysis of the log data revealed markedly different interaction patterns. Users of the BP/CI condition cranked for a significantly shorter total time than BF/CI participants, produced a lower mean crank power (indicating less intense cranking), and engaged in fewer active cranking periods. As BP/CI participants were not at risk of intermittency due to power failure, their cranking tended to be lighter and less explored. This contrast between indistinguishable subjective evaluations and substantially different cranking behaviours illustrates that **perceived workload or intention to use does not entirely reflect the actual cranking work performed**. Further, although in both conditions the crank served as an optional beneficial game input, only the battery-free case elicited sustained and patterned cranking rhythms. With a battery present, users had little incentive to weave cranking into their ongoing play and often treated it as a brief novelty, whereas the battery-free condition encouraged more continuous and deliberate modulation of effort. These findings show that making the system battery-free not only increased participants' use of the crank but also shifted it from an occasional novelty to a more integrated part of gameplay—a shift echoed in interviews where participants described the crank as creatively integrated and forming a mini-game or enhancement to the experience. This suggests that battery-free design can shape player behaviour and deepen engagement through the necessarily tighter coupling of game input and maintaining system functionality.

6.3 Interpreting Workload Through the Interplay of Gameplay and Energy Input

Testing H_{2c}, which assumed that increased game difficulty would raise perceived workload, revealed no significant differences in overall workload across all games for either battery-free configuration. Exploratory analyses of TLX components showed more localised effects however. In BF/NCI, Tetris was rated as less physically demanding than both DOOM sessions, with further variation in frustration and a trend toward higher effort in DOOM B, offering partial but limited support for H_{2c}. In BF/CI, several components varied across games, though no pairwise comparisons survived correction. Interview and log data help contextualise these subtleties. In BF/CI, participants often described DOOM's crank integration as better aligned with its pace and mechanics than in Tetris, where the mapping sometimes felt counter-intuitive. In BF/NCI, where the crank was decoupled from gameplay, participants tended to divide their attention between harvesting and button-based play, which may have made differences in game tempo and task demands more perceptible. These accounts suggest that elements of workload may be shaped not only by application difficulty, but also by the additional complexity introduced by the physical crank interaction and its integration as a game input, which can **blur distinctions between workload arising from gameplay and workload arising from harvesting**. This highlights how designers can purposefully shape this integration to influence which aspects of workload players notice—whether the demands of the game, the effort of harvesting, or the interplay between the two, opening space for new experiential possibilities in battery-free play.

6.4 From Disruption to Experience: How Battery-Free Users Reframed and Imagined Surfacing Power Failure

Our post-study interviews suggest that whilst participants often began by evaluating battery-free play through the lens of battery-powered norms they did not treat power failure as a fixed or wholly obstructive limitation. Their relationship to it evolved as play progressed. What began as surprise or disruption shifted toward accommodation and, eventually, anticipation of system behaviour. In this process, players reframed power loss not merely as breakdowns to be tolerated but as emergent challenges to be engaged with; several even described this as a *game within a game*, indicating how intermittency itself became part of the experience. This reframing afforded a sense of agency, as participants actively incorporated intermittency into their play rather than resisting it. These dynamics extend prior discussions of how users creatively engage with failure [21], marking a shift from *out-of-loop* to *in-loop* failure behaviour [7]. Together, they show how interruptions can be re-appropriated into experience and generate novel play behaviour beyond the original application.

As participants' framing of power loss shifted from disruption to engagement, their expectations for system support evolved accordingly. Participant feedback and log data from the connected battery-free variant indicate that the simple nudging strategy of displaying percentage charge was insufficient to prevent failures. Interviews further suggested that participants wanted more developed nudging strategies, including representations that communicated the timing or likelihood of upcoming failures more clearly, rather than static charge percentages alone. Players also envisioned richer representations, such as displaying power as in-game failure statistics, elevating energy from a passive status indicator to an active game mechanic. Viewed through the lens of seamful design [12], such representations can be seen as ways of making the seams of energy intermittency more visible and playable, encouraging participants to engage with them strategically. In this sense, **participants were not only seeking to avoid failure but to understand and work with the system's energetic behaviour**, reinforcing the broader shift from experiencing intermittency as disruption to treating it as part of the game's expressive surface. This shift would allow energy to move beyond a background constraint to become a key component of the gameplay itself.

6.5 The Challenges of Aesthetics, Ergonomics, and Social Acceptability in Energy Harvesting Devices

Post-study interviews highlighted ergonomics as a frequent concern, with participants noting issues around grip, device size, and screen brightness. Some also questioned the social acceptability of the crank, particularly the noise it produced, which would be a clear barrier to public play. Several users also found coordinating cranking with gameplay challenging, reinforcing that simultaneous play and power input created friction. Participants further suggested that more naturalistic ways of integrating physical action with input, such as raising an object with the crank turns, would better harmonise harvesting with game semantics.

These concerns intersected with how well the crank's physical action aligned with gameplay. Participants responded more positively when the crank's function resonated with natural expectations of what a crank should do, such as generating force or triggering impactful actions. This helps explain why its integration as a weapon input in DOOM was viewed more favourably than its role in slowing the pace of Tetris. In line with the ideas of natural mappings [43] and work on exertion games [41], intuitive mappings between physical effort and game outcomes were easier for players to adopt than more abstract uses of the mechanism.

These findings underline that, whilst the crank generated far more power than earlier battery-free systems of de Winkel et al. [14] and [63], its use was not always experienced as comfortable or natural. As Pierce and Paulos [48] suggest, *"acceptance of human-powered microgeneration is likely highly dependent on pleasurable and aesthetic engagement"*, which the crank did not universally deliver. This highlights the value of exploring alternative harvesting mechanics, aligning with Pierce and Paulos [48], who found that *"squeezing was often found to be a natural and pleasing interaction, more so than cranking"*. Inputs such as squeeze, pull, or twist may therefore offer more ergonomic and socially acceptable ways to integrate energy harvesting into play. The modular architecture of TURNER supports such exploration.

6.6 The Limitations of Leveraging Nostalgia in System Design

Gaming nostalgia gave participants an initial sense of familiarity, an intentional design choice in TURNER to reduce adaptation effort. Yet this familiarity also narrowed expectations, as users anticipated conventional play and uninterrupted interaction. Users who resisted modifying retro games revealed deep attachments to gaming touchstones, particularly those formed in childhood. In this way, nostalgia acted as both a strength and a constraint, easing entry while limiting willingness to reimagine interaction around intermittency. This stands in contrast to de Winkel et al. [14], who position retro gaming as an advantage for battery-free systems. Since battery-free computing represents a fundamental shift in how systems operate, we argue that it requires novel game design, rather than reliance on retro aesthetics, to push battery-free gaming forward.

7 Design Recommendations and the Future of Interactive Battery-Free Gaming

In this section we translate our findings from studying and working with TURNER into design recommendations for future interactive battery-free gaming systems. In doing so, we also highlight broader opportunities for expanding the design space of battery-free gaming.

7.1 Explore Novel Approaches to Exposing System Power Behaviour to Users

Existing battery-free systems tend to obscure when power is running low or how player actions might influence energy levels. In TURNER, available energy was shown through a simple capacitor icon, analogous to a battery indicator. However, our results highlight the need for clearer and more expressive representations of power behaviour in mobile interfaces, moving beyond basic gauges toward more intuitive and meaningful forms of feedback. Using highly-visible interface elements could signal impending outages, while metaphorical in-game representations could help players form intuitive mental models of energy flow. **Future work should identify which representations of energy and power failure best help players anticipate outages and manage their harvesting workload.**

7.2 Design Intuitive Energy Harvesting to Application Input Mappings and Explore New Levels of Integration Between Harvesting and Application Input

Energy-harvesting actions carry natural affordances such as effort, rhythm, and intensity, which can be aligned with in-game responses to create more intuitive and learnable interactions. Our study suggests a spectrum of integration between input and application feature which we name and define: *Core Connections* link harvesting to essential resources such as health or survival, *Kinetic Coupling* ties it to movement or timing actions such as firing or slowing pieces and *Full Disconnection* treats harvesting as a separate prerequisite for play. While *Kinetic Coupling* and *Full Disconnection* offer novelty and predictability, our findings show they can also create ambiguous or uneven mappings between effort and outcome, making it harder for players to form stable expectations. *Core Connections* may offer stronger agency by embedding energy management in core mechanics. **Future work should investigate which mappings best align with player expectations and enable long-term engagement with intermittent systems.**

7.3 Support User-Directed Input Remapping

Connecting energy harvesting to application features is not a catch-all solution for users, as demonstrated by the large variations in perception of the TURNER console. Just as button remapping is central to accessibility in games [8], energy harvesting likewise demands an inclusive approach that gives players control over how, when, and whether harvesting is tied to gameplay. **Future work should champion reconfigurable energy-game inputs as a way to support diverse user needs and play styles.**

7.4 Explore Dynamic and Context-Aware Integration of Energy Harvesting

Future designs could shift between harvesting–application input modes in response to system demand and gameplay rhythm. Disconnected energy harvesting might be introduced strategically during high-power moments to elicit stronger output, while connected input could be used to support engagement with the game content. **Future systems may also incorporate lightweight modelling and predictive logic to anticipate upcoming outages, enabling the console to adjust game pacing or structure events around expected energy availability**, treating intermittency as a design material rather than a limitation. Adaptive integration could also make harvesting effort itself meaningful: for instance, allowing stronger input to yield more powerful actions or greater slowdown effects. **Future work should explore how adaptive, effort-sensitive mappings shape strategy, pacing and long-term play.**

7.5 Prioritise Ergonomic Refinement and Social Acceptability

Designers should treat ergonomics and social context as central considerations for energy-harvesting consoles. Iteration on grip, weight distribution and screen visibility will be critical, alongside careful attention to how public use is perceived. Technical work on reducing cranking noise may also ease the social burden of energy harvesting, while subtle design choices that normalise cranking as part of play can increase acceptability and support sustained engagement. **Future work should investigate how the physical form of battery-free devices can better support sustained, comfortable harvesting across diverse contexts of use. Future research should also include longitudinal, in-situ studies to capture effects that extend beyond short-term sessions.**

7.6 Leverage TURNER's Modularity to Explore Alternative Harvesting Interactions

We recommend that future systems build on TURNER 's modular architecture to explore a wider range of harvesting mechanics. Supporting interchangeable inputs such as squeezing, pulling, or twisting would allow designers to tailor energy generation to different contexts and user needs. This approach could extend battery-free systems beyond gaming into areas such as rehabilitation, education and wellbeing. **Future work should test different harvesting modalities in real contexts to determine which inputs produce the most usable energy and highest user acceptance.**

7.7 Explore Anthropomorphic System Emotions to Encourage Power Generation

Although not examined directly in our study, inspiration from discussions in HRI [29, 51] suggests that participants' tendency to *keep the console alive*, shaped by the system's reliance on users to power it, may be strengthened through subtle anthropomorphic cues such as expressive feedback or light emotional framing, provided such strategies are applied with ethical care. Simple emotional signals linked to energy levels (for example relief when recharged or mild frustration when low) could prompt harvesting without disrupting flow, reframing energy generation as part of the interaction rather than a technical burden. **Future work should examine how anthropomorphic expressions might encourage harvesting and sustain engagement without fatigue.**

8 Limitations

8.1 Study-Related

A limitation of our study was the **short session duration and limited ecological validity**. To balance a full gameplay session with a sample size suitable for analysis, each participant played for 18–20 minutes including the tutorial. Extended use may affect fatigue, power management strategies, and overall system usability. Sessions took place indoors under controlled conditions, whereas portable consoles are also typically used in varied environments, including outdoors and public spaces. These conditions introduce lighting variability not examined in our work.

Another limitation concerns the **diversity of our participant sample, a lack of younger users, and sample size**. Participants were predominantly university educated and likely had an above-average awareness of battery-free computing. We did not include individuals under 18 years, a key demographic for handheld gaming, and our **sample size limited detection of medium and small effects**. Future studies should engage more diverse populations to capture a broader range of experiences and target smaller effects not captured in our work. Further to this, we conducted a small number of exploratory analyses to better understand user interaction, however such analyses inherently increase the chance of identifying coincidental rather than genuine effects.

To preserve DOOM's natural progression, the lower-complexity level was always presented before the more complex one. Although task order was counterbalanced with the Tetris task, this fixed ordering introduces a **potential learning or fatigue confound between the two DOOM levels.**

Finally, there were limitations in the **clarity and framing of questionnaire instruments**. As discussed in Section 5.4.2, the "*game within a game*" mechanic may have led participants to conflate NASA-TLX workload scores for *powering the console* and playing the *game*. The weighting task also disrupted flow for some participants. Likewise, some participants struggled with interpreting constructs in the HMSAM, which may have reduced its sensitivity.

8.2 System-Related

Our analysis revealed potential conflicts with social norms due to the sound and physicality of cranking. TURNER 's design configuration aimed to replicate modern console ergonomics, however **the crank ultimately compromised physical stability during use**. This demonstrates that *mechanically-powered systems need more than retrofitted energy harvesters*, they require early consideration of physical constraints and may necessitate bulkier grips. **The DC motor also produced noticeable cranking noise**, which affected playability. While charging was audible, **the system did not produce audio relating to gameplay**, limiting the ecological validity of TURNER compared to modern systems with integrated audio. Although we believe audio can be incorporated into battery-free gaming, existing soundtracks may feel disjointed due to system intermittency. Future work should aim to make mechanical energy harvesters quieter, explore sound design for intermittent systems, and evaluate energy-harvesting consoles in more ecologically valid settings. The physical demands of cranking also warrant longitudinal study.

We also note that **system failures were sometimes caused by factors unrelated to energy availability**, complicating interpretation. Whilst TURNER was stable overall, it remains a prototype and occasionally experienced hardware or software issues. For example, DOOM B's graphic-intensive moments could cause screen freezes requiring a manual reset.[7] Future work should robustly

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[7] These failures were quickly resolved by the attending researcher but nonetheless represent a limitation. Failure due to factors other than power intermittency was distributed across all console configurations and occurred in approximately one in four or five participants.

stress-test prototypes through extended pilots to limit the risk of failures beyond those inherent to its power architecture.

TURNER's display choice was informed by a desire to align with commercial systems. An initial black-and-white prototype lacked immersion, leading to a shift towards colour. However, **the limited backlighting hindered usability in brighter environments**. While the screen size marked an improvement over prior systems [14], we suggest it may be *more effective to prioritise a bright display over a larger display* to improve usability.

Unlike de Winkel et al. [14] and Zhu et al. [63], TURNER featured an onboard logger that supported both usage tracking and the BP/CI configuration described in Section 4. While it operated reliably, **the logger required a full charge prior to use to ensure it functioned correctly, and its power level was not visible within the software**. To improve usability, we recommend *integrating a menu with power and status indicators for the logger.*

9 Conclusion

In this work, we introduced TURNER, a state-of-the-art modular handheld console powered by a crank and solar cells, to explore how energy harvesting and power intermittency shape interaction. In a 60-participant mixed-methods study, we examined how embedding harvesting into gameplay affects behaviour, workload, and intention to use the system. Our study shows that participants adapted varied cranking behaviours and reflected on both the challenges and opportunities of intermittent power. Our findings highlight strategies for interactive battery-free gaming, including flexible input remapping, increasing awareness of power failures, and recognising the ergonomic limits of harvesting. By viewing intermittency not only as a limitation but as a design opportunity, we contribute insights for sustainable, engaging battery-free computing.

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A Semi-Structured Interview Questions

The following shows the semi-structured guide for interview with participants following their gameplay sessions. Additional questions outside this set were asked depending on the context and content of each participant interview.

- What was your overall impression of the system?
- What did you consider the strongest and weakest aspects of the games console experience?
- To what extent did you feel connected to the console and its approach to energy harvesting?
- How did you make use of the pause feature during gameplay?
- Can you envisage any other games or applications in which the energy-harvesting mechanics could be linked to in-application features?
- Are there any additional methods of harvesting energy you can imagine, and how might these relate to gameplay?

B Additional User Study Results

In this paper we follow standard statistical conventions to present our analyses, which we briefly explain here:

- $t(d)$: Represents a t-statistic with d degrees of freedom.
- $H(d)$: Denotes the H-statistic for a Kruskal-Wallis test, with d degrees of freedom.
- $F(d_1, d_2)$: Refers to the F-statistic from an ANOVA test, where d_1 and d_2 indicate the degrees of freedom for the between-group and within-group variances, respectively.
- **Effect Sizes**: We report effect sizes (e.g., d, η^2, η_p^2, ϵ^2, or r) where applicable to quantify the magnitude of observed effects.

In Table 5 the central tendency values for the factors measured in the user study are presented. Please note that the scores for HMSAM represent scaled composite scores for entire factors. For instance, while individual items within the *Joy* factor were assessed using a 7-point scale, the composite score is the mean of all scales comprising the *Joy* factor. Therefore, median scores are reported to two decimal places.

Table 5: Descriptive statistics across measured factors.

Metric	**BF/CI**		**BF/NCI**		**BP/CI**	
	Median	Mean ± SD	Median	Mean ± SD	Median	Mean ± SD
Total Crank Time (s)	212.6	220.9 ± 83.6	182.9	182.0 ± 41.3	30.4	40.9 ± 35.2
Total Number of Power Failures	7.5	8.3 ± 4.3	6.0	6.8 ± 3.1	0.0	0.0 ± 0.0
Mean Crank Power When Active (W)	0.22	0.23 ± 0.07	0.35	0.34 ± 0.07	0.10	0.10 ± 0.05
Joy	5.17	5.08 ± 1.19	5.17	5.05 ± 1.16	5.08	5.02 ± 1.28
Control	5.08	4.74 ± 1.31	4.75	4.73 ± 1.34	4.58	4.78 ± 1.10
Focused Immersion	5.88	5.83 ± 0.85	5.38	5.44 ± 0.99	5.88	5.35 ± 1.47
Temporal Dissociation	5.17	5.00 ± 1.49	5.83	5.57 ± 1.16	5.00	4.63 ± 1.76
Curiosity	5.33	5.05 ± 1.60	5.17	5.25 ± 0.91	4.67	4.42 ± 1.33
Perceived Ease of Use	5.06	4.68 ± 1.40	5.69	5.23 ± 1.06	4.88	4.53 ± 1.38
Perceived Usefulness	4.20	4.20 ± 1.44	4.40	4.52 ± 1.24	4.00	3.94 ± 1.67
Behavioral Intention to Use	3.83	3.82 ± 1.91	4.67	4.35 ± 1.37	4.33	3.90 ± 1.73
Tetris Mental Demand	10.0	10.40 ± 5.11	13.5	13.25 ± 3.26	11.0	10.80 ± 5.37
Tetris Physical Demand	13.5	11.80 ± 6.01	10.0	11.10 ± 4.72	5.5	5.75 ± 3.65
Tetris Temporal Demand	12.0	10.70 ± 5.53	13.0	12.70 ± 4.23	11.0	9.75 ± 4.67
Tetris Performance	8.0	9.45 ± 6.31	9.0	9.85 ± 4.43	8.0	9.05 ± 5.53
Tetris Effort	13.5	11.30 ± 4.60	13.0	12.40 ± 3.82	9.0	9.70 ± 5.07
Tetris Frustration	8.0	9.25 ± 6.35	9.0	9.10 ± 4.27	7.5	7.50 ± 4.47
DOOM A Mental Demand	8.5	9.90 ± 5.05	14.0	12.75 ± 3.54	12.0	10.95 ± 3.59
DOOM A Physical Demand	14.5	12.60 ± 5.78	14.5	14.00 ± 4.35	8.5	9.80 ± 5.58
DOOM A Temporal Demand	8.5	9.35 ± 5.23	12.0	12.00 ± 3.81	11.5	10.95 ± 4.03
DOOM A Performance	14.5	13.15 ± 6.35	10.0	11.85 ± 4.97	15.5	13.55 ± 5.61
DOOM A Effort	13.0	11.90 ± 4.97	13.0	12.90 ± 2.92	10.0	10.25 ± 3.85
DOOM A Frustration	12.5	10.70 ± 7.31	9.0	9.15 ± 4.67	12.5	11.70 ± 5.30
DOOM B Mental Demand	10.5	10.60 ± 5.41	14.5	13.90 ± 3.67	14.0	12.75 ± 3.82
DOOM B Physical Demand	14.5	12.50 ± 6.02	16.0	14.75 ± 3.64	14.5	12.85 ± 5.16
DOOM B Temporal Demand	15.0	13.10 ± 5.01	14.0	14.45 ± 3.61	14.0	14.35 ± 3.95
DOOM B Performance	16.0	14.10 ± 6.30	13.0	12.90 ± 4.29	16.0	14.65 ± 4.80
DOOM B Effort	14.5	14.60 ± 4.06	14.0	14.85 ± 2.52	14.5	13.80 ± 2.40
DOOM B Frustration	12.5	11.05 ± 6.73	12.5	11.50 ± 4.92	13.5	13.10 ± 4.30