Chapter - 48
An Insight into Impact of Dark Mode on Energy Conservation across Devices

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Abstract

This study underscores the energy-saving potential of Dark Mode by examining its impact on smartphones, laptops, and desktops. Our results demonstrate substantial energy consumption reductions, reaching up to 30% on OLED screens and 20% on LCD screens. Notably, these energy savings varied depending on the device, operating system, and user demographics. These findings have significant implications for the electronics industry, encouraging the integration of Dark Mode as a standard energy-saving feature. This paper bridges the gap in current research by identifying key factors-display technology, ambient lighting, and software optimization-that significantly impact Dark Mode's energy-saving potential. This actionable knowledge empowers the tech industry, policymakers, and users to leverage Dark Mode effectively. Furthermore, the paper outlines a roadmap for future research to fully unlock Dark Mode's potential as a sustainable solution in the digital age.

Keywords: Dark Mode, energy consumption and conservation, sustainable technologies, device energy efficiency

Introduction

The rapid evolution of technology has driven a significant surge in global energy consumption, with the digital sector emerging as a key contributor to this trend [1]. Devices such as smartphones, laptops, and displays have become indispensable in modern life, but their widespread use has raised concerns about their environmental footprint. Issues such as climate change, energy sustainability, and electronic waste have pushed the tech industry to explore innovative solutions to reduce energy consumption and promote eco-friendly practices [2]. One such solution that has garnered considerable attention is Dark Mode, a display setting that employs a dark color scheme.

Originally designed to enhance user comfort by reducing eye strain and improving visual aesthetics, Dark Mode has now become a ubiquitous feature across operating systems, apps, and devices [3] for its potential to significantly reduce energy consumption, particularly on devices utilizing OLED and AMOLED display technologies. These displays illuminate individual pixels, consuming less power when displaying darker content. The researches revealed that enabling Dark Mode on OLED screens can reduce energy consumption by up to 60%. Similarly, studies on LCD screens, though less pronounced in energy savings, suggest reductions of up to 30% depending on brightness and usage scenarios [4].

However, the effectiveness of Dark Mode in conserving energy is influenced by several factors, including display technology, screen brightness, and user behaviour. This study helps us explore the impact of Dark Mode on energy consumption by synthesizing empirical evidences across various display technologies and devices. It also seeks to assess the broader implications of Dark Mode for the tech industry, environmental sustainability, and user habits. Through this exploration, the paper highlights the conditions under which Dark Mode is most effective, providing insights for future research and adoption strategies.

Display Technologies and Energy Consumption

Overview of Display Technologies

LCD (Liquid Crystal Display)

LCDs, one of the most widely used display technologies, rely on a backlighting mechanism to produce images. In this setup, a layer of liquid crystals modulates the light emitted by a constant backlight to create visuals.

Energy Consumption Behaviour

Dark Mode, which primarily changes the content's color scheme, has limited impact on energy consumption in LCDs.

OLED/AMOLED (Organic Light-Emitting Diode)

Unlike LCDs, OLED and AMOLED displays utilize a per-pixel lighting mechanism where each pixel emits light independently. Hence less power is required to illuminate them, and fully black pixels consume no energy at all.

Energy Saving Mechanism

- In Dark Mode, where large portions of the screen remain dark or black, OLED displays reduce energy consumption proportionally to the number of dark pixels.
- The studies suggest energy savings of up to 60% on OLED screens in Dark Mode compared to light-themed interfaces.

Real-World Efficiency Results

- Devices like smartphones and smartwatches, with OLED displays, demonstrate noticeable battery life improvements when users enable Dark Mode.
- Energy savings depend on factors such as screen brightness, resolution, and content composition. For example, apps with predominantly dark themes (e.g., night modes in browsers) achieve greater efficiency.

Micro-LED and Emerging Technologies

Micro-LED is an emerging display technology that builds on the per-pixel lighting concept of OLED but offers improved energy efficiency, brightness, and durability. In Micro-LED displays, individual micro-scale LEDs produce light, eliminating the need for backlighting while providing higher luminance and reduced power consumption.

Potential Energy Profiles with Dark Mode

- Like OLED, Micro-LED displays are expected to benefit from Dark Mode, as dark pixels consume minimal or no energy.
- Due to their higher efficiency and reduced leakage current compared to OLEDs, Micro-LEDs may amplify the energy-saving advantages of Dark Mode.

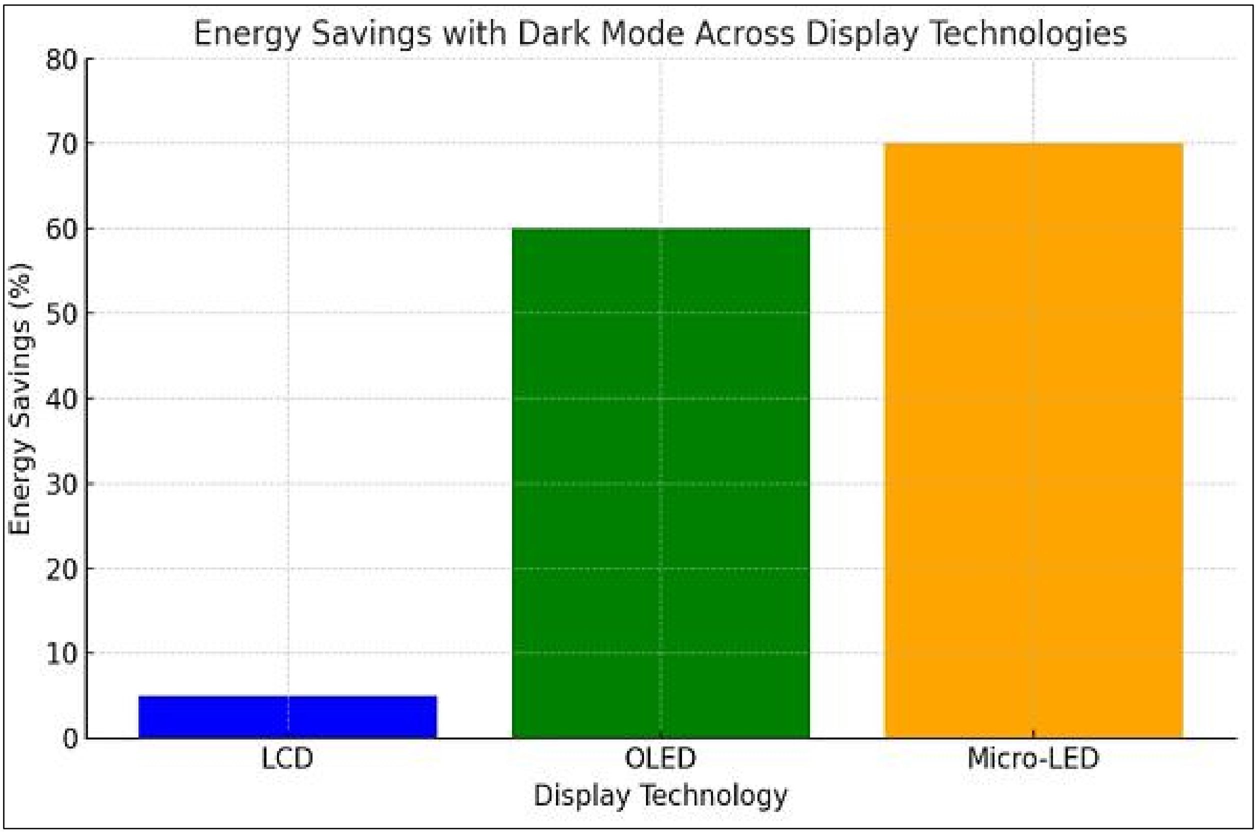

Fig 1: Energy Savings with Dark Mode across Display Technologies

Table 1: Energy Saving Percentage across Different Display Technologies in Dark Mode

Display Technology	Energy Savings with Dark Mode (%)	Brightness Dependency	Maturity Level
LCD	5%	High	Commercial
OLED	60%	Medium	Commercial
Micro-LED	70%	Low	Emerging

Comparison of Energy Usage by Technology

Energy Consumption of Dark Mode on OLED vs. LCD

- **OLED Screens:** OLED (Organic Light-Emitting Diode) displays operate with individual pixels that emit their own light, and consume minimal or no power. Energy consumption is directly proportional to the brightness of each pixel, leading to power reduction by 60%.
- **LCD Screens:** In contrast, LCDs rely on a constant backlight, resulting in minimal energy savings of around 5% on LCD screens.

Importance of Screen Brightness, Contrast Settings, and Usage Patterns

The energy savings associated with Dark Mode are heavily influenced by three key factors.

- **Screen Brightness:** Reducing screen brightness by 50% while using Dark Mode on an OLED screen could result in a 40% reduction in power consumption [4].
- **Contrast Settings:** Higher contrast settings, where dark pixels are closer to pure black, further reduce energy consumption in OLED displays.
- **Usage Patterns:** Devices like smartphones that are often used in various environments (e.g., indoors, outdoors, bright or dim settings) benefit from adaptive brightness adjustments. For example, in a well-lit environment, the screen will automatically brighten but in dim environments, Dark Mode can contribute to greater energy savings as the screen brightness is lower.

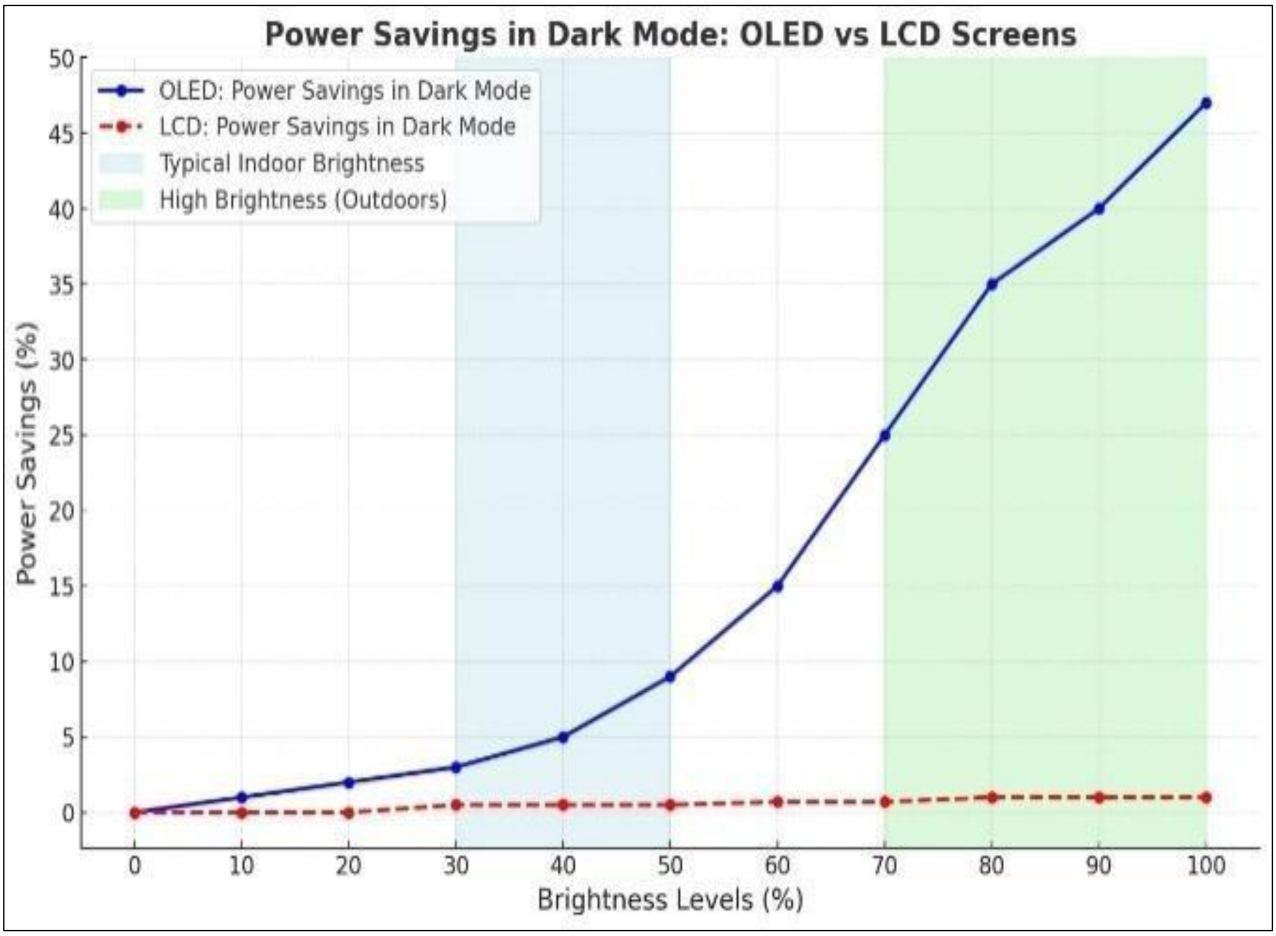

Fig 2: Power Savings with Dark Mode vs Brightness Levels on OLED and LCD Screens

Device-Specific Impacts of Dark Mode

Smartphones

- **Battery Life Improvement in OLED Smartphones:** Dark Mode significantly impacts battery life, leading to reduced power consumption of up to **20-50%**.
- **Operating System Differences (Android vs. iOS):** For instance, Android introduced system-wide Dark Mode in **Android 10**. Meanwhile, iOS integrates Dark Mode as a feature from **iOS 13**.
- **Google's Studies and Interaction Statistics:** Google's internal tests reported up to **63% power savings** when switching from Light to Dark Mode on OLED displays with reduced eye strain, contributing to longer device use and interaction time.

Laptops and Desktops

- **Productivity Apps, Browsers and Dark-Themed Software:** Applications such as Microsoft Office, Google Chrome, and Adobe Creative Suite now support Dark Mode.
- **Office vs. Gaming Use Cases:** Office settings emphasize text-heavy, static content. However, gaming environments often feature dynamic, high-brightness visuals and energy savings are comparatively less.

IoT Devices and Wearables

- **Smartwatches and Fitness Trackers:** Dark Mode adoption in wearables like smartwatches varies. Devices with AMOLED displays (e.g., Samsung Galaxy Watch) benefit from reduced energy consumption.

Factors Influencing Dark Mode's Effectiveness

Screen Brightness and Ambient Lighting

Studies on Energy Savings at Different Brightness Levels

Numerous studies have investigated the impact of screen brightness on energy consumption.

- **OLED Screens:** Reducing screen brightness from 100% to 50% can lead to energy savings of up to 50% on OLED screens and reducing screen brightness from 100% to 20% can lead to energy savings of up to 70% on OLED screens [4].
- **LCD Screens:** Reducing screen brightness from 100% to 50% can lead to energy savings of up to 30% on LCD screens [5] and reducing screen brightness from 100% to 20% can lead to energy savings of up to 50% on LCD screens [6].

User Behaviour

User Interaction and Energy Consumption in Dark Mode

Key factors include:

- **Extended Usage Duration:** A smartphone user spending **5-6 hours daily** in Dark Mode on an OLED device could save **10-20% more battery life** per charge cycle compared to Light Mode usage.
- **App Usage Patterns:** Text-based apps (e.g., messaging, email) yield higher savings in Dark Mode, while video streaming apps with minimal dark content provide little to no benefit.
- **Day-Night Mode Switching:** Some users toggle between Light and Dark Modes based on ambient lighting conditions, reducing potential for long-term energy savings.
- **Behavioural Insights:** Data from **Google and Apple user studies** show that Dark Mode adoption is higher in regions with longer daylight hours. However, users in darker or overcast regions spend more time in Dark Mode, maximizing energy savings on OLED devices.
- **Psychological and Aesthetic Preferences:** Beyond energy savings, user preference for Dark Mode often stems from reduced eye strain and a perceived modern aesthetic, leading to incremental energy savings over time.

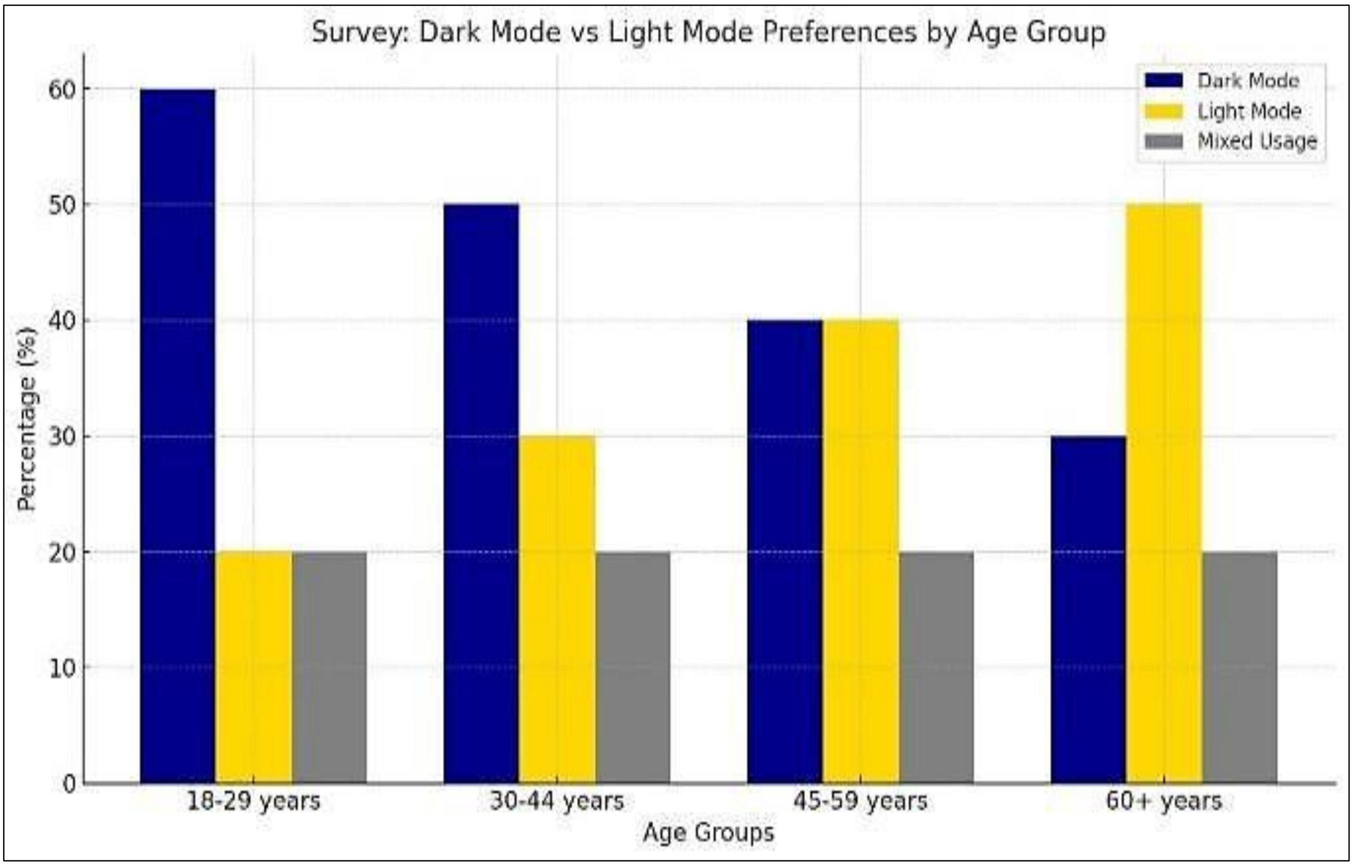

Fig 3: Dark Mode vs Light Mode Preference across Different Age Groups

Software and Optimization

Google

Case Study: Android & Google Apps

Implementation

a) Google introduced system-wide Dark Mode with Android 10, integrating it across native apps (Gmail, YouTube, Google Maps, etc.).

b) UI adjustments included reduced luminance levels, contrast ratios, and the use of pure black (#000000) for OLED screens to maximize energy savings.

Energy Efficiency Results

a) Google tested YouTube in Dark Mode and reported a **43% power reduction of 50% brightness** and **60% at 100% brightness** on OLED devices compared to Light Mode.

Key Features

a) Dynamic app theming (e.g., apps adapt to system-wide Light/Dark settings).

b) The "Material You" design (introduced in Android 12) adapts colors dynamically, blending Dark Mode with personalized accents.

Apple

Case Study: iOS/macOS Ecosystem

Implementation

a) Apple introduced Dark Mode with macOS Mojave and iOS 13. Native apps (e.g., Safari, Messages, and Mail) and third-party apps were encouraged to follow Apple's Human Interface Guidelines.

b) The company emphasized “True Black” backgrounds on OLED iPhones and subtle dark grey tones on non-OLED devices for visual consistency.

Energy Efficiency Results

a) Tests on OLED iPhones (e.g., iPhone 12 Pro) showed **up to 30% battery savings** when using Dark Mode versus Light Mode.

b) Long-term testing by Apple emphasized user comfort (e.g., reduced eye strain in low-light conditions) as a key driver for adoption.

Key Features

a) Dark Mode in Apple apps extends to the entire UI, including notifications, widgets, and system animations.

b) macOS leverages Dark Mode in productivity apps like Xcode, improving developer workflows while lowering energy usage on OLED-equipped MacBook Pro models.

Microsoft

Case Study: Windows 10/11 UI & Microsoft Office

Implementation

a) Microsoft introduced Dark Mode in Windows 10 and expanded its capabilities in Windows 11 with a more refined UI. Native apps like File Explorer, Microsoft Edge, and Settings support Dark Mode.

b) Microsoft Office apps (Word, Excel, and PowerPoint) offer Dark Mode, adjusting both UI elements and document canvas themes.

Energy Efficiency Results

a) On devices like the Surface Pro X (equipped with OLED/AMOLED displays), using Dark Mode reduced battery consumption by approximately **9-15%** over Light Mode.

b) Studies have shown improved battery life on OLED-equipped laptops while using system-wide Dark Mode.

Key Features

a) **Adaptive UI in Microsoft Office:** Users can toggle between Light, Dark, or "Use System Settings" for seamless transitions.

b) Windows 11 integrates Dark Mode with Fluent Design, optimizing translucency effects and improving performance on low-power devices.

Key Observations across Platforms

- **Consistency in Implementation:** All three companies emphasize uniform Dark Mode behaviour across ecosystems, encouraging developers to adopt similar design principles in third-party apps.
- **OLED Advantage:** Energy savings are more pronounced on OLED displays across Google Pixel devices, iPhones, and OLED Surface laptops, highlighting the importance of hardware and software optimization [7].

Table 2: Power reduction when switching from light to dark mode at different screen brightness levels

	Brightness Level											
	Pixel 2			Moto Z3			Pixel 4			Pixel 5		
App	30%	50%	100%	30%	50%	100%	30%	50%	100%	30%	50%	100%
Calculator	21%/ 7%	36%/ 12%	81%/ 54%	24%/ 10%	38%/ 12%	82%/ 58%	13%/ 6%	23%/ 10%	70%/ 51%	16%/ 2%	30%/ 11%	77%/ 58%
Google Phone	18%/ 4%	34%/ 9%	81%/ 50%	-	-	-	12%/ 5%	25%/ 11%	76%/ 56%	16%/ 8%	32%/ 14%	83%/ 63%
Google Calendar	21%/ 6%	34%/ 16%	79%/ 57%	21%/ 0%	37%/ 15%	80%/ 58%	13%/ 9%	25%/ 11%	73%/ 59%	19%/ 10%	32%/ 18%	80%/ 69%
Google Maps	8%/ -1%	15%/ 4%	40%/ 19%	8%/ 4%	14%/ 5%	34%/ 19%	6%/ 10%	11%/ 2%	36%/ 21%	7%/ 0%	14%/ 0%	40%/ 20%
Google News	11%/ -1%	22%/ 5%	64%/ 29%	15%/ 9%	27%/ 6%	63%/ 34%	8%/ 4%	15%/ 6%	56%/ 36%	9%/ 4%	20%/ 5%	63%/ 40%
YouTube	12%/ -1%	21%/ 6%	56%/ 28%	13%/ 6%	24%/ 8%	62%/ 28%	8%/ 1%	15%/ 3%	49%/ 27%	10%/ 2%	18%/ 6%	52%/ 31%
Average	15%/ 3%	27%/ 9%	67%/ 40%	16%/ 6%	28%/ 9%	64%/ 39%	10%/ 6%	19%/ 7%	60%/ 42%	13%/ 4%	24%/ 9%	66%/ 47%

- **Focus on Usability:** In addition to energy efficiency, Dark Mode UI design reduces eye strain and enhances readability, ensuring a better user experience in low-light environments.

Environmental and Industry Implications

Dark Mode Adoption Trends

User Preferences and Adoption Rates

- **General Usage:** Approximately 82% of users have enabled dark mode on their devices. [WiFiTalents]
- **Age Demographics:** Dark mode is particularly popular among users aged 18-34, with a 72% adoption rate. [Gitnux]
- **Aesthetic Appeal:** 76% of surveyed users find dark mode aesthetically pleasing. [Gitnux]

Platform-Specific Adoption

- **Reddit:** As of 2021, 83% of Reddit app users have adopted dark mode, reflecting its popularity among the platform's user base. [Helpfultech]
- **Email Clients:** While only 7.5% of users utilize dark mode in Apple Mail, nearly 37% have adopted it on their iOS devices. [Mailmodo]

Benefits of Dark Mode

- **Battery Efficiency:** On devices with AMOLED screens, dark mode can lead to battery savings of up to 63%, leading to energy conservation. [forms.app: Online Form Builder]
- **Eye Comfort:** Users report that dark mode reduces eye strain, especially in low-light conditions, enhancing user experience. [Gitnux]

Industry Adoption

- **Software Development:** An overwhelming 95% of software developers prefer dark mode in their integrated development environments (IDEs), highlighting its importance in the tech community. [Helpfultech]
- **Marketing Emails:** In 2022, 35% of consumers used dark mode when opening emails, prompting marketers to optimize their content accordingly. [forms.app: Online Form Builder]

Environmental Benefits if Adoption Scales Globally

Carbon Emissions Reduction

Energy Savings across Devices

a) **Global Smartphone Users:** As of 2025, there are approximately **6.8 billion smartphone users**, and about **50% of these devices** feature OLED/AMOLED screens.

Energy Savings per Device

a) Studies show that dark mode on OLED screens can save **15-60% energy**.

b) For an average smartphone, dark mode can save about **0.1-0.5 watt-hours (Wh)** per hour of active use.

Global Impact (Smartphones)

If **3.4 billion devices** (50% of global smartphones) adopt Dark Mode and save an average of **0.3 Wh/day**:

a) **Total Daily Savings:** 1.02 billion Wh (1.02 GWh) per day.

b) **Annual Savings:** ~372 GWh/year.

Carbon Emissions Avoided

Assuming a global average carbon intensity of **0.475 kg CO_2 per kWh**,

Annual Emissions Avoided: 372 GWh × 0.475 = **176,700 metric tons of CO_2**.

Equivalent Benefits

a) Removing **38,000 gasoline-powered cars** from the road annually.

b) Preventing the burning of over **92,000 metric tons of coal**.

Reduced Energy Demand on Power Grids

With reduced device energy consumption:

- Peak energy demand could decrease in regions with high smartphone and laptop usage.
- Lower grid strain reduces reliance on fossil-fuel-based energy during peak hours.

Prolonged Device Lifespan

- **Battery Longevity:** Prolonging battery life by even **10%** reduces e-waste since fewer batteries need replacement.
- **Environmental Impact:** The production of one smartphone battery emits **56 kg of CO_2**. If dark mode extends device lifespans and reduces replacements for even **1% of users**, it could prevent the emission of **millions of kilograms of CO_2 annually**.

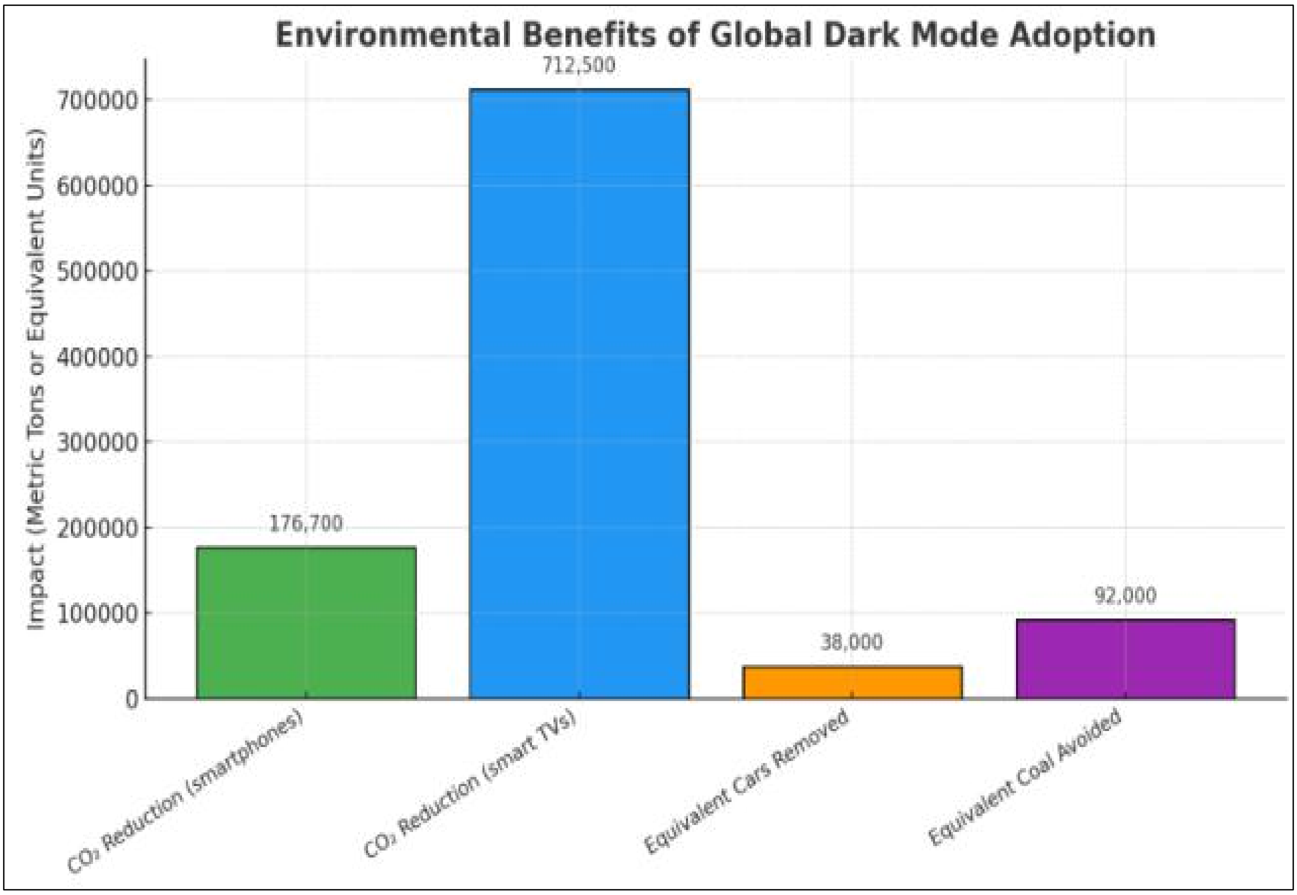

Fig 3: Environmental Benefits of Dark Mode Adoption Globally as Against Equivalent Processes

Future Directions-Discussion

Standardization of Metrics and Protocols

a) **Development of Standardized Evaluation Methodologies-Display Power Management (DPM)** Standard, developed by the Video Electronics Standards Association (VESA), and **Energy Star Program**, run by the U.S. Environmental Protection Agency (EPA) are some developments observed in this area.

b) **Creation of Benchmarking Tools-Display Benchmarking Tool (DBT)**, developed by the University of California, Los Angeles (UCLA), and **Power Consumption Analyzer (PCA)**, developed by the National Taiwan University are some ongoing developments.

Advancing Display Technologies

a) **Micro-LED Display Research:** Researchers are exploring the potential of Micro-LED displays to achieve even greater energy efficiency when combined with Dark Mode.

b) **Investigation of New Display Materials: Quantum Dot Display Research** by researchers at the University of California, Berkeley, and Nanocrystal **Display Development** by companies like Nanosys are being explored.

Incorporating AI and Machine Learning

a) **Development of AI-powered Dark Mode Optimization:** Researchers are working on integrating AI and machine learning to optimize Dark Mode dynamically based on usage patterns and ambient lighting conditions.

b) **Personalized Dark Mode Experiences:** Ongoing efforts aim to develop personalized Dark Mode experiences tailored to individual users' preferences and environments.

Ongoing Processes

a) **IEEE's Power-Aware Computing Standards:** The IEEE is developing standards for power-aware computing, which includes guidelines for Dark Mode implementation.

b) **Display Industry's Adoption of Dark Mode:** The display industry is increasingly adopting Dark Mode, with major manufacturers incorporating the feature into their devices.

c) **Research Initiatives:** Various research initiatives, such as the "Dark Mode for Sustainability" project, are exploring the potential of Dark Mode to reduce energy consumption and mitigate climate change.

Additional Future Directions

a) **Investigating Dark Mode's Impact on Human Health:** Researchers are exploring the effects of Dark Mode on eye strain, sleep patterns, and overall well-being.

b) **Developing Dark Mode for Specialized Applications:** Ongoing efforts aim to develop customized Dark Mode solutions for domains like gaming, video editing, and healthcare.

Conclusion

The study highlights the significant impact of Dark Mode on energy consumption across devices, particularly those with OLED and AMOLED screens. Key findings suggest that Dark Mode can reduce energy usage by up to 40% under specific conditions, such as high screen brightness and predominantly dark content. While the energy savings are most pronounced on mobile devices, laptops, and other OLED-equipped gadgets also benefit from its implementation.

Dark Mode's potential for energy savings reinforces its role as a simple yet effective feature to enhance battery life, particularly in energy-intensive scenarios.

Broader implications extend to environmental sustainability, aligning with global goals to minimize carbon footprints and promote energy efficiency. To maximize its impact, future adoption strategies should consider standardizing Dark Mode across applications, improving readability and accessibility, and educating users about its benefits.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

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