2nd Proceeding of International Conference on Science and Technology UISU (ICST)
"Engineering for Suistanable Future: Innovation in Renewable Energy, Green Technology, and Circular Economy"
ISSN: 3063-7929 (Online)
DOI: https://doi.org/10.30743/icst

Practical Applications of Augmented Reality in Sustainability

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Abstract—Addressing the growing challenges of climate change, environmental degradation and resource scarcity requires innovative and accessible approaches to sustainability. Augmented Reality (AR), a technology that overlays digital content onto the physical environment, offers new possibilities for engaging with complex environmental systems through interactive and location-specific experiences. While AR has been widely adopted in cultural heritage settings to enrich museum exhibitions and enhance visitor engagement, its potential is now being explored in response to environmental and sustainability concerns. This paper examines AR use cases across three key domains: renewable energy, green technology and the circular economy. These examples show how AR supports data visualisation, system monitoring and real-time guidance to enable more sustainable practices. Applications include energy system planning, environmental awareness, sustainable mobility and waste reduction through recycling, repair and creative reuse. Through these applications, AR translates abstract sustainability concepts into accessible and actionable experiences that enhance understanding, foster behavioural change and support informed decision making. In addition, the paper considers AR's broader capacity to connect knowledge, place and emotion, making it a valuable tool for public education, technical training and community engagement. By extending immersive technologies beyond entertainment and traditional learning contexts, AR presents a promising contribution to the design and delivery of sustainability strategies. This paper supports the wider integration of digital innovation into sustainability efforts and positions AR as a meaningful enabler of environmental awareness and practical action.

Keywords: Augmented Reality, Sustainability, Renewable Energy, Green Technology, Circular Economy

1. INTRODUCTION

Sustainability has become a defining imperative of the twenty-first century, demanding urgent and coordinated responses across environmental, economic, and social dimensions. As outlined in the United Nations Sustainable Development Goals (SDGs), innovation and education are essential in addressing climate change and achieving long-term sustainability [1]. Technological advancement plays a critical role in this transformation, particularly in raising awareness, enhancing learning, and improving operational efficiency across various sectors. Among the many innovations being explored, immersive technologies such as augmented reality (AR), virtual reality (VR), mixed reality (MR), and the broader category of extended reality (XR) are increasingly recognised for their potential to communicate complex environmental issues. Augmented reality (AR) refers to the real-time integration of digital information with the physical environment, enhancing users' perception and interaction with the world around them. These technologies provide engaging and interactive experiences that help users understand critical topics such as climate change, biodiversity loss, and resource scarcity [2].

XR technologies have gained momentum in environmental research and education, where they serve not only to inform but also to emotionally engage users. In particular, AR and VR are being widely adopted in educational contexts due to their capacity to simulate real-world scenarios and support experiential learning. These multisensory experiences influence perspectives, attitudes, and behaviours, helping users connect with sustainability issues on a more personal level [3]. By enabling individuals to visualise future outcomes, explore the consequences of environmental decisions, and interact with simulated systems, immersive technologies support public understanding of sustainable practices. This includes areas such as renewable energy, environmental conservation, and the circular economy. Immersive experiences have also been shown to improve knowledge retention and increase motivation to act on sustainability concerns [4].

While VR offers fully simulated environments, AR presents a unique advantage through its ability to overlay digital content onto real-world settings. This provides a practical and context-aware means of encouraging sustainable behaviour. Unlike VR, AR is more accessible and scalable, as it can be deployed through commonly available mobile devices. It allows users to engage with their immediate surroundings while accessing real-time data, visualisations, and simulations that support environmentally responsible decisions. Understanding which specific features of AR and VR, beyond immersion alone, effectively engage and motivate individuals to adopt sustainable behaviours is a critical area of inquiry. AR's potential to deliver location-based, interactive, and real-time experiences positions it as a powerful tool for advancing environmental goals. This paper explores how augmented reality can contribute to the global sustainability agenda, with particular focus on its applications in renewable energy, green technology, and the circular economy.

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2. AUGMENTED REALITY AND SUSTAINABILITY

Immersive technologies have demonstrated significant potential in creating meaningful and interactive experiences that engage users across various sectors. Among these technologies, augmented reality is particularly distinguished by its capacity to enhance understanding while maintaining users' awareness of their physical environment. AR integrates digital content into real-world settings through devices such as smartphones, tablets or AR glasses, making it especially suitable for education, training and public engagement in physical contexts.A key area where AR has been successfully applied is cultural heritage. Museums around the world have adopted AR to enrich visitor experiences, allowing for dynamic engagement with historical artefacts and narratives. AR is embedded within exhibitions to overlay visual and textual information directly onto physical displays, enabling layered interpretation and interactive storytelling through personal devices [5]. These implementations have proven effective in making historical content more accessible, emotionally resonant and engaging.

Examples include the AR heritage experiences at Kota Kuala Kedah in Malaysia and Maimun Palace in Medan, Indonesia. At Kota Kuala Kedah, AR is used to reconstruct the historical context of the 1821 Kedah-Siam War, enabling visitors to engage with narratives of colonial defence and local resistance through mobile-based overlays in a site specific setting [6][7]. At Maimun Palace, AR enhances the presentation of Malay royal heritage by providing interactive visualisations of royal attire, cultural stories and artefacts. These examples demonstrate how AR not only preserves cultural memory but also transforms traditional exhibition viewing into immersive and place based learning.The strengths of AR in cultural heritage, particularly its capacity to connect people with place, time and narrative, are directly transferable to the domain of sustainability. AR is more than a tool for visual overlays. It has the capacity to influence perception, deepen learning and support more informed decision making. Its ability to combine knowledge, location and emotion makes it a flexible and impactful platform. The same technologies that animate the past can be adapted to raise awareness about contemporary environmental challenges and promote sustainable behaviour.

Sustainability refers to practices that support environmental protection, resource efficiency and social wellbeing. It involves balancing ecological, economic and social objectives to ensure long term benefits for both people and the planet. Achieving sustainability requires widespread behavioural change, informed decision making and engagement with systems that are often invisible in daily life, such as energy consumption, waste management or environmental degradation. AR can help address this challenge by making these systems visible, interactive and locally relevant.Table I presents key sustainability concepts and the objectives they aim to support.

Table 1. Sustainability Concepts

Concept	**Definition**	**Environmental Protection**	**Social Wellbeing**	**Economic Growth**
Renewable Energy	Energy from sustainable sources	Lowers emissions and reduces fossil fuel use	Improves air quality and energy accessibility	Creates green jobs and supports energy markets
Green Technology	Innovative tools, systems or processes	Minimises environmental damage	Encourages healthier living environments	Enhances efficiency and supports technological progress
Circular Economy	Eliminates waste and maximises reuse	Preserves resources and reduces landfill	Promotes responsible consumption	Enables cost savings through reuse and recycling

The effectiveness of AR in museum contexts, particularly in storytelling, education and public engagement, suggests its strong potential for sustainability initiatives. For example, AR can be used to visualise environmental scenarios, allowing users to explore the effects of climate change, urban development or energy use within their immediate surroundings. This ability to simulate outcomes and examine alternatives helps make complex sustainability issues more tangible and easier to understand.AR also supports practical applications in engineering and environmental planning. It can provide context sensitive guidance for tasks such as the installation, monitoring or maintenance of green technologies. Engineers and planners can use AR to visualise energy usage or inefficiencies in real time, thereby supporting faster and more accurate decisions. AR provides scalable and cost effective solutions that can be accessed through widely available personal devices, eliminating the need for specialised equipment and enabling broader adoption.Table II highlights how the strengths of cultural heritage AR can be adapted to sustainability contexts.

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Table 2. From Culture Heritage Ar to Sustainability Ar

Cultural Heritage AR	**Sustainability AR**
Builds historical awareness	Builds environmental awareness
Visitors learn through place-based narratives	Engineers and users receive location-based guidance
Enhances museum exhibitions	Enhances sustainable engineering and decision making

In addition to awareness, AR supports sustainable practices through simulation, education and innovation. It reduces the need for physical resources by enabling virtual site visits and prototyping. It can help individuals better understand environmental issues such as pollution, energy consumption or waste management and encourage them to adopt more responsible behaviours [4]. In educational settings, AR has been shown to improve learners' understanding of environmental topics and foster more positive attitudes towards sustainability [8].AR does not merely communicate information. It enhances delivery by clarifying complex content, stimulating curiosity and encouraging active learning. It enables users to rethink, redesign and reimagine systems with creativity and innovation. By making abstract concepts visible and potential futures imaginable, AR offers new ways of thinking about how we live, work and interact with the environment.

3. APPLICATIONS OF AR FOR A SUSTAINABLE FUTURE

With sustainability becoming an urgent global priority, emerging technologies such as AR are increasingly recognised for their capacity to address complex environmental challenges. AR enables interactive and context sensitive experiences by embedding digital content within physical spaces, allowing users to engage more directly with sustainability issues.AR supports a wide range of sustainability efforts, from accelerating renewable energy uptake to enhancing environmental data interpretation and waste reduction. It also encourages behavioural change by translating abstract systems into tangible and locally relevant experiences.Beyond its technical potential, AR contributes meaningfully to sustainability through education, public engagement and creative learning. These qualities help make environmental issues more relatable and encourage broader participation.The following subsections examine practical applications of AR across three focus areas: renewable energy, green technology and the circular economy.

Renewable Energy

There is a growing interest in using AR to promote renewable energy technologies such as household wind turbines. One example involves encouraging the installation of vertical-axis wind turbines in urban areas where cost and space are main concerns [9]. The AR system allows users to visualise turbine performance and assess wind conditions in real time situation. This supports informed decisions based on local energy needs and prioritises user experience over industrial metrics. As a result, AR plays a vital role in making wind energy more accessible.Another application of AR improves monitoring and maintenance in nuclear energy systems. A notable example is a 3D AR mobile app used at the RTP nuclear site in Malaysia [10]. It enables real time monitoring of water coolant processes. Research shows that AR can help monitor up to 90% of plant performance. By overlaying data in real world environments, AR enhances operational safety, reduces human error and improves situational awareness. This supports international best practices and highlights AR's role in a safer and more sustainable nuclear energy operations.

AR has also been used in assembling hybrid energy systems like GreenCube (GC), which operate without the need for specialist software or trained personnel [11]. The AR tool provides step-by-step visual instructions, improving accuracy and reducing health risks. In real world settings, users completed tasks more safely and efficiently without printed manuals. This approach demonstrates how AR can improve industrial processes and support the broader use of hybrid energy solutions.In education sector, AR has proven effective in teaching solar energy concepts. One AR app visualises how solar cells work, helping students grasp complex topics through interactive content [12]. Compared to traditional methods, AR increases engagement and improves retention. This shows how AR can transform science education, making abstract subjects like solar energy more accessible and engaging.

Green Technology

AR can help make invisible environmental issues, like air pollution, more understandable. One application, called AiR, visualises twelve major air pollutants in real-world settings [13]. Instead of overwhelming users with data, AiR presents time and location specific information in a clear and engaging way. Users can compare pollution levels across different dates and locations, gaining better insight into environmental impacts. This experience encourages public awareness and promotes more sustainable behaviour through visual storytelling. Another important application of AR enhances navigation and safety for electric vehicle (EV) drivers, including those with colour blindness. The AR Head-Up Display (ARHUD) system projects real time navigation and contextual road information directly onto

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the vehicle windshield [14]. It assists drivers in selecting optimal charging stations by visualising relevant details such as safety ratings, charger availability and nearby amenities. For colour blind users, the interface can be customised to interpret traffic signs and signals, thereby reducing risks related to colour perception. This inclusive AR solution supports safer, more confident driving for a broader range of users.

AR technology also holds significant potential in promoting healthier consumption habits through interactive packaging. By scanning AR enabled product labels, consumers gain access to clear and engaging information about the health risks associated with excessive intake of sugar, salt, and fat (SSF) [15]. This approach transforms packaging into an effective platform for delivering accessible health messages. Users can explore nutritional information in an interactive and memorable way, increasing awareness and encouraging informed food choices. Research indicates that AR packaging successfully captures attention and improves message retention particularly among younger audiences. These findings highlight AR's value as a practical tool for public health communication and behaviour change initiatives.

Circular Economy

The circular economy aims to reduce waste through reuse, recycling, and repair. AR can assist consumers by providing real-time information about the sustainability of products, such as visual indicators of recyclability or material sources. Repair-focused AR applications can overlay repair instructions on physical objects, promoting product longevity and reducing consumption. Such systems empower individuals to participate more actively in circular practices.To meet the need for accessible recycling education, a mobile AR app was developed to guide users through proper waste separation. It helps users identify different types of waste and provides instructions tailored to each case scenario [16]. A key feature is a product scanner that uses markers to detect waste type and recommend disposal methods. This AR tool links digital information with real life actions, improving understanding and motivation. It supports habit change and enables more effective participation in recycling initiatives.AR can also encourage creativity in promoting zero waste practices. In one project, students used AR to turn plastic waste into collage art [17]. The approach on art-based research, helped students interpret waste reduction through hands on learning. The AR app used visual slides and short videos to simplify artistic concepts. Media experts validated the tool, noting that it made learning more engaging and helped students achieve both technical and creative goals. This shows how AR can support sustainability through innovative and meaningful educational experiences.

4. CONCLUSION

1. Augmented reality offers a powerful and underutilised approach to sustainability. By enabling real-time, interactive engagement with complex systems, AR can foster understanding, promote behavioural change and support practical action across key domains including renewable energy, green technology and the circular economy. As global efforts increasingly prioritise sustainable development, immersive technologies such as AR should be recognised not only as tools for education or entertainment, but as integral components in the design and implementation of sustainability strategies. This paper has demonstrated how AR contributes meaningfully to sustainability through applications that facilitate data visualisation, enhance environmental awareness and improve decision making. Whether supporting site-specific energy planning, visualising air quality or enabling creative reuse through educational interventions, AR helps translate complex environmental challenges into accessible and engaging experiences.
2. Despite its promise, AR faces several challenges in the sustainability context. Access to AR-capable devices remains limited in certain regions, and the development of high-quality AR content often requires technical expertise and substantial resources. There are also design considerations in ensuring that AR applications are intuitive, inclusive and contextually appropriate. However, the opportunities are considerable. AR can be integrated with complementary technologies such as the Internet of Things (IoT), Artificial Intelligence (AI) and geolocation services to create smart, adaptive environments. In education, AR has the potential to transform sustainability learning into participatory experiences. In public policy, it can support visualisation of the real-time impact of environmental interventions. As AR tools and platforms become increasingly accessible, the integration of immersive technologies into sustainability efforts is becoming both more feasible and impactful.
3. The incorporation of AR into sustainability initiatives presents an opportunity to bridge the gap between abstract environmental concepts and tangible actions. Realising this potential will require interdisciplinary collaboration among technologists, educators, designers and environmental practitioners, as well as continued evaluation of long-term outcomes and user engagement. As immersive technologies continue to evolve, AR is well positioned to contribute meaningfully to sustainable development at both strategic and practical levels. Its ability to connect people, environments and knowledge through interactive digital media offers a valuable framework for advancing sustainability in an increasingly interconnected and resource-conscious world.

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