Asia-Pacific Tech Monitor

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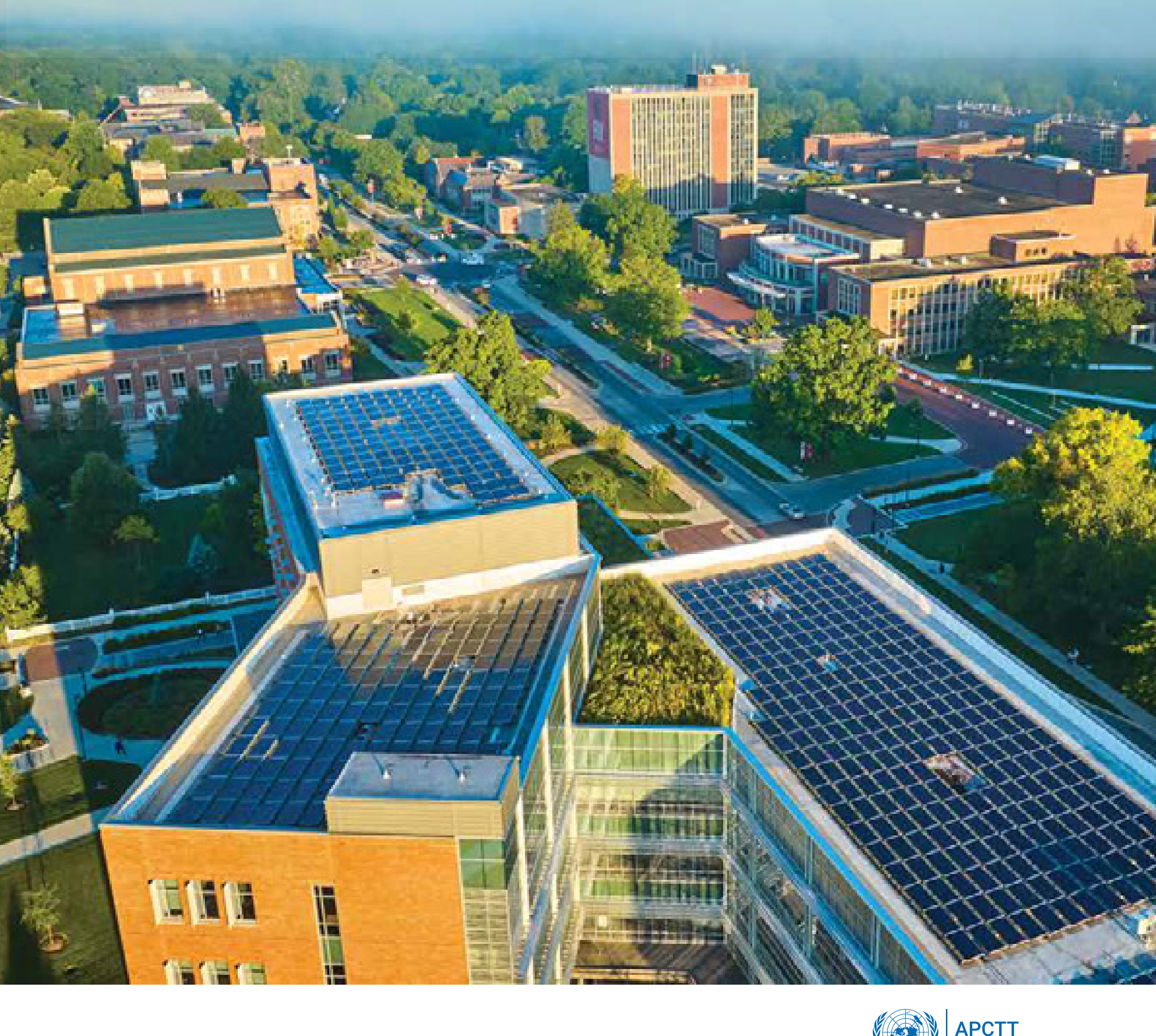
Innovative technologies for building climate-resilient cities in Asia and the Pacific



ESCAP
APCTT
Asian and Pacific Centre for Transfer of Technology

*The shaded areas of the map indicate ESCAP members and associate members.**

The Economic and Social Commission for Asia and the Pacific (ESCAP) is the most inclusive intergovernmental platform in the Asia-Pacific region. The Commission promotes cooperation among its 53 member States and 9 associate members in pursuit of solutions to sustainable development challenges. ESCAP is one of the five regional commissions of the United Nations.

The ESCAP secretariat supports inclusive, resilient and sustainable development in the region by generating action-oriented knowledge, and by providing technical assistance and capacity-building services in support of national development objectives, regional agreements and the implementation of the 2030 Agenda for Sustainable Development.

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The **Asia-Pacific Tech Monitor** is a quarterly periodical of the Asian and Pacific Centre for Transfer of Technology (APCTT) that brings you up-to-date information on trends in technology transfer and development, technology policies, and latest technology innovations.

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Foreword

Climate change impacts and related disasters are escalating threats to the rapidly growing cities in the Asia-Pacific region. Building climate-resilient cities involves integrating cutting-edge technologies that enable urban areas to adapt to and recover from climate related impacts such as heatwaves, flooding, sea-level rise, water scarcity and extreme weather events. Innovative technologies have played a pivotal role in enhancing climate resilience, minimizing environmental risks and driving sustainable urban development. Key examples include AI-powered platforms to predict risks of floods, heat and droughts; digital twins for resilient urban planning; smart water systems using sensors, IoT and automation to optimize water usage and detect leaks; modular and floating infrastructure in flood-prone or coastal zones; and localized microgrids for energy resilience.

The potential of innovative technologies for building climate-resilient cities is promising; however, it comes with technological challenges including infrastructural constraints, costs, cybersecurity and data privacy, and equity and accessibility. Overcoming these challenges requires a blend of policy innovation, effective governance, strategic investments, and inclusive planning. For Asia-Pacific countries to effectively leverage innovative technologies, they require a combination of regulatory, financial, institutional, and technical support tailored to their distinctive capacities and climate vulnerabilities. Regional cooperation is critical in this regard for knowledge-sharing, resource mobilization, policy harmonization, capacity building and technical training, and collaborative innovation.

This special issue of *Tech Monitor* focuses on “Innovative technologies for building climate-resilient cities in Asia and the Pacific” The issue delves into AI applications in renewable energy forecasting, urban climate adaptation and governance, applications of satellite informatics, datasets and remote sensing instruments and environmentally friendly firefighting agents. The articles provide interesting case studies on innovative technology applications and models to mitigate climatic challenges in Asia-Pacific cities.

We hope this edition of *Tech Monitor* supports policymakers, technical experts and practitioners in making informed decisions and strategies, driving adoption of innovative technologies to enhance climate resilience of cities in the Asia-Pacific region.

Preeti Soni
Head, APCTT

Technology Market Scan

ASIA-PACIFIC

CHINA

Action plan to speed up digitalization of the finance sector

The People's Bank of China, together with six other departments, released a development action plan to promote the high-quality development of digital finance, aiming to establish a financial system that highly adapts to the development of the digital economy by the end of 2027. The action plan vows to accelerate the digital transformation of financial institutions, improve the convenience and competitiveness of financial services, implement the digital yuan, and contribute to the country's construction of a strong financial sector, along with the development of relevant fields.

Efforts will be made to systematically promote the digital transformation of financial institutions, elevate financial services through digital technologies, and strengthen the foundation for digital finance development as well as improve the digital financial governance system. For instance, the action plan proposes guiding financial institutions to integrate financial services into digital scenarios such as industrial internet, artificial intelligence (AI), and industry, and supporting the development and upgrading of core industries involved in the digital sector. At the same time, it also encourages financial institutions to set up cross-border digital platforms and support the digitalization of maritime trade.

As for enhancing the construction of new infrastructure related to digital finance, the plan says that the deployment of advanced and efficient computing power systems would be expanded, such as accelerating the standardized application of cloud computing, AI, and other technologies. In addition, it will also explore the use of cutting-edge computing and quantum technology to break through the existing arithmetic bottleneck and provide accurate and efficient arithmetic support for financial digital transformation. Regarding optimizing the governance system for digital finance, the plan calls for active participation in international cooperation on digital financial regulations organized by global institutions such as the International Monetary Fund (IMF).

https://www.globaltimes.cn/

Measures to boost innovation

The eastern Chinese tech city of Hangzhou, home to e-commerce giant Alibaba and rising AI star DeepSeek has announced a series of measures to further elevate its status as a high-level innovation hub. The measures are aimed at enhancing high-level innovation platforms, promoting the technology transfer and application, and strengthening the role of enterprises as the main drivers of technological innovation, Lou Xiuhua, head of the municipal bureau of science and technology, said at a press conference.

Among the measures is a partnership plan, which encourages collaboration between tech innovation platforms, universities, enterprises, and industrial chains. The city will accelerate its construction of facilities and foundational projects, such as large-scale models and computing power infrastructure. More computing power vouchers will also be allocated, Lou said.

Computing power vouchers are a government subsidy tool designed to help small and medium-sized enterprises (SMEs) access more computing resources at lower costs, aiming to promote innovative applications of AI technologies and digital transformation. Additionally, Hangzhou will launch an "AI+" initiative to promote the integration and application of AI across industries. It will also introduce a reform related to the application of technological achievements, encouraging universities and research institutions to license their technological fruits to SMEs under a "use first, pay later" model.

https://news.cgtn.com/

R&D spending

China's spending in research and development (R&D) maintained rapid growth last year thanks to efforts to support technological innovation. The total R&D expenditure exceeded 3.6 trillion yuan (about $500 billion) in 2024, up 8.3 percent year on year, the National Bureau of Statistics (NBS) said Thursday. The input accounted for 2.68 percent of China's gross domestic product in 2024, up 0.1 percentage points from the previous year.

China's improved favourable policies, diversified investment landscape, and stronger business participation have provided robust support for the sustained growth of R&D spending, NBS statistician Zhang Qilong said. With the continued innovation drive, China's R&D input remains the second largest worldwide.

China's 2.68-percent R&D intensity ranked 12th among major countries in the world, higher than the average of European Union countries of 2.11 percent and approaching that of the Organisation for Economic Co-operation and Development (OECD) of 2.73 percent. In particular, investment in basic research climbed 10.5 percent last year from 2023 to 249.7 billion yuan, representing 6.91 percent of the total R&D spending.

In recent years, China has attached great importance to basic research, making significant progress in the construction of major scientific appliances and infrastructure, with a number of original achievements in fields such as quantum technology, life science, materials science, and space science, Zhang said.

https://global.chinadaily.com.cn/

INDIA

Cloud powers India's digital leap

Indian businesses are embracing cloud transformation as a critical enabler of artificial intelligence adoption, underscoring the vital role of cloud in India's digital leap, according to an EY study of cloud implementation. As many as nine out of 10 Indian companies said that AI adoption would not have been possible without cloud migration, with nearly seven in 10 currently transitioning applications to the cloud, the survey found.

"The rapid adoption of cloud technology in India is more than just a technological upgrade — it's a transformational shift that empowers businesses to reimagine their operating model, products, or services," said Abhinav Johri, technology consulting partner, EY India. "By leveraging the cloud to enable AI capabilities, companies can now respond faster to evolving client needs and market changes and deliver enhanced value through AI-led solutions. This marks a new wave of progress, which may potentially position India as a global leader," Johri said.

Most Indian companies follow a hybrid approach, managing applications partly on the cloud and partly on-premises, which makes for a balanced strategy allowing for flexibility while enabling gradual progress toward full cloud migration, the study noted. The 20% of organizations that are fully on the cloud are typically the new-age, digital native companies. Of the 80% that follow a hybrid approach, 30-40% have cloud-native business applications, including their software-as-a-service applications, Johri noted. "This is a very encouraging trend, showing that there is an enhanced level of confidence in the functionality provided by these cloud applications," he said. "This also means that there is a standardization happening and capabilities are being offered vis-a-vis something that you might want to develop yourself."

Companies may want to maintain on-premises capabilities due to operating models or sectoral limitations, for instance, banks, non-banking financial companies, telcos, and others where data protection and high levels of confidentiality are of major importance. Improving cloud adoption could require more awareness regarding its advantages and greater investment by companies in cybersecurity, Johri said, which continues to be a concern as some decision-makers see security as an afterthought.

https://economictimes.indiatimes.com/

MALAYSIA

Public sector embraces generative AI

The Malaysian government is equipping 445,000 public officers with generative artificial intelligence (AI) tools through the AI at Work 2.0 programme initiated by the Ministry of Digital's National AI Office and Google Cloud. The programme expands on an earlier pilot project and provides access to the advanced capabilities of Google Workspace with Gemini in a bid to improve the delivery of public services and free up civil servants to focus on more strategic tasks.

Officiating the launch of the programme, Malaysia's minister for digital Gobind Singh Deo noted the vital role of technology in driving Malaysia's economic growth and highlighted the government's commitment to harnessing generative AI responsibly, with appropriate safeguards, to improve services for all Malaysians.

During the pilot, some 270 public officers reported saving an average of 3.25 hours per week, with the vast majority noting improvements in work quality thanks to generative AI assistance. "We are swiftly progressing beyond the pilot, which reinforced our belief that AI can uplift the productivity and efficacy of a workforce. In the coming months, we look forward to highlighting the tangible value generated by our public-private AI partnerships, as we drive further AI adoption momentum across government agencies and our broader business ecosystem," Gobind said.

Google Workspace with Gemini offers a range of benefits for public officers, enabling them to generate contextually relevant content within applications like Gmail, Docs, and Slides. Gemini can summarise information, analyse data, and draft text, reducing the time spent on routine tasks. Furthermore, the integration of Gemini into Google Meet enhances meeting experiences by providing AI-generated notes, improving audio and video quality, and offering summaries for latecomers.

The programme will also enable public officers to create more engaging communications with Google Vids, a generative AI-powered video creation tool. Even without professional video production experience, employees can easily produce informative videos, organisational updates, and training materials. The platform simplifies the process with suggested visuals, scripts, and music, and features a built-in teleprompter for smoother recording.

For more complex tasks like coding, data analysis, and brainstorming, the Gemini Advanced app offers specialised support on both laptops and mobile devices. Public officers can even create customised AI experts, called Gems, to automate repetitive or specialised tasks, such as analysing citizen feedback.

https://www.computerweekly.com/

PHILIPPINES

Quantum computing, AI, and smart agriculture

The Department of Science and Technology (DOST) has launched eight transformative research and development (R&D) programs that leverage emerging and frontier technologies to address significant challenges and provide solutions for large-scale issues. These initiatives are strategically developed to tackle critical problems in key sectors such as agriculture, healthcare, and manufacturing.

Dubbed as "ELEV8PH: Pushing S&T Frontiers for National Development," the launch was held at the Dusit Thani Manila on February 5, 2025. It brought together stakeholders from various sectors, including industry representatives, academia, international partners, and the DOST research community.

Opening the event, DOST Undersecretary for Research and Development Leah J. Buendia highlighted the immense potential of innovation and the collective drive that propels progress forward. "Together, we embody the spirit of innovation and collaboration that turns visions into reality," Buendia declared.

According to the Secretary, these key research and development programs are designed to advance science and technology for national development. The eight transformative R&D priority areas include:

Artificial Intelligence (AI) Virtual Hubs. With the rise of AI, there are concerns that developing countries like the Philippines may be left behind. However, the recently released AI Readiness Index 2024 shows that the Philippines has improved its ranking from 65th in 2023 to 56th in 2024, positioning the country to take a leadership role in the global AI landscape.

One of the program's major components, the Artificial Intelligence (AI) Virtual Hubs, was established through the Advancing Computing Analytics, Big Data, and Artificial Intelligence in the Philippines (ACABAI-PH) initiative. This program offers accessible AI tools that enable businesses, researchers, and communities to utilize AI solutions without needing extensive technical expertise, ensuring practical and innovative answers to meet the needs of Filipinos.

Quantum Computing Technology. The Department of Science and Technology (DOST) is committed to enhancing the computing power and capabilities of the local industry through quantum computing technology. This cutting-edge computing surpasses the capabilities of classical computers and has advanced features that can support growth in various fields, including cryptography, cybersecurity, pharmaceutical development, materials science, climate forecasting, and financial services.

Geospatial Analytics Solution (GATES Hub). The Geospatial Analytics Solution or GATES Hub aims to advance the application of geospatial science in addressing critical issues, such as disaster risk reduction, urban planning, and environmental management. This program is envisioned to be adopted by the government to mitigate disaster risk, tackle urban planning challenges, and improve scientific datasets for environmental management.

Industry 4.0. At the heart of this initiative is the Cuatro program. Implemented by DOST, this R&D program helps strengthen companies' capabilities in utilizing core technologies such as additive manufacturing, autonomous robots, augmented reality, the Internet of Things (IoT), cybersecurity, system integration, simulation, big data, and cloud computing. These technologies will support the technological needs and upgrades of micro, small, and medium enterprises. Additionally, a Smart Manufacturing Hub will be established to assist clients within Metro Manila in upgrading their technology.

Circular Economy. The concept of a Circular Economy is gaining global traction as economies increasingly focus on sustainable manufacturing to protect the environment. This initiative aims to develop strategic human resource capabilities and promote innovative R&D technologies, facilities, and by developing policies on resource recovery plans to ensure compliance with solid waste management.

Smart Agriculture. To confront significant challenges in the agriculture sector—such as farm damage from natural disasters and other phenomena, oversupply of vegetables, pest infestations, and commodity price fluctuations—science-based solutions using smart technologies are crucial. This program seeks to leverage existing R&D initiatives in precision farming, digital agriculture, and the use of drones, sensors, and data analytics to enhance productivity in agriculture. It aims to address challenges related to climate change, food security, and the sustainable use of natural resources.

Biologics in Pharmaceuticals. Through this initiative, the DOST-Philippine Council for Health Research has launched various programs to encourage local industries to engage in manufacturing, as well as in drug discovery, diagnostics, and therapeutics. The focus is on improving public health outcomes by providing precise and personalized treatments for all.

Smart Technologies. DOST is creating advanced and interconnected systems that improve efficiency, sustainability, and quality of life by integrating smart technologies such as the Internet of Things (IoT), 5G, AI, and Big Data. This effort aims to accelerate the development and widespread adoption of these technologies across various sectors, including smart communities, industries, healthcare, and beyond, ensuring that these devices and technologies are accessible to all.

ELEV8PH is one of DOST's programs launched this year to strengthen industry innovation and promote technological advancement through collaborative research among academia, industries, and government sectors.

https://pia.gov.ph/

Programme to drive global competitiveness

The Department of Science and Technology (DOST) has launched a program aimed at transforming local innovations into globally competitive enterprises. PROPEL, or "Accelerating Innovation in the Philippines, Propelling Innovation from the Philippines" was introduced to stakeholders in Southern Luzon and the National Capital Region (NCR) on Wednesday during the Zonal Conference at the Batangas State University. The program seeks to bridge the gap between scientific advancements and market success.

In his message, DOST Secretary Renato Solidum Jr. said the PROPEL program embodies a strategic shift focusing not just on the development of science-based technology solutions but ensuring that it reaches end-users, transforms markets, and creates impact locally and globally.

"Science and technology-driven innovation is the cornerstone of social and economic transformation... PROPEL is designed to accelerate this transformation by aligning our programs and services at the [DOST] with the needs of communities, businesses, and industries," he said. Solidum said DOST envisions a more proactive role in understanding market demands, guiding research and development, and facilitating technology transfer.

The program prioritizes science-based technologies addressing critical needs in health and wellness, agriculture and food security, environmental sustainability, information and communication technology (ICT), energy, and transportation. It also supports innovators in showcasing their products at international exhibitions to attract global investors.

https://www.pna.gov.ph/

REPUBLIC OF KOREA

R&D investment

The Republic of Korea ranked No. 5 in terms of the amount of research and development (R&D) investments by the country's businesses in 2023, with Samsung Electronics standing as the world's top R&D investor in the chip industry, a report on the world's top 2,000 investors showed. According to the Korea Chamber of Commerce and Industry's (KCCI) analysis of the European Union's Industrial R&D Investment Scoreboard, the Republic of Korean companies included in the list invested 42.5 billion euros ($44.1 billion) in 2023, trailing behind the United States, China, Germany and Japan. Compared to that of 2013, the country's R&D investment grew 2.2 times from 19.3 billion euros, pushing up the rankings two spots from No. 7 to No. 5. During the same period, however, the number of the Republic of Korean companies included in the top 2,000 R&D investor list declined from 54 to 40, as 405 Chinese firms made their entry into the list over the past decade.

Among countries, China showed the most noticeable improvement. In 2013, China ranked eighth in total amount of investment with 18.8 billion euros, but jumped to world No. 2 in 2023 with 215.8 billion euros, achieving an 11.5 times growth.

In the chip industry, Samsung Electronics led the pack with 19.9 billion euros of R&D investment in 2023, doubling from that of 2013. During the past decade, Nvidia showed the sharpest growth in R&D investment, surging 8.2 times from 960 million euros to 7.9 billion euros. It was followed by SK hynix with 6.7 times, AMD with 6.1 times, and MediaTek with 5.1 times.

In the software and platform industry, Meta showed the sharpest growth at 32.4 times to 33.2 billion euros, followed by Tencent with 15 times and Salesforce with 10.1 times. Among the Republic of Korean firms, Naver showed a two-fold growth to 1.4 billion euros during the 10-year period.

https://www.koreatimes.co.kr/

Domestic R&D spending

Domestic research and development (R&D) last year ranked second in the world as a percentage of gross domestic product (GDP) with KRW 119.74 trillion. The Ministry of Science and ICT on Dec. 27 announced this in releasing the results of a survey on R&D activity last year. Domestic R&D spending last year reached KRW 119.74 trillion, up 5.7% or KRW 6.42 trillion year on year and accounting for 4.96% of GDP, No. 2 in the world after Israel.

The largest source of R&D funding was the government with KRW 28.12 trillion or 23.6%, up from 23.4% in 2022, followed by private and foreign funds with 90.94 trillion (76.4%). By entity, companies spent the most on R&D with KRW 94.29 trillion (79.2%), followed by public think tanks with KRW 13.88 trillion (11.7%) and universities KRW 10.89 trillion (9.1%). In R&D expenditures by stage, KRW 17.74 trillion went to basic research (14.9%), KRW 23.47 to applied research, and KRW 77.85 to developmental research.

The country had a combined 603,566 researchers, up 2,036 or 0.3% from 2022. That of R&D staff including research assistants was 827,963, up 14,200 (1.7%), and that of female researchers 143,127, with the latter's percentage rising each year.

https://www.korea.net/

Joint project with ASEAN for digital innovation

The science ministry here said it will begin a five-year joint project with the Association of Southeast Asian Nations (ASEAN) worth $30 million this year to foster digital innovation in the ASEAN region. The project is aimed at applying South Korea's advanced digital technologies in ASEAN nations to facilitate their digital transformation and foster economic growth, reports Yonhap news agency. In detail, the two sides will invest a combined $30 million from their cooperation fund until 2029 to create data and advanced computing infrastructure in the region. The fund will also be used to develop human resources and artificial intelligence (AI) solutions.

The Republic of Korea's exports of information and communication technology (ICT) products jumped 24 per cent in December from a year earlier, helped by robust sales of semiconductors. Outbound shipments of ICT products came to $22.66 billion last month, compared with $18.25 billion a year earlier, the Ministry of Science and ICT said in a press release. The country's ICT imports in December stood at $13.32 billion, resulting in a trade surplus of $9.33 billion in the sector. By product, semiconductor exports jumped 31.1 per cent on-year to $14.51 billion on high demand for artificial intelligence-related chips.

https://morungexpress.com/

IoT patent applications

The country's number of applications for standard essential patents related to the internet of things (IoT) based on the 3rd Generation Partnership Project, aka 3GPP, a general term for several standards organizations that develop protocols for mobile telecommunications, has jumped over fivefold over a 10-year period. The Korean Intellectual Property Office (KIPO) on Dec. 1 said the number of such filings with IP5, referring to the world's five largest patent offices, jumped from just 2,401 in 2012 to 12,110 in 2021.

By country, China accounted for the largest share of applications filed (33.1%), followed by the U.S. (25.9%), the Republic of Korea (19.1%), and Japan (9.5%), but the Republic of Korea had the highest growth of such filings with 25%. By company, Qualcomm was No. 1 with 21.3% of such applications, followed by Samsung Electronics (16.3%), Huawei (15.6%) and LG Electronics (13.7%). Samsung and LG combined accounted for 30% of the filings, highlighting Korea's status as a global telecommunications power.

By technology type, Narrowband IoT, a low-power, wide-area communications technology, led with 63.9%, followed by Sidelink, which enables direct communication between machines without a base station, with 21.3%.

https://www.korea.net/

SRI LANKA

Initiative for R&D commercialization

President Anura Kumara Disanayake emphasized that Sri Lanka can enhance its position in the global market through a robust new product development strategy, which will also create new market opportunities. He made these remarks today (08) during the official launch of the "National Initiative for R&D Commercialization" held at the Presidential Secretariat.

As part of the initiative, the newly developed website nirdc.gov.lk was also launched. This platform aims to facilitate the commercialization of research and development, thereby contributing to sustainable economic growth through the production of value-added goods and services, which will ultimately drive national economic development and social progress.

The recently established Ministry of Science and Technology has already begun implementing a long-term, well-structured R&D strategy. The immediate priority will be to convert near-complete or completed research projects into marketable, value-added products and services, providing a quick boost to the economy.

https://pmd.gov.lk/

THAILAND

Support for startups with AI, FinTech, Green Tech

Thailand's National Innovation Agency (NIA) is advancing its Co-Maker Space initiative to strengthen the country's startup ecosystem, focusing on artificial intelligence (AI), green technology, and financial technology startups as the nation looks ahead to 2025. Krithpaka Boonfueng, NIA executive director, revealed at a media roundtable on Tuesday that Thailand's startup landscape has shown remarkable resilience, with a cumulative growth of 3.3% since 2021.

The Thai startup ecosystem currently comprises approximately 2,100 ventures, with 700 at the pre-seed stage and 1,400 in the growth or go-to-market phase. The country ranks 54th globally and fourth in Southeast Asia on the Global Startup Ecosystem Index, trailing behind Singapore, Indonesia, and Malaysia.

The NIA has identified three primary technology sectors with high growth potential:

1. Artificial Intelligence: With particular emphasis on Generative AI and AI Agentic Systems. *"More than 70% of executives and investors are confident that AI Agents will become crucial for organisational operations, from problem-solving to service delivery,"* Krithpaka said.

2. Green Technology: The global environmental technology market is projected to grow by nearly 25% annually over the next decade. This includes clean technology (CleanTech) and Climate Tech solutions addressing environmental challenges.

3.Financial Technology: FinTech continues to lead investment attraction in Southeast Asia, with blockchain technology following closely at 20% of seed funding.

To strengthen the country's startup ecosystem, the government has accelerated infrastructure development.

https://www.nationthailand.com/

Energy Policy 2025 focuses on clean energy

The Thai government has set a strategic energy policy for 2025, aiming to promote clean energy while securing new domestic energy sources. At the same time, the three key electricity authorities—the Electricity Generating Authority of Thailand (EGAT), the Metropolitan Electricity Authority (MEA), and the Provincial Electricity Authority (PEA)—are preparing to invest in infrastructure to accommodate the growing share of renewable energy.

Currently, approximately 60% of the country's electricity production comes from natural gas, while clean energy accounts for around 26%. Under the draft Power Development Plan (PDP2024), the share of natural gas will decrease to 41% by 2035, while clean energy will rise to 51%. This shift aligns with global trends focusing on climate change mitigation, where countries are setting clear targets to reduce greenhouse gas emissions.

Thailand's energy policy is also focused on enhancing the country's competitiveness by promoting clean energy to attract foreign investment. The government is positioning Thailand as a Digital Hub for ASEAN, with strong investor interest in data centers and cloud services. This is reflected in the 46 investment promotion applications submitted to the Board of Investment (BOI), totalling over 167.99 billion baht.

Additionally, Thailand is preparing for over 2,000 megawatts of Direct Power Purchase Agreements (PPA) and a Utility Green Tariff policy. Many investors require 100% clean energy, or RE100, and high-quality electricity. This presents a challenge for EGAT, MEA, and PEA to ensure a stable, uninterrupted power supply. While electricity costs are a secondary concern for investors, the primary focus remains on reliability and sustainability.

The 2025 energy policy also supports the development of new energy technologies to facilitate the energy transition. This includes infrastructure and regulatory preparations for hydrogen energy, increasing the supply of raw materials for sustainable aviation fuel (SAF) production by 2026, and utilizing petroleum fields for carbon capture and storage (CCS). Thailand is collaborating with Japan to study petroleum sources in the Arthit field, Gulf of Thailand, while onshore sites such as Mae Moh and Nam Phong are also under consideration.

https://solarquarter.com/

VIET NAM

Action plan for innovation, digital transformation

The Minister of Science and Technology has released an action plan for implementing Government Resolution No.01/NQ-CP (dated January 8, 2025), concerning key tasks and solutions for the 2025 socio-economic development plan and state budget estimates, and Resolution No.02/NQ-CP (dated January 8, 2025), addressing key tasks and solutions for improving the business environment and enhancing national competitiveness in 2025.

Within this plan, the Ministry of Science and Technology (MoST) identifies institutional breakthroughs as the core one. Currently, the MoST is collaborating closely with National Assembly bodies to review and incorporate feedback from deputies, refining the draft Law amending and supplementing several articles of the Law on Standards and Technical Regulations. Simultaneously, the ministry is developing and finalizing another three draft laws, namely the Law amending and supplementing several articles of the Law on Product and Goods Quality; the Law on Science-Technology and Innovation; and the revised Law on Atomic Energy.

In accordance with Resolution No. 57-NQ/TW (dated December 22, 2024) of the Politburo on breakthrough developments in science-technology, innovation, and national digital transformation, the MoST will prioritize amending, supplementing, and completing the legal framework to implement piloting, breakthrough, and specific mechanisms for science and technology and innovation.

This includes continuing to refine mechanisms and policies for developing public science-technology organizations, and building and perfecting institutions and policies to foster a rapid, healthy, and effective market for science-technology, startup, and innovation, as well as science-technology enterprises.

According to Deputy Minister Bui The Duy of Science and Technology, Resolution No.57-NQ/TW offers highly innovative perspectives to address institutional bottlenecks in science-technology and innovation. For instance, it establishes the principle that investment in science-technology, innovation, and digital transformation is a long-term endeavor, not a short-term one. This implies accepting a degree of latency and risk.

Coupled with the decisive implementation of streamlining and reorganizing the political system, Resolution No.57-NQ/TW is seen as a “golden key” to facilitate the nation’s transformation and entry into a new era. Science-technology, innovation, and digital transformation are the foundation and the means to achieve the goals set for 2030 and 2045.

https://en.sggp.org.vn/

Digital technology

As of late 2024, Viet Nam had 73,788 digital technology enterprises, marking a 10.1% increase from the same period in 2023. Nearly 1.26 million workers are employed in the Information and Communication Technology (ICT) sector. Total revenue of Viet Nam’s digital tech companies reached nearly 158 billion USD in 2024, a 10.2% year-on-year increase, according to the Ministry of Information and Communications (MIC). Significantly, around 1,900 digital tech enterprises reported revenue from international markets. Total overseas revenue surged by 54% compared to 2023, reaching 11.5 billion USD in 2024.

Export revenue from hardware and electronics was estimated at 133.2 billion USD, up 10.4% from 2023. Additionally, the domestic value-added ratio in the ICT sector accounted for an estimated 31.8% of total industry revenue, a 3.1% increase from the previous year. This highlights the improving capabilities of Viet Nam’s local tech enterprises, which significantly contribute to the country’s tech value chain.

Globally, Viet Nam has maintained prominent rankings across five categories of digital tech products. The country ranked second in smartphone exports, fifth in computer component exports, sixth in computer devices, eighth in electronic devices and components, and seventh in software outsourcing services. To foster the sector’s development, Viet Nam established a digital tech enterprise community in 2019 under the ‘Make in Vietnam’ vision, focusing on research, innovation, and domestic production.

Looking forward, MIC projects ICT industry revenue to reach 169.3 billion USD this year, an 11.4% increase from 2024. Hardware and electronics exports, the industry’s key segment, are expected to hit 148.5 billion USD, growing 12.3% year-on-year. To solidify the digital tech industry as a cornerstone of the economy, MIC is finalising the Law on Digital Technology Industry. This legal framework is set to provide a solid foundation, ensuring businesses and investors have the confidence to grow and innovate in Viet Nam.

https://en.vietnamplus.vn/

Technology Scan

Focus: Technologies for climate-resilient cities

ASIA-PACIFIC

AUSTRALIA

National index to combat urban overheating

In response to the growing threat of urban overheating, researchers at the University of New South Wales (UNSW) have created a National Heat Vulnerability Observatory Index (NaHVO) to measure and mitigate heat vulnerability across Australia's towns and cities.

The NaHVO provides a standardised approach to data collection and measurement of heat vulnerability, considering factors such as the built environment and population demographics. The index identifies areas where populations are more susceptible to the adverse effects of urban heat and informs effective cooling interventions. This data is then used to model the impact of various heat mitigation strategies, offering tailored advice to local authorities.

In its initial phase, the project has already demonstrated significant potential. Pilot studies in Dubbo Region and Maitland City have shown that implementing a combination of cooling strategies, such as cool materials for roads and roofs, increased urban greenery, and water-misting systems, could reduce air temperatures by up to 2 degrees Celsius and surface temperatures by over 10 degrees Celsius.

As urban planners, developers, and architects face the challenge of designing climate-resilient towns and cities, the NaHVO emerges as a crucial tool. It enables decision-makers at all levels of government to visualise and measure the effects of urban overheating while providing location-specific data on the impact of various cooling strategies.

https://www.buildaustralia.com.au/

CHINA

Radiative cooling technology

City University of Hong Kong (CityUHK) researchers have made a remarkable scientific breakthrough in developing next-generation passive radiative cooling technology. Their pioneering work on cooling ceramics, pavements, and textiles helps mitigate heat impacts without additional energy consumption. This innovation has promising application potential in buildings, roads, and clothing, addressing issues such as urban heat islands and greenhouse gas emissions to combat the challenges of climate change.

The team established the start-up i2Cool in 2021 under the incubation of CityUHK's HK Tech 300 programme and developed a cooling paint for roofs and walls. The recent approval of funding from the Hong Kong government's "Research, Academic and Industry Sectors One-plus Scheme" (RAISe+ Scheme) marks a significant step forward in accelerating the commercialisation and application of this groundbreaking innovation. The CityUHK team plans to establish manufacturing facilities and production lines by the end of 2026.

A research team led by Professor Edwin Tso Chi-yan, from CityUHK's School of Energy and Environment, has been focusing on developing passive radiative cooling (PRC) technology. "PRC technology is a universal solution to global warming, as it leverages high solar reflectivity and high mid-infrared emissivity to cool surfaces naturally by reflecting incoming sunlight and emitting thermal radiation to the cold universe, potentially reducing the surface temperature by at least 2°C," explained Professor Tso. "This technology offers an electricity- and refrigerant-free cooling solution, mitigating the heat impact without additional energy consumption."

The innovation involves developing passive radiative cooling ceramics (PRCCs) with high solar reflectivity and superb mid-infrared (MIR) emissivity. PRCCs have a porous structure that minimises solar absorption and resists degradation caused by ultraviolet (UV) radiation. Composed of pure inorganic materials that have low absorption of sunlight and heat, PRCCs offer excellent chemical stability and robust mechanical properties. These eco-friendly ceramics are suitable for long-term outdoor use, making them ideal for building envelopes, pedestrian paths, and public squares. They can reduce solar heat gain and enhance the thermal radiation to the universe, thereby reducing the need for air-conditioning.

https://www.cityu.edu.hk/

Radiative cooling coating for energy saving

Hong Kong Polytechnic University (PolyU) researchers have developed an environmentally friendly solar-driven adaptive radiative cooling (SARC) coating for building roofs and walls. This coating can reduce a building's surface temperature by up to 25°C and lower indoor temperatures by 2 to 3°C, all without consuming any energy. The non-toxic, metal-free, and durable coating can also be produced on a large scale, promoting an eco-friendly and energy-saving method to mitigate urban heat island effects and support the achievement of carbon neutrality.

Coating a building in a reflective material enables the self-regulation of its thermal environment to minimize indoor temperatures. However, traditional passive radiative cooling materials cannot automatically adjust cooling capacity in response to environmental changes, which limits their applications.

To address this challenge, a research team led by Prof. Lu Lin Vivien, Professor of the Department of Building Environment and Energy Engineering at PolyU, along with key team member Dr. Quan Gong, Postdoctoral Fellow of the same department, has invented a carbon dots (CDs)-driven SARC coating that can adjust cooling capacity based on solar irradiance. The work is published in the *Chemical Engineering Journal.*

However, traditional photoluminescent cooling materials typically rely on rare earth metals and perovskite materials, which pose environmental risks. To address these issues, the team has introduced groundbreaking, environmentally friendly polymer-based CDs as photoluminescent materials into the radiative cooling coating. Nano-sized CDs were embedded into polymers to create a biologically harmless material. The polymer CDs were uniformly coated onto hollow glass particles to create smart cooling beads, enabling the coating to effectively convert ultraviolet light into visible light photons and increase effective solar reflectance. This water-soluble SARC only requires the evaporation of water to form a coating on building surfaces without releasing any volatile organic compounds, thereby reducing air pollution.

Results have shown that compared to conventional radiative cooling coating, the new SARC coating improved effective daytime solar reflectance from 92.5% to 95% and increased the cooling effect by 10% to 20%. For example, it can reduce the temperature by up to 25°C when applied to concrete rooftops.

https://techxplore.com/

INDIA

New AI feature to tackle air pollution

In a bid to combat the rising air pollution woes of India, tech giant Google on Wednesday launched Air View+ -- an artificial intelligence-based solution that can help the government and the people with useful hyperlocal air quality information. Air View+ is powered by Google AI and works in collaboration with local climate tech firms. This can enable real-time hyperlocal air quality information, which includes local sustainability startups, researchers/climate action groups, corporations, city administrators, and citizens.

The ecosystem can provide "valuable air quality insights to government agencies responsible for environmental monitoring and urban planning," said Google in a blog post. It will also provide "real-time hyperlocal air quality information in Google Maps for users across India," it added.

Air View+ empowers local municipal corporations with hyperlocal air quality data for their cities. This can be used to develop their in-house AQ dashboards via the researchers and sustainability partners. "These dashboards provide air quality data for unmonitored areas and help urban planners identify hotspots and make necessary interventions," Google said.

The capabilities of Air View+ were tested in a pilot run last year. The partnerships with municipal corporations including Navi Mumbai, Chhatrapati Sambhaji Nagar, and Greater Chennai have yielded hugely encouraging results, Google said. Further, Air View+ also helps common people access hyperlocal air quality information across the country in Google Maps.

The information garnered may help vulnerable populations such as young children or the elderly to take appropriate preventative measures and precautions for their health such as using N95 masks or reducing outdoor exposure. People can readily access AQI in Google Maps by selecting the Air Quality layer from the Layer button on the home screen and tapping on any location on the map. Clicking the Weather widget on the Explore tab on the home screen can help them access AQI info at their current location.

https://morungexpress.com/

Pervious pavements to combat urban flooding

In a novel urban solution, researchers at the Indian Institute of Technology (IIT) Bhubaneswar here have developed pervious concrete pavements, a substitute for bituminous and concrete ones, that will help combat urban flooding and heat island effect in cities. According to the researchers of the School of Infrastructure at the institute, widespread construction and use of impervious pavements like bituminous and concrete surfaces exacerbate storm water runoff during rainfall, causing flood-like conditions in cities. Additionally, these have led to significant depletion of groundwater reserves.

Recognising the issue, the researchers have come up with pervious concrete pavements with the objective of curbing storm water runoff and promoting groundwater recharge. Unlike traditional pavements, pervious concrete features interconnected voids with at least 15 per cent porosity, allowing storm water to percolate through the pavement and recharge the groundwater.

As part of the experiment, IIT-BBS used pervious concrete pavements in the cycle parking area, covering 150 square metres with 18 slabs produced at a ready-mix concrete (RMC) plant. Students from the Transportation Engineering section participated in it, placing 150 mm thick pervious concrete slabs of 3.5X2.5 metre over a 250-300 mm reservoir layer atop the subgrade. The system was found capable of storing over 20 cubic metres of water without a runoff.

To assess pervious concrete pavements' efficiency, rainfall data from June 27 was also obtained from the GMAG lab of the School of Earth, Ocean, and Climate Sciences. It was found that the pavement infiltrated 6.8 cubic metre of storm water per hour during 47.24 mm/hr rainfall from 1.30 pm to 4.00 pm without any runoff.

https://www.newindianexpress.com/

JAPAN

Machine learning model enhances urban resilience

To make cities more resilient to the effects of liquefaction, Professor Shinya Inazumi and his student Yuxin Cong from Shibaura Institute of Technology in Japan have been developing machine learning models that predict how soil will react during earthquakes. These models use geological data to create detailed 3D maps of the soil layers, identifying stable areas and those more prone to liquefaction. Unlike manual soil testing methods, which cannot cover every location, this approach offers a broader and more detailed view of soil behaviour.

In their recent study published in Smart Cities on 8 October 2024, they used artificial neural networks (ANNs) and ensemble learning techniques to accurately estimate the depth of the bearing layers, a crucial indicator of how stable the soil is and how likely it is to experience liquefaction during an earthquake.

Predicting areas with deep and stable bearing layers helps identify locations where the soil can provide better support for buildings, especially during events like liquefaction. The researchers collected bearing depth data from 433 points in Setagaya-ku, Tokyo, using standard penetration tests and mini-ram sounding tests. In addition to the depth of the bearing layer, they also recorded key information about each location, such as longitude, latitude, and elevation.

The data was used to train an ANN to predict the bearing layer depth at 10 locations, utilizing the actual site measurements to evaluate the accuracy of the predictions. To improve the accuracy of these predictions, the researchers applied a technique called bagging (bootstrap aggregation), which involves training the model multiple times on different subsets of the training data. This approach resulted in a 20% improvement in prediction accuracy.

Using the predicted values, the researchers created a contour map illustrating the depth of bearing layers within a 1 km radius around four selected locations in Setagaya Ward. This map is a valuable visual aid for civil engineers, helping them identify suitable construction sites with stable soil conditions. It also assists disaster management experts in pinpointing areas that are more vulnerable to soil liquefaction, enabling better risk assessment and mitigation strategies.

https://www.eurekalert.org/

SINGAPORE

Digital solutions to address urban land scarcity

As the global population continues to grow, land and resource limitations are becoming increasingly urgent concerns, particularly in densely populated megacities. In response, researchers from Nanyang Technological University's (NTU) School of Civil and Environmental Engineering (CEE) are working on solutions that focus on utilising underground space and strengthening coastal protection measures.

Underground development presents a potential solution to urban land scarcity, offering new opportunities for social, economic, and environmental advancements. Coastal cities, meanwhile, face the growing threat of rising sea levels and erosion, making it essential to implement measures that protect shorelines and low-lying areas.

At NTU, the Centre for Urban Solutions (CUS) plays a key role in addressing these challenges. This multidisciplinary initiative focuses on integrating digital technologies, including artificial intelligence (AI), to improve urban planning and construction. One of CUS's main areas of research is underground engineering. With land becoming increasingly scarce, cities are expanding upwards with high-rise buildings and downwards. This approach creates additional space while ensuring cities are prepared for future growth.

Assoc Prof Wu Wei, who leads the Underground Engineering Cluster at CUS, oversees teams developing digital solutions to improve the safety and efficiency of underground construction. "Digging up to 100 metres deep poses significant engineering challenges, such as managing costs and controlling surface settlement to prevent accidents like the ground collapsing," he explains, referring to cases where sinkholes have formed during construction. His team employs AI-driven methods to map underground structures more accurately. By using machine learning, they can detect anomalies such as hidden cavities or boulders, improving precision while reducing costs and minimising the need for human supervision.

Similarly, Assistant Prof Shi Chao is applying digital technologies to underground and coastal engineering. His team uses digital twins—virtual models that simulate underground conditions—to optimise construction planning. These models enhance predictive analysis, reducing the reliance on physical site testing.

"We harness emerging AI technology to combine geological knowledge and site-specific data to automatically build and update digital twins," says Assistant Professor Shi. Accurate underground modelling is crucial for mitigating safety risks and preventing project failures. His team has successfully implemented digital twin technology in Hong Kong, which has been used to assess slope stability and seabed conditions for land reclamation and tunnelling. In cities with limited land availability, these tools can help engineers navigate challenging soil conditions while reducing construction risks.

Beyond underground expansion, researchers are also addressing the challenges posed by rising sea levels. According to Singapore's latest national climate study, sea levels could increase by up to 1.15 metres by the end of the century, surpassing previous projections.

https://theindependent.sg/

EUROPE

UK

IoT and AI to combat urban flooding

The University of Bath has unveiled an IoT solution aimed at tackling urban flooding by combining smart cameras with AI. The software, called 'AI on The River,' identifies blockages in culverts by detecting debris and waste. Culverts, critical for enabling waterways to flow under urban infrastructure, are fitted with trash screens to avert debris penetration. However, blockages at these screens can swiftly lead to flooding. By leveraging IoT capabilities, this system offers proactive monitoring and alerts. The system is attracting global interest, particularly from nations like South Africa where data scarcity hampers similar technological developments.

The system underwent trials at a site in Cardiff, achieving nearly 90% accuracy in spotting potential obstructions. Traditionally, culverts have been manually monitored via CCTV, necessitating continuous human intervention.

Incorporating IoT with AI ensures local authorities can optimise resource allocation, focusing on genuine issues and enhancing immediate response capabilities. This facilitates safer, more efficient interventions without exposing teams to hazardous conditions.

With climate change increasing flood risks globally, this IoT-focused research marks a significant advancement in managing urban water challenges. The system's flexibility paves the way for a sustainable, intelligent approach to flood forecasting, setting a new benchmark for IoT applications in infrastructure. The study, 'CCTV Image-based classification of blocked trash screens,' is published in *The Journal of Flood Risk Management* and supported by the Engineering and Physical Sciences Research Council (EPSRC).

https://iottechnews.com/

Molecular trap to clean pollution from water

Scientists from The University of Manchester have developed a new material that could help reduce water pollution caused by harmful chemicals, such as from leftover medicines and hygiene products, that end up in rivers and lakes. The research, published in the journal Cell Reports Physical Science, describes a new method using a molecular structure called a metal-organic cage (MOC). These tiny cages act like traps designed to catch and hold harmful molecules commonly found in our water supplies.

While MOCs have been studied before for gas and chemical capture, they are most commonly studied in chemical solvents where their performance differs significantly from that observed in water. Being able to demonstrate the capture of established wastewater pollutants in water is thus a step towards the application of these cages for real-world applications.

Jack Wright, a researcher at The University of Manchester, who completed the research as part of his PhD, said: "Being able to use MOCs in water is a really exciting development. We know how valuable MOCs are for capturing unwanted substances, but until now researchers have not been able to apply them to real-world water systems.

"Many harmful chemicals are difficult to remove from water, and with water pollution becoming a global crisis, this new MOC technology could provide a valuable tool to help clean up water systems and prevent pollutants from entering our ecosystem, particularly in rivers and lakes near urban or industrial areas where wastewater discharge is most common."

The cages are made up of metal ions connected by organic molecules, forming a hollow pyramid-like structure. These hollow spaces at the centre of these structures are where the MOCs trap specific molecules, like pollutants or gases. The new structure incorporates chemical groups called sulfonates to make it compatible with water, allowing it to function in real-world water systems, like rivers or wastewater.

It uses a natural effect called hydrophobic binding, where contaminant molecules preferentially "stick" to the inside of the cage rather than staying in the water. This allows the material to selectively capture and hold pollutants, even in challenging water environments.

Dr. Imogen Riddell, PhD supervisor and researcher at The University of Manchester said: "One of the real strengths of this method is its flexibility. The approach we have developed could be used to design other water-soluble MOCs with different sizes or properties. This opens the door to many future applications, including cleaning up different kinds of pollutants, development of green catalysts, or even development of drug delivery strategies ."

Now, the researchers will look to further expand the water-soluble cages, to enable the capture of more, different contaminants, and are working towards the development of robust routes to recycling the cages to support their development as sustainable water purification aids.

https://smartwatermagazine.com/

NORTH AMERICA

USA

AI system models urban trees to tackle climate change

Tree-D Fusion, developed by MIT, Google, and Purdue researchers, uses AI to create 3D models of urban trees, predicting growth under climate scenarios. These models aid city planning by anticipating challenges like branch interference and improving urban cooling. The technology also addresses environmental equity by mapping urban tree canopies with unprecedented detail.

The novel "Tree-D Fusion" system developed by researchers at the MIT Computer Science and Artificial Intelligence Laboratory (CSAIL), Google, and Purdue University merges AI and tree-growth models with Google's Auto Arborist data to create accurate 3D models of existing urban trees. The project has produced the first-ever large-scale database of 600,000 environmentally aware, simulation-ready tree models across North America.

Tree-D Fusion builds on previous urban forest monitoring efforts that used Google Street View data but branches it forward by generating complete 3D models from single images. While earlier attempts at tree modeling were limited to specific neighborhoods or struggled with accuracy at scale, Tree-D Fusion can create detailed models that include typically hidden features, such as the back side of trees that aren't visible in street-view photos.

The technology's practical applications extend far beyond mere observation. City planners could use Tree-D Fusion to one day peer into the future, anticipating where growing branches might tangle with power lines, or identifying neighborhoods where strategic tree placement could maximize cooling effects and air quality improvements. These predictive capabilities, the team says, could change urban forest management from reactive maintenance to proactive planning.

The researchers took a hybrid approach to their method, using deep learning to create a 3D envelope of each tree's shape, and then using traditional procedural models to simulate realistic branch and leaf patterns based on the tree's genus. This combo helped the model predict how trees would grow under different environmental conditions and climate scenarios, such as different possible local temperatures and varying access to groundwater.

While Tree-D fusion marks some major "growth" in the field, trees can be uniquely challenging for computer vision systems. Unlike the rigid structures of buildings or vehicles that current 3D modeling techniques handle well, trees are nature's shape-shifters — swaying in the wind, interweaving branches with neighbors, and constantly changing their form as they grow. The Tree-D fusion models are "simulation-ready" in that they can estimate the shape of the trees in the future, depending on the environmental conditions.

https://www.technologynetworks.com/

AI to predict climate-change related diarrheal outbreaks

A study published in *Environmental Research Letters* by an international team of investigators led by a senior author from the University of Maryland's School of Public Health (UMD SPH) Amir Sapkota, offers a way to predict the risk of such deadly outbreaks using AI modeling, giving public health systems weeks or even months to prepare and to save lives.

The multidisciplinary team, working across several institutions, relied on temperature, precipitation, previous disease rates, El Niño climate patterns as well as other geographic and environmental factors in Nepal, Taiwan province of China, and Viet Nam - between 2000 and 2019. Using this data, the researchers trained AI-based models that can predict area-level disease burden with weeks to months ahead of time.

https://www.preventionweb.net/

AI-driven high-performance data analytics for climate-resilient smart cities and energy systems

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Abstract

Smart cities require AI-driven solutions to enhance climate resilience, energy sustainability, and adaptive urban management. This paper explores the role of artificial intelligence (AI), big data, high-performance computing (HPC), and edge computing in improving renewable energy forecasting, climate adaptation, and AI governance. Case studies demonstrate advancements in solar and wind energy forecasting, showcasing adaptive model selection, attention-based learning, and hybrid deep learning techniques for enhanced predictive reliability. The findings highlight the potential of AI-driven smart grids and governance frameworks in optimizing energy efficiency. Future research should focus on integrating edge AI for real-time decision-making, improving scalable AI architectures, and developing standardized governance frameworks to ensure sustainable, efficient, and climate-resilient smart cities in an increasingly urbanized world.

Introduction

Climate change poses significant challenges to urban environments, requiring cities to adopt resilient, adaptive, and sustainable solutions. (Kandt and Batty 2021; Yigitcanlar, Butler, et al. 2020; Mehmood et al. 2024; Kashef, Visvizi, and Troisi 2021). The rapid expansion of smart cities, driven by advancements in artificial intelligence (AI), big data analytics, high-performance computing (HPC), edge computing, and high-performance data analytics (HPDA), offers an opportunity to enhance urban sustainability, optimize energy management, and improve climate resilience. (Janbi, Katib, and Mehmood 2023; Mehmood et al. 2023; Alahmari et al. 2023; Javed et al. 2022; Majeed et al. 2021) (see Figure 1 for a layered architecture of technology-driven smart cities (Janbi et al. 2020), further elaborated in Section 5). AI-driven predictive modelling, real-time data analytics, and autonomous decision-making enable cities to mitigate climate risks, manage renewable energy integration, and improve infrastructure efficiency. (Yigitcanlar, Mehmood, and Corchado 2021; Alkhayat and Mehmood 2021; Kandt and Batty 2021; Alahmari et al. 2023; Herath and Mittal 2022). However, integrating these technologies at scale necessitates robust governance frameworks, energy-efficient computational architectures, and climate-aware urban policies. (Alsaigh et al. 2024; Mehmood et al. 2025; Yigitcanlar et al. 2021).

This paper explores the technological foundations and AI-driven strategies for climate resilience in smart cities. It examines how big data and HPC facilitate large-scale environmental modelling, AI, machine learning (ML), and deep learning (DL), enhance energy forecasting, and enables real-time climate adaptation through edge computing. Special emphasis is placed on renewable energy forecasting, a critical factor in reducing fossil fuel dependence and ensuring stable energy grids.

To illustrate these concepts, the paper presents four case studies demonstrating AI applications in renewable energy forecasting and governance. These studies build on our work in AI-driven energy forecasting and governance, covering SENERGY, an AI-driven model selection tool for solar energy forecasting. (Alkhayat, Hasan, and Mehmood 2022) (Section 7), an attention-based deep learning approach for solar power generation forecasting (Almaghrabi et al. 2024) (Section 8), a hybrid deep learning model for wind energy forecasting (Alkhayat, Hasan, and Mehmood 2023) (Section 9), and an AI governance framework for smart energy systems (Alsaigh, Mehmood, and Katib 2023) (Section 10).

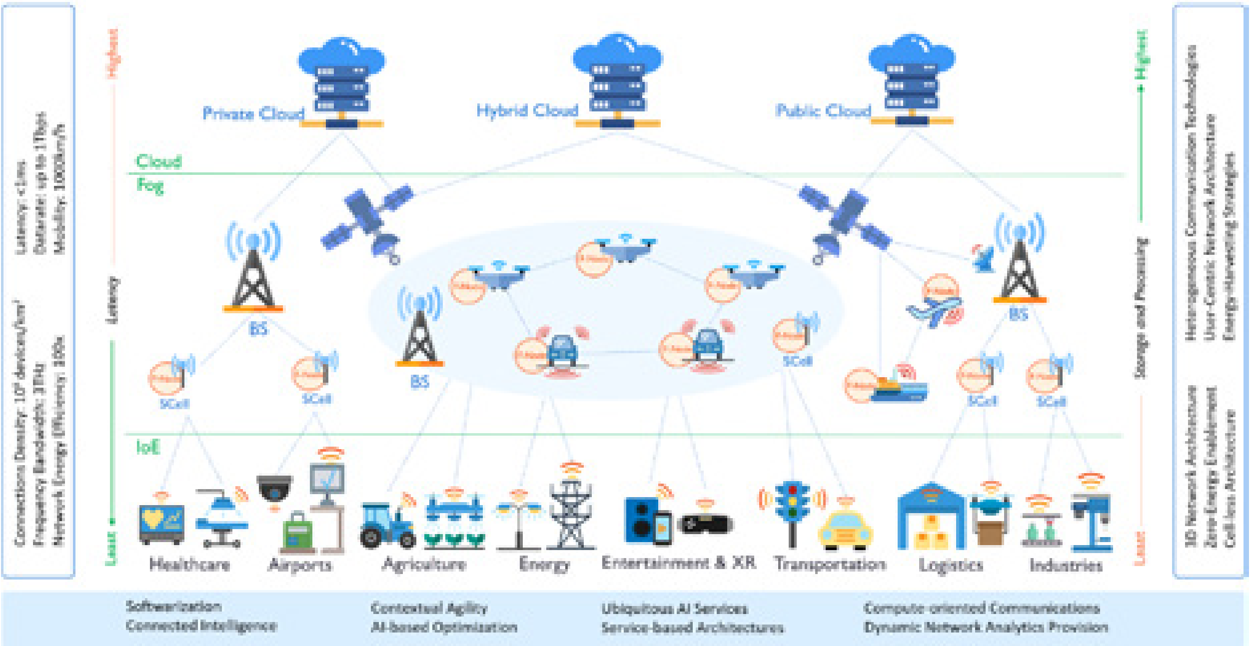


Figure 1: Smart city architecture enabled by edge computing and 6th Gen Networks (Janbi et al. 2020)

The following sections provide a structured exploration of these topics, starting with the evolution of smart cities (Section. 2) and their reliance on AI (Section 4), followed by discussions on big data and HPC (Section 3), AI-driven forecasting techniques (Section 6), and the role of edge computing (Section 5). The case studies further demonstrate AI applications in solar and wind energy forecasting as well as governance, culminating in a discussion on key challenges and future directions for AI-powered climate resilience in smart cities (Section. 11).

Technologies shaping climate-resilient smart cities

The shift from traditional cities to smart, climate-resilient cities is driven by the need for sustainability, adaptive infrastructure, and AI-driven decision-making. (Yigitcanlar, Butler, et al. 2020; Mehmood et al. 2024). Unlike conventional cities, which rely on centralized, reactive systems, smart cities leverage real-time data, AI, and automation to optimize energy use, enhance resilience, and mitigate climate risks. (Alotaibi et al. 2020; Schrotter and Hürzeler 2020). AI enables predictive urban planning, disaster preparedness, and environmental monitoring, making cities more adaptable to global challenges. (Son et al. 2023).

Data and AI serve as the foundation of smart cities, enabling evidence-based decision-making. (Yigitcanlar, Kankanamge, et al. 2020; Alomari, Katib, Albeshri, Yigitcanlar, et al. 2021). The integration of IoT sensors, satellite imagery, and HPC facilitates climate modelling, energy forecasting, and smart grid optimization. (Döscher et al. 2022; Abbasi et al. 2025; Yigitcanlar, Butler, et al. 2020). AI-driven simulations have improved urban flood prediction, water resource management, and renewable energy forecasting, reducing reliance on fossil fuels. (Groves et al. 2015; Xiang et al. 2021; Q. Huang et al. 2013; Yigitcanlar et al. 2022). However, the increasing use of urban data raises concerns about privacy, cybersecurity, and regulatory compliance, requiring strong AI governance frameworks. (Alsaigh et al. 2024; Yigitcanlar et al. 2021; D. Chen, Wawrzynski, and Lv 2021).

AI has also revolutionized urban governance, enhancing policy-making, infrastructure planning, and autonomous monitoring. (Alomari;, Katib;, and Mehmood 2023; Yigitcanlar, Butler, et al. 2020). Digital twins, AI-powered virtual replicas of cities, allow for climate impact simulations, traffic flow optimization, and energy efficiency planning. (Sivarethinamohan and Reddy 2024; Aloupogianni et al. 2024). Cities such as Singapore (X. Liu, Gou, and Yuan 2024; Zhan, Hwang, and Krishnankutty 2024), Zurich (Schrotter and Hürzeler 2020), and Amsterdam (Lohman et al. 2023) Employ digital twin technology for sustainability efforts (Faliagka et al. 2024; Shahat, Hyun, and Yeom 2021).

AI-driven energy management improves sustainability by forecasting energy demand and integrating renewables. (Almaghrabi et al. 2024; Alkhayat and Mehmood 2021; Alkhayat, Hasan, and Mehmood 2022; 2023). In healthcare, AI optimizes resource allocation and public health monitoring, helping cities adapt to climate-related health risks. (Alotaibi et al. 2020; Alomari, Katib, Albeshri, and Mehmood 2021; Alswedani, Mehmood, and Katib 2022; Alswedani et al. 2023; Verma 2022).

Despite its advantages, AI-driven smart cities face challenges in data privacy, cybersecurity, and ethical governance. Addressing these issues through robust AI policies and regulatory frameworks is essential for equitable, sustainable urban development.

Big Data and high-performance computing in climate-resilient cities

Big data and HPC are fundamental to processing vast and complex datasets in smart cities. (Arfat et al. 2020a; 2020b; Usman et al. 2022). Big data refers to the massive volume of structured and unstructured data generated from IoT sensors, climate monitoring systems, energy grids, and urban infrastructure. (Cesario 2023; Bhattarai et al. 2019; Taherdoost 2024). It enables data-driven decision-making through real-time analytics and predictive modelling. (Kandt and Batty 2021). HPC, on the other hand, provides the computational power needed to process and analyse these large datasets efficiently, running advanced simulations, deep learning models, and large-scale AI applications (Alomari, Katib, Albeshri, Yigitcanlar, et al. 2021; Alomari, Katib, Albeshri, and Mehmood 2021). While traditionally separate, big data and HPC are increasingly converging to enable HPDA, providing real-time insights for climate resilience and urban sustainability (Usman, Mehmood, and Katib 2020; Usman et al. 2022; Elia, Fiore, and Aloisio 2021).

In smart cities, HPC accelerates climate modelling. (Döscher et al. 2022; Wang et al. 2021), energy forecasting (Abbasi et al. 2025; Rodriguez et al. 2021), and disaster prediction (Bates 2021; Hori et al. 2018), allowing urban planners to implement proactive adaptation strategies. AI-powered climate risk assessment models utilize HPC to analyse weather patterns, predict extreme events such as floods and heatwaves, and optimize water resource management. (Groves et al. 2015; Xiang et al. 2021; Q. Huang et al. 2013). In the energy sector, HPC-driven AI models improve renewable energy forecasting, optimize smart grids, and enhance power distribution, reducing reliance on fossil fuels. (Parizad and Hatziadoniu 2022; Rodriguez et al. 2021).

However, the integration of HPC and big data presents challenges, particularly regarding high energy consumption, scalability, and data privacy. (Gilman et al. 2024; Haoyang Liu and Zhai 2025). The computational demands of AI-driven smart cities necessitate energy-efficient HPC architectures, incorporating green computing techniques, workload optimization, and edge AI solutions to reduce reliance on centralized infrastructure. (Usman et al. 2022). Addressing these challenges will be crucial for ensuring scalable, sustainable, and climate-resilient smart cities. (Mehmood et al. 2020; 2023).

AI, Machine Learning (ML), and Deep Learning (DL)

AI encompasses a broad range of technologies that enable machines to perform tasks typically requiring human intelligence. A key component of AI is ML, which allows systems to learn from data and improve their performance over time. ML could be categorized into supervised, unsupervised, and reinforcement learning (RL) (Janiesch, Zschech, and Heinrich 2021).

Supervised ML models learn from labelled datasets where both input and output data are provided. This approach is widely used in classification and regression tasks, such as image recognition, medical diagnostics, and financial forecasting. Common supervised learning algorithms include support vector machines, decision trees, random forests (RF), and linear regression models. (Taye 2023). In contrast, unsupervised ML models identify hidden patterns in unlabelled data. These models are useful for clustering and association tasks, such as customer segmentation and anomaly detection. Clustering algorithms include K-means, mean-shift, and principal component analysis (PCA), while association rule learning relies on techniques including Apriori and FP-growth (Pichler and Hartig 2023). RL mimics trial-and-error learning, allowing models to interact with an environment and optimize their actions based on rewards or penalties. RL is widely used in robotics, self-driving cars, and game-playing AI. A key algorithm in this field is Q-learning (Morales 2020).

The development of artificial neural networks (ANNs), inspired by the human brain, has led to major advancements in ML. An ANN consists of an input layer, multiple hidden layers, and an output layer, where connected nodes (neurons) adjust their weights through learning. As ANNs evolved into deeper architectures, the field of DL emerged. (Pramod, Naicker, and Tyagi 2021). DL models, particularly convolutional neural networks (CNNs) and recurrent neural networks (RNNs), have revolutionized AI applications requiring large, high-dimensional data processing, such as image recognition, speech processing, and predictive analytics. (S. Dong, Wang, and Abbas 2021). CNNs are highly effective in computer vision tasks, using convolutional and pooling layers to detect features and patterns in images. (Trask 2019). RNNs, designed for sequential data, excel in natural language processing and time-series forecasting. Advanced variants, including long short-term memory (LSTM) and gated recurrent units (GRU), help overcome the vanishing gradient problem. (Ilya Sutskever 2013).

Other DL architectures have expanded AI's capabilities. Autoencoders (AEs) are useful for data compression and anomaly detection, while variational autoencoders (VAEs) allow for generating diverse variations of input data. (Gensler et al. 2016). Generative adversarial networks (GANs) produce realistic synthetic data, with applications ranging from image generation to data augmentation. (Khodayar, Wang, and Manthouri 2018). Transformer models, a breakthrough in natural language processing, leverage self-attention mechanisms to process text more efficiently than traditional RNNs (Q. Chen et al. 2019). Hybrid DL models combine multiple architectures to enhance performance in complex tasks. In renewable energy applications, DL models are frequently integrated with traditional ML or physical models to improve forecasting accuracy. For more insights into DL and its uses in renewable energy, see (Alkhayat and Mehmood 2021; Forootan et al. 2022).

Edge computing for smart cities: extending cloud and fog architectures

Edge computing is a distributed computing paradigm that brings computation and data storage closer to the

Figure 2: The role of edge computing in climate resilience

source of data generation, reducing latency and improving real-time processing capabilities (Janbi, Katib, and Mehmood 2023; Janbi et al. 2022). Unlike traditional cloud computing, where data must travel to distant data centres for processing, edge computing distributes computational load to localized nodes. This approach minimizes delays and bandwidth usage, improves security and privacy by keeping sensitive data local, and reduces reliance on internet connectivity (Singh and Gill 2023). Figure 1 illustrates a smart city architecture enhanced by edge computing, showing how different computing layers work together to optimize connectivity and processing across urban environments (Janbi et al. 2020). At the top, the cloud layer provides centralized storage and high computational power but with increased latency. In the middle, the fog computing layer brings processing closer to end devices, enabling faster responses. At the bottom, the edge layer comprises Internet of Everything (IoE) devices such as mobile devices, autonomous vehicles, drones, smart traffic lights, and other connected technologies, powering various smart city applications, including healthcare, airports, agriculture, energy, entertainment & XR, transportation, logistics, and industries. This illustration highlights how edge computing decentralizes processing, reducing dependence on distant cloud data centres and enabling real-time, intelligent urban infrastructure, which can make smart cities more efficient, adaptive, and sustainable.

Similarly, these features of edge computing can play an important role in enhancing climate resilience (see Figure 2). By processing data closer to its source, edge computing can enable real-time decision-making for critical systems, such as smart grids, transportation networks, and emergency services, to remain operational during climate disruptions. (Minh et al. 2022; Gill et al. 2025). Moreover, localized data processing can ensure continued services despite central system failures as services are distributed across multiple devices. (Shinde, Hemanth, and Elhoseny 2023). Edge computing combined with distributed intelligence can also support predictive maintenance and self-healing infrastructure, helping to prevent system failures before they occur, thereby reducing downtime and improving reliability. (M. Dong et al. 2021; Jin et al. 2022). Additionally, it can enhance cybersecurity and privacy by reducing reliance on centralized cloud systems and minimizing the risk of large-scale data breaches. (Cao et al. 2020; Gill et al. 2025). Keeping sensitive data localized reduces exposure to cyber threats while ensuring compliance with data protection regulations. This is particularly important for climate monitoring systems, emergency response networks, and energy grids, where secure and private data handling is essential. Furthermore, edge computing can contribute to renewable energy resilience by optimizing solar energy forecasting and defect detection in solar cells, improving the sustainability of power generation. (Venitourakis et al. 2023). Overall, edge computing can strengthen climate resilience by ensuring operational continuity, reducing latency, enhancing privacy and security, and providing localized, intelligent responses to environmental challenges, making smart cities more robust.

Applications for edge computing for climate resilience span a variety of industries, including smart grids, transportation networks, water and waste management, telecommunications infrastructure, and healthcare systems, improving efficiency and adaptability in the face of climate change. Smart grids can benefit from edge computing integrated with AI to balance energy loads, incorporate renewable energy sources, and prevent blackouts during extreme weather (Minh et al. 2022). Transportation networks leverage edge computing for real-time traffic management, autonomous vehicle operations, and railway monitoring, ensuring mobility during climate-related disasters such as floods and earthquakes (Arthurs et al. 2022; Bhambri and Khang 2025). Water and waste management systems can utilize edge computing to monitor water quality, detect leaks, and predict flood risks in real-time, enabling swift responses to protect water supplies and mitigate cascading impacts on urban populations (Amesho et al. 2024; Ren, Zhu, and Wang 2022). Telecommunications infrastructure can integrate edge computing to maintain communication networks during natural disasters, enhancing 5G and 6G networks with AI to dynamically manage bandwidth, optimize traffic flow, and sustain mission-critical communications during peak loads or severe storms (Letaief et al. 2022; Park et al. 2019). Healthcare systems can also benefit from edge computing through real-time patient monitoring and disaster response, which is crucial during climate-induced health crises such as heat waves and floods (Hartmann, Hashmi, and Imran 2022; Abdellatif et al. 2019).

In Asia and the Pacific region, the resilience of urban infrastructure and essential services are further challenged by the intensifying climate threats the region faces, including typhoons, floods, rising sea levels, and extreme heat waves. (Nunn et al. 2024; Prizzia and Levy 2018). As cities in the region become more digitally connected, the role of edge computing in enabling real-time, localized responses to climate-induced disruptions will become increasingly critical. By enabling adaptive, real-time, and decentralized decision-making, edge computing can strengthen climate resilience across Asia and the Pacific, ensuring that cities remain operational, secure, and efficient in the face of escalating climate challenges. As the region continues to urbanize, integrating edge AI with smart city applications will be key to building sustainable, future-proof urban environments capable of withstanding climate-induced disruptions.

Renewable energy forecasting for climate-resilient smart cities

Renewable energy forecasting plays a crucial role in ensuring grid stability, energy market efficiency, and climate resilience. While various forecasting techniques apply to multiple renewable energy sources, such as solar, wind, and hydro, this section focuses on solar energy forecasting due to space constraints. Some methodologies and challenges discussed here are also relevant to other forms of renewable energy, though each source has unique forecasting requirements.

Solar power generation forecasting and climate resilience: The variability of solar power presents a challenge for renewable energy integration, as photovoltaic (PV) systems depend on fluctuating weather conditions (Zhang et al. 2015). Unlike fossil-fuel power plants that provide a steady energy output, solar generation varies daily and seasonally. Accurate forecasting helps grid operators balance supply and demand, prevent voltage fluctuations, and minimize reliance on fossil fuel reserves, reducing carbon emissions. Energy storage systems, such as lithium-ion batteries and pumped hydro storage, are key to mitigating solar power intermittency. However, they are costly and require precise management. Forecasting enables optimized charging and discharging schedules, improving storage efficiency and cost-effectiveness (Suberu, Mustafa, and Bashir 2014). Climate resilience planning also benefits from forecasting, particularly for extreme weather events such as hurricanes, heat waves, and wildfires, which disrupt energy generation and grid operations. (Nyangon 2024). Reliable forecasts allow utilities to take preventive measures, such as disconnecting solar arrays before storms or deploying mobile storage solutions. In electricity markets, supply-demand balance dictates energy pricing. In high solar penetration regions, forecasting enables producers to predict output and bid efficiently in electricity markets. (Da Silva, Ilić, and Karnouskos 2013). It also supports power purchase agreements (PPAs) and grid feed-in mechanisms, ensuring stable pricing and minimizing financial risks for investors.

Methods of solar power generation forecasting: Solar power forecasting methods fall into physical models, non-physical models, and hybrid approaches. Physical models use atmospheric physics to simulate solar irradiance and PV power generation. These models incorporate numerical weather prediction (NWP) systems, where meteorological forecasts are converted into solar energy estimates. However, their accuracy depends on NWP precision, and errors can propagate through the system (Geraldi, Romano, and Ricciardelli 2012). Studies using European Centre for Medium-Range Weather Forecasts data have shown systematic overestimations of PV power output during winter (Lorenz, Heinemann, and Kurz 2012). Bias correction algorithms improve accuracy under cloudy conditions (Lorenz et al. 2011). Non-physical models, or empirical models, analyse historical solar power data using statistical, ML and DL techniques [54]. These methods identify patterns in past data to predict future power generation without relying on atmospheric equations. Traditional statistical models, such as auto-regressive integrated moving average (ARIMA), perform well under stable weather conditions [55], while AI-driven models better handle complex dependencies (Antonanzas et al. 2016). Studies show that support vector regression (SVR) (Awad and Khanna 2015; Shi et al. 2012) and multiple linear regression (MLR) models improve forecasting accuracy when incorporating weather variables (Abuella and Chowdhury 2015). DL models, including ANNs (Abdi, Valentin, and Edelman 1999; Changsong Chen et al. 2011; Rana and Koprinska 2016), CNNs (Gu et al. 2018; Shih, Sun, and Lee 2019;

C.-J. Huang and Kuo 2019), and RNNs (Medsker and Jain 2001), offer superior predictive accuracy. CNNs process satellite imagery and irradiance maps, while LSTM networks capture temporal dependencies in solar power data (du Plessis, Strauss, and Rix 2021; Abdel-Nasser and Mahmoud 2019). Studies have validated AI-based forecasting, such as Shi et al.'s SVR model in China (Shi et al. 2012) and Rana et al.'s study in Australia, where SVR outperformed traditional models (Rana, Rahman, and Jin 2020). Hybrid models integrate physical and data-driven approaches to combine their strengths. For example, Mathe et al. developed a CNN-LSTM hybrid model for Germany, significantly reducing forecasting errors (Mathe et al. 2019).

Challenges in solar power generation forecasting: Despite advancements, data quality, computational efficiency, and model interpretability remain key challenges. Data availability and reliability are concerns, as ML and DL models require high-resolution datasets that are often incomplete in some regions. (Sarmas et al. 2022a). Sensor malfunctions and missing values further degrade model performance, necessitating preprocessing techniques such as normalization and outlier detections. (Almaghrabi et al. 2021). Computational complexity presents another challenge, as deep learning models demand significant processing power, making real-time deployment difficult. (Chunlei Chen et al. 2020). Model interpretability and explainability are concerns since deep learning models often function as black boxes. While traditional models such as ARIMA provide transparent predictions, DL-based forecasting lacks explainability. Explainable AI (XAI) techniques, such as SHapley Additive Explanations (SHAP) and Local Interpretable Model-Agnostic Explanations (LIME), improve transparency. (Hassija et al. 2024; Lundberg and Lee 2017; Ribeiro, Singh, and Guestrin 2016). Generalization across locations is also a challenge, as solar energy generation is climate-dependent. A model trained on desert conditions may not perform well in coastal or mountainous areas. Transfer learning and domain adaptation techniques help improve generalization. (Sarmas et al. 2022b).

Case Study 1: SENERGY- An ML model selection tool for solar energy forecasting

As previously mentioned, Smart cities increasingly depend on accurate solar energy forecasting to ensure grid stability, energy efficiency, and market operations. Due to the variability of weather conditions, forecasting errors can lead to imbalances in energy supply and demand, requiring backup storage or alternative power sources. Addressing these challenges, we developed SENERGY, an AI-based deep learning model selection tool specifically designed for solar energy forecasting (see (Alkhayat, Hasan, and Mehmood 2022) For details). SENERGY improves forecasting accuracy by automatically selecting the best-performing model based on real-time meteorological data, ensuring adaptability across diverse climate conditions. Unlike conventional forecasting approaches that rely on a fixed model architecture, SENERGY employs an adaptive selection strategy, making it a valuable tool for smart grid management and renewable energy integration.

SENERGY consists of a model prediction engine and a forecasting engine. The prediction engine selects the most suitable deep learning model for a given dataset, while the forecasting engine applies the selected model to generate next-hour global horizontal irradiance (GHI) predictions (see Figure 3 For system architecture). The system was trained and evaluated using meteorological datasets from ten locations across three distinct climate zones, including Saudi Arabia, Canada, and Venezuela. These datasets contain 33 meteorological features, such as forecasting hour, temperature, wind speed, humidity, and solar radiation components. Five deep learning models, LSTM, GRU, CNN, CNN-Bidirectional LSTM (CNN-BiLSTM), and LSTM Autoencoder (LSTM-AE), were tested and evaluated under varying weather conditions (Alkhayat, Hasan, and Mehmood 2022).

SENERGY's forecasting engine applies all five models and determines the best-performing architecture dynamically. The LSTM-AE model demonstrated the highest accuracy across climate conditions, leveraging an encoder-decoder structure with two LSTM layers and a dense output layer to capture temporal dependencies

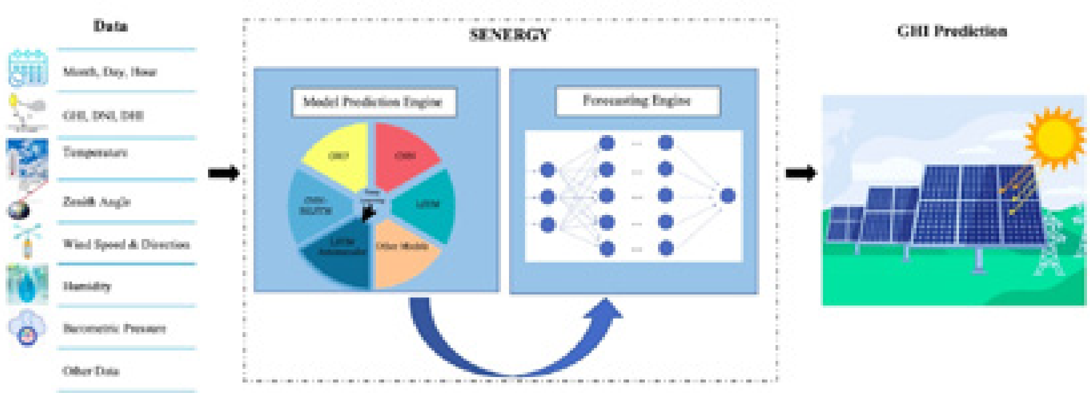


Figure 3: SENERGY framework (Alkhayat, Hasan, and Mehmood 2022)

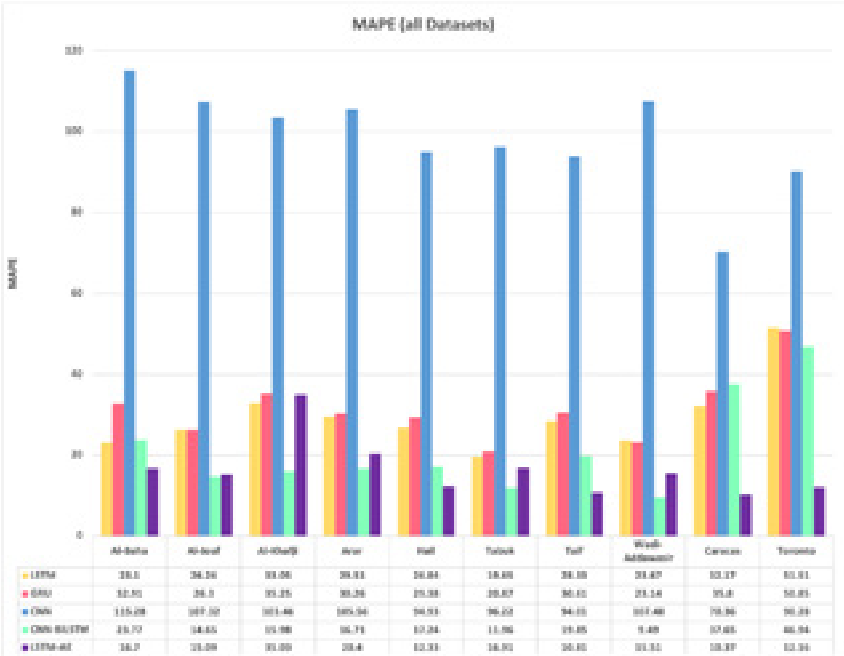


Figure 4: MAPE results of 5 models for next-hour GHI forecasting (Alkhayat, Hasan, and Mehmood 2022)

and improve sequence learning. To automate model selection, an LSTM-based classifier was trained on a merged dataset from all ten locations, assigning the optimal model based on historical performance. The classifier achieved an 81% classification accuracy and was optimized for binary selection between LSTM-AE and CNN-BiLSTM, which outperformed other models in most cases. The mean absolute percentage error (MAPE) results confirm that these two models provide superior forecasting accuracy (Figure 4).

By dynamically adapting to changing weather conditions, SENERGY represents a major advancement in AI-driven renewable energy forecasting, improving the efficiency and reliability of smart grid operations. The tool reduces dependence on static forecasting methods and enhances energy resilience by enabling more reliable solar energy predictions. Beyond solar forecasting, SENERGY's approach is scalable to wind energy predictions, smart grid optimization, and energy load forecasting. Future enhancements could expand the selection of candidate models, incorporate multi-criteria decision-making based on computational efficiency, and integrate real-time optimization techniques.

Case Study 2: Attention-based interpretable predictions for solar power generation forecasting

As stated earlier, smart cities increasingly rely on AI-driven energy forecasting models to ensure grid stability and optimize renewable energy integration. Solar power, despite its advantages in sustainability, presents significant forecasting challenges due to its dependence on fluctuating weather conditions. Addressing these challenges, we developed the Multidimensional Dynamic Attention (MDA) model, specifically designed for solar power generation forecasting (see (Almaghrabi et al. 2024) for details). MDA enhances prediction reliability and interpretability by dynamically identifying key meteorological variables influencing solar power output at different time horizons. These insights assist grid operators, policymakers, and energy analysts in making informed decisions for efficient energy management.

Forecasting solar power generation is complex due to the non-stationary and multivariate nature of the data. Solar energy production depends on various meteorological variables, including solar irradiance, wind speed, cloud opacity, and temperature, each exhibiting changing influences over time. Many existing forecasting models rely on static attention mechanisms, which fail to capture these dynamic dependencies, leading to limited interpretability and reduced accuracy. The MDA model overcomes this limitation by introducing a dynamic representation learner that adjusts attention weights over time, allowing for more flexible and explainable predictions. (Almaghrabi et al. 2024).

MDA was evaluated on solar power generation data from New South Wales (NSW) and Queensland (QLD), Australia, spanning January 2019 to November 2021. The dataset includes aggregated PV power output and multiple meteorological features collected from weather monitoring stations. These features include solar irradiance metrics, atmospheric conditions, and environmental factors, all recorded at 30-minute intervals. The model architecture consists of two main components: the Multidimensional Dynamic Attention Layer (MDAL), which captures temporal and variable dependencies, and the Task Learner (TL), which generates the final solar power predictions (see Figure 5).

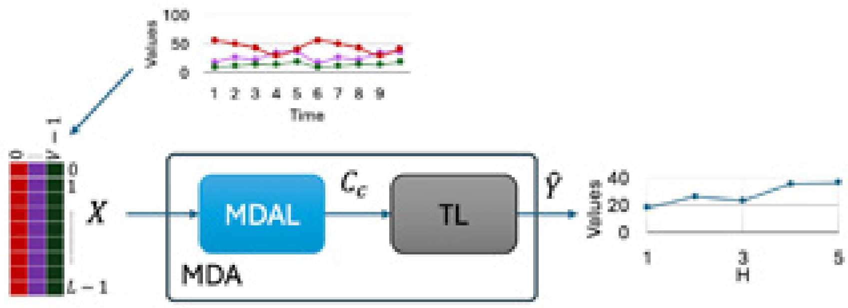


Figure 5: MDA Model

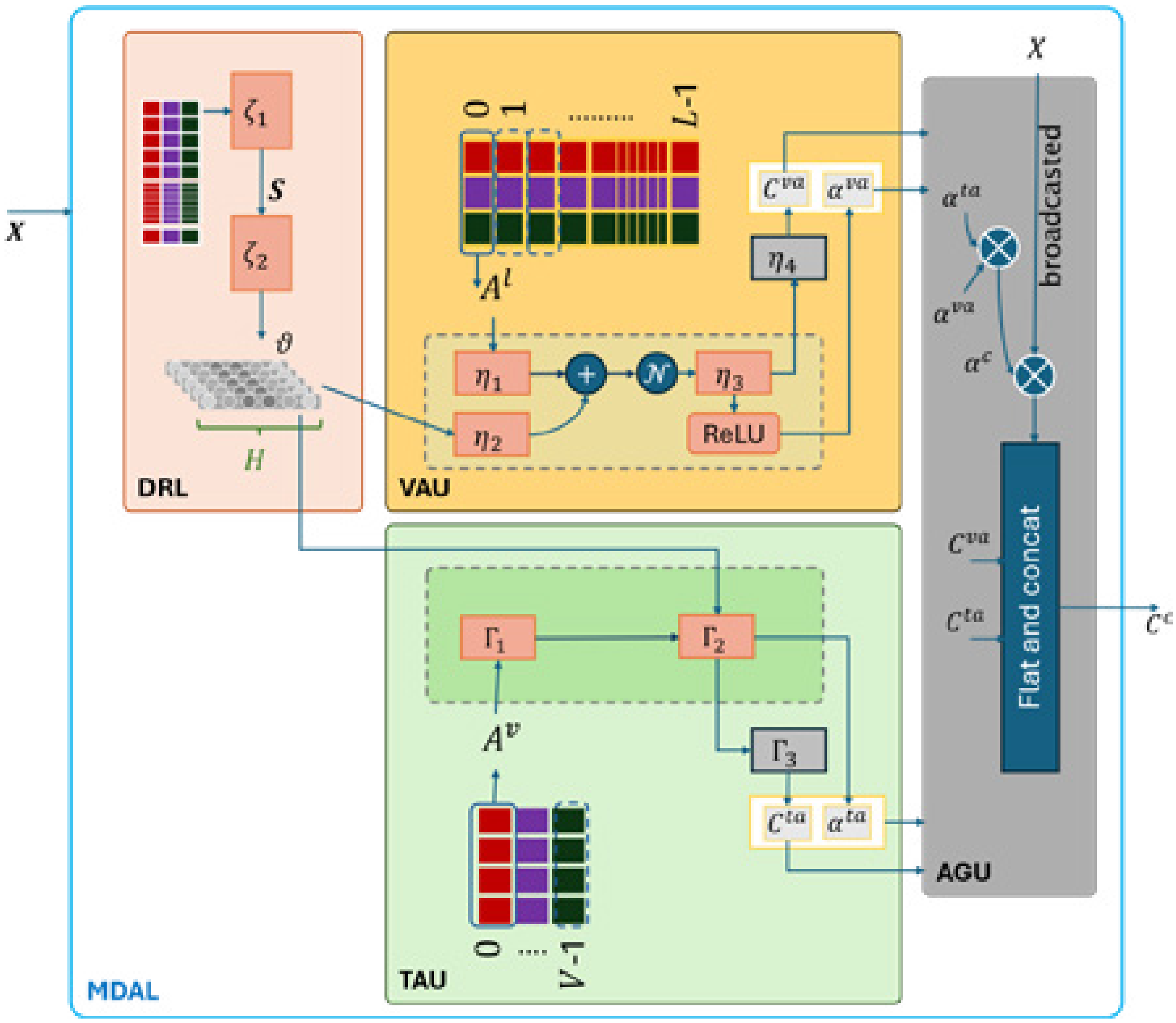


Figure 6: Architecture Diagram of MDAL

MDAL introduces three key mechanisms: the Dynamic Representation Learner (DRL), which adjusts feature importance dynamically over time; the Variable Attention Unit (VAU), which assigns relevance scores to different meteorological features at each time step; and the Temporal Attention Unit (TAU), which adjusts feature importance across different prediction horizons (see Figure 6). We implemented two architectural variants: MDA_{par}, which processes variable and temporal attention in parallel, and MDA_{seq}, which refines attention weights sequentially, allowing dependencies to evolve dynamically (Almaghrabi et al. 2024).

MDA demonstrated superior forecasting performance and interpretability compared to baseline models. Figure 7 illustrates feature importance over dif-

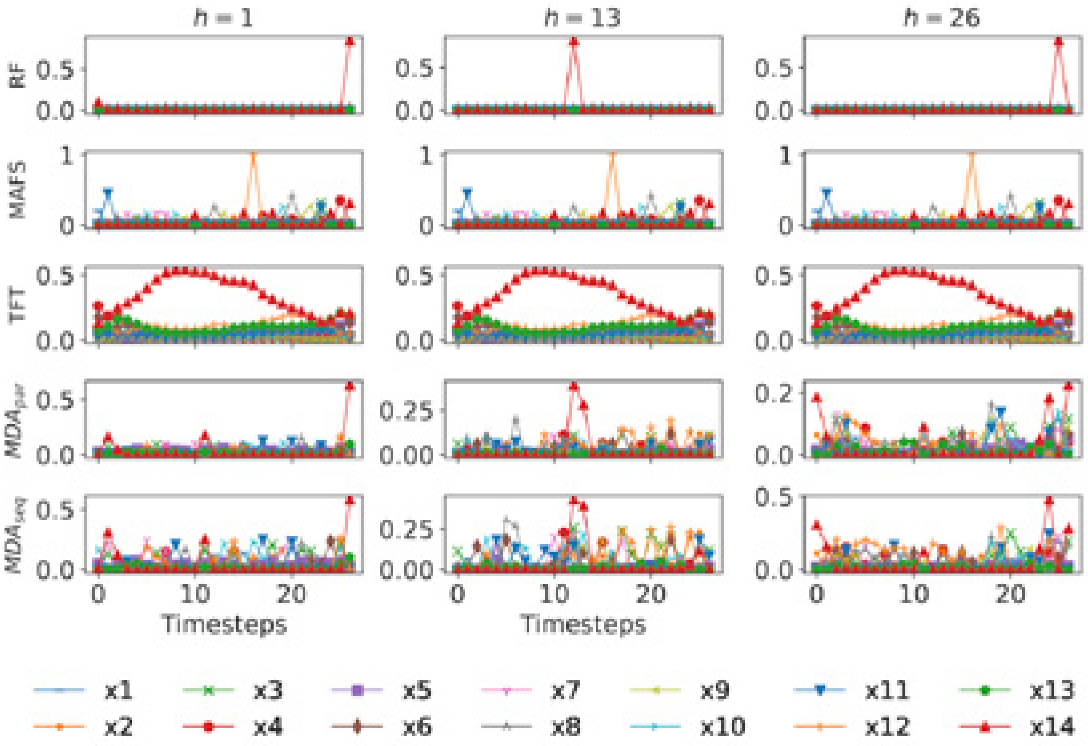


Figure 7: Lagged variables importance in NSW at different horizons (h)

ferent forecasting horizons, highlighting the most influential meteorological variables affecting solar power generation in NSW. The MDA variants (MDA_{par} and MDA_{seq}) consistently outperformed traditional models such as RF, Moving Average Forecasting Systems (MAFS), and Temporal Fusion Transformers (TFT). The MAPE results confirm MDA's ability to adaptively capture evolving feature dependencies (see Figure 7 for performance comparison).

A major advantage of MDA is its explainability. Unlike conventional deep learning models that function as black-box predictors, MDA provides interpretable insights, allowing energy analysts and grid operators to understand how specific weather variables influence solar power generation over time. This interpretability is critical for developing energy management strategies, helping stakeholders anticipate variations in solar power availability and take proactive measures to maintain grid stability.

The MDA model advances solar power forecasting by offering both high predictive accuracy and interpretability. By dynamically adjusting feature importance across time horizons, MDA provides a scalable and explainable solution for smart city energy management. These insights support climate resilience initiatives by enabling smarter grid planning, improved renewable energy integration, and more reliable solar power forecasting.

Case Study 3: A hybrid DL-based wind energy forecasting across three climates

Wind energy plays a crucial role in smart city sustainability, but its high variability and nonstationary nature make forecasting challenging. Unlike solar power, which follows predictable diurnal cycles, wind speed is influenced by complex atmospheric and meteorological conditions, requiring advanced AI-driven forecasting models. Single DL models have demonstrated superior performance compared to traditional statistical methods in wind energy forecasting (Abualigah et al. 2022; Bali, Kumar, and Gangwar 2019). However, hybrid models that integrate DL with decomposition techniques have shown higher forecasting accuracy than standalone DL models (Deng et al. 2020; Hui Liu et al. 2019). Addressing these challenges, we developed a hybrid DL model combining Variational Mode Decomposition (VMD) and LSTM networks for next-hour wind speed forecasting (see (Alkhayat, Hasan, and Mehmood 2023) for details). This approach improves accuracy by decomposing wind speed time series into multiple components, allowing LSTM networks to extract relevant patterns more effectively. The model was tested across three distinct climate zones, hot desert (Saudi Arabia), tropical (Caracas, Venezuela), and cold temperate (Toronto, Canada), to assess its robustness in climate-resilient smart grid planning.

The hybrid model consists of two main stages. First, VMD decomposes wind speed data into four subseries, each capturing distinct frequency components. Second, four separate LSTM models are trained to predict next-hour wind speed, with each model focusing on a specific decomposed subseries.

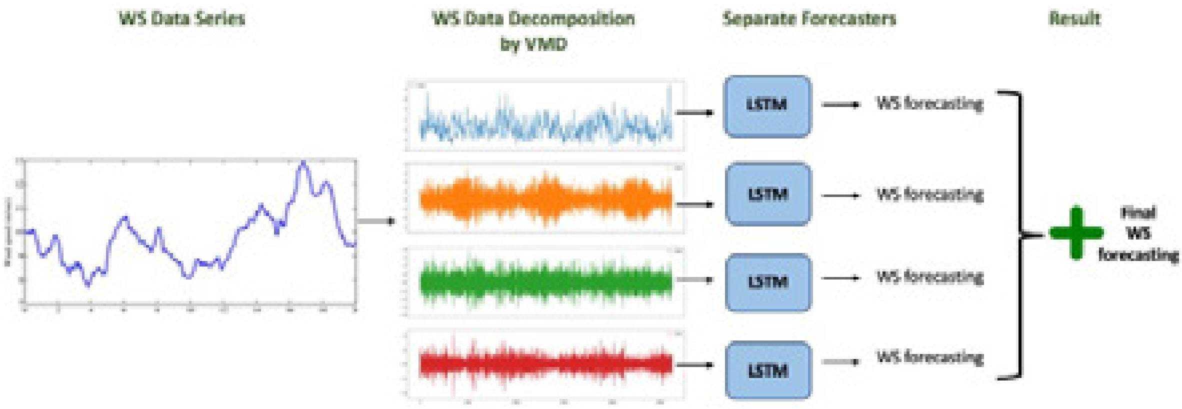
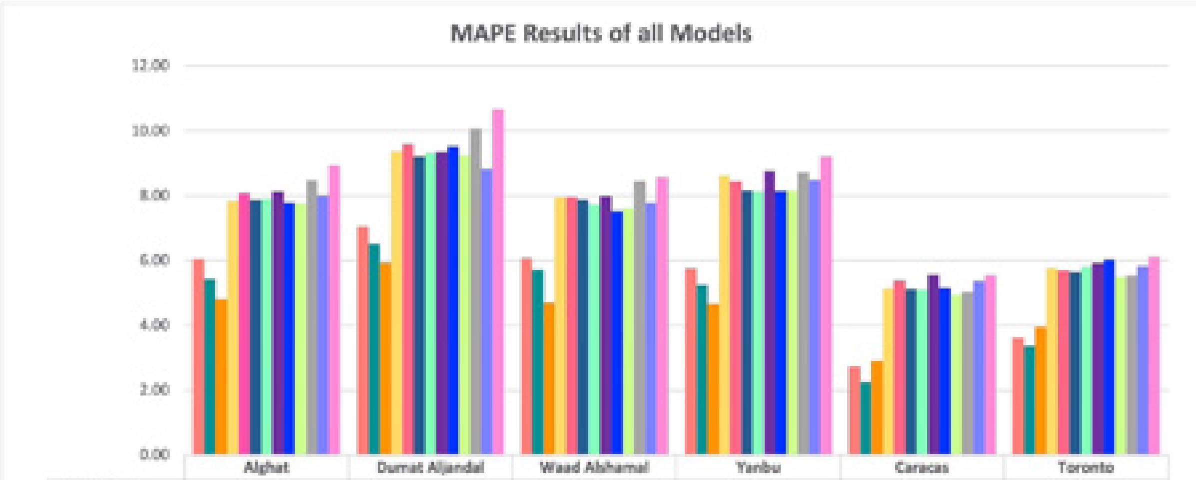


Figure 8: Hybrid model of VMD and LSTM framework (Alkhayat, Hasan, and Mehmood 2023)



	Alghat	Dumat Aljandal	Waad Alshamal	Yanbu	Caracas	Toronto
EMD-LSTM	6.06	7.04	6.08	5.76	2.73	3.63
CEEMDAN-LSTM	5.43	6.53	5.72	5.25	2.25	3.38
VMD-LSTM	4.81	5.93	4.70	4.66	2.91	3.96
LSTM	7.84	9.37	7.95	8.61	5.14	5.78
GRU	8.09	9.59	7.95	8.44	5.38	5.70
BILSTM	7.86	9.21	7.88	8.17	5.12	5.65
BIGRU	7.91	9.32	7.73	8.13	5.11	5.82
LSTM-AE	8.12	9.35	8.00	8.77	5.57	5.92
CNN-LSTM	7.79	9.53	7.53	8.14	5.15	6.03
SVR	7.77	9.25	7.62	8.17	4.95	5.49
MLR	8.48	10.06	8.45	8.73	5.04	5.55
XGB	8.02	8.83	7.78	8.49	5.37	5.83
RFR	8.94	10.67	8.57	9.21	5.56	6.11

Figure 9: MAPE results of 13 models for WS forecasting (Alkhayat, Hasan, and Mehmood 2023)

The final wind speed forecast is obtained by aggregating the predictions from these models. The LSTM architecture includes two stacked layers with 256 and 128 neurons, followed by two dense layers with 64 and 32 neurons, using TanH activation. The model was trained and evaluated using meteorological datasets from diverse climate zones, ensuring robustness across different atmospheric conditions. These datasets contain 18 meteorological features, including wind speed history, solar radiation, temperature, and humidity. The hybrid model's framework is illustrated in Figure 8.

Performance comparisons against six single DL models (LSTM, GRU, Bidirectional LSTM, Bidirectional GRU, LSTM Autoencoder, and CNN-LSTM) and four machine learning models (SVR, RF Regression (RFR), Extreme Gradient Boosting (EGB), and MLR) confirmed the superiority of VMD-LSTM. The model outperformed LSTM alone by 39-47% in MAE, RMSE, and MAPE for the Saudi Arabian datasets. In Caracas and Toronto, the best-performing model was CEEMDAN-LSTM, achieving 50-63% improvement over LSTM in Caracas

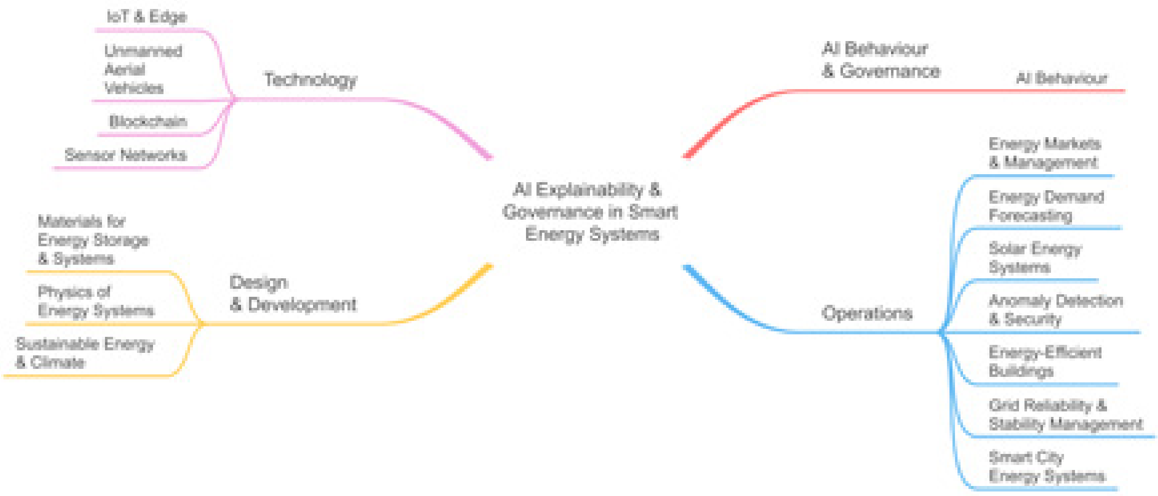


Figure 10: Taxonomy of Parameters for AI Explainability and Governance in Smart Energy Systems (Alsaigh, Mehmood, and Katib 2023)

and 39-42% improvement in Toronto. The MAPE results, illustrated in Figure 9, highlight the importance of choosing decomposition methods based on regional climate characteristics.

The results demonstrate that hybrid AI models effectively handle complex, nonstationary time series data, making them valuable for wind energy forecasting in diverse climates. The success of VMD-LSTM suggests that decomposition-enhanced DL models could be extended to solar and hydroelectric power forecasting, further improving smart grid resilience. Future research could explore alternative decomposition techniques, optimize hybrid architectures for real-time deployment, and integrate these models into edge computing frameworks to enhance AI-driven renewable energy forecasting in climate-resilient smart cities.

Case Study 4: AI explainability and governance in smart energy systems

Smart energy systems integrate renewable energy sources, decentralized grids, and intelligent automation to enhance sustainability and efficiency (Ceglia et al. 2020; Serna Torre and Hidalgo-Gonzalez 2022; Ashworth 1990). However, as AI plays an increasing role in energy forecasting, grid optimization, and power distribution (López Santos et al. 2022; Sun et al. 2022), its lack of transparency and governance raises concerns about trust, accountability, and regulatory oversight (Zhao et al. 2021; Nitzberg and Zysman 2022). As stated earlier, AI models often function as black boxes, making it difficult for stakeholders to interpret decisions, which can hinder public trust and policy enforcement (Castelvecchi 2016). While AI-powered smart grids enhance efficiency and resilience (Abdel-Razek et al. 2022; Hussain, Bui, and Kim 2019), they also introduce challenges related to bias, security vulnerabilities, and compliance with energy regulations, necessitating governance frameworks that ensure fair, explainable, and trustworthy AI systems (Phillips et al. 2021; Przhedetsky 2021; Nitzberg and Zysman 2022; Volkova et al. 2022). AI governance has become crucial with the increasing number of worldwide regulations on data protection, privacy, and AI, including the EU AI Act (European Union 2024), General Data Protection Regulation (GDPR) (European Union 2016), U.S. Blueprint for an AI Bill of Rights (The White House 2022), China's Personal Information Protection Law (PIPL) (China Briefing Team 2021), and others.

Addressing these challenges requires a systematic understanding of AI governance in smart energy systems, identifying key parameters that shape transparency, regulatory compliance, and decision accountability. To contribute to this effort, we conducted a comprehensive review of AI governance in energy systems by analysing 3,568 papers from the Scopus database covering research of over five decades, focusing on emerging governance frameworks, explainability techniques, and policy gaps (see (Alsaigh, Mehmood, and Katib 2023) for details). By adopting a data-driven DL-based big data analytics approach, the study identified 15 key governance parameters and classified them into four overarching themes: AI Behaviour and Governance, Technology, Design and Development, and Operations (see Figure 10). AI Behaviour and Governance covers AI responsibility, ethics, legal compliance, and bias mitigation (Volkova et al. 2022; Nitzberg and Zysman 2022; Niet, van Est, and Veraart 2021). Technology includes AI applications in IoT, edge computing, blockchain, and sensor networks to enhance security and efficiency (Haseeb et al. 2022; Nemer et al. 2022; Yang et al. 2022; Kolangiappan and Kumar 2022). Design and Development focuses on XAI, sustainable energy system designs, and interpretable machine learning (IML) techniques for energy optimization (Lee et al. 2020; Du, Pablos, and Tywoniuk 2021; D'amore et al. 2022; L. Huang and Ling 2020). Operations addresses AI-driven energy forecasting, market regulation, anomaly detection, and grid stability management (Sun et al. 2022; Luo et al. 2021; Xie, Ueda, and Sugiyama 2021; Ardito et al. 2022).

Our study also revealed significant gaps in AI governance research, where studies often focus on narrow AI aspects such as fairness and transparency while neglecting broader governance issues such as accountability, cybersecurity, and compliance with energy market regulations. A key challenge in AI-driven energy management is ensuring interpretability in decision-making, particularly for energy demand forecasting, grid stability assessments, and renewable energy availability predictions (Gao and Yu 2021). The complexity of AI models in smart energy systems makes it difficult for stakeholders to understand how decisions are made, assess reliability, and ensure regulatory compliance.

To address these challenges, explainability techniques such as SHAP and LIME have been introduced to improve transparency in energy forecasting models (Pinson, Han, and Kazempour 2021; Tsoka et al. 2022). However, these methods are applied inconsistently, limiting their effectiveness across different energy applications. Furthermore, research on integrating cybersecurity and AI trustworthiness in energy systems remains underdeveloped, increasing the risk of adversarial attacks, data poisoning, and algorithmic manipulation (Bhattacharjee, Islam, and Abedzadeh 2022). Feature importance analysis and visualization techniques have been explored to enhance AI transparency (Pinson, Han, and Kazempour 2021; Tsoka et al. 2022; Ardito et al. 2022), but explainability remains a major barrier to regulatory compliance and stakeholder trust.

Key governance challenges include bias mitigation in AI decision-making, cybersecurity risks in AI-powered energy grids, and the absence of clear legal standards for AI accountability in energy markets (Bhattacharjee, Islam, and Abedzadeh 2022; Bhattacharjee, Madhavarapu, and Das 2021; Niet, van Est, and Veraart 2021). Bias in energy forecasting models is often due to skewed training datasets, necessitating fairness-aware AI techniques to ensure equitable energy distribution (Liao et al. 2016; Spinelli et al. 2022). AI security risks, such as adversarial attacks and manipulation of energy trading algorithms (Figueroa, Wang, and Giakos 2022; Samy et al. 2021), require the development of robust cybersecurity frameworks. Regulatory gaps must be addressed by establishing policy-driven AI governance to enforce algorithmic accountability and compliance with industry standards.

These findings have significant implications for AI adoption in smart cities as they transition to sustainable energy ecosystems. Ensuring AI transparency, cybersecurity resilience, and regulatory compliance is critical for the long-term success of AI-powered energy systems.

Conclusion and outlook

AI, big data, HPC, and edge computing are transforming smart cities, enabling climate resilience, energy sustainability, and real-time decision-making. This paper explored how these technologies enhance renewable energy forecasting, urban climate adaptation, and AI governance, emphasizing the importance of scalable, adaptive, and explainable AI models. The presented case studies demonstrated AI-driven approaches for solar and wind energy forecasting and governance, showcasing how model selection, attention-based learning, and hybrid deep learning techniques improve prediction accuracy and reliability. These advancements support efficient energy management, grid stability, and climate adaptation in urban settings.

Despite progress, challenges remain in AI explainability, computational efficiency, and ethical governance. The complexity of deep learning models requires improved interpretability to ensure trust in AI-driven decision-making. Additionally, scalability and energy-efficient AI architectures are critical as cities increase reliance on HPC and edge computing. Addressing data privacy, regulatory compliance, and AI fairness is also crucial in developing sustainable, equitable smart cities. Future research should focus on integrating edge AI for decentralized real-time processing, allowing for localized climate adaptation strategies and smart energy management. Advancing hybrid AI architectures for energy forecasting, improving energy-efficient AI deployments in edge environments, and establishing standardized AI governance frameworks will be essential. As urbanization accelerates, advancing AI-driven climate resilience strategies through intelligent, decentralized, and adaptive systems will be key to ensuring sustainable and efficient smart cities.

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Application of satellite informatics in mitigating climatic challenges within the atmosphere

Selected case studies of Asian cities

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Abstract

The climate crisis is considered one of the most pressing global issues today, due to its devastating impacts on the natural environment, urban resilience, and human health in affected cities. Recent extreme weather events in the atmosphere have also brought climate shocks to not only developing cities but also to urban clusters of developed countries. Some local governments and city-dwellers of Asia were found lacking of comprehensive plans to regain resilience after encountering a serious climatic disaster, thus the use of innovative latest technologies has become crucial for identifying variations of selected environmental attributes, assessing potential climatic risks, and predicting the probability of occurrence of extreme weather events via scientific approaches. This article examines how remotely sensed datasets and satellite informatics can be effectively integrated to mitigate climatic challenges at urban scales. Selected case studies in Asia were extracted as illustrations, to shed light to combat with relevant climatic risks, as well as maintaining a sustainable and healthy neighbourhood environment via data analytic means.

Introduction

Climate change, which refers to the long-term and widespread change in average weather patterns, has exacerbated and imposed threats to environmental and human well-being within different means (Abbass et al., 2022), for example, global warming in land and ocean (Venegas et al., 2023), accelerated rate of rising global mean sea level (Horton et al., 2020), the loss of ice sheets at Greenland and West Antarctic (Wunderling et al., 2020), as well as the occurrence of extreme weather events, like heatwaves, flooding, droughts, changing intensities and frequencies of tropical cyclones (Konisky et al., 2016; Kropf et al., 2025). The persistence of high temperature and drought for 79 consecutive days in China during Summer and Autumn 2022 (Chen and Wang, 2022); the heavy rainfall event in South Korea in August 2022 (Park et al., 2024); the record-breaking monsoon rainfall in China and South Korea in 2020 (Liu et al., 2020; Park et al., 2021); and extreme landslide events in Hong Kong due to super typhoons in 2017 and 2018 (CEDD, 2022), have all imposed pervasive impacts on agriculture and vegetation cover, ecosystem and moisture transport (Drumond et al., 2024; Liu et al., 2023). As a result, irretrievable altering of climatic system has led to environmental and public health challenges, for example, environmental degradation and biodiversity loss (Price et al., 2024), enhanced risks of illnesses (e.g., cardiovascular diseases and heatstroke) due to heatwaves and excessive traffic pollutants (Mak and Ng, 2021; Patel et al., 2022). The impacts are more grievous in developing cities and can exacerbate the already existing urban social and health inequities, as well as the urban-rural income gap (Xie et al., 2023), because climate change can directly influence mobility trends (McMichael, 2023). Nevertheless, the actual impact of climate changes will depend on resilience of individual city, the level of engagement from government officials and town planners to individual city-dwellers (Mak and Lam, 2021), community involvement (Daniel and Fernandes, 2024), together with the advancement of digital technology and information management (Dwivedi et al., 2022) in establishing short-term and long-term plans to combat with induced spatial challenges and promoting sustainability. According to the Resilient Cities Index 2023, developed cities like New York and Los Angeles were in top positions in terms of resilience, but there is still room for improvement in the recovery from extreme weather events (Economist Impact, 2023). Wealthy cities and places could also be unprepared for a spectrum of environmental shocks, for example, Hong Kong, as a cosmopolitan city, is still highly vulnerable to flooding and tropical cyclones (Choy et al., 2020). On the other hand, devastating impacts could take place for groups settling in cities without a detailed heat map, like Bangkok, Jakarta, and New Delhi (PreventionWeb, 2023), and Indian cities rank poorly in terms of congestion management within the Index as well. In recent years, some Asian cities have established ground monitoring networks to trace and detect climatic patterns; however, due to observational sparsity and the impossibility of obtaining complete raw datasets, the actual spatial and temporal features and transitions cannot be systematically reviewed (Kennedy, 2013). Further, the amount and quality of observational datasets could vary temporally and spatially (Garcia-Soto et al., 2021), which induces bias, misinterpretations, and uncertainties when these in-situ measurements are adopted for future climatic predictions (Brune et al., 2015). Thus, one attempts to seek an alternative approach that provides consistent measurements of concerned climatic attributes in both space and time so that respective historical and current trends can be acquired for conducting risk analysis. Given the need, climate data records (CDRs) have become indispensable for monitoring change detection, retrieving historical variations, and predicting environmental changes in local, continental, and global contexts (Yang et al., 2016). To develop informative CDPs, sensors installed onboard both polar-orbiting and geostationary satellites have become essential because they can provide trustworthy informatics of land, oceans, atmosphere, and ice sheets in continuous manners (NCEI, NOAA). This article explores how the advancement of data analytics, remote sensing technologies, and satellite informatics can effectively monitor part of our climate system and then focus on their applications in selected case studies of Asia. With these inspirations, one can gain insights into establishing a robust, sustainable, and healthy neighbourhood environment, mitigating negative impacts due to sudden climatic variations, and at the same time developing strategies to cope with associated environmental challenges in the future.

Brief review of selected climatic risks in Asia

According to the report from the World Meteorological Organization (WMO), the mean temperature of Asia in 2023 reached its second highest in history (WMO, 2024), and was 0.84 °C–0.96 °C above the corresponding average level from 1991-2020 and 1.81 °C-1.92 °C above that from 1961-1990 (IPCC, 2021). Doubled warming trend took place in Asia and was particularly serious from western Siberia to central Asia (Li et al., 2021) and from eastern China to Japan (Zhang et al., 2021). Figure 1 shows the mean surface air temperature trends of all 6 WMO regions and the corresponding mean in land and ocean over 4 specific time periods. On top, it was also reported that climatic, weather, and water-related hazards were most frequent in Asia in 2023. Out of 163 natural disasters attained, 17, 17, 15, and 15 of them occurred in China, India, Indonesia, and the Philippines, respectively (CRED, 2024), which included heatwaves, drought, storm, flooding, and wildfires. The Emergency Events Database also recorded that over 80% of these natural disasters were related to flood and storm events, which altered the prevailing natural system and ecosystems (Walz et al., 2021). The effect was further amplified by phenomena like the rise of sea level (Hens et al., 2018), projected rising atmospheric CO_2 level in Asia (Labzovskii et al., 2019), and the decreased cumulative mass balance of glaciers in the High Mountain Asia region (WMO, 2024).

Recently, the El Niño–Southern Oscillation (ENSO) event had also led to unusual wet and warm winters in the

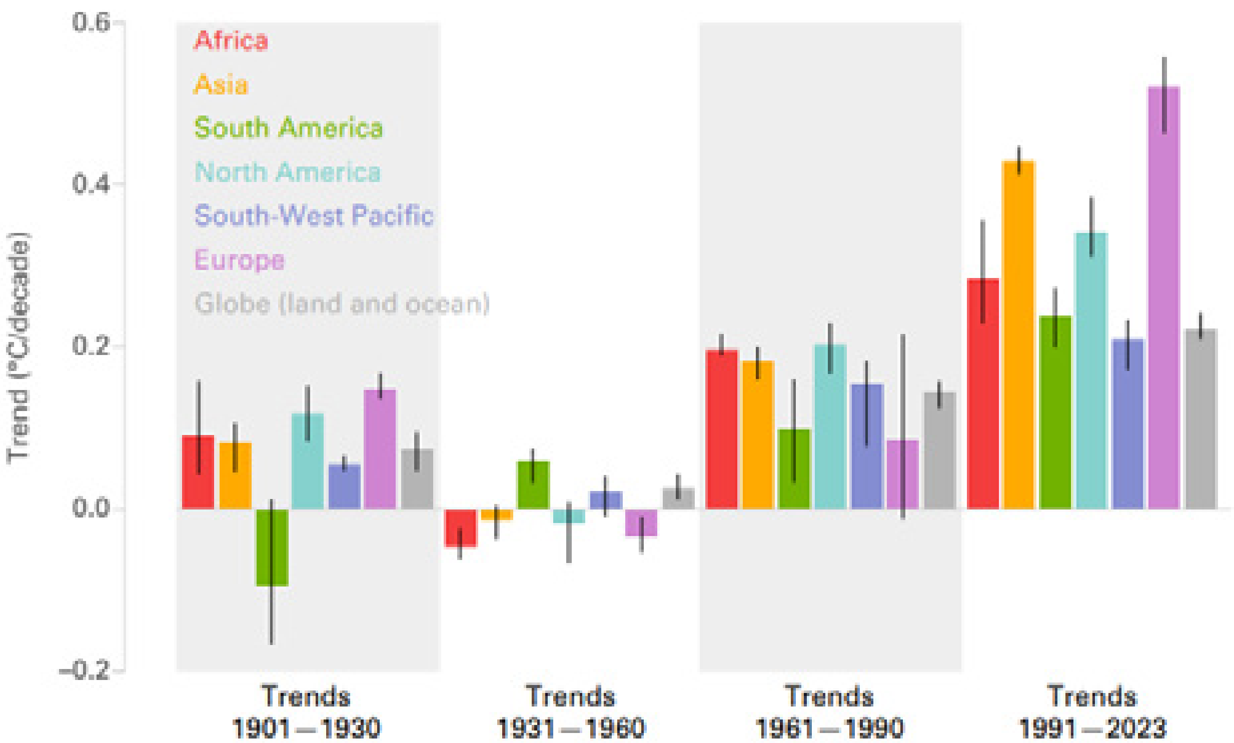

Figure 1: Mean surface air temperature of all 6 WMO regions (Africa, Asia, South America, North America, South-West Pacific, Europe), and the corresponding mean temperature trend in globe (land and ocean) over 4 periods (1901-1930, 1931-1960, 1961-1990, 1991-2023) - Figure 4 of WMO's 2024 report: https://www.uncclearn.org/wp-content/uploads/library/1350_State-of-the-Climate-in-Asia-2023.pdf

Republic of Korea and eastern China, summer monsoon in Asia, hot and dry summer in southern Asia during summer-autumn 2023, the highest monthly averaged temperature and deficit of rainfall in India (WMO, 2024), as well as huge spatiotemporal variability of rainfall content and precipitation in various Asian countries (An et al., 2023). As a result, massive flooding and fatalities occurred in selected countries or cities, namely South Korea (summer 2023), Hong Kong (Sep 2023), central provinces of Vietnam (Oct 2023), Madinah of Saudi Arabia (Nov 2023), and Dubai (Nov 2023). The climatic phenomenon Mei-yu was also observed in East Asia, and the persistent rain belt posed huge challenges to water management and urban planning (Takahashi and Fujinami, 2021; Sun et al., 2023), at the same time leading to the widespread of waterborne diseases and increased risk of vector-borne illnesses (Acosta-España et al., 2024). In particular, a fog event off the coast of the Hangzhou Bay occurred in 2013 (Wang et al., 2018), increased rainfall and severe flooding were found in Hangzhou and Jakarta (Climate, 2025), extreme rainfall events and enhanced rainfall during afternoons at Kuala Lumpur (Miniandi et al., 2024), and elevated mortality risks for respiratory diseases in 30 cities across mainland China, Taiwan, South Korea and Japan due to exposure to heavy rainfall (He et al., 2024).

On top of the aforementioned unexpected phenomenon, many countries in Asia experienced prolonged heatwaves in 2023, especially from April to July. The highest or second highest land temperature on record was detected in cities of China, India, Japan, Lao People's Democratic Republic, Singapore, Thailand and Vietnam (Lyu et al., 2024; Satyanarayana et al., 2024; Sun et al., 2024; Today's WorldView, 2023; WMO, 2024). In the presence of urban heat island (UHI) effects, around 25 heatwave days were found in Phnom Penh, Cambodia per year (GFDRR, 2025); heatwaves amplified urban warming in Guangzhou, China (Luo et al., 2023); and different synoptic patterns led to contrasting interactions between UHIs and heatwaves in Seoul, South Korea, from 1997-2021 (Park et al., 2023). These heatwaves were not only formed on land but also along the marine, which led to the restructuring of the ecosystem and coral bleaching. Thus, it is of paramount importance to fully utilize the strengths of modern technological frameworks to perform precise climate projections, identify high risk spatial regions, and then develop early warning systems and appropriate public health infrastructures that can minimize potential damages induced by sudden climatic changes. Moreover, communication with relevant government organizations and the engagement of the community in adapting to climate change phenomena are equally crucial for strengthening a country's resilience in the long run.

Roles of satellite informatics and remote sensing in assessing climatic conditions of Asian cities

Due to sparsity of in-situ monitoring network, numerical uncertainties in filling data gaps, the complicated spatial correlations of different meteorological attributes for determining overall climatic condition, technical shortcoming of handling datasets of different formats and resolutions, as well as surrounding environmental constraints that possibly diminish data quality, it is almost impossible to perfectly describe spatiotemporal variations of climatic conditions within Asia and the Pacific. Global climate models (GCMs) established as many realistic and high-resolution climate scenarios as possible, so that associated risks of climate change can be anticipated (Wang et al., 2014; Wang et al., 2022), however the reliability of these projected figures depends on model inputs and settings, for example, greenhouse gas emissions, physical parametrization schemes adopted, and the resolution chosen for performing simulations (Wang et al., 2022). With the advancement of technologies, scientists have developed high-resolution regional climate models, statistical downscaling approaches, and even artificial intelligence techniques to retrieve, quantify and predict climatic attributes, then connect the useful informatics with disease prevention and city management (Camps-Valls et al., 2025; Esfandeh et al., 2024; Li et al., 2019). Despite concerted efforts spent, downscaling approaches require intermediate projection and location-specific error of up to 9.8% (Miller et al., 2025), while it is not easy to understand the physical significance of specific climatic attributes when artificial intelligence is applied (O'Loughlin et al., 2025).

In view of aforementioned deficiencies and to provide continuous measurements against time, satellite products have become useful for regional applications, because satellites can measure different aspects of weather conditions on Earth, provide multi-decade datasets for monitoring and assessing climatic variations at sufficiently high spatiotemporal resolutions (ESA, 2021), and possibly fill up spatial subgrids with missing attributes. Satellite imagery and missions can also govern the change in different portions of our nature, including the atmosphere, land, ocean, and ice, which are hugely influenced by climate change. Table 1 shows some selected environmental risks or undesirable natural events due to climate change, as well as highlighted satellite retrieval mechanisms and/or missions that were implemented for monitoring and forecasting within Asia. Overall, after a series of data pre-processing and radiometric calibration stages, raw datasets obtained from sensors installed onboard or from remotely sensed instruments are ingested into climate models. Afterward, Geographic Information System (GIS) provides a standardized interpretation of the Earth's surface (Yang et al., 2024), while the integration of machine learning and data analytic approaches allow more accurate digital assessments within a prescribed timeframe, especially for attributes of land and ocean. Such approach facilitates climate risk assessments and encourages humanitarian efforts in tackling climate change problems (Yang et al., 2024), and the detected footprints could verify changes impacted by natural disasters arisen from climate change (Wu et al., 2021), which are tremendously useful for spatial risk management and laying down urban planning strategies from national perspective.

Table 1: Selected environmental risks associated with climate change and respective satellite products/missions used for conducting spatiotemporal assessments in Asia

Environmental Risk	Highlighted Satellite Products / Missions at City / Country level
Increased Greenhouse gases (e.g., CO_2 and CH_4)	Greenhouse gases Observing SATellite (GOSAT) and the TROPOspheric Monitoring Instrument (TROPOMI) aboard Sentinel-5: XCH_4 concentration in the Asian monsoon region (North China Plain, southern China, South Asia, and Southeast Asia) (Song et al., 2023) China National Space Administration's TanSat mission provides continuously measured datasets of greenhouse gas concentrations *(Source: https://earth.esa.int/eogateway/missions/tansat)* Greenhouse gases Observing SATellite (IBUKI) in Japan, covering Zhangjiakou, Anshan, Harbin, and Tianjin (China), Kolkata (India), eastern Uzbekistan, etc. *(Source: https://www.nies.go.jp/whatsnew/2014/20141210/20141210-e.html)*
Changing meteorological conditions (e.g., precipitation, ground temperature)	MODIS (moderate resolution imaging spectroradiometer) for estimating land surface temperature (LST) over South Asia (Shawky et al., 2023) FengYun geostationary meteorological satellites (Du et al., 2024) – focus on Chinese cities TRMM 3B42, the IMERG Final Run, the PERSIANN-CDR, and the PERSIANN-CCS-CDR (Huang et al., 2022) – focus on Luzon and adjacent seas South Korean Geo-KOMPSAT-2A (GK-2A) across Northeast Asia (Yin et al., 2022)
Air Pollution (e.g., increased $PM_{2.5}$, NO_2 and O_3 concentrations)	BEHR-HK OMI-based NO_2 products for more accurate and promising tropospheric NO_2 columns in southern China (Mak et al., 2018) Geostationary Environment Monitoring Spectrometer (GEMS) for estimating and retrieving columns of atmospheric pollutants (e.g., O_3, NO_2, SO_2, HCHO, CHOCHO, aerosols, etc.) in Korea (Kim et al., 2020) Ozone Monitoring Instrument (OMI) daily VCD of NO_2, SO_2, and O_3, and MOPITT for AOD product in Guangdong Province (Li et al., 2024)
High-altitude cirrus clouds	Ground-based Aerosol Robotic Network (AERONET) sun photometer data for baseline AOD product in Singapore (Chew et al., 2024) CloudSat 2B-CLDCLASS-LIDAR in East Asian countries (Li et al., 2018)
Variation of ozone layer and ozone depletion	Variations of Antarctic total column ozone (TCO) in East Asia (Zhu and Wu, 2024) SBUV merged ozone datasets (MOD) from SBUV/SBUV-2 satellite in East Asia (Shin et al., 2021) Suomi NPP OMPS, Aura MLS, and Sentinel-5P TROPOMI are useful for acquiring vertical profiles of ozone in Asia (Malina et al., 2024)
Increased drought	Geostationary operational environmental satellite (GOES) - produce Evaporative stress index (ESI) of East Asia based on LST and leaf area index (LAI) - focus on South Korea (Yoon et al., 2020) GIMMS NDVI3g bimonthly dataset and NASA's MERRA dataset in the East Asian region (including Mongolia, China, Korea, and Japan) (Ali et al., 2023)
Warming and rising ocean (e.g., increase of sea level)	Gridded sea-level anomalies (SLA) produced by the Copernicus Climate Change Service and coastal along-track SLA produced by the Climate Change Initiative Coastal Sea Level Team, adopted in Southeast Asia (e.g., Manila, Bangkok, Indonesia, etc.) (Peng et al., 2024) TOPEX, Jason-1, Jason-2, Jason-3, ERS-1, ERS-2, Envisat, CryoSat-2, SARAL, and Sentinel-3A - satellite altimetry missions in the Southeast Asian region (Affandi et al., 2025)

Declining crop yields due to diminished water and grasslands for grazing	CHARMS - NDVI anomaly maps and development in Chinese cities & CropWatch - NDVI anomaly and VCIx over the last five years, NDVI development and clustering (Wu et al., 2015) Four multispectral RapidEye datasets and one Landsat5 TM image, conducted in Fergana Valley, Uzbekistan (Conrad et al., 2013)
Change in ice cover within Asia domain	ERA5-Land reanalysed dataset for categorizing Frost Days (FD) and Frost-Free Periods (FFP) in China (Li et al., 2022) Landsat-7 panchromatic images and Sentinel-2 panchromatic images for assessing changes in glacier velocity and flow patterns in the Himalayas, Asia (Zhou et al., 2021)
Change in sea-surface temperature and salinity – influence ocean circulation patterns	Ocean Color and Temperature Scanner (COCTS) onboard the China HY-1C satellite – measured sea-surface temperature in Southeast Asia seas (Sun et al., 2023) Optimal Interpolation SST (OISST) version 2 based on measurements by the Advanced Very High-Resolution Radiometer (AVHRR), CMEMS based on observation of multi-mission satellite altimeters – quantified sea-surface temperature and salinity of the Oyashio Region, Japan (Miyama et al., 2021)
Fluctuations in the carbon-rich biomass, soil, and variations of Land Cover	Landsat datasets together with the selection of remote-sensing classifiers for detecting land-use land-cover (LULC) changes in Pakistan (Ul Din and Mak, 2021) Advanced Microwave Scanning Radiometer 2 (AMSR2), The Soil Moisture Active Passive (SMAP) satellite, The Soil Moisture and Ocean Salinity (SMOS) satellite, The European Space Agency (ESA)'s Climate Change Initiative (CCI) for soil moisture dataset in northern China (Liu et al., 2022)
Occurrence of wildfires	Copernicus Sentinel-2, Sentinel-3, and Sentinel-5P missions provide a wealth of information for monitoring blazes Landsat (30 m resolution), VIIRS (S-NPP, NOAA-20 & NOAA-21) (375 m resolution), MODIS (Aqua & Terra) (1 km) in FIRMS (Fire Information for Resource Management System) provide dynamic imageries for acquiring the spatial location of wildfire via graphical display *(Source: https://firms.modaps.eosdis.nasa.gov/map/#d:24hrs;@0.0,0.0,3.0z)*
Massive flooding and landslides	Gaofen (GF) series and Zhuhai-1 hyperspectral satellite datasets for flood monitoring in Chinese cities situated at the Yangtze River Delta Plain, as well as Dabie Mountain, Xuefeng Mountain, and Luoxiao Mountain (Zhang and Xia, 2022) A high-resolution (1 m) diverse mountainous landslide remote sensing dataset (DMLD), including 990 landslide instances across different terrain in Yunnan, China (Chen et al., 2024)

Selected case studies from Asia contexts

The following are two case studies in Asia that illustrate how satellite informatics and remotely sensed datasets can be synergized to identify, analyze and mitigate environmental challenges ahead, thus provide insights for future scientists and policymakers to fully utilize the strengths of remote sensing in environmental monitoring, climate assessments and implementing relevant policies and governance within city-level.

Assessing flood risks in Jakarta

According to "Environmental Risk Outlook 2021", Jakarta is one of the world's most vulnerable cities when facing environmental hazards caused by climate change (Verisk Maplecroft, 2021), however it still suffers from "riverine floods" and "coastal floods", where the former one is normally influenced by rainfall, while the later one is due to the rise of sea-level, tides and storms. Yang et al. (2024) attempted to assess hazards induced within city-level, where the level of riverine floods is determined via a modelling approach, and coastal floods are analyzed via a digital elevation model. The overall

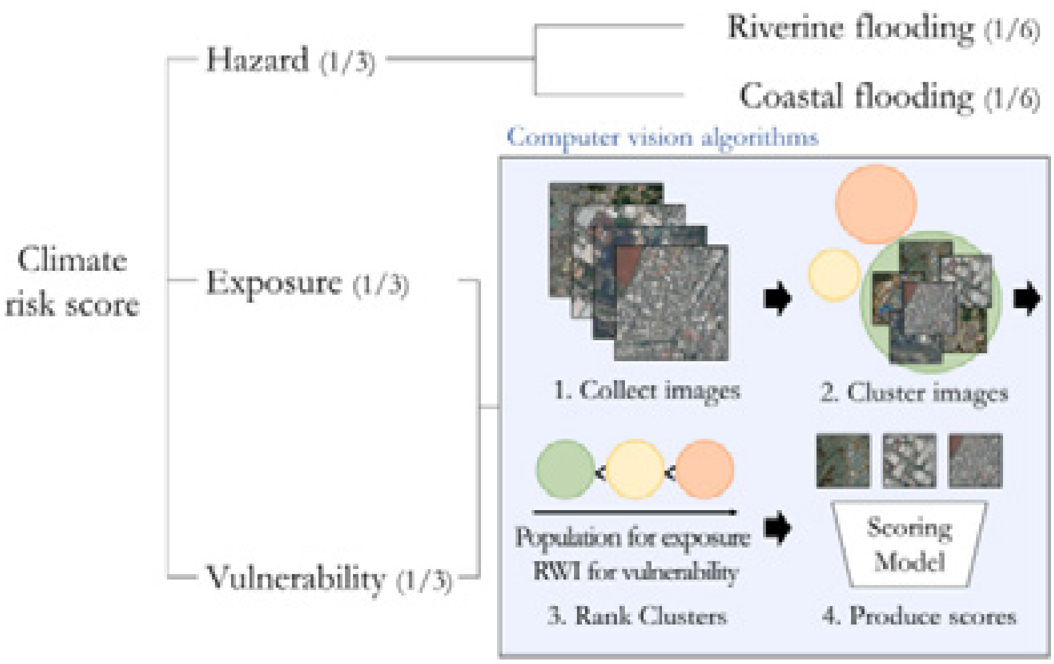

Figure 2: Three components of climate risk assessment in Jakarta, Indonesia, as well as the measurements and procedures needed. The figure extracted from Yang et al. (2024).

climate risk score consists of three equal-weighted components, namely hazard, exposure, and vulnerability, and is defined as in Figure 2.

Satellite images from The World Imagery dataset were first downloaded from the ESRI ArcGIS REST API website (https://tiledbasemaps.arcgis.com/arcgis/rest/services/World_Imagery/MapServer). The images acquired from three visible bands cover the entire Jakarta (excluding small inland areas), with exposure and vulnerability scores assigned at each prescribed sub-grid. Rescaling of available geospatial datasets is conducted for the assignment of hazard score, and the climate risk score of each grid was then calculated and aggregated into the 262 districts of Jakarta.

When determining hazard scores, the riverine flood hazard score at each sub-grid is estimated by the SOBEK model (Deltares, 2024), which integrates a set of hydrological and hydraulic indicators to perform simulations, while the coastal flood hazard score was based on a global digital elevation model of 30 m spatial resolution. Available satellite images were grouped into 20 clusters based on the supervised Deep Cluster Algorithm (Caron et al., 2018), followed by the combination of a machine learning model that considers interpolated and extrapolated population density and Relative Wealth Index (RWI) parameters, so that respective exposure and vulnerability scores of each grid were computed at cluster level, with learning process conducted at the same time. Spatial results and scoring obtained were intercompared against two regression models and validated by building and road footprints obtained from OpenStreetMap, together with municipal statistics. As a result, the occurrence of compound floods, human exposure patterns, and vulnerability of each individual district within Jakarta can be identified so that its sensitivity to climate change can be revealed, and rainfall trends can be more effectively predicted in the future.

Retrieval of Land Surface Temperature (LST) over the Tibetan Plateau

LST is crucial in monitoring climate variability (Oduro et al., 2025) and estimating urban heat island phenomenon (Mohamed et al., 2017). The Tibetan Plateau (TP), situated mainly in southwestern China, spans through central and eastern Asia, experiences significant environmental changes due to rapid surface warming, and exerts strong thermal forcing over the Asian monsoon region (Yang et al., 2014). Due to the coarse spatial resolution of land surface models in China and the heterogenous nature of its surface types, uncertainty of LST in TP often arises (Jiang et al., 2020). Due to the complicated surface properties and hydrometeorological conditions of TP, obtaining synchronized atmospheric profiles in TP has become challenging. Most satellite retrieval algorithms have assumed clear-sky conditions (Wan and Dozier, 1996) and possessed prescribed sensor characteristics and geographical contexts (Becker and Li, 1995), but these assumptions are usually not applicable for TP. Novel LST retrieval algorithms were proposed in recent years, for example, predicting LST via a deep learning and knowledge-driven model (Wang et al., 2021) and Random Forest approach (Wang et al., 2022). Although these algorithms have effectively accounted for atmospheric effects and changes over time, they have not considered the spatiotemporal relationship in between all input environmental variables, and require vast amount of training data for distinguishing the complicated spa-

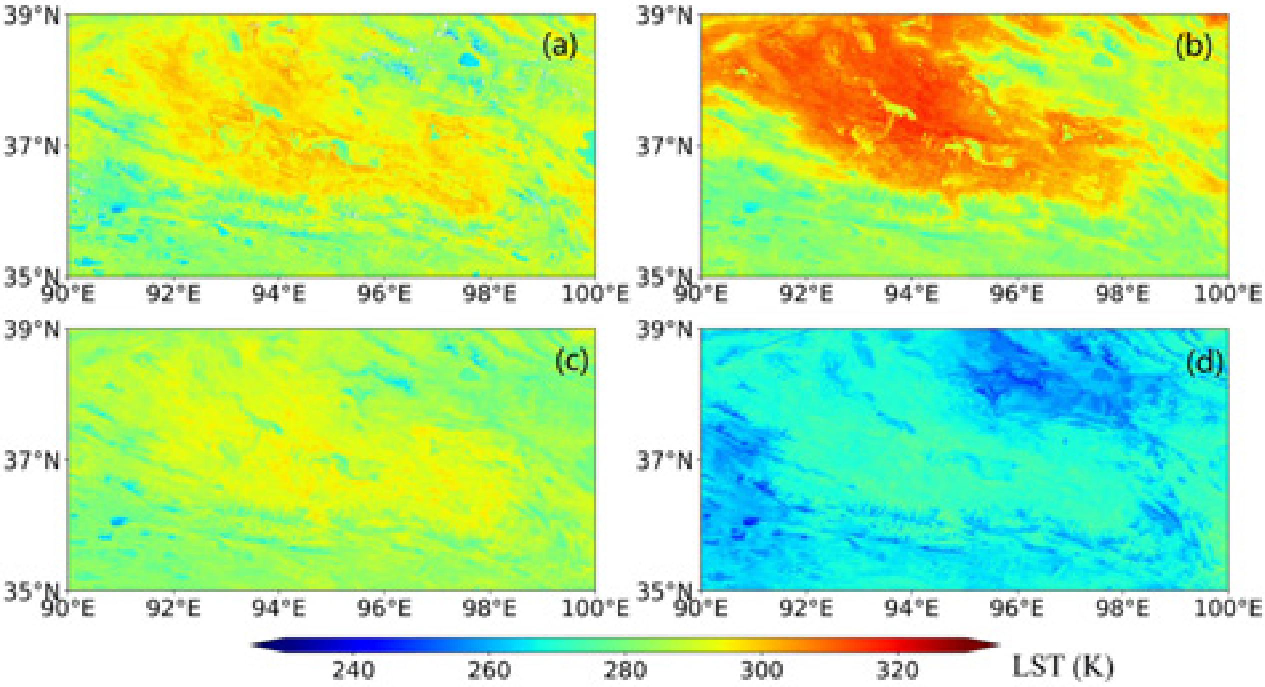

Figure 3: Spatial distribution of averaged seasonal daytime LST ((a) Spring 2020; (b) Summer 2020; (c) Autumn 2020; (d) Winter 2020) from SLSTR satellite datasets in Qaidam Basin. Figure extracted from Qi et al. (2023).

tial and temporal LST patterns. Thus, these deficiencies have laid down the importance of combining satellite sensor outputs with an optimized machine learning model for TP or other developing cities in Asia.

Qi et al. (2023) adopted remotely sensed datasets acquired from sea and land surface temperature radiometer (SLSTR) installed on Sentinel-3, which provide radiometric measurements, fractional vegetation cover, land cover type, total column water vapor, SZA and quality control flags, together with high resolution Landsat images for LST retrieval. MODIS/Terra LST products (MOD11A1) and MODIS Level 1B Calibrated Radiances serve as datasets for validating and calibrating aforementioned datasets before introducing inputs into the machine learning based model for training (Li et al., 2021). The near-surface air temperature, specific humidity and air pressure from CLDAS V2.0 were used to calculate the atmospheric total column water vapor (TCWV) in TP (Shi et al., 2011). All these datasets together with specific coefficients and Land Surface Emissivity (LSE) retrieved from SLSTR, were fit into the well-established single-channel (SC) and split-window (SW) algorithms for estimating the spatial distribution of LST in TP.

Within the case study, 4190 samples (with 2933 training samples and 1257 validation samples), together with relevant meteorological attributes from satellites were fit into the traditional Linear Regression model, Decision Tree model, Random Forest model and Back Propagation Neural Network for retrieving and predicting LST across different regions of TP. Upon validating against the derived in-situ LSTs from the 6 stations in TP, it was found that Random Forest model best describes the spatiotemporal distribution of LST in the prescribed spatial context, and the retrieval uncertainties are mainly attributed to the attenuation of water vapor content and land surface emissivity. It was also found that hot and humid atmospheric conditions could lead to significant errors when estimating LST (Jimenez-Munoz and Sobrino, 2010), which has to be dealt with when designing geostationary satellites for atmospheric retrieval. Figure 3 shows the spatial distribution of the SLSTR-based daytime LST in four seasons of 2020 over the Qaidam Basin, where significant discrepancies of LST and temporal variations could be observed.

Insights in technological advancement, city development and conclusion

The amplification of frequency and intensity of global climatic risks and disasters during the past decades has caused undesirable impacts to city development, economic and political instability, as well as diminishing overall health qualities of individuals and liveability of Asian cities, as a result hinder the future smart city development (Chi and Mak, 2021). Strengthening the environmental dimension of early warning has become one of the key focuses of the UN Environment Programme, Agenda 2030, thus the existing approaches, strategies and measures of conducting climatic assessments should be continuously reflected, so that the city's environmental conditions can be kept under review in timely basis. Meanwhile, modelling approaches should be adopted into tackling environmental problems of selected thematic areas (United Nations, 2012; United Nations, 2019), which range from climate change, nature and environmental pollution, so that new strategic repositioning can be effectively implemented.

Regional meetings of UN have also reached consensus to advance four key multi-hazard early warning systems pillars, namely risk knowledge and management, observations and forecasting, dissemination and communication, preparedness and response (WMO, 2024). The preparatory efforts in facing environmental challenges, the ways of regaining resilience after natural disasters, and the plans of incorporating innovative technologies and data analytics into understanding causes and possible consequences of natural disasters are currently the most important tasks for all Asian countries. In particular, a city government should first promote scientific advancement in relevant disciplines, like healthcare technologies, air pollution monitoring and the way of delivering information to public; create a harmonious, sustainable and low-carbon economy within the society; as well as associate technological breakthrough with practical environmental needs of individual city. With the advancement of algorithms and satellite informatics, humans possess the potential to monitor and project the spatial and temporal transitions of highlighted environmental quantities in nature, for example, ground pollutant concentrations (Mak, 2019), greenhouse gas concentrations (Imasu et al., 2023), and ice motion in Antarctica (Dirscherl et al., 2020), so that potential climatic risks in specific region can be effectively identified. These information should then be associated with health-risk and liveability assessments, and can act as advice and suggestions for policymakers and decision-makers to implement practical actions that combat with climate crises, thus steering city development forward in gradual but continuous manners.

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Introducing environmentally friendly soap-based firefighting agent for extinguishing forest and peatland fire in Central Kalimantan, Indonesia

Technology Acceptance Model

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Abstract

Central Kalimantan experienced the highest rates of burning and the most repeated fire incidents. Water is the most common means of extinguishing forest fires in Indonesia. However, it is less efficient at wetting and penetrating hydrophobic surfaces during the extinction of peatland fires. Firefighting agents with high penetration capabilities are added to improve the performance in fire extinguishing forest fire. Introducing an environmentally friendly soap-based firefighting agent (SFA) for extinguishing forest fire require a socio-technological transition process. This paper aims provides comprehensive information on the process of introducing technology, quantifying multiple benefits and interview survey to evaluate the perceived acceptance of technology of firefighting agents. There is no gap of expectation on what the potential user can get and cannot get from the technology. We also confirm the technology acceptance model of SFA in Central Kalimantan. Technology-inclusive system transitions supported by appropriate enabling conditions, including effective multi-level governance and institutional capacity, policy design, and implementation can generate benefits across different sectors at a local and national level.

Introduction

Kalimantan experienced the highest rates of burning and the most repeated fire incidents, indicating a shift from extensive to recurrent fires (UNDRR, 2023). The peat fires severely degraded air quality in the cities of Kalimantan and Sumatra, with air pollution levels rapidly reaching very unhealthy levels due to the increased hotspot counts. The pervasive air pollution from wildfires and peatland fires in 2019 led to school closures, depriving children of learning opportunities and other health issues (Lohberger, 2018). The impact of forest fires and haze is particularly significant for vulnerable communities, especially those with chronic risk factors. The fire directly impacts and destroys biomass, organic matter, plant composition, and diversity. The fires in 2015 alone resulted in the loss of over 760,000 hectares of Indonesian forests (UNDRR, 2023). The largest recent fire in Indonesia, in 2015, burned approximately 4.6 Mha, releasing 0.89 Gt of carbon dioxide equivalent (Subekti et al., 2016) and causing economic losses for US$28 billion (Kiely, et al, 2021).

The Indonesian government continues its efforts to limit forest and peatland fire, and Indonesia's regulatory interventions have been more effective in reducing forest fire incidents. These regulations generally fall into four main categories: fire management, forest exploitation and management, disaster management, and decentralization. The government also supports multilevel operations, facilitates fire care community groups, provides technical training, and conducts public awareness campaigns on forest fires and prevention (UNDRR, 2023). Water is the most common means of extinguishing large-scale forest and peatland fires in Indonesia. However, it is less efficient at wetting and penetrating hydrophobic surfaces during the extinction of peat fires (Rakowska et al., 2017). Firefighting agents with high penetration capabilities are added to improve the performance in fire extinguishing peat fire (Kanyama, 2025). Adding surfactants to water enhances the extinguishing performance by lowering the water's surface tension and significantly increasing its ability to penetrate burning materials (Mizuki et al., 2007; Santoso et al., 2021). The existing studies reported that the application of an environmentally friendly firefighting agent is effective in reducing the amount of time and water required to extinguish the fire compared to the use of water alone (Subekti et al., 2017; Kanyama et al., 2025) and cost saving (Samejima, 2025). Society and technology intertwine and coevolve, culture and social structures shape the design and use of technology, and technology, in turn,influences cultural and social experience (Cerezo & Verdadero, 2003). Although the use of chemical based synthetic foam was more effective during the extinguished forest and peatland fire in 2015 (VOA, 2015); 2019 (Katadata, 2019); and 2023 (Ditjen PPI, 2023; Matakalteng, 2023), however, chemical firefighting agent was invasive; toxic and irritate to human skin (Damkar, 2020; Yilmaz-Atay,2022). Certain technologies are accepted (to varying degrees) while many, though not apparent, are rejected. Rejection of technology may be expressed as a phenomenon wherein society, ranging from individual users, community groups, through states (nations), capable of availing the services of a particular technology, deliberately choose to refrain from its use, in full of part. The technology acceptance model explains how society accepts and uses a technology through a process of introducing a new technology and ends up tusing the technology (Davis, 1989). An understanding of the complex relationship between users and technology is important from sociology and technology points of view.

Introducing an environmentally friendly soap-based firefighting agent (SFA) for extinguishing forest and peat fire requires a socio-technological transition process. The process includes knowledge transfer of new technology to improve the perceived evaluation of usefulness and perceived ease-of-use, diffusion of technology, and uptake at the local level in Central Kalimantan (Ozili, 2024). While the role of SFA in firefighting to extinguish forest and peat fire is recognized as an important approach for combatting forest and peatland fire in Indonesia, the enabling conditions for the transfer, diffusion, and uptake of those technologies are not well understood or documented (UNEPCCC, 2023). The information related to those processes is ad hoc, spread across many sources, and not well documented. This paper aims to fulfil the knowledge gap through analysis of the interaction between users and the introduction of environmentally friendly SFA for extinguishing forest fire in Central Kalimantan, Indonesia. It is expected to contribute as a practical tool to inform stakeholders (government, academia, and industry) on improving the transfer, diffusion, and uptake of technologies, which are expected to play a leading role in countries meeting disaster risk reduction on forest and peatland fire. The article will be organized through the following sections: (a) the next section will discuss theliterature review and methodology; (b) following by an empirical analysis and (c) discussion and conclusion.

Literature review and methodology

Introducing an environmentally friendly SFA for extinguishing forest and peat fire is not only about the supply of new technology across international frontiers but also the complex process of sharing knowledge and adapting technology to meet local conditions along with the demand management (Connick, 2015). A sociotechnical system comprises technology, regulation, user practices and markets, cultural meaning and dictum, infrastructure, maintenance network, and supply network. Scholars try to describe interventions that may influence the progress of introducing a new technology into the marketplace and approach the issue on a systemic level (Hekkert et al., 2007; Sagar et al., 2009). It has to be a fit between the incumbent socio-technical system for a new technology to diffuse, or an opening needs to be created or formed (by intervention or a coincidental combination of circumstances) to provide an opportunity for a technology to emerge (Geels, 2005). The transitions begin by altering technologies; competencies, skills, and knowledge; and meanings and common understanding of the use of SFA for extinguishing forest and peatland fire. They can then work through at least three diffusion paths through which they bring about larger changes: (a) Embedding: a process of combining and adapting technologies and integrating them into existing structures, as well as giving these technologies meaning (Wirth et al.,2018); (b) Translation: a horizontal diffusion, where there is replication and reproduction elsewhere (in different communities, organizations or institutional contexts, or across sectors (firefighting division, disaster resilience team, environment and forestry, etc); (c) Scaling: the internal development and growth of niche experiments (Liedtke et al., 2015).

The transitions process emphasizes purposive experimentation as a powerful driver of change because it facilitates a learning process where technologies and new social relations can forge new sustainable socio-technical systems (L. Fuenfschilling, Frantzeskaki, and Coenen,2018). The experiments on utilizing soap-based firefighting foam consist of two sets of activities: (1) small initiatives for the earliest stages of learning take place in local level; and (2) the emergence of networks of key stakeholders with knowledge, capabilities and resources, cooperating in a process of mutual learning (Bai, et al 2010; Berkhout et al., 2010). The experiments are expected to be able to respond the basic questions of operation and the reconciliation of classic business considerations (e.g., cost reductions) and sustainability orientations (maximizing benefit for local environment) at a time of climate disaster emergency (Meelen, 2023). The efficiency, environmental, and economic gains can be enablers for adoption technology. The role of emotions was also identified as an emerging topic in the adoption of new technology. Researchers find a positive effect of “technophilia” on the perceived ease of using new technology (Wolff and Madlener 2019). While these adoption models can help to identify factors that might stimulate or hamper innovation embedding, they also have shortcomings in the context of socio-technical transitions (Geel and Johnson, 2018). To overcome those challenging issues, a related quandary is that complexity necessitates combining evidence-based decision-making with experiential knowledge to ensure a new technology is forward-looking as well as context-appropriate (Friend et al., 2014). The article provides comprehensive information on the process of introducing technology, quantifying multiple benefits, and evaluating perceived acceptance of technology of firefighting agents based on empirical field experiments and verification survey. It was part of the project on the business verification survey of Japanese technologies to extinguish forest and peatland fire using environmentally friendly SFA in Central Kalimantan, Indonesia, from 2023 to 2025, funded by Japan International Cooperation Agency (JICA) in collaboration with the University of Palangkaraya.

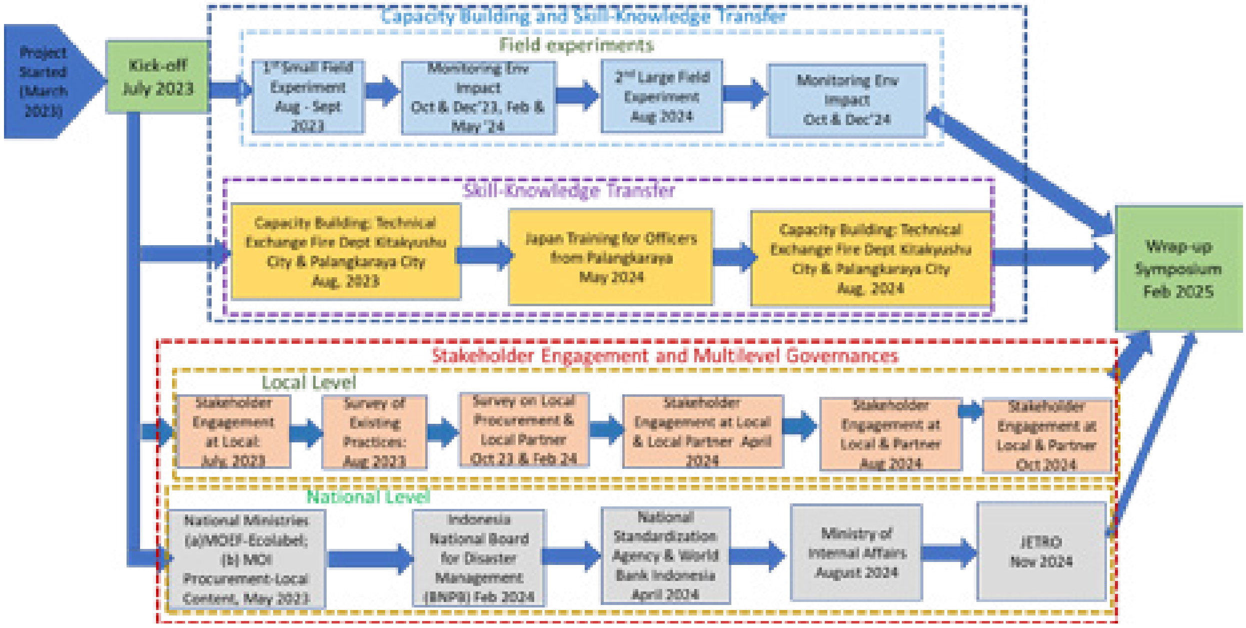

Figure 1: Progress of introducing soap-based firefighting agent in Central Kalimantan

Introducing an environmentally friendly soap-based firefighting agent solution at local level

The project on the business verification survey of Japanese technologies to extinguish forest and peatland fire using environmentally friendly SFA in Central Kalimantan, Indonesia, was begun in 2023 (figure 1). The project duration is two years, funded by the Japan International Cooperation Agency (JICA). There are three main activities under the project as follows: (a) field experiment; (b) skill & knowledge transfer and (c) policy studies; stakeholder engagement and multi-level governance. The field experiment focuses on the verification of SFA's performance and its multiple benefits on environments and economic benefits. Skill and knowledge transfers aim to introduce know-how technology and compliment it with technical training on how to use and maximize the benefits. Skill and knowledge transfer were conducted mostly by main actors of firefighting under the cooperation in between Kitakyushu City fire department and relevant agencies in Palangkaraya and Central Kalimantan such as fire department, disaster and rescue team of central Kalimantan and Palangkaraya city. The policy studies focus on these following aspects: (a) public procurement involving government agencies; (b) incentive of local product of technology in the electronic purchasing system; (c) standardization and labelling of product to enter market. While conducting the policy study, we also conduct stakeholder engagement for information sharing on the technology and market research simultaneously at the local and national level in collaboration with partners and collaborators.

Field experiments for knowledge transfer of know-how technology

The field experiments were carried out within the University of Palangkaraya campus, Central Kalimantan. The experiments on utilizing SFA consist of two sets of activities: (1) initiatives for the earliest stages of learning take place about the technology and attributes; and (2) the emergence of networks of key stakeholders in Palangkaraya city and surrounding cities with knowledge, capabilities and resources, cooperating in a process of mutual learning. The field experiment aims to do these following activities: (a) assess the safety of the soap-based fire-fighting agent against human body and environment using the Globally Harmonized System (GHS), which is used as the national standard by the Government of Japan and the Government of Indonesia; (b) to collect basic data on the performance of soap-based technology compared with the common practice using water only; (c) analyse the impact to the environment by using the indicator of the regeneration of plants on the land after the basic experiment.

The basic experiment was conducted two times (figure 1) with small boxes in the first year and was enlarged to a real forest with the size of 25 x 20 metres to have a more real simulation in the second year. Both experiments were done within the university areas, as shown in figure 2. The first small-scale experiment was conducted from September 15 to 23, 2023. It was done at dried peat soil packed in 1.5m x 1.5m, which was burned for 24 hours. Water or 1% Soap-based firefighting agent (SFA) was sprayed using a backpack-type water tank until the peat surface temperature was below 50°C. Additional firefighting activities were conducted if the peats were reignited. The amount of water and time required for firefighting activities were measured to evaluate the actual performance of the

2a. Small Scale Experiment – Small Boxes

2b. Large-scale demonstration & techno show - August 2024

Figure 2: Small-scale and large-scale demonstrations in Palangkaraya

soap. The large demonstration onsite was conducted at the area of 20m x 25 m. The peat soil was burned for about 30 minutes, and soap was sprayed using pumps and hoses and also using a back-pack type water tank. A large demonstration was conducted on August 2024. The large experiments also aim to provide an opportunity for stakeholders to have an experience of the technology. The experience is important as it may determine technology acceptance and intention to use it (Murthy & Mani, 2013).

Measuring multiple benefits of soap-based firefighting agent (SFA)

Besides experiment to introduce the usefulness and ease-of-use of the technology and, measurement actual performance of soap is important to provide an evidence-based analysis. The team conducts monitoring the multiple benefits of soap on environment and economic aspects.

Monitoring environmental benefits

Introducing environmentally friendly soap-based firefighting agents to extinguish forest fire show high economic feasibility and large potential to reduce greenhouse gas emissions and other environmental benefits (Kitso, 2025). Environmental benefits were monitored through field experiments on the water and SFAS usage at the dried peat boxes, toxicity test, and effects on ferns test.

A. Water conservation (water saving)

Water saving was monitored through an experiment with the dried peat boxes. It was conducted through a comparison analysis of the fire extinguishing using water only as the business as usual (BAU) and soap-based firefighting agent solution (SFAS). The intervention of technology reduced water consumption by 75%, as shown in Figure 3.

B. Effects on vegetation

A toxicity test was conducted at the laboratory, while effect on the fern test was conducted for the actual fern plant. It was complimented with field monitoring of tree component in the ecosystem at both dried peat soil packed and the location of large-scale demonstration in 2024 (figure 4).

Quantifying economic benefits

A. Time saving and human resource saving

In parallel with the water saving, time used was also monitored through an

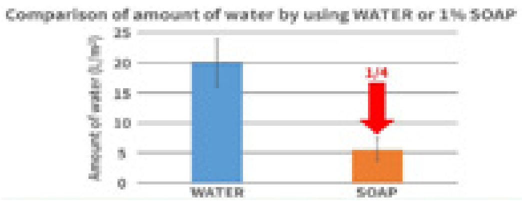

Figure 3: Environmental benefit on water saving (Source: Kanyama, 2025)

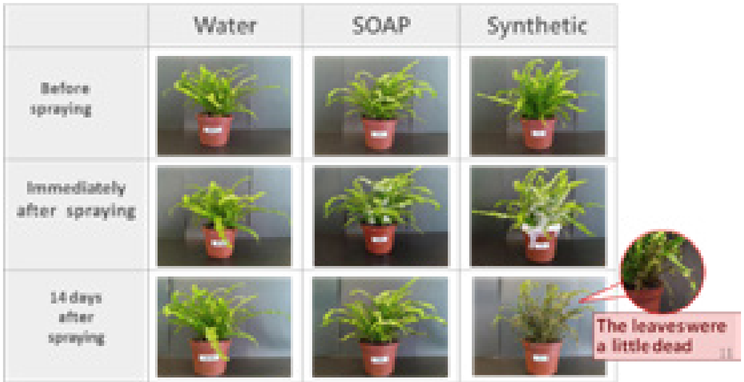

Figure 4: Effects on Fern Test (Source: Kitso, 2025)

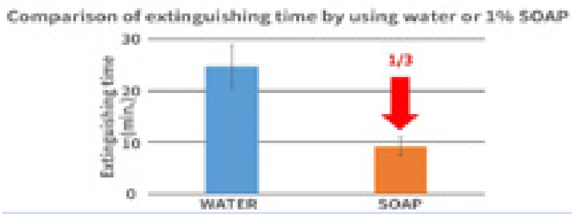

Figure 5: Economic Benefits – Time Saving (Source: Kanyama, 2025)

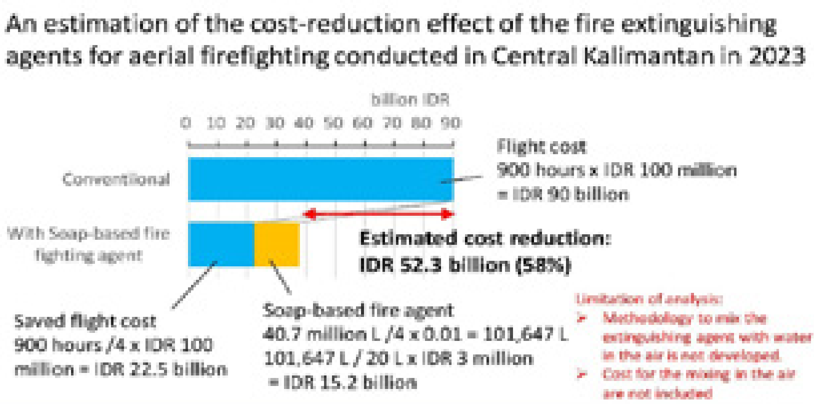

Figure 6: Economic benefits (Source: Samejima, 2025)

experiment with the dried peat boxes. Through a comparison analysis of the fire extinguishing using water only as the business as usual (BAU) and soap-based firefighting agent solution (SFAS), we found the intervention of technology reduces extinguishing time by almost 67%, as shown in figure 5.

B. Cost saving

Due to the availability of robust data, the team conducts a comparison analysis Aerial bombing with water as business as usual versus intervention with additional of innovation technology of a soap-based fire-fighting agent into the water used for aerial bombing. The scenario for using soap are as follows: (a) retail price of soap around 3 million rupiah per gallon; (b) dilution ratio 1%; (c) efficiency of water use 400%. The reference cost for aerial fire-fighting is about 100 million rupiah per hour (Samejima, 2025). It is estimated that the cost saving of about 52.3% or equal to 58% compared to business as usual. The results are shown in figure 6. However, the calculation doesn't include the cost for mixing of water with soap because of the undetermined methodology for mixing the soap and water. The simulation shows the cost-effectiveness of technology intervention. However, it is not a one solution fit for all situations. The interventions show more efficiency and effective for aerial bombing, extinguishing deep peat fires to prevent repeating peatland fires after finishing extinguishing at the surface level. It is important to explore and analysts the best practices for utilizing soap-based fire-fighting agent for extinguishing forest and peat land fire.

Discussion

Perceived evaluation was conducted to evaluate the progress of the interaction between users and the introduction of technology on environmentally friendly SFA for extinguishing forest fire in Central Kalimantan, Indonesia. It was conducted through an interview survey (online) to the stakeholders who joined the large-scale experiments in August 2024. In total, 47 person from respective organisations and NGO participated in large-scale onsite experiment. About 44.7% out of 47 attendants participated in the interview survey. Most of the respondents are working related to the firefighting around 66.7%. They come from government related agency around 71.4%; academia/NGO, around 19% from academia/NGOs, and the remaining 9.5% from private sector/companies.

Technology acceptance model of SFA in Central Kalimantan

The interview survey of multiple responses to the main challenging issues on firefighting to extinguish forest and peat fire. The top mind of the respondents answering about the availability of water (located far away) is on top of the main challenging issues, around 57.1%. The availability of water during firefighting to extinguish forest fires was already identified (Alfaro et al., 2024), and several countermeasures have already been implemented to overcome this issue in Indonesia (Pustandpi, 2024). However, facing the scarcity in dry season and future trends, the introduction of SFA may contribute to a better solution to solve limited water availability on the field. Insufficient equipment (infrastructure) comes as the second concern at around 47.6 %. We didn't further explore the detailed information about this aspect in our survey, however, another study confirms this finding (Pustandpi, 2023). About 42.9% respondent also concerned about the reignite problem of peatland fire, and limited human resources is the lowest, around 33.3%. The limited capacity and human resources are challenging factors in implementing forest management units (FMUs) in Central Kalimantan (Budiningsih, 2022). Time saving of SFA could contribute to overcoming the issue on the number of personnel in each FMU. By reducing time-use by 67% compared to business as usual approach, implementing fire extinguishing using SFA would improve time allocation for human resources efficiently. The implementation of firefighting to extinguish forest and peat fire is a complex and multidimensional issues that require synergy and collaborative efforts among stakeholders, technology intervention could improve the overall performance. Looking at the current performance based on local experiments in Central Kalimantan, it provides evidence on the advantage of SFA for extinguishing forest and peatland fire due to its advantages on small water consumption and shortened time-use compare to the business as usual practice of using water only.

Through the process of introducing the technology, capacity building and training and also dissemination of the product and research activities during the project period had elevated stakeholders' understanding of SFA. The highest response was about "no impact on natural environment," around 52.4%. Having experiences of repeated forest fires and the recovery process are influential on the individual expectation about the environmentally friendly technology. The second consideration is the performance on the ability to have a depth penetration to soil to prevent reignition of peat fire and less water consumption at around 47.6%. The penetration below the surface reduce the chance of reignition after several days, especially peat fire. The impact to the human is 42.9%, it is least priority of respondent. These findings confirm that the respondents understanding and knowledge about SFA is at a high level. There is no gap between the presence of a technology and the expectation from the society. The education during the project activities increases users' knowledge of what they can get and cannot get from the technology (Ozili, 2024).

Those above individual perceptions of the technology and perceived evaluation on the SFA's performance influence the acceptance of technology from potential users of SFA in central Kalimantan. It was observed through the high response on the interest and willingness to implement real tests about the performance of SFA at around 66.7% of respondents. The respondents also had the confidence to conduct performance tests by themselves, representing the ease-of-use of the technology. This finding explains how an individual accepts and uses a technology, starting by an introduction of technology and ending with stakeholders acceptance and willingness to use it (Davis, 1989). Through the questionnaire survey, we couldn't find the partial rejection or expression of "not interested in the SFA".

Enabling environment for socio-technological transitions

Moving forward from the perceived evaluation about the multiple benefits of technology and intention to use, respondents were asked to respond on a question related to the dissemination of SFA for diffusion and local uptake by policymakers in Central Kalimantan. The top priority is the price of the product, around 52.4%. Information about retail price is important in order to convince the decision makers. During the interview survey, we didn't provide information about retail price of product and its potential cost-saving compare to aerial bombing (figure 6). From the perspective of respondents, price is sensitive issue. Providing additional information on cost and time saving potentials which led to the quantification of economic benefits may help to provide evidence-based for the decision-making process at local level. The efforts to increase cost performance and reduce retail price will increase the diffusion rate and uptake at local level.

A second important aspect is registration to the national portal for the electric catalogue (e-Katalog) around 38.1%. The e-Katalog is an Indonesian-language online procurement platform managed by the Government of Indonesia (GOI) Goods and Services Procurement Policy Agency (LKPP), which allows public organizations and government institutions to purchase required technology, including soap-based firefighting agents. The government implemented a firefighting agent procurement process based on an electronic catalogue (e-catalogue) through the mechanism of e-purchasing. It was established to increase transparency and prevent corruption in public procurement. Manufacturer or their local agents can set their product prices in the sectoral e-Katalog. Under the new policy, price control to the manufacturer and market-based. Having the product listed in the e-katalog as the main entry point for e-procurement transaction means increasing probability of SFA to be accessed and purchased under the public procurement process. It removes barriers to organizational or institutional policies on the decision-making processes on purchasing SFA by government organizations or agencies (Muhammed et al., 2020). The implementation of this system will affect the uptake of technology at the local level. Combining the effort to produce SFA locally will increase the share of local content, which will increase the rank of technology. The national government already set a clear policy about products over the threshold of local content of technology will be highly recommended for the government procurement. It will increase the diffusion rate and uptake not only in central Kalimantan but across the country.

The third important aspect is additional information such as water saving and time saving, around 33.3 % respondents. During the interview survey, the questionnaire was distributed in parallel to the ongoing process of the onsite experiment in August 2024. Thus, it makes it difficult to provide additional supporting evidence on the performance of SFA and other environmental performance indicators to support an evidence-based policy process. It is consistent with previous indicators on the expectation of stakeholders on the minimum or no impact of SFA on the environment. The other two factors are supporting equipment 28.6% which is associated with the fact about limited capacity and infrastructure at the local level. The labelling national standard of Indonesian products will ensure the quality of product, however, it is least important from the viewpoint of respondents.

Conclusion

Introducing an environmentally friendly soap-based firefighting agent (SFA) for extinguishing forest and peat fire requires a socio-technological transition process at a local level. The process includes knowledge transfer of new technology to improve the perceived evaluation of usefulness and perceived ease-of-use, diffusion of technology, and uptake in Central Kalimantan. Perceived evaluation was conducted to evaluate the interaction between potential users and the introduction of technology on environmentally friendly SFA for extinguishing forest fire in Central Kalimantan, Indonesia. Through the process of introducing the technology, capacity building and training and also dissemination of the product and research activities during the project period has elevated

stakeholder's understanding of SFA. There is no gap of expectation on what they can get and cannot get from the technology. The study also confirms the technology acceptance model of SFA for extinguishing forest and peatland fire in Central Kalimantan.

Socio-technological transitions need an enabling environment for diffusion and uptake at a local level. Although economic benefit is clear and quantitative, however, price scheme is sensitive and cost performance of product should be improved. One option is a localized product, manufacturing the soap within Indonesia. It will increase the local content of the product, which is useful to leverage the rank of technology in E-Katalog. It will increase adoption rate and uptake not only locally but also at a country level and ensure transparency of transaction process involving public procurement process. Finally, it helps to remove the barrier of local government agencies in decision-making process for procurement. Technology-inclusive system transitions supported by appropriate enabling conditions, including effective multi-level governance and institutional capacity, policy design, and implementation could generate benefits across different sectors at a local and national level.

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Tech Events

2025

May 7-8, 2025
Cleantech Forum Asia
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Contact:
Secretariat
Email: forums@cleantech.com.
https://www.cleantech.com/event/cleantech-forum-asia/

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Solar Media Limited, 123 Buckingham Palace Road, London, SW1W 9SR, United Kingdom
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November 8-10, 2025
10th Asia Conference on Environment and Sustainable Development (ACESD 2025)
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Tel: +86-13290000003
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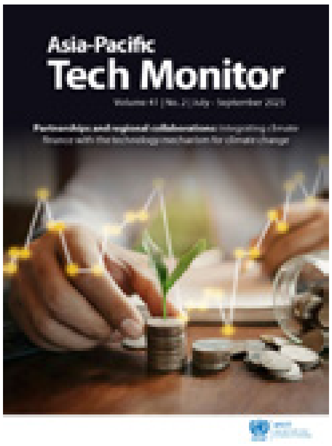
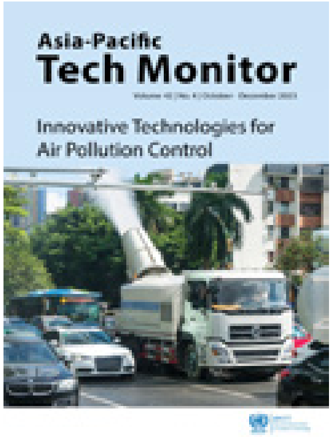


Jul-Sep 2023

Partnerships and regional collaborations:

Integrating climate finance with the technology mechanism for climate change



Oct-Dec 2023

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Jan-Mar 2024

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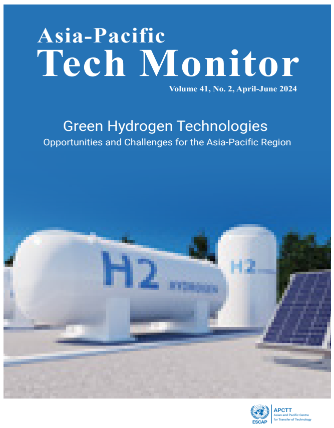
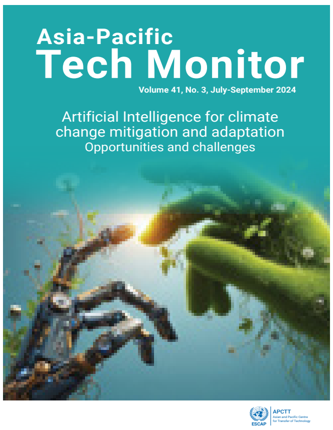


April-June 2024

Green Hydrogen Technologies

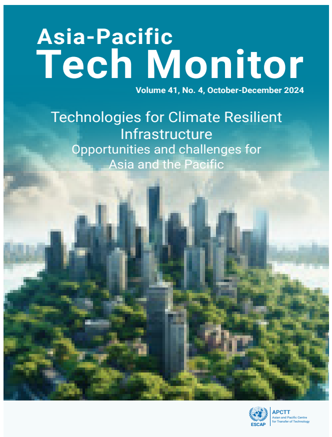
Opportunities and Challenges for the Asia-Pacific Region



July-September 2024

Artificial Intelligence for climate change mitigation and adaptation

Opportunities and challenges



Oct-Dec 2024

Technologies for Climate-Resilient Infrastructure

Opportunities and challenges for Asia and the Pacific

The **Asia-Pacific Tech Monitor** has been the flagship periodical of APCTT since 1993. It is an online quarterly periodical featuring theme-based articles that provide trends in technology transfer and development, innovation and technology policies, market, data and analysis with respect to relevant issues, case studies, good practices and innovative technologies. Each issue of Tech Monitor focuses on a special theme and the articles are written by authors/experts of national and international repute. The periodical aims to enhance the technology intelligence of relevant stakeholders from member States of ESCAP to meet the challenges of today's dynamic business and technological setting.

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