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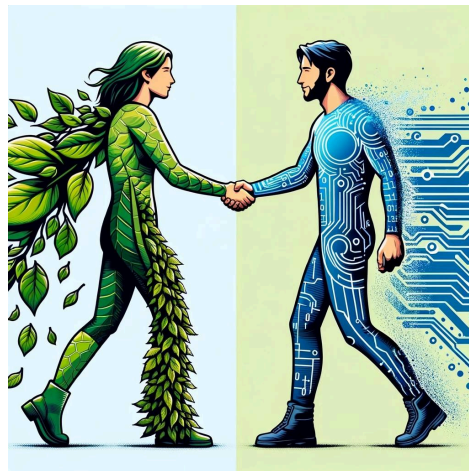
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Digital Technologies for Environmental Sustainability



Recommendations of the Climate Change and Digital Technology Task Force

Raimundo Macêdo, Marcelo Pias, Liwan Liyanage, David Cook, Yuko Murayama,
Otthein Herzog, Gülgün Kayakutlu, and David Kreps.

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Introduction and Overview

Recognizing the immense challenges posed by climate change and aligning with the UN Sustainable Development Goals (SDGs), particularly SDG 13, which focuses on climate action, the International Federation for Information Processing (IFIP) established the Digital Technology and Climate Change Task Force in December 2022. The Task Force aims to identify opportunities to leverage digital technologies effectively in combating climate change

and to provide recommendations for professionals and relevant institutions. Since its inception, the Task Force has met regularly. After conducting a scoping exercise and defining a taxonomy, a comprehensive questionnaire was distributed twice among IFIP stakeholders, namely, technical committees and member societies, to gather insights and understand the diverse perspectives of the IFIP community on this specific matter.

This document presents the Task Force's findings and is structured into two parts. The first part introduces the main concepts and challenges of climate change and digital technologies. It discusses the key challenges and concepts related to climate change, the widely adopted strategies for combating it, and the digital technologies and skills required to enhance the efficiency and effectiveness of these strategies.

The second part of the document focuses on recommendations tailored to various stakeholders, including individuals, computer societies, governments, the information and communication technology (ICT) industry, the research and development sector, and specific industries considered strategic in the fight against climate change: energy, manufacturing, agriculture, and transportation. Additionally, it emphasizes the importance of public awareness and education.

The Final Remarks section summarizes the findings and proposed actions, emphasizing the critical role of digital technologies in mitigating and addressing climate change. This section also presents general recommendations for various stakeholders. The Task Force Composition and Historical Background section introduces the task force members and provides a brief historical overview. Finally, the References section lists sources and additional reading materials.

The illustration on the cover page, created by DALL·E on March 24, 2024, through interactions with Raimundo Macêdo, depicts two people shaking hands—one representing the green transition and the other representing the digital transition.

Chapter I - Climate Change and Digital Technology

The United Nations has recognized climate change as one of the most critical challenges of our time [1]. It is driven primarily by human activities since the Industrial Revolution, such as burning fossil fuels for energy, industrial processes, and transportation. These activities have dramatically increased the concentration of greenhouse gasses in the Earth's atmosphere, intensifying the natural greenhouse effect and warming the planet's climate. According to NASA, Earth's average surface temperature in 2023 was the warmest since 1880 [2]. This has led to severe consequences, including melting glaciers and ice sheets, rising sea levels,

and changes in weather patterns, such as more frequent and intense heat waves, droughts, floods, and storms. The enhanced greenhouse effect is causing a wide range of interconnected and devastating impacts on Earth's climate and ecosystems, with consequences for human society, including threats to food security, water scarcity, increased health risks, and economic disruption.

At the twenty-first session of the Conference of the Parties (COP21) to the United Nations Framework Convention on Climate Change (UNFCCC), held in Paris on December 12, 2015, world leaders reached an agreement to substantially reduce global greenhouse gas emissions. The goal is to limit the temperature increase to well below 2°C above pre-industrial levels, while pursuing efforts to limit it to 1.5°C above pre-industrial levels [3]. In line with this, Sustainable Development Goal 13 (SDG 13), "Climate Action," as part of the 2030 United Nations Agenda for Sustainable Development, calls for urgent action to combat climate change and its impacts.

Unfortunately, as reported in UN Climate Change News on November 14, 2023, national climate action plans are still insufficient to achieve the Paris Agreement's goal of limiting the global temperature to 1.5 degrees Celsius [4]. Despite increased efforts by some countries, the report emphasizes the urgent need for significantly more ambitious action to reduce global emissions, prevent the most severe consequences of climate change, mitigate its impact, and build resilience.

The International Telecommunication Union (ITU), the United Nations specialized agency for information and communication technology (ICT), recognizes that the increasing number of connected devices in our digital lives contributes to rising carbon emissions and e-waste [5]. However, digital technologies can also play a key role in mitigating these challenges by helping reduce carbon footprints. For example, teleconferencing can substitute for travel, significantly cutting emissions associated with transportation. Furthermore, digital services offer critical advantages, such as monitoring extreme weather events and tracking climate change. Digital technologies provide a powerful toolkit for addressing this complex issue, offering solutions that empower individuals, organizations, and governments—ranging from optimizing energy use to raising public awareness [6].

A holistic approach integrating digital transformation and sustainability efforts is required. This comprehensive approach is commonly called a **“twin transition”** strategy. **It involves combining digital and sustainability strategies rather than treating them separately.** Fundamentally, a twin transition is about leveraging the power of digitalization to drive sustainability, recognizing that these two areas are profoundly interconnected and can reinforce each other to achieve a more significant impact [7,8].

1.1 Climate Change Concepts

Understanding climate change and effectively addressing its impacts requires a shared comprehension of critical concepts and terms. This common ground ensures improved communication among the ICT community, policymakers, organisations, and the public.

Climate change refers to long-term shifts in temperature and weather patterns. It is primarily caused by human activities, notably the burning of fossil fuels like coal, oil, and gas. This releases greenhouse gases (GHGs) into the atmosphere, which act like a blanket, trapping heat from the sun within the Earth's atmosphere. While this greenhouse effect is a natural process essential for life, excessive GHGs lead to an enhanced greenhouse effect, causing the planet to warm.

The most significant greenhouse gas resulting from human activities is carbon dioxide (CO₂). Burning fossil fuels, deforestation, and various industrial processes produce this gas. In addition to carbon dioxide, methane (CH₄) plays a significant role. Methane is released from livestock, agricultural practices, and landfills. Another significant greenhouse gas is nitrous oxide (N₂O) from agricultural and industrial activities. Fluorinated gases, used in refrigeration, air conditioning, and specific industrial processes, are also potent greenhouse gases.

The effects of climate change are becoming increasingly evident across the globe. Rising temperatures are causing more frequent and severe heat waves, droughts, and wildfires. Changes in precipitation patterns result in floods in some regions, while others experience prolonged droughts. The melting of ice caps and glaciers leads to rising sea levels, threatening coastal communities and ecosystems. Additionally, the ocean's absorption of excess carbon dioxide is causing ocean acidification, negatively impacting marine life. Extreme weather events are also rising, with storms, hurricanes, and cyclones becoming more frequent and intense.

In the following, we provide concise definitions of essential terms related to climate change. We draw on the Sixth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) [9] and the IPCC glossary to ensure accuracy and clarity.

Impact Management

Managing impact in the context of climate change refers to strategies and actions taken to mitigate or adapt to the effects of climate change on ecosystems, communities, economies, and infrastructure.

Mitigation

Mitigation refers to efforts to reduce or prevent the emission of greenhouse gases. It can involve using new technologies and renewable energies, improving energy efficiency, or

changing management practices or consumer behaviour. Mitigation strategies aim to limit the magnitude and rate of long-term climate change.

Adaptation

Adaptation in human systems is adjusting to actual or expected climate and its effects to moderate harm or take advantage of beneficial opportunities. In natural systems, it involves adapting to the actual climate and its effects, while human intervention helps facilitate adaptation to expected climate impacts.

Resilience

Resilience refers to the ability of interconnected social, economic, and ecological systems to withstand and recover from a hazardous event, trend, or disturbance. This can include responding or reorganizing to allow the systems to maintain their essential function, identity, and structure. Resilience is a positive attribute when it enables adaptation, learning, and transformation.

Carbon Neutrality / Net Zero

Carbon neutrality, or net-zero, is a balance between human-generated carbon dioxide (CO₂) emissions produced and the amount removed from the atmosphere over a specified period. At a global scale, the terms carbon neutrality and net-zero CO₂ emissions are equivalent. At sub-global scales, net-zero CO₂ emissions generally apply to emissions and removals under the reporting entity's direct control or territorial responsibility. At the same time, carbon neutrality includes emissions and removals within and beyond direct control.

Vulnerability

Vulnerability is the propensity or predisposition to be adversely affected by climate change. It includes both the sensitivity or susceptibility to harm and the lack of capacity to cope and adapt. Vulnerability varies among and within communities and ecosystems and can change over time.

Exposure

Exposure refers to the presence of people, livelihoods, species or ecosystems, environmental functions, services, resources, infrastructure, or economic, social, or cultural assets in places and contexts that climate change could adversely affect.

Risk

Risk in the context of climate change refers to the potential for adverse consequences for human or ecological systems. It recognizes the diversity of values and objectives associated with such systems. This includes risks arising from the impacts of climate change itself and risks arising from human responses to climate change.

Adverse consequences can affect lives, livelihoods, health, well-being, economic, social, cultural assets, infrastructure, services (including ecosystem services), ecosystems, and

species. Uncertainty regarding the magnitude and likelihood of hazards, exposure, and vulnerability may change over time and space due to socioeconomic changes and human decision-making. Climate change responses also pose risks, as they may not achieve their intended objectives or have trade-offs or adverse side effects on other societal objectives, such as the Sustainable Development Goals (SDGs). Risks can arise from the uncertainty in the implementation, effectiveness, or outcomes of climate policy, climate-related investments, technology development or adoption, and system transitions.

Ecosystem Services

Ecosystem services refer to the benefits that humans derive from ecosystems. These include provisioning services such as food and water and regulating services such as flood and disease control. They also comprise cultural services, including recreational benefits and supporting services like nutrient cycling.

Climate Resilient Development

Climate resilient development refers to implementing greenhouse gas mitigation and adaptation measures to support sustainable development for all. It aims to reduce vulnerabilities and build the resilience of communities and ecosystems while promoting sustainable development.

Extreme Events

Extreme events are high-impact meteorological, hydrological, or climatological events, such as heatwaves, droughts, floods, or hurricanes. These events can severely affect ecosystems and human societies, becoming more frequent and intense due to climate change.

1.2 Strategies to Combat Climate Change

The fight against climate change is multifaceted, encompassing mitigation strategies to reduce greenhouse gas emissions and adaptation strategies to cope with the inevitable impacts.

Transitioning to renewable energy sources like solar, wind, and hydropower while modernizing the energy grid and improving energy efficiency forms the backbone of mitigation. Meanwhile, carbon capture and storage technologies aim to trap emissions from significant sources. At the same time, nature-based solutions such as forest conservation and sustainable agriculture harness the power of ecosystems to absorb carbon dioxide. Additionally, embracing the principles of a circular economy—emphasizing reducing, reusing, and recycling materials to minimize waste and pollution—is essential to decreasing the carbon footprint of production and consumption.

Adaptation strategies focus on building resilience against the effects of climate change. This includes constructing robust infrastructure, developing early warning systems, implementing water management techniques like drought-resistant crops and efficient irrigation, and protecting coastal communities through measures like seawalls and managed retreats. Public health initiatives also play a crucial role in preparing for and responding to spreading diseases and protecting vulnerable populations during heat waves.

Furthermore, robust disaster management plans and protocols are critical. These plans should include preparedness measures, such as evacuation drills and emergency response training, as well as strategies for recovery and rebuilding after extreme weather events.

Policy and international cooperation are essential, with carbon pricing mechanisms, regulations, and international agreements like the Paris Agreement driving systemic change. However, individual actions are equally vital, with choices such as reducing energy consumption, adopting sustainable transportation, and supporting environmentally responsible businesses that contribute to the collective effort.

In the face of climate change, combining technological innovation, policy intervention, individual responsibility, a shift towards a circular economy, and effective disaster management offers the best hope for mitigating its effects and adapting to a changing world.

1.3 Required Technologies and Related Knowledge

Digital technologies provide powerful tools to combat, adapt, and mitigate climate change. They offer solutions for monitoring environmental conditions, predicting future impacts, managing climate risks, enhancing energy efficiency, and improving disaster response. The deployment and diffusion of these technologies are crucial for realizing their potential in addressing climate challenges. This section presents key areas where digital technologies can make contributions.

1.3.1 Monitoring and Data Collection

Remote sensing, which includes satellite imagery and in-situ sensing using IoT (Internet of Things) sensors, provides real-time data on environmental conditions. This data can be used to track climate change indicators such as temperature, precipitation, and greenhouse gas emissions.

- *Satellite remote sensing*: Provides detailed data on climate patterns, land use, and environmental changes. Satellite data offers a broad and detailed view, essential for monitoring large-scale environmental conditions.
- *Ground-based sensing*: Offers precise, localized environmental data to complement satellite observational data. Interconnected sensor systems (IoT) often enable this type of sensing.

- *Aquatic and underwater monitoring*: Systems capable of tracking aquatic ecosystems and underwater environmental changes, helping to monitor the health of marine environments and the impacts of climate change on water bodies.
- *Unmanned aerial vehicles (UAVs or drones)*: Systems that capture in-situ high-resolution imagery and sensory data from otherwise inaccessible areas, providing detailed and timely information on various environmental parameters.

1.3.2 Predictive Modelling and Simulation

Models and simulations can help predict future impacts of climate change under different scenarios. These tools can assess potential outcomes of various strategies for mitigating and adapting to climate change, which can be important for making informed decisions.

- *Machine learning and data analytics*: analyses datasets to identify patterns, building AI models to predict outcomes and inform decision-making. The emergent areas of physics-informed machine learning [10] will be necessary for developing more reliable models based on linked observational data.
- *Earth digital twins*: a new data-driven technology that creates digital replicas of real-world objects, systems, and individuals at the global scale. This provides policymakers with high-quality data for decision-making across various fields, including industrial manufacturing, Earth system modelling, and citizen-driven initiatives. Using digital twin emulations, "what-if" scenarios can be tested and evaluated to impact real-world applications.

1.3.3 Climate Risk Management

Digital platforms use various data sources and tools for analysis and visualization to help manage climate risks. Geographic Information Systems (GIS) technology assists in mapping and analysing spatial data, identifying trends, and visualizing climate risks, aiding policymakers, businesses, and communities in developing effective climate action plans.

1.3.4 Technologies for Energy Efficiency

Digital technologies, including smart grids, smart meters, IoT, and AI-driven analytics, improve energy efficiency by optimizing energy distribution, reducing waste, and integrating renewable energy sources. IoT devices are essential for monitoring and managing energy consumption in organisations and residential households.

1.3.5 Data cleaning, imputation, calibration, and security

In addressing the climate crisis, the ability to collect, analyse, and interpret accurate climate data is paramount. Innovative technologies play a crucial role in ensuring this data's quality, integrity, and security, driving effective climate action:

Data Cleaning: The first step in ensuring the reliability of climate data is cleaning, which involves identifying and correcting errors, inconsistencies, and missing values. Machine learning algorithms and natural language processing (NLP) techniques are powerful tools in this process, detecting and correcting anomalies in data.

Imputation: Climate data often has gaps due to sensor failures or other issues. Imputation, which estimates and fills in these missing values, ensures the completeness of datasets. Advanced statistical models and machine learning techniques are employed to predict missing values based on patterns in existing data.

Calibration: Data from different sources and sensors can exhibit variations. Calibration aims to harmonize this data, ensuring its consistency and accuracy. Sensor fusion techniques and AI-based calibration algorithms correct discrepancies and ensure data comparability.

Security: Protecting climate data from unauthorized access, manipulation, or loss is essential. Technologies like blockchain, encryption, and anomaly detection systems ensure data integrity, confidentiality, and availability for research and decision-making.

Effective climate action relies on trustworthy and secure data. By optimizing the cleaning, imputation, calibration, and security of climate data, innovative technologies empower researchers, policymakers, and society at large to make informed decisions and develop practical solutions to address the challenges of climate change.

1.3.6 Distributed Systems Technology Deployment

Technology deployment in practical situations involves various participants and activities aimed at introducing, facilitating, and/or supporting its implementation. Expanding these deployments across different groups, users, and markets enhances the ability to effectively address climate change.

- **Blockchain for Partnership and Contracting:** Facilitates secure collaboration and contracting among stakeholders, enhancing trust in technology deployments for climate action initiatives.
- **Edge Computing:** Reduces latency and enables real-time decision-making in climate-related applications.
- **Cloud-Based Data Storage and Analysis:** Supports the management and analysis of large climate-related datasets.

Chapter II - Recommendations

While the increasing reliance on Information and Communication Technology (ICT) contributes to global carbon emissions and e-waste, it also offers a powerful toolkit to combat climate change. Digital technologies can enable sustainable land use and urban planning, including sustainable supply chain practices through energy optimization, resource management, and the development of sustainable solutions. This highlights the dual nature of ICT as both a contributor to and a potential solution to the climate crisis.

This chapter offers recommendations targeted at strategic areas deemed essential for addressing climate change within the context of the twin transition—the seamless integration of digital innovation with the pursuit of environmental sustainability. The first section focuses on the ICT Domain, exploring how its industry can be a model by embracing sustainable practices and addressing the main research and development challenges within this domain. The second section discusses how digital technologies can be applied across key applications to foster sustainable development. The third section covers disaster management and recovery, and the fourth section emphasizes the indispensable role of public awareness and education in catalysing widespread change. A comprehensive approach to these areas has the potential to forge a robust synergy between digital innovation and environmental sustainability, thereby making a substantial contribution to mitigating and adapting to climate change.

2.1 The ICT Domain

2.1.1 Industry

The ICT sector's significant environmental impact necessitates a shift towards circular economy principles, prioritizing energy efficiency, resource conservation, and waste reduction throughout ICT product lifecycles. Addressing current e-waste challenges requires a cultural shift from a throwaway mentality to one focused on recycling and reuse, with manufacturers leading this transformation.

Recommendations:

- **Reuse:** Utilize waste resources, such as excess heat from data centers, for secondary purposes like district heating.
- **Reduce:** Prioritize energy efficiency in software development at all levels to minimize consumption.

- **Research:** Invest in research and development to explore alternative materials, reducing reliance on rare earth elements.
- **Recycle:** Treat e-waste as a valuable resource by promoting equipment reuse, material recycling, and designing for longevity and easy disassembly. Implement take-back programs to ensure responsible end-of-life electronics handling.

2.1.2 Research and Development

Digital technologies are crucial in developing solutions to address environmental challenges and climate action. A prime example is digital twins, high-precision models integrating data from diverse sources, including IoT devices and historical records. These models provide a comprehensive understanding of environmental conditions. Further refinement is achieved by combining mathematical models with machine learning techniques, enabling the estimation of current conditions and predicting future scenarios. This data's large volume and complexity necessitate High-Performance Computing (HPC) infrastructures for efficient processing and storage.

Digital twins not only offer insights but also facilitate interventions in the environment. They can control IoT devices and robotic systems in real-time (online) or provide recommendations for human action and policymaking (offline). The interaction between a digital twin and its physical counterpart creates a cyber-physical system (CPS). Empowered by the Internet of Things (IoT), these systems can integrate with other digital twins, forming large-scale, distributed automation systems for environmental management. Cloud computing supports this integration by enabling efficient resource sharing.

Recommendations

Challenges in Environmental Data Management

Modern society faces significant environmental challenges, such as food security, water security, and disaster resilience, all exacerbated by climate change. Scientists addressing these issues generate and analyse massive amounts of diverse data, from historical climate records to real-time satellite imagery and weather forecasts. However, this data is often scattered across institutions, in non-standard formats, and using outdated technology, hindering integration and decision-making. **To overcome these challenges, effective data governance strategies are vital** [11]. These strategies ensure process efficiency, data quality improvement, real-time access, control, and improved security and integrity, enabling the production and integration of data for rapid, informed decision-making.

Principles and Technical Challenges

Several fundamental principles and technical challenges must be addressed for effective digital systems deployment and environmental data management [11]:

Openness: Data and code should be freely accessible, modifiable, and shareable to accelerate climate change monitoring and mitigation efforts.

Interoperability: Systems must seamlessly work together to ensure data integration and availability.

Confidentiality, Integrity, and Authenticity: Protecting sensitive data and ensuring the trustworthiness of data and interacting agents are crucial.

Availability: Data and systems should be readily accessible with acceptable levels of trust.

Data Quality Control: Mechanisms for tracking data history, traceability, and quality assurance are essential.

By addressing these challenges and adhering to these principles, we can harness the power of environmental data and digital technologies to inform science-driven decisions and promote sustainable practices in the face of climate change.

2.2 Key Application Areas

In the context of the twin transition, we explore specific recommendations for key application areas in the fight against climate change: energy, manufacturing, agriculture, and transportation. Each of the following applications faces unique challenges and presents distinct opportunities for implementing digital technologies and sustainable practices. We will examine how innovation and collaboration can drive the transformation of these sectors towards a greener and more resilient future.

2.2.1 Energy

The energy sector's reliance on fossil fuels places it at the epicenter of the climate crisis. Burning coal, oil, and natural gas for electricity, heat, and transportation releases massive amounts of greenhouse gases, primarily carbon dioxide, into the atmosphere. Fossil fuels are the most significant contributor to global climate change, accounting for over 75 percent of global greenhouse gas emissions and nearly 90 percent of all carbon dioxide

emissions [12]. This significantly contributes to the planet's warming, making the transition to clean energy—such as hydro, wind, and solar power—not just an aspiration but a necessity.

Digital transformation is crucial for advancing environmental sustainability in the energy sector. The energy sector can enhance efficiency, reduce emissions, and optimize resource use by integrating advanced technologies such as smart grids, real-time data analytics, and digital twins. For example, smart grids enable precise monitoring and management of energy distribution, reducing waste and integrating renewable energy sources more effectively. Real-time data analytics provide insights into energy consumption patterns, allowing for more informed decision-making and targeted energy-saving measures. Digital twins simulate and optimize energy systems, predicting potential issues and improving operational performance. Together, these innovations contribute to a more resilient and sustainable energy infrastructure, minimizing environmental impact and supporting the transition to a low-carbon economy.

Though this transformation is underway, with increasing investment in renewable energy, stability issues have been observed in energy systems. Prosumers (electricity consumers who also produce electricity) and regional hub operators are becoming partners with distributors, necessitating new control strategies for local managers. Flexibility has become a critical need in both electricity and gas markets. The market is evolving with the addition of new energy consumption types, such as electric vehicles, and new energy storage activities. **Data centers present challenges for electricity distribution due to the heavy energy use of Generative AI.** Aggregators play new roles by maximizing grid usage, while demand-side management service companies work to decrease power consumption with new tactics proposed by distributors [13].

Energy markets need novel optimization systems to create well-integrated and efficient smart systems. New renewable resource and storage-integrated grids are intended to become multi-source, multi-level, and multi-center systems that cannot be operated without full digitization [14]. These new systems, characterized by their stochastic nature, are more challenging to balance due to the integration of renewable sources. Therefore, all players in the energy market—suppliers, regulators, operators, distributors, sales, and service companies—are using data analysis, short-term prediction, long-term forecasting, and control systems that consider correlations among suppliers and consumers. Pan-European projects are being developed to use AI to monitor Europe-wide transportation, residential, and industrial energy consumption management. Regional comparisons regarding efficiency and consumption enable local and central optimizations through surplus exchange among communities [15]. Currently, technologies used to manage these integrated systems reflect classical consumption scenarios, but new AI scenario analysis is needed to allow for flexibility.

AI can be pivotal in optimizing smart grids, demand response, predictive maintenance, uncertainty forecasting, carbon capture, and energy trading. However, challenges still need to be addressed, including the high cost of implementing new technologies, cybersecurity concerns, and a shortage of skilled IT and AI talent.

Recommendations

Accelerate Smart Grid Adoption:

- Invest in developing and deploying smart grid technologies across the energy sector.
- Prioritize integrating renewable energy sources into smart grids for improved efficiency and reduced emissions.
- Utilize real-time data analytics to optimize energy distribution and minimize waste.

Leverage Data Analytics and Digital Twins:

- Implement advanced data analytics tools to gain insights into energy consumption patterns and identify opportunities for efficiency improvements.
- Develop and deploy digital twins for energy systems to simulate and optimize operations, predict potential issues, and improve overall performance.

Embrace AI for Optimization and Efficiency:

- Utilize AI algorithms to improve the accuracy of energy demand forecasting, allowing for better resource allocation and reduced waste.
- Implement AI-driven predictive maintenance solutions to identify potential equipment failures before they occur, minimizing downtime and optimizing maintenance schedules.
- Explore the use of AI in carbon capture and utilization technologies to enhance efficiency and reduce emissions.

Address Implementation Challenges:

- Develop strategies to mitigate the high costs associated with implementing new technologies, such as exploring public-private partnerships or incentivizing investments in digital infrastructure.

- Prioritize cybersecurity measures to protect critical energy infrastructure and sensitive data from cyberattacks.
- Invest in education and training programs to develop a skilled workforce capable of implementing and managing digital technologies in the energy sector.

Support Collaborative, Multidisciplinary Approaches

- Encourage collaboration between Science, Technology, Engineering, and Mathematics (STEM) and social science experts to accelerate community engagement and implementation.

By embracing these recommendations, the energy sector can leverage the power of digital transformation to accelerate the transition to a more sustainable and resilient energy future. Smart grids, demand response projects, predictive maintenance, carbon capture, utilization, and storage (CCUS), nuclear energy projects, fossil energy, and hydrogen exploration will all benefit from the broader use of AI. Increasing the number of IT personnel with energy expertise will open up new possibilities. Energy sector organizations should support governments in renewing and maintaining energy infrastructure, while energy companies must invest more in cybersecurity and talent acquisition to maintain their competitive edge.

2.2.2 Manufacturing

Global industrial manufacturing significantly contributed to greenhouse gas emissions, accounting for 17% worldwide in 2022 [16]. The 3rd Industrial Revolution began around 1970 and was driven by the introduction of the first electronic Programmable Logic Controllers (PLCs). These advanced automation technologies facilitated production beyond manual production lines with little regard for sustainability. The primary goal was to enable cheap mass production. The Fourth Industrial Revolution (Industry 4.0) was initiated in 2012 [17]. It focused on mass production, allowing for the control and customization of each product throughout the manufacturing process. This revolution also integrated smart services and combined Operational Technologies with Information Technologies for business processes. As a result of this comprehensive digitalization of manufacturing, sustainability considerations for the entire industrial sector became more attainable, leading to the concept of a Circular Economy applied to manufacturing. This approach provides a holistic view of the complete product life cycle, from conceptualization, design, production, and logistics to the product's use and end-of-life phase, including recycling [18,19].

ICT-based methods enable the detailed capture and analysis of each phase of product development, production, and use, differentiating between embodied and operational

carbon footprints. This systematic approach to all product phases, including the necessary supply networks, makes adopting sustainable manufacturing practices feasible.

Embodied and operational carbon footprints can be reduced by, for instance:

- Using fewer materials.
- Using recycled materials.
- Using low-impact materials.
- Using local materials.
- Designing for recycling.
- Designing for product flexibility.
- Designing for longer product use.
- Designing for repairability.
- Implementing low fossil-carbon process planning and production scheduling.
- Minimizing supply network carbon emissions.
- Designing for less operational energy during product use.

Recommendation

Implement the Circular Economy through ICT-based measures: Utilize Digital Twins across all product life cycle phases to support sustainability. This approach will be essential for a global reduction in the extensive greenhouse gas emissions from industrial manufacturing.

2.2.3 Agriculture

To achieve a sustainable and resilient agricultural sector, the integration of digital technologies is crucial. This approach enables data-driven decision-making, optimizes resource use, and minimizes environmental impact, ultimately leading to increased productivity and profitability while ensuring food security and environmental stewardship [20]. By leveraging tools such as precision agriculture, remote sensing, and agricultural data analytics, farmers can monitor crop health, soil conditions, and weather patterns more accurately, allowing them to make informed decisions on irrigation, fertilization, and pest control. This level of precision helps reduce waste, conserve water, and decrease the use of harmful chemicals, contributing to both environmental stewardship and cost savings.

Data-driven agriculture also fosters collaboration among farmers, researchers, policymakers, and technology providers, enabling continuous evolution through information exchange and adopting new technologies. Integrating digital tools, data-driven strategies, and effective communication can significantly enhance agricultural productivity, sustainability, and resilience. This approach supports climate change mitigation by optimizing resource use, reducing emissions, and promoting sustainable land

management, ultimately leading to sustainable agricultural development and economic growth that meets current and future needs [21].

Recommendations

- **Implement precision farming on farms of all sizes:** Leverage GPS and IoT devices for real-time monitoring of soil and weather conditions, optimizing irrigation, and improving yields. This approach can be applied to large-scale and small/local farms, reducing water usage and enhancing crop health through targeted interventions [21].
- **Utilize remote sensing and satellite imagery:** These technologies allow for the monitoring of crop health, early detection of pests, and assessment of natural disaster damage, enabling timely interventions and reducing crop losses [22].
- **Develop agricultural data analytics tools:** By analysing crop performance, soil conditions, and weather patterns, these tools can predict optimal planting times and crop rotations, thereby increasing yields and mitigating climate risks [23].
- **Establish robust data collection infrastructure:** Creating systems for collecting, storing, and analysing agricultural data is essential, making this data accessible to farmers and researchers to inform better decision-making [24].
- **Enhance supply chain transparency with blockchain:** Implementing blockchain technology to track produce from farm to table can reduce fraud, increase transparency, and build consumer trust [25].
- **Enhance the connection between farmers and consumers through e-commerce:** E-commerce platforms can enable direct sales from farmers to consumers, ensuring fresher produce and supporting local agriculture [26].

2.3.4 Transportation

The transportation sector significantly contributes to the climate crisis, accounting for a substantial portion of global greenhouse gas (GHG) emissions. Burning fossil fuels in cars, trucks, ships, and airplanes releases vast amounts of carbon dioxide and other pollutants into the atmosphere, intensifying the greenhouse effect and driving climate change. The ever-increasing demand for mobility, driven by population growth and economic development, further compounds this challenge, making the transition to sustainable transportation an urgent imperative.

Digital transformation provides a critical opportunity to address this challenge. We can reshape the transportation landscape toward a greener and more sustainable future by

leveraging data, connectivity, and intelligent systems. The following approaches outline how this can be achieved:

Optimization and Efficiency:

- Real-time data analytics and intelligent transportation systems can optimize traffic flow, reduce congestion, and minimize fuel consumption, leading to significant emission reductions.

Electrification and Smart Grids:

- Digital technologies can accelerate the adoption of electric vehicles (EVs) by enabling smart charging infrastructure and integrating EVs into the power grid, facilitating using renewable energy sources.

Shared Mobility and Demand-Responsive Transport:

- Digital platforms can promote shared mobility options, reducing the need for private car ownership and fostering a more efficient and sustainable transportation system.

Logistics and Supply Chain Optimization:

- Digital solutions can streamline logistics and supply chain operations, reducing empty miles and optimizing routes for improved fuel efficiency and lower emissions.

Recommendations:

To fully realize the potential of digital transformation in creating a sustainable transportation sector, concerted action is required from both individuals and the industry:

Individuals:

- **Embrace sustainable modes of transport:** Opt for public transport, cycling, or walking whenever feasible.
- **Adopt shared mobility solutions:** Consider carpooling or ride-sharing services to reduce individual vehicle usage.

- **Support sustainable transport policies:** Advocate for policies that incentivize sustainable transportation choices and investments in infrastructure.

Transportation Industry:

- **Invest in digital technologies:** Embrace data analytics, intelligent transportation systems, and other digital solutions to optimize operations and reduce emissions.
- **Accelerate the transition to electric vehicles:** Develop and deploy electric vehicle infrastructure and promote their adoption.
- **Foster collaboration and data sharing:** Work with governments and other stakeholders to create a connected transportation ecosystem.

By embracing these recommendations, we can harness the power of digital transformation to revolutionize the transportation sector and create a future of sustainable mobility that benefits both our planet and its inhabitants.

2.3 Disaster Response and Recovery

As depicted in Figure 1, the disaster management cycle encompasses four critical phases: response, recovery, mitigation, and preparedness [27,28].



Figure 1: Disaster Management Cycle

During the response phase, immediately following a disaster, the primary objectives are to save lives and minimize property losses. Prompt alerts must be issued to ensure public awareness and facilitate evacuation. Concurrently, responders must provide shelter for victims and manage their immediate needs, including restoring essential services such as water supply and energy provision (electricity, petrol, gas, etc.).

The recovery phase commences a few months later as displaced individuals transition from temporary shelters to more permanent housing solutions. This phase focuses on restoring social infrastructure, including public transportation, roads, government services, healthcare, and educational facilities, among others necessary for daily life.

In the mitigation phase, the focus shifts to identifying risks and implementing countermeasures by modifying infrastructure, policies, and regulations to mitigate these risks. Effective risk communication to the public is crucial during this phase, with IT tools playing a vital role in identifying and addressing potential hazards.

The preparedness phase involves training disaster responders and conducting evacuation exercises to ensure readiness for future events.

The increasing frequency and intensity of natural disasters driven by climate change—such as floods, droughts, heatwaves, wildfires, and landslides—has heightened the need for effective disaster management. Many communities remain inadequately prepared. Effective disaster management depends on situation awareness, which includes perceiving environmental elements, understanding their implications, and forecasting future developments. Communication is vital for enhancing situation awareness and ensuring that all relevant stakeholders have a unified understanding. According to Endsley [30], situation awareness comprises three stages: perceiving environmental elements, comprehending their significance, and anticipating their future status. Essential to disaster management is sharing basic information and exchanging more detailed insights and future projections.

Recommendations

Digital communication tools and early warning systems enhance disaster response and recovery efforts. These technologies facilitate efficient information sharing, coordination of emergency services, and support for affected populations.

Data logging systems are indispensable for recording and storing environmental data, which is crucial for long-term analysis and improving future disaster response strategies. Additionally, they provide valuable data for training AI models in tasks such as object and hazard detection in complex environments.

Robust communication protocols ensure reliable data transfer during emergencies, allowing critical information to reach the appropriate recipients on time.

2.4 Public Awareness and Education

Raising public awareness and promoting education on climate change and sustainable practices are essential for ensuring a sustainable future. Information and Communication Technology (ICT) can significantly contribute to this goal through various initiatives and platforms. Notable examples include the UN's Global Schools Program, which demonstrates how interactive online platforms can enhance education on Sustainable Development Goals (SDGs) among youth, and UNESCO's *YouthMobile* Initiative, which empowers young people to tackle community challenges through mobile applications, promoting digital skills and innovation for sustainable development [29].

These examples highlight the transformative potential of ICT in advancing sustainable development. Building on these successes, the following recommendations are proposed for scientific, professional, and educational organizations to further leverage ICT in combating climate change:

Recommendations for Utilizing ICT Capabilities for Climate Change Education

Content Creation

- **Podcasts:**
 - Develop and launch a series of podcasts focused on climate change and digital technologies.
 - Provide links to relevant publications and encourage engagement through comments and subscriptions.
 - Refine and expand podcast content based on feedback to reach a broader audience.
- **Video Platforms and Social Media:**
 - Use video platforms for panel discussions and to broadcast podcasts.
 - Promote content across social media platforms to highlight key areas of expertise and engage audiences through shares and interactions.

Event-Based Strategies

- **Webinars and Roundtables:**

- Organize webinars and roundtables featuring keynote speakers and relevant research themes.
- Record these events as podcasts and promote them through established channels.
- **Conferences:**
 - Record additional podcasts featuring keynote speakers and popular research themes from conferences.
 - Utilize existing promotional strategies to enhance the reach of these podcasts.

Cross-Media Promotion

- **Publications:**
 - Integrate hyperlinks to podcasts and climate change-related publications across all media platforms.

Inclusivity and Relevance

- **Inclusivity:**
 - Ensure that podcasts and social media content are inclusive and address diverse audiences.
- **Knowledge Dissemination:**
 - Disseminate curated knowledge and information to educators, teachers, students, and mentors to increase awareness of digital technologies' role in environmental sustainability.

By implementing these recommendations, organizations can effectively utilize their existing platforms and resources to foster a more informed and engaged public, thereby advancing efforts to combat climate change and promote a sustainable future.

Final Remarks

The IFIP Digital Technology and Climate Change Task Force, established in response to the urgent challenges posed by climate change, has rigorously explored how digital technologies can be leveraged to support a sustainable future. Through extensive in-depth discussions,

the Task Force has identified numerous opportunities and developed actionable recommendations to harness ICT in the fight against climate change.

This document has presented the Task Force's findings, beginning with an overview of the key concepts and challenges related to climate change, followed by an examination of the role of digital technologies. It then offered specific recommendations for various stakeholders and sectors. Central to these recommendations is the emphasis on collaboration, innovation, and the need to elevate public awareness.

The overarching message is clear: by adopting sustainable practices, investing in research and development, and fostering a culture of environmental responsibility, we can effectively utilize the digital world to combat climate change.

The urgency of the climate crisis necessitates immediate action. The Task Force strongly urges all stakeholders to implement the specific recommendations outlined in Chapter II and the general recommendations listed below without delay:

- **Individuals:** Reduce energy consumption, adopt sustainable digital practices, and manage e-waste responsibly through recycling and proper disposal.
- **Computer Societies:** Promote sustainability within the ICT industry by organizing educational events, supporting research and development of ICT solutions, fostering collaboration, and advocating for Open Science. Recognize and reward best practices through awards, and encourage the adoption of energy-efficient technologies and software.
- **Organizations (Public & Private):** Implement green ICT practices, invest in renewable energy, develop sustainable products and services, and actively engage employees in sustainability initiatives. Encourage supply chain sustainability and prioritize eco-friendly procurement policies.
- **Governments:** Establish supportive policies, invest in ICT research and development, lead by example in adopting sustainable practices, and collaborate on international sustainability efforts. Incentivize green innovation, enforce regulations for e-waste management, and promote public awareness campaigns on digital sustainability.
- **Educational Institutions:** Integrate sustainability into curricula, promote research in sustainable ICT, and encourage students to engage in projects and initiatives that address environmental challenges.

- **Communities:** Foster a culture of sustainability by organizing local initiatives, such as community e-waste collection drives, digital literacy programs focused on sustainability, and collaborative projects that reduce the digital divide.

A successful, sustainability-driven digital transformation requires a collaborative ecosystem and proactive measures to address potential challenges. To achieve this, we must foster global cooperation for digital sustainability, ensure that technological advancements adhere to a "do no harm" principle, and prioritize human and environmental well-being throughout the digital transformation.

The potential for digital technologies to drive positive change is immense, but the window for action is closing. Let us commit to these recommendations and work together towards a sustainable future. The time for action is now.

Task Force Composition and Historical Overview

The IFIP Task Force on Climate Change and Digital Technology was established on November 30, 2022, following an invitation from IFIP President Anthony Wong and a draft proposal by Raimundo Macêdo and Marcelo Pias. The Task Force comprises representatives from Australia, Brazil, Canada, the United Kingdom, Germany, Ireland, Japan, and Turkey. The members are as follows:

- **Raimundo José de Araújo Macêdo (Task Force Chair):** Immediate Past President of the Brazilian Computer Society (SBC), Federal University of Bahia, Brazil.
- **Marcelo Pias (Task Force General Secretary):** Center for Computational Sciences, Federal University of Rio Grande, Brazil.
- **Liwan Liyanage:** School of Computer, Data, and Mathematical Sciences, Western Sydney University, Australia.
- **David Cook:** IFIP Vice President and National Representative of the Australian Computer Society (ACS), Edith Cowan University, Australia.
- **Yuko Murayama:** Chair of IFIP WG5.15, Tsuda University, Japan.
- **Otthein Herzog:** University of Bremen, Germany, and Tongji University, Shanghai, PRC.
- **Gülgün Kayakutlu:** Chair of IFIP WG 12.11, Istanbul Technical University, Turkey.
- **David Kreps:** Chair of the IFIP Technical Assembly, University of Galway, Ireland.

- **John Higgins (until May 1, 2024):** Immediate Past President and nominee of the British Computer Society (BCS), United Kingdom.
- **Greg Lane (from April 1, 2024):** Canadian Information Processing Society (CIPS), Canada.

The Task Force was formed to explore how digital technologies can address climate change challenges and to propose actionable recommendations. The group's activities included defining the scope of work, proposing a model and taxonomy to guide discussions, and developing recommendations for technical solutions using digital technologies to combat climate change. Additionally, the Task Force focused on building human capacity to meet sustainable development challenges. To gain broader insights from the IFIP community, two rounds of a survey questionnaire were distributed among key IFIP stakeholders, including member societies and technical committees, resulting in 18 responses.

The task force members regularly conducted online meetings at suitable times to accommodate the members' geographical diversity of time zones. Meeting documents, such as calls for meetings, minutes, slides, and supplementary materials, were stored in a secure cloud to provide task progress information to the task members and the IFIP community.

The task force produced an intermediate report that included the outcome of the scoping exercise discussions and developed a related model and taxonomy to guide further discussions and recommendations for technical solutions using digital technologies to combat climate change. Following this, during the general meeting on June 14, 2023, the task force chair suggested forming two subgroups focused on digital technology (Subgroup 01) and education/awareness (Subgroup 02), requesting volunteers. Liwan Liyanage and David Cook volunteered to lead these subgroups, respectively.

At the task force general meeting on March 27, 2024, building on the previous modelling, taxonomy, and the work developed within the subgroups—particularly the report produced by Subgroup 01 on the required digital technologies and related skill sets—the task force chair proposed a shift toward a macro-level approach. This approach focused on a broad set of skills and technologies, such as data science, cloud computing, and IoT, to facilitate the generation of recommendations applicable to various scenarios. Following that meeting, 12 additional general meetings were held to adjust, consolidate, and finalize the recommendations, with some task force members assigned to contribute to some specific topics.

Progress updates were presented during an online session at the IFIP Strategy Day on April 13, 2023, at the IFIP General Assembly in Bratislava, Slovakia, in September 2023, and via

remote presentation at the IFIP Board meeting in Canada in March 2024. The task force chair, Raimundo Macêdo, also presented the preliminary findings at the WSIS Forum 2023, specifically during the online workshop on IT in Disaster Risk Reduction (ITDRR) on April 20, 2023. The task force concluded its work in September 2024, presenting its final report at the IFIP General Assembly in Lisbon, Portugal.

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