María Pérez-Ortiz
Associate Professor, Centre for AI, University College London, UK

1. Introduction

By 2050, the United Nations predicts that nearly 70% of the global population will live in urban areas (as opposed to the current 56% (UN-Habitat, 2022)). As the world continues to urbanise at an unprecedented rate, the challenges that cities face – ranging from mobility, provision of services and housing, pollution and urban health, and resource usage – are growing ever more pressing. With this rapid urban growth comes the urgent need to develop innovative solutions to ensure that cities are livable, supportive of human development, efficient and environmentally friendly.

One of the most discussed developments in addressing these challenges is the integration of technology, and more specifically Artificial Intelligence (AI), into urban settings. However, as AI becomes more widely adopted, concerns about its sustainability – both environmental and social – are emerging. In this work, we explore the concept of sustainable AI, focusing on the role it should have in the deployment of these technologies in urban settings. We analyse the environmental, social and economic considerations of AI deployment in cities, highlighting the benefits, challenges and future directions for AI in the quest for sustainable and equitable urban futures.

2. The pursuit of sustainability

Sustainability, and more specifically sustainable development, as it is currently defined by the United Nations (Keeble, 1988), relates to the ability to make development meet present and future human needs (e.g. health and well-being, quality education, decent work, social equality) and how to do so within socioecological limits at present. Sustainability is commonly divided into three pillars:

- **Environmental sustainability**: living within the means of our natural resources and protecting and supporting our ecosystems. In urban settings, a key challenge is reducing greenhouse gas emissions

and improving urban air quality. For example, cities can implement low-emission zones, expand public transportation and promote energy-efficient buildings to reduce urban pollution and mitigate the heat island effect.
- **Social sustainability**: persistently achieving good social well-being. In cities, this often means fostering inclusivity, accessibility, equity and more sustainable living in urban developments. A current challenge is creating affordable housing and ensuring equitable access to green spaces, transportation and essential services. For instance, cities can design mixed-use neighbourhoods that are walkable, prioritise social integration and landscape with native plant species to integrate greener environments.
- **Economic sustainability**: using resources efficiently and responsibly. The economic dimension of sustainability focuses on fair, green and circular economies rather than simply continuous economic growth. In the context of urban sustainability, the focus is on developing resilient, low-carbon economies. One example is promoting sustainable urban infrastructure that supports green jobs and circular economy principles, such as creating sustainable urban mobility systems (e.g. bike-sharing, electric vehicle infrastructure) and supporting local green industries.

Sustainable AI includes the use of AI for social, environmental, and economic sustainability, but also, importantly, the sustainability of AI, addressing a variety of concerns, including its energy consumption, resource use, and social equity, to ensure that AI solutions contribute positively to society and the environment over time.

While we often think of sustainability as just the environmental pillar, the three examples of social, environmental and economic sustainability above demonstrate the interconnectedness of all the pillars and the need to consider them together. As environmental philosopher John Muir put it: "When we try to pick out anything by itself, we find it hitched to everything else in the Universe" (Muir, 1911). Similarly, cities are complex systems, requiring considerations of the system as a whole and approaches that multi-solve goals and take into account the social, environmental and economic pillars.

3. Technology meets sustainability

Could technological advances influence our ability to secure a sustainable future? (GACGC, 2019). It is crucial to understand the impact of technology on sustainability, especially as disruptive technologies such as AI accelerate global and human-led change at an unprecedented pace and without a clear unified agenda.

In the last few years, we have seen a new set of desired principles towards sustainability emerge for AI systems (Vinuesa, 2020; Van Wynsberghe, 2021). In particular, sustainable AI refers to a rapidly evolving framework that aims to shape the development, deployment and use of AI technologies in a way that is environmentally, socially and ethically responsible, seeking to balance the tensions between the risks and opportunities of AI.

At its core, sustainable AI also considers the three major dimensions of sustainability: social, environmental and economic. However, sustainable AI is more than the sum of its parts. Sustainable AI includes the use of AI for social, environmental and economic sustainability, but also, importantly, the sustainability of AI (Van Wynsberghe, 2021), addressing a variety of concerns, including its energy consumption, resource use and social equity, to ensure that AI solutions contribute positively to society and the environment over time.

One of the core challenges in developing sustainable AI is addressing the environmental footprint of AI itself. AI systems, particularly large-scale models like those used in deep learning, require vast computational power, resulting in significant energy consumption and carbon emissions. For example, in 2019 it was estimated that training a single large language model can emit as much carbon as five cars over their lifetimes (Strubell et al., 2019), an estimate that is likely to have increased significantly since then. This is only training, not considering the footprint of its usage (e.g. it is estimated that making an image with generative AI uses as much energy as charging your phone (Heikkilä, 2023)). In addition to operational emissions, it is important to consider embodied emissions – the carbon footprint associated with the production, transportation and disposal of the hardware used for AI, such as servers and GPUs. Sustainable AI seeks to minimise both operational and embodied environmental impacts by promoting more energy-efficient algorithms such as model distillation or quantisation.

Sustainable AI is not just about a subset of technologies designed specifically for sustainability, but about reshaping the entire field of AI to ensure it consistently contributes to long-term social, environmental and economic well-being.

Beyond its environmental impacts, social sustainability in AI is also a pressing concern. AI systems, if not carefully designed, can reinforce existing social inequalities, through biased algorithms or unequal access to AI technologies. Sustainable AI calls for the creation of AI systems that promote social inclusion and fairness, ensuring that marginalised groups are not harmed by AI-driven decisions in areas such as hiring, housing or criminal justice. This involves embedding ethical considerations and human rights into the design and implementation of AI, with robust transparency, accountability and governance frameworks to guard against unintended harms. Further exploration of fairness in AI systems is discussed in the fairness chapter of this monograph.

In terms of economic sustainability, AI has the potential to both drive and disrupt sustainable development. AI can optimise urban infrastructure, energy grids and transportation systems, promoting more efficient resource use and reducing waste in cities. It can also enable the transition to a circular economy by improving processes like supply chain management, waste reduction and product life cycle optimisation. However, if not carefully managed, AI may exacerbate economic inequality, automating jobs without creating new employment opportunities or increasing wealth concentration. Sustainable AI, therefore, advocates for AI-driven economic models that prioritise long-term societal benefits over short-term profit, ensuring that the economic gains from AI are distributed equitably.

Some of the questions proposed for inclusion in the design of AI systems by frameworks of sustainable AI include (Vinuesa, 2020; Van Wynsberghe, 2021):

- What are the trade-offs between the direct and indirect impacts of AI technology on society, the environment and the economy? How can we design AI systems to be more sustainable from the outset? What risk assessment frameworks can help us anticipate unintended consequences before they arise?

- How can we address the broader sociotechnical system surrounding AI, including the social impacts on individuals who use or are affected by these technologies? What steps can we take to develop AI that aligns with the preservation of environmental resources for current and future generations, supports sustainable economic models and respects the core societal values of different communities?
- How can we promote change throughout the entire AI life cycle – from idea generation, training and fine-tuning to evaluation, implementation and governance – towards greater ecological sustainability and social equity? What measures are necessary to ensure AI systems operate within the planet's ecological limits, such as energy consumption, freshwater use and reliance on scarce minerals?

AI technologies in cities have a significant environmental impact due to their reliance on data centres and computational resources. A sustainable approach to urban AI would involve optimising these systems for energy efficiency.

Ultimately, sustainable AI advocates for an approach where AI serves as a force multiplier for sustainability goals, enhancing efforts to mitigate climate change, reduce inequality and foster inclusive, resilient economies, while also ensuring that the development and use of AI technologies themselves are aligned with principles of sustainability. It is important to recognise that technologies, including AI, can pose both extrinsic and intrinsic risks to sustainability. In the case of intrinsic risks, even when a technology is not directly applied to sustainability challenges, if it is faulty, non-robust or unfair, it may unintentionally undermine sustainability goals by exacerbating inequality, environmental harm or economic instability through indirect channels. Therefore, sustainable AI is not just about a subset of technologies designed specifically for sustainability, but about reshaping the entire field of AI to ensure it consistently contributes to long-term social, environmental and economic well-being.

4. Sustainable AI in urban settings

While more frameworks for the sustainability of AI are starting to emerge (Vinuesa, 2020; Van Wynsberghe, 2021; Wu, 2022; Wilson, 2022; Nishant, 2020), very few works at present focus on urban futures (Yigitcanlar, 2020; Bibri, 2021; Pastor-Escuredo, 2022). Towards this goal, we aim to introduce a perspective that exemplifies the foundations that would be needed to ensure that AI systems deployed in cities are not only technologically advanced but also responsible, equitable and beneficial for both the environment and urban populations.

Environmental impact in urban AI systems. One of the relevant challenges of AI is its environmental impact, which includes but is not restricted to its significant energy consumption and freshwater usage (Luccioni, 2024). In urban settings, where AI is increasingly used in applications such as smart traffic systems, energy grids and building management, the cumulative demands of these systems can become substantial. AI technologies in cities have a significant environmental impact due to their reliance on data centres and computational resources. A sustainable approach to urban AI would involve optimising these systems for energy efficiency through methods such as tiny machine learning, green computing software engineering practices, knowledge distillation, model pruning or quantisation. This could also mean learning from smaller, high-quality datasets (i.e. doing more with less), using renewable energy, supporting sustainable consumption and production patterns, and minimising the carbon footprint of city-wide AI deployments. For example, AI-powered smart grids could dynamically adjust energy usage based on real-time data, reducing waste and supporting the integration of renewable energy sources like solar and wind. Federated learning is another promising approach for sustainability in urban AI. Rather than relying on centralised data centres for large-scale model training, federated learning enables smaller models to be trained directly on decentralised devices, such as Internet of Things (IOT) sensors embedded in urban infrastructure. This reduces the need to transmit vast amounts of data to centralised servers, cutting down on energy-intensive data processing and storage. By leveraging existing local computing resources, federated learning also reduces the overall demand for new hardware and mitigates the environmental footprint of large-scale AI operations. Additionally, it enhances privacy and data security by keeping sensitive information on local devices, reducing the need for data sharing while supporting sustainable AI practices.

Social sustainability: equity and fairness. As cities increasingly adopt AI to power services such as security, healthcare and public resource allocation, it is essential that these systems contribute to social sustainability by promoting fairness, equity and inclusivity. In urban planning, for example, sustainable AI could be leveraged to identify and address inequalities, such as ensuring underserved neighbourhoods receive equitable access to transportation, healthcare and education. However, the social component of sustainable AI not only involves the purpose for its use, designing algorithms that minimise bias and ensuring marginalised communities are not harmed by AI-driven decisions, but also addressing the ethical implications of how AI systems are developed and deployed. Many AI systems are trained and maintained by underpaid and overworked workers in Global South communities (Rowe, 2023), who are often employed by third-party companies. This labour, crucial to training many AI systems, highlights deep inequalities in the global AI supply chain, as these workers often face poor working conditions while bearing the toll of repetitive, underappreciated tasks. The true social sustainability of these systems must also consider the ethics of their development process, ensuring fair practices across the entire AI life cycle. This helps advance social sustainability by fostering more just and inclusive cities while addressing global inequities in AI production.

The true social sustainability of these systems must also consider the ethics of their development process, ensuring fair practices across the entire AI life cycle. This helps advance social sustainability by fostering more just and inclusive cities while addressing global inequities in AI production.

Ethical governance and accountability. Urban AI systems must be governed by strong ethical frameworks that prioritise transparency and accountability. City governments and stakeholders should ensure that AI systems are explainable and that decision-making processes are clear to the public. This would build trust and ensure that any errors or unintended consequences can be identified and addressed promptly. For example, AI systems used for surveillance or law enforcement in cities should be designed with clear accountability structures, protecting citizens' privacy and civil rights. Further exploration on the operationalisation of these principles in AI systems is discussed in the transparency and accountability chapter of this monograph.

Economic sustainability in cities. For AI to be sustainable in urban environments, it must also be economically viable in the long run. This involves developing AI systems that integrate seamlessly with existing city infrastructure, scale to meet future demands and are built for long-term use. Cities can support circular economy models by encouraging the reuse and recycling of AI technologies, data and hardware, thereby reducing waste and lowering costs.

For AI to be sustainable in urban environments, it must also be economically viable in the long run. This involves developing AI systems that integrate seamlessly with existing city infrastructure, scale to meet future demands and are built for long-term use.

Alignment with urban sustainability goals. AI systems deployed in cities should not only support urban sustainability goals – such as reducing pollution, enhancing public health and improving quality of life – but also ensure that the use of AI technologies themselves contributes to sustainability. One way this can be achieved is by repurposing the energy and resources used by AI infrastructure. For example, reusing excess heat from data centres – a significant byproduct of AI's computational demands – can contribute to urban sustainability by reducing overall energy consumption. In Stockholm, the Stockholm Data Parks project[1] has shown how waste heat from data centres can be redirected to heat residential and commercial buildings, demonstrating how AI infrastructure can be integrated into a circular economy model, aligning with climate goals while reducing public energy needs. Beyond resource efficiency (connected with the concept of the sustainability of AI), AI can optimise urban systems for sustainability. By leveraging AI to enhance resource management, reduce energy consumption and support climate resilience initiatives, cities can address pressing challenges like climate change and urbanisation. For instance, urban areas are particularly vulnerable to the impacts of climate change, such as rising temperatures and extreme weather events. AI can play a crucial role in increasing the climate resilience of cities by providing advanced predictive analytics and early warning systems for climate-related risks. These systems can alert authorities to potential environmental hazards and enable rapid response, helping to mitigate the health and environmental impacts of urban pollution.

AI for urban planning and development. AI is transforming the way cities are planned and developed (Jha, 2021) fostering greater social, environmental and economic sustainability. By analysing large datasets on population growth, land use, transportation patterns and environmental factors, among many others, AI can help urban planners and policymakers design more sustainable and efficient cities using so-called digital twins. For example, AI models can predict how changes in infrastructure, such as the construction of new roads or public transit systems, will impact traffic patterns, pollution levels and energy consumption. This helps planners anticipate the future and engage in responsible foresight, allowing for more informed decisions that promote long-term sustainability. AI can also be used to optimise land use and zoning policies, ensuring that urban development is balanced with the preservation of green spaces and natural resources. This is particularly important in rapidly growing cities, where the demand for housing and infrastructure often leads to urban sprawl and the loss of valuable ecosystems. However, beyond its application to urban systems, it is crucial that the development and deployment of AI itself aligns with sustainable practices. While digital twins are powerful tools for simulating urban planning scenarios, their sustainability depends on the efficiency of the underlying AI models and the infrastructure supporting them. It is worth noting however, as reported by many studies (Andersson, 2021), that digital twins built with AI can be a more resource efficient approach than their physics-based counterpart simulations, running on laptop CPUs in seconds as opposed to necessitating supercomputers for days.

1. https://stockholmdataparks.com/

5. Policy recommendations and concluding remarks

Innovation and technology will play an increasingly central role in planning for sustainable urban futures (UN-Habitat, 2022). As we discuss next with our list of policy recommendations, the design and deployment of technology should be tailored to suit the large diversity of the urban context:

a. Environmental sustainability recommendations

- The urgency to decarbonise urban economies should drive the **convergence of green and smart technologies**. Policies should emphasise energy efficiency, environmental preservation and resilience. This includes the establishment of green AI standards that prioritise energy-efficient algorithms and hardware, as well as creating circular economies surrounding data centres, e.g. recycling excess heat. Life cycle management policies should promote the responsible sourcing, reuse and recycling of AI hardware to minimise electronic waste.
- Impact assessments should carefully weigh whether deploying **AI for sustainability projects justifies the environmental cost of the technology**, as highlighted by previous work (Dixon, 2022). New frameworks are essential to measure and compare the full life cycle costs of AI, ensuring a comprehensive evaluation of its sustainability.
- **AI energy star rating frameworks** are beginning to emerge (Luccioni, 2024) and these should be added to IOT urban devices, offering users valuable insights to better understand the environmental impact of the tools they use and to adopt them more responsibly.
- Public-private partnerships and collaboration can drive the development of sustainable AI technologies in urban areas. Creating **AI for sustainable cities consortiums** can foster partnerships between governments, tech companies and research institutions to tackle urban challenges such as energy management, transportation and waste reduction. Cities should incentivise sustainable AI development by offering tax credits or subsidies to companies developing environmentally friendly AI solutions.
- Urban resilience and smart infrastructure should be supported through **policies that encourage AI for climate and biodiversity resilience**. This includes the use of AI-driven early warning systems for natural disasters, tipping points of biodiversity loss and extreme climate events.

b. Social sustainability recommendations

- Since all the dimensions of sustainable AI are intertwined, ethical and responsible AI deployment are also a critical dimension in urban environments. AI systems must be audited for fairness to prevent discrimination and social inequality. The creation of **local AI ethics boards** should ensure that urban AI projects adhere to privacy, fairness and accountability standards.
- Data privacy and security are also key areas of focus. **Strong urban data privacy laws** should be enacted to protect personal

data collected from sensors, cameras and mobile apps. This includes anonymisation and the use of explicit consent. In addition, secure and transparent frameworks for data sharing between governments, private companies and AI developers are necessary to ensure responsible use of citizen data without compromising privacy.

- To foster public support and understanding, policies should promote **public engagement and digital literacy**. Cities should encourage **participatory governance models** that involve citizens in AI decision-making processes, while also launching digital literacy campaigns to educate the public on AI technologies, their impacts and how to protect their rights.
- Ensuring **equal access to AI-driven public services**, particularly for marginalised and underserved communities, is essential to promote inclusivity.
- Fostering **open science** is essential, enabling public audits of these systems while ensuring robust cybersecurity measures are in place to protect sensitive data and utilities. Transparency is also key, with regulations requiring AI systems used in public services to be explainable, enabling both stakeholders and the public to understand how decisions are made.

c. General recommendations

- To address the economic impact of AI, policies should **support job transition and workforce development**. Public funding should be allocated to reskilling programmes that help workers transition into new jobs, particularly in emerging sectors where automation may cause job displacement. Promoting the growth of AI-based green jobs, such as those related to renewable energy management and sustainable urban infrastructure, can further drive sustainable economic growth.
- Monitoring and accountability frameworks are essential to ensure AI systems align with sustainability goals over time. **Mandatory AI impact assessments**, similar to environmental impact assessments, should evaluate the social, economic and environmental effects of AI deployment in cities. Continuous **monitoring and auditing** of urban AI systems can help ensure they remain adaptable to new challenges and ethical considerations.
- **Include considerations into environmental, social and governance standards** that account for the sustainability of the data, algorithms and computational resources used by businesses, as well as the support provided to renewable energy sources and circular computational economies.
- Regulatory standards for smart city infrastructure must ensure that **AI technologies are adaptable, interoperable and scalable for future urban needs**, especially in areas like traffic management, waste reduction and energy efficiency.
- Finally, at the global level, **international collaboration and standardisation** should be encouraged. Cities should work together to develop global sustainability standards for AI and share best practices (Strubell, 2019), ensuring alignment with international goals. Platforms for cross-city knowledge sharing can help accelerate the adoption of sustainable AI practices worldwide.

References

Andersson, T. R., et al. "Seasonal Arctic sea ice forecasting with probabilistic deep learning". *Nature Communications* 12.1 (2021): 5124.

Bibri, S. E. "Data-driven smart sustainable cities of the future: Urban computing and intelligence for strategic, short-term, and joined-up planning". *Computational Urban Science* 1.1 (2021): 8.

Dixon, B., Pérez-Ortiz, M. and Bieker, J. "Comparing the carbon costs and benefits of low-resource solar nowcasting". NeurIPS Workshop on Tackling Climate Change with Machine Learning (2022).

German Advisory Council on Global Change, *Towards Our Common Digital Future*, Flagship Report, 2019.

Heikkilä, M. "Making an image with generative AI uses as much energy as charging your phone", *MIT Technology Review* (2023).

Jha, A. K. *et al*. "A review of AI for urban planning: Towards building sustainable smart cities". *2021 6th International Conference on Inventive Computation Technologies (ICICT)*. IEEE, 2021.

Keeble, B. R. "The Brundtland Report: 'Our Common Future'". *Medicine and War*, vol. 4, no. 1 (1988), p. 17-25.

Luccioni, S., Trevelin, B. and Mitchell, M. "The Environmental Impacts of AI—Primer", 2024.

Muir, J. "My first summer in the Sierra", in: *British Politics and the Environment in the Long Nineteenth Century*. Routledge, 1911 (republished in 2023), p. 291-296.

Nishant, R., Kennedy, M. and Corbett, J. "Artificial intelligence for sustainability: Challenges, opportunities, and a research agenda". *International Journal of Information Management* 53 (2020): 102104.

Pastor-Escuredo, D., Treleaven, P. and Vinuesa, R. "An Ethical framework for artificial intelligence and sustainable cities". *Ai* 3.4 (2022), p. 961-974.

Rowe, N. "Millions of Workers Are Training AI Models for Pennies", *WIRED* (2023).

Strubell, E., Ganesh, A. and McCallum, A. "Energy and policy considerations for modern deep learning research". *Proceedings of the AAAI Conference on Artificial Intelligence.* Vol. 34. No. 09. 2020.

UN Habitat, "Envisaging the Future of Cities", *World Cities Report 2022*.

Van Wynsberghe, A. "Sustainable AI: AI for sustainability and the sustainability of AI". *AI and Ethics* 1.3 (2021), p. 213-218.

Vinuesa, R. *et al*. "The role of artificial intelligence in achieving the Sustainable Development Goals". *Nature Communications* 11.1 (2020), p. 1-10.

Wilson, C. and Van Der Velden, M. "Sustainable AI: An integrated model to guide public sector decision-making". *Technology in Society* 68 (2022): 101926.

Wu, C-J. *et al.* "Sustainable AI: Environmental implications, challenges and opportunities". *Proceedings of Machine Learning and Systems* 4 (2022), p. 795-813.

Yigitcanlar, T. and Cugurullo, F. "The sustainability of artificial intelligence: An urbanistic viewpoint from the lens of smart and sustainable cities". *Sustainability* 12.20 (2020): 8548.