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INNOVATION AND KNOWLEDGE-BASED GROWTH FOR LOW CARBON TRANSITIONS IN THE BUILT ENVIRONMENT. CHALLENGES AND OPEN RESEARCH QUESTIONS

Massimiliano Manfren

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Abstract

Humanity faces global challenges in climate change mitigation, water sustainability, and other areas. In order to address these challenges, radical innovation is needed to accelerate multiple "sustainability transitions" and create dynamism. Transitions research has focused on small niches and scales where empirical analysis can be done effectively. Niches and bottom-up initiatives for low carbon transitions in the built environment can help adjust policies and reconcile grand visions (top-down perspective) with ground implementation experiences (bottom-up perspective). Multiple factors can contribute to the creation of effective policies, and digitalisation and AI/ML applications, in the context of increasing automation, can be an opportunity to create new prosperity in a knowledge-based growth perspective, considering, however, the underlying critical assumptions, limitations and threats. Ten research questions deemed relevant for low carbon transitions from a bottom-up perspective have been proposed to generate multiple hypotheses for field testing.

Keywords

Sustainability transitions, Low carbon transitions, Innovation paradigms, Knowledge-based growth, Digitalisation, Built environment.

Massimiliano Manfren
Faculty of Engineering and Physical Sciences, University of Southampton, Southampton (United Kingdom)

Corresponding author:
e-mail: m.manfren@soton.ac.uk

1. INTRODUCTION

The United Nations (UN) initiative to achieve 17 Sustainable Development Goals (SDGs) and the increased focus on climate change agreements since the 21st Conference Of Parties (COP 21) in Paris in 2015 are just two examples of the growing awareness of the fundamental challenges that humanity is facing on a global scale regarding climate change mitigation, sustainable use of water, prevention of ecosystem degradation, reduction of waste production and disposal, reduction of poverty and inequality.

The ability to understand the dynamics of radical innovations and to combat inertia is at the heart of an emerging field of research dealing with "sustainability transitions" [1], which has brought an "agenda" to the attention of the research community [2] in recent years. From a socio-technical standpoint, the transition can be viewed as a "Great Reconfiguration" [3], in which the (quick) decline of existing technologies and services may coincide with the emergence of new ones at a rate never experienced before by humanity.

This "Great Reconfiguration" necessitates a horizontal and vertical integration of policy efforts towards "acceleration challenges" [4]. Horizontal integration due to the need to coordinate actions across different sectors of the economy (e.g. transport, energy, agriculture, etc.) and targeted cross-sectoral actions (e.g. education and fiscal policies); vertical integration due to the need to coordinate actions across scales, from international to national to regional and local initiatives. Both horizontal and vertical integration issues may delay acceleration in transitions.

The transition to a built environment with a low carbon footprint presents some peculiar aspects. The 6th Intergovernmental Panel on Climate Change Assessment Report [5] emphasises the importance of energy efficiency and renewables but also states that "sufficiency" – broadly defined as avoiding the demand for energy, materials, land, and water while delivering human well-being – has a crucial role in reducing greenhouse gas emissions. In order to reduce the carbon footprint of the built environment, "sufficiency" policies that decrease the need for new building spaces and make more efficient use of floor spaces in buildings will be crucial. For instance, "sufficiency" policies may consider dense and compact design, multi-functional spaces, shared spaces, and the repurposing of existing buildings as potential interventions.

The IPCC notes that behavioural change has the potential to decrease global emissions by 40 to 70 percent by 2050. Changes in lifestyle must occur on a systemic level throughout all facets of society. This includes, but is not limited to, increased recycling, decreased air travel, decreased meat consumption, and lowering thermostat temperature for heating. Motivation for behavioural change must be evaluated in accordance with socio-economic, awareness, risk perception contexts, etc. The persistence of behavioural changes will also represent a relevant problem to be monitored.

Closely related to the issue of behavioural change is the necessity of exploiting building efficiency and flexibility on a national scale to enable increased variable renewable-energy supply. Energy systems in numerous nations are undergoing rapid transformations as a result of increased renewable generation capacity. Grid decarbonisation through renewables is essential for low carbon transitions in the building sector (i.e., to decarbonise end-uses for heating, domestic hot water, etc.), but demand side policies are required as the increasing proportion of renewables necessitates a greater ability to adjust supply and demand balance dynamically (i.e. energy flexibility) to enable efficient and secure grid operation.

In this context, characterised by multiple concomitant changes, innovation models are especially relevant; for instance, the Quintuple Helix innovation model [6] is quite comprehensive and incorporates the aspects of academia, industry, government, civil society, and the environment. It is derived from the Quadruple Helix, and the helix (and perspective) of the "natural environments of society" is included. In turn, the Quadruple Helix added to the original Triple Helix innovation model vision (centred on academia-industry-government connections) a fourth helix representing the "media-based and culture-based public" and "civil society".

Already implicit in the original Triple Helix concept is the significance of higher education for innovation. On the one hand, the Triple Helix emphasises innovation and knowledge production in the economy; hence it is compatible with the concept of knowledge-based growth. On the other hand, the Quadruple Helix already promotes the knowledge society and democracy perspectives for knowledge production and innovation (by emphasising the role of "civil society").

According to the Quadruple Helix framework, the sustainable development of a knowledge economy involves co-evolution with the knowledge society. The Quintuple Helix emphasises the required socio-ecological transition of the twenty-first century's society and economy. Within the framework of the Quintuple Helix innovation model, the natural environments of society and the economy should also be considered drivers of knowledge creation and innovation, thus outlining opportunities for the knowledge economy (in multiple related research areas).

The underlying assumption of innovation models such as the Quintuple Helix model is that it is feasible to generate win-win conditions between ecology, knowledge, and innovation, hence building synergies between the economy, society, and democracy throughout socio-ecological transformations. Climate change is an ecological concern (substantiated by ample scientific evidence) to which innovation models should be used more effectively. A second essential assumption is that the (successful) exploitation of this potential could result in the formation of entrepreneurial ecosystems [7], which can have significant local and regional repercussions.

Increasingly, regions are viewed as eco-systemic aggregations of organisational and institutional entities or stakeholders with socio-technical, socio-economic, and sociopolitical conflicting, as well as converging (co-opetitive), goals, priorities, expectations, and behaviours, which they pursue through entrepreneurial development, exploration, exploitation, and deployment actions, reactions, and interactions. From a scientific standpoint, the proper conceptualisation of innovation ecosystems that are fractal, multi-level, multi-modal, multi-nodal, and multi-lateral arrangements of dynamic tangible and intangible assets is an incredibly difficult issue. Concurrently, there are several competing interests at stake.

Specifically, climate change and the financial and economic crises are bringing new difficulties on a global scale while also calling into question the quality of democracies. Detailing the relationship between the Green New Deal and the Quintuple Helix Model, Barth [8] examines this issue in great depth. In fact, the stagnant economic growth in established democracies, concurrent climate change and financial and economic crises, and the loss of biodiversity and depletion of resources all increase the risk of growing social disparity. These factors are already altering our daily lives and endangering the economy and the environment. Rethinking paradigms of innovation in light of accelerated change (transition) towards sustainability somehow becomes "the" present problem for humanity.

Progressive policymakers in developed democracies have hailed the "knowledge economy" and "knowledge-based growth" as a significant engine of future prosperity since the 1990s in reference to the multifaceted problem of knowledge. According to proponents, organisations and countries alike would flourish in the knowledge economy by nurturing knowledge from diverse viewpoints, so changing the emphasis away from capital investments, infrastructure, and machines, which dominated the "conventional" conception of capitalism. Even while manual labour and the goods and services it creates are not eliminated in the knowledge economy, their level of significance decreases. In principle, the role of "knowledge work" is that of increasing the efficiency of manual operations by introducing improved management practises or by automating some manual tasks.

In this paper, some of the assumptions of the "knowledge-based" growth paradigm are critiqued in regard to low carbon transitions for the built-environment, highlighting the mismatch between rhetoric and reality and proposing relevant research questions. While a high-level sketch of the problem of knowledge in relation to low carbon transitions is provided, which calls into question key assumptions of "knowledge-based" growth regimes, additional research is required to fully explore the future evolution of this concept in relation to breakthroughs in Artificial Intelligence (AI), Machine Learning (ML), and automation, as well as the effects these technologies may have on the global economy and environment. For this reason, in Section 2, key concepts needed to question "knowledge-based" growth paradigms are reported together with examples deemed relevant for their implication on the built environment. After that, in Section 3, the premises for the formulation of research questions in the broad area of "knowledge-based" growth in the built environment are reported; finally, 10 research questions are proposed in Section 3.3.

2. QUESTIONING THE ASSUMPTIONS OF KNOWLEDGE-BASED GROWTH IN LOW TRANSITIONS

The use of innovation models such as the previously mentioned Quintuple Helix [6] in a variety of situations demonstrates that policymakers continue to place a premium on knowledge-based growth. However, the mismatch between rhetoric and reality poses a concern, as it is obviously related to the danger of poor execution of policies supported by exaggerated expectations, arrogance, and insufficient understanding and conceptualisation of the underlying (multi-level) processes.

Since the focus is on growth [9], if the business models that are appropriate in the knowledge economy are capital-intensive tech corporations that require significant investment until they achieve market dominance, then education alone is unlikely to deliver social inclusion or competitive dynamism in and of itself. This is not intended to be a simplistic critique of education investment (how can we even conceive any type of human development [10] without carefully examining the dimension of education and knowledge growth?), but rather to identify pertinent research issues that must be considered when tackling the problem of accelerating knowledge creation and innovation in a setting of rising digitalisation and automation.

In the subsequent parts, the emphasis is placed on the identification of fundamental assumptions underlying the knowledge-based growth paradigm, the role of information and knowledge from science to policy, and, lastly, the issue of enhancing the public's understanding of the issues at stake (i.e. energy, environment and economy literacy). All of these factors are taken into account in an effort to provide a useful framework for identifying challenges and open research questions related to innovation and knowledge-based growth for low-carbon transitions in the built environment.

2.1. CRITICAL ASSUMPTIONS BEHIND THE KNOWLEDGE-BASED GROWTH PARADIGM

The fact that investment in education, deregulation of labour markets, increased financial rewards for entrepreneurs, and international openness could produce inclusive prosperity was an important aspect of the original knowledge economy's vision. In the past two decades, this vision has been challenged by issues such as business models, social inclusion, job polarisation, and conflicts between economic openness and regional development.

By starting from the problem of business models underlying knowledge-based growth, software companies were viewed as the ideal examples, but they were not the only type of business cited by proponents of the knowledge economy: financial services, creative industries, and science and engineering firms were also thought to have a high potential [11]. Unfortunately, the entry-level barriers in many of these cases are not as low as indicated by the theorists of knowledge-based growth, and businesses need to attract substantial capital investment to take these innovations through trial processes to market.

The assumed growth potential can be partially attributed to an idealised view of the digital industry in the 90s and to the business model of software companies in particular. In the software industry, a person who wishes to develop a new programme incurs minimal startup expenses, assuming they possess the necessary skills and have access to basic hardware. Manufacturing and distribution costs for digital products are negligible. Development costs for digital products are primarily comprised of their time.

Nonetheless, the evolution of business models in the Information and Communication Technology (ICT) industry has been substantial in the last two decades. In the case of Microsoft, the assets were intellectual property, and the advantage was determined by market dominance, at least in the beginning. They were selling a clearly defined product that was produced by the knowledge work of their employees, with near-zero marginal production and distribution costs once the product was ready for the market.

However, large tech companies such as Google and Facebook offer today their software services for free; they then sell market insights (to third parties) extracted algorithmically from users' interactions with their platforms, as well as advertising space on those platforms. This results in a shift in perspective as users, not employees (software programmers), become the primary assets. A large user base is essential for the creation of value for this type of business, and growing a large enough user base to make such a business model viable, constitutes a substantial entry barrier in the "new" digital economy.

In analogy to the ICT industry, the other types of businesses with a high potential for knowledge-based growth (e.g. engineering and science firms, creative industries, etc.) face difficulties when attempting to create economies of scale and network effects enjoyed by large tech companies. Financing emerging companies through lengthy periods of losses while they expand their user base calls for a substantial investment of capital. In analogy to what occurred in the software industry in the 90s, lowering the entry barriers for innovative businesses appears crucial for creating more dynamic conditions and stimulating business evolution through digitalisation across multiple sectors in a Quintuple Helix Framework.

However, how can these entry-level barriers be lowered when education, labour market flexibility, and increased financial incentives for entrepreneurial activities have not been sufficient to stimulate the market in recent years? In other words, if barriers to entry in the knowledge economy are higher than initially assumed, interventions such as public investment in education or tax cuts are unlikely to generate competitive dynamism on their own. This is a key point for reflection regarding the role of information and knowledge from science to policy and society, discussed in Section 2.2, and the role of literacy in data analytics in the energy and environmental sector, discussed in Section 2.3.

Another critical aspect of innovation from a policy-making perspective is its capacity to foster inclusiveness while fostering dynamism. One of the most alluring aspects of the knowledge economy (at least in its original vision) was its potential to facilitate social inclusion (defined as greater access to better work and concomitantly higher levels of material prosperity) via "social investment" in education and digital infrastructure.

The promise of an abundance of well-paid, highly-skilled jobs was essential to the marketability-based empowerment of workers and the appeal of the knowledge economy as a whole. However, the expectation that the knowledge economy will generate proportionally more new opportunities for better work and, therefore, that technological and economic change (i.e., innovation in Quintuple Helix Framework) will improve the lives of the vast majority of people has to be critically considered. From the perspective of the progressive case for the knowledge economy, what truly matters is whether the newly created work compensates workers adequately for the lost jobs.

This is discussed extensively by O'Donovan [12], who concentrates his attention on the problem of "automation anxiety" in our present economic landscape. Far from being a simple labour market problem, the coming wave of automation, described by different authors as a second machine age [13], a technological singularity [14], or a fourth industrial revolution [15], can result in equity and inclusion problems that can deeply affect society and threatens democracy.

In this context, the problem of "upskilling" becomes central as the knowledge economy did appear to offer workers the chance to move up the value chain and into more skill-intensive employment. These effects should be clearly monitored in time to ensure the limitation of the polarisation between new higher-skilled job opportunities and low-skilled, lower-paid roles and to prevent, to some extent, the disappearance of mid-skilled jobs while considering the issue of productivity.

The "upskilling" of workers is also relevant from the perspective of regional entrepreneurial ecosystems. According to the original knowledge economy vision, openness to globalisation was essential for countries to reap the benefits of knowledge-based growth. This allowed knowledge-intensive economies to export their innovative ideas and services to a variety of markets while importing the lower value-added physical goods and services they continued to consume. Additionally, economic openness facilitated the influx of talented workers, investment capital, and ideas, allowing knowledge-based companies to maintain and improve their global competitiveness.

Unsurprisingly, emerging economies have also prioritised investment in skills that enable them to compete at the top of global value chains, and increased interregional inequalities can mirror the previously mentioned risk of job polarisation due to the extremely uneven geographical distribution of high-skilled knowledge work that exists even in developed nations. This can exacerbate existing patterns of interregional inequality. In contrast, openness is currently threatened by critical factors such as geopolitical instability, which has an impact on energy and other vital commodities (such as raw materials), and by the impact of global supply chains on energy consumption and carbon emissions, which must be clearly accounted for in low carbon transitions. Understanding how business models can be implemented in the building sector and construction industry to overcome entry-level barriers and external factors, such as geopolitical instability, while simultaneously ensuring benefits and co-benefits (at the system level) is a major challenge in the energy transition.

2.2. THE ROLE OF INFORMATION AND KNOWLEDGE FROM SCIENCE TO POLICY AND SOCIETY

It is essential to begin with the issue of evidence when considering the role of information and knowledge in science, policy, and society. The evidence-based movement began with evidence-based medicine in the field of health. The scope of the movement was advocating for accountability in medicine based on a rigorous examination of which policies and practises were actually effective on the field. Experiment or trial concepts, and specifically the use of randomised controlled trials and systematic reviews of their results, are central to the evidence-based approach. While the initial emphasis on evidence-based programmes was primarily ethical, it led to criticisms related to the role of scientists on the one hand [16] and its technocratic stance and apparent neglect of power relations: «Policy-relevant facts are the result of an intensive and complex struggle for political and epistemic authority» [17], or to put it plainly, when «evidence-based policy become policy-based evidence». Indeed, an evidence-based policy can be used instrumentally to neutralise ideologies and to hide power asymmetries in decision-making processes.

A sceptical position regarding the role of science in policy action is the one by Collingridge and Reeve [18], which indicates two problematic assumptions regarding science-policy interaction:

1. policy action can be predicated on the accumulation of facts and the taming of uncertainty;
2. science has the power to provide dispassionate facts to adjudicate controversies.

The second assumption, in particular, is extremely interesting because the cases where science is called upon to adjudicate a policy appear to be associated with an escalating level of conflict, with opposing sides using scientific evidence to bolster their positions [19]. The definition of Post-Normal Science (PNS) proposed by Funtowicz and Ravetz in the 90s appears to be highly applicable to our present state condition. PNS is a novel approach to using science in situations where "facts are uncertain, values are contested, the stakes are high, and decisions are urgent". More extensively, the problem of the science crisis is analysed in detail by Benessia et al. in their book *Science on the Verge* [20].

Saltelli and Giampietro [21] clearly summarise the limitations of evidence-based policy, highlighting three relevant aspects. The first is the responsible use of quantitative information in quantitative storytelling, which proceeds primarily "via negativa" by falsifying the available options in terms of their feasibility (external constraints), viability (internal constraints), and desirability (compatibility with societal values). The second aspect, which is the one needed to test the salience and relevance of model-generated numbers, is the use of data and model appraisal strategies developed in the tradition of PNS, which are extensively reviewed by Carrozza [22] in a paper devoted to democratising expertise and environmental governance. The third key aspect is that quantification methods must maintain coherence across scales and dimensions (e.g., economic, demographic, energetic) when generating quantitative assessments with different metrics.

In this regard, while the Science of Science [23] transdisciplinary approach based on large data sets aims to study the mechanisms underlying the doing of science (e.g. choice of research problems, career trajectories and progress within a field) and to explain the underlying rationale, the pressure to publish, and the critical dimensions inherent to the definition of "impactful" science must be critically considered [24]. At the same time, new metrics, such as the ones proposed for open research [25], may be considered.

When referring back to the problem of science-policy interaction, the scholarly literature on science-policy interaction is typically divided between advocating that science and policy should be brought closer together or separated. However, Thoni and Livingston [26] found that science-policy practitioners were not as divided as the scholarly debate assumed them to be. They emphasise the importance of the discussion going beyond the relationship between science and policy and an unproductive battle between extremes. It is neither possible nor normatively desirable to demarcate "science", "policy", and other actors. While this discussion is of central importance to the actors of the Intergovernmental Panel on Climate Change (IPCC), greater emphasis should be placed on its relationship with society, where literacy could play a significant role, as discussed in Section 2.3, because we need to be able to capture the advantages (cost reduction, carbon emission reduction, etc.) and co-benefits (health, productivity, etc.) of re-inventing "efficiency" and encouraging "sufficiency" across several levels of society and built environment, exposing them transparently. This is deeply intertwined with quantitative storytelling.

The rigorous quantitative storytelling approach presented by Saltelli and Gianpietro [21] and discussed at the beginning of this section is highly related to the problem of critical thinking in the current debate around the interaction with society. This is discussed by Levitin [27] in *Weaponised Lies: How to Think Critically in the Post-Truth Era*, a reprint of *A Field Guide to Lies: Critical Thinking in the Information Age*. In a Post-Truth Era, the author proposes strategies to identify cognitive biases and logical fallacies and evaluate the credibility of information. The issues of recognising confirmation bias and belief perseverance, which lead to rash decisions and faulty reasoning, assessing the reliability of studies or surveys, and, for science and health news, searching for control groups and avoiding single-study results appear to be particularly pertinent today (especially after COVID-19 pandemic). In addition, the author cautions that "statistics are not facts"; numbers, statistics, charts, and graphs can (inadvertently or intentionally) be skewed to support particular viewpoints and should not be taken at face value. This can imply that people are susceptible to being "misled by numbers and logic".

Similarly, in the book *Weapons of math destruction: How Big Data Increases Inequality and Threatens Democracy* [28], O'Neil analyses how biases in the modelling process can lead to "automated" decisions that harm the poor, reinforce racism, and exacerbate inequality. Rather than being abstract, these problems are already experienced in numerous fields, such as insurance, advertising, education, and law enforcement. In light of these issues (already evident at the societal level), we must improve the data and statistical literacy level in the energy and environmental sectors, as will be discussed in the following section. This could contribute to the democratisation of science-policy-society interactions and stimulate new pathways for the knowledge-based growth illustrated in Section 2.1.

2.3. LITERACY REGARDING DATA ANALYTICS IN THE ENERGY AND ENVIRONMENTAL SECTOR

As described in Section 2.2, the use of mathematical modelling and indicators may create a false impression of precision but does not necessarily reveal "uncomfortable knowledge," which is typically avoided in policy discussions due to the potential for conflict. As proposed by [21], rigorous quantitative storytelling must be supported by accurate estimates, which can be achieved by making energy and environmental data more readily available in both open and synthetic forms. Regarding the built environment, digitalisation can improve the livability of cities in a number of areas, including healthcare and well-being, economic development and housing, engagement and community, management and operation of mobility, water, and energy infrastructures [29].

Open energy models and related data are crucial for promoting open research practises and fostering effective science-policy interaction [30]. By enhancing them compared to the current state of the art, for instance, they can promote multidisciplinary research that addresses the co-evolution of energy technology and human behaviour more transparently and, more generally, they can enhance the interaction of numerous linked models and data. Focusing on energy and environmental data in the built environment, the paper by Ahmad et al. [31] examines in depth the social, economic, environmental, and legislative drivers for the installation of metering technologies. While energy laws and regulations vary from country to country, there is a high level of technological standardisation and widespread use of advanced metering technology, which could serve as a basis for data collection at scale.

In light of the fact that the technology to collect energy data at scale already exists and that energy information is accessible (although not always easily accessible), it becomes possible to leverage literacy to make energy data understandable to a broad audience and facilitate change. This involves addressing the technological and social aspects of energy. In fact, researchers from a variety of fields are paying increasing attention to the concept of energy literacy. However, the energy literacy literature is characterised by a wide variety of definitions and techniques, making comparisons and the generalisability of results difficult. For example, Van den Broek et al. provide a classification framework for the numerous conceptual and practical approaches to household energy literacy [32]. Energy literacy is essential for informing people about their energy consumption habits and altering their mindset. As demonstrated by a number of studies, energy literacy encompasses not only the cognitive domain but also the affective and behavioural domains [33]. Essentially, it involves knowledge of technologies and devices, energy-saving actions, financial considerations, and other related factors. Better knowledge can pave the way for more innovative services and technologies [34], which must be evaluated from a whole life-cycle perspective, taking into account Life Cycle Assessment (LCA) and Life Cycle Cost (LCC). In conclusion, literacy is crucial to target behavioural change and make end-users behave rationally as prosumers (producers-consumers) in the future energy market, where greater investment in energy efficiency is needed.

3. OPEN RESEARCH QUESTIONS REGARDING LOW CARBON TRANSITIONS IN THE BUILT ENVIRONMENT

As described by Geels and Turnheim, low-carbon transitions in the built environment are part of a "Great Reconfiguration" (multi-level) process [3]. In order to meet IPCC-recommended environmental objectives, these transitions process must be accelerated. For this reason, innovation models are especially relevant today, and the Quintuple Helix innovation model [6], which includes the environment as the fifth helix, emphasises the problems of innovation to address sustainable development, including the problem of climate change.

Innovation models such as the Quintuple Helix model assume that creating win-win conditions between ecology, knowledge, and innovation is possible, thereby creating synergies between the economy, society, and democracy during socio-ecological transformations. It is believed that these transformations will have a significant impact on the knowledge society and knowledge economy. Thus, knowledge-based growth (e.g. growth for good [9]) is viewed as an opportunity to engage capitalism in the fight against climate catastrophe, thereby generating new employment opportunities.

As discussed in Section 2.1, this vision has been challenged over the past two decades by issues such as the evolution of business models, social inclusion, job polarisation, economic openness and regional development. While the knowledge dimension remains essential to innovation and fostering inclusiveness while promoting dynamism, the entry-level barriers in the knowledge economy are higher than initially thought. Policy interventions such as public investment in education or tax cuts are unlikely to generate competitive dynamism on their own. For this reason, Sections 2.2 and 2.3 discussed, respectively, the role of information and knowledge from science to policy and society and the significance of data analytics and literacy in the energy and environmental sector (as well as their economic implications).

This section aims to move from general considerations to specific issues to be addressed during the transition to a low-carbon built environment. In Section 3.1, some of the most pertinent global and local problems are summarised. In Section 3.2, issues of local innovation, productivity, and acceleration of low carbon transitions are discussed, and in Section 3.3, ten research questions are posed for field testing.

3.1. GLOBAL AND LOCAL SCALE PROBLEMS RELATED TO LOW CARBON TRANSITIONS IN THE BUILT ENVIRONMENT

The paper by [35] documents in detail global and local scale issues associated with low carbon transitions in the built environment, related to its present and future energy consumption, which are summarised below.

First of all, greenhouse gas Emissions and Global Climate Change: The building and construction sector accounted for about 39% of the process-related carbon dioxide emissions in 2018 [36]. Subject to the degree of the current and future decarbonisation of the building energy needs and of the power generation system capacity dedicated to buildings (which is almost 50% today), the building sector may be carbon neutral by 2050 or later, or may continue to be carbon intensive.

The second issue, future scenarios on the energy consumption of buildings, propose pathways to minimise the energy consumption of the sector by 2050 or later through intensive use of clean electricity and improved energy efficiency measures in buildings. However, such an objective requires the adoption of intensive green policies and a considerable increase in investments. No explicit engagements or even promises towards the adoption of such policies are undertaken, and there is a real risk that the energy consumption and the production of greenhouse gases in the building sector will continue to increase.

The third issue is the high global environmental impact. The building sector has a considerable impact on the global environment. The sector produces pollution and waste and consumes resources and raw materials. Future decarbonisation of the building sector is also associated with extensive additional use of raw materials. An increase in manufacturing efficiency, recycling, and adherence to the principles of the circular economy seems to be a reasonable policy; however, it is an open and difficult challenge for the construction sector.

The fourth issue is overpopulation and fast urbanisation. According to the United Nations [37], the world population may increase by up to 11 billion people by 2050, with most of the new population living in cities, increasing the urban population up to 6.5 billion people capacity of the building sector to meet the additional needs for new housing, commercial and community buildings and infrastructures.

The fifth issue is urban overheating and local climate change. Intensive urbanisation and industrialisation result in a considerable increase in the ambient temperature in cities. The phenomenon, known as Urban Heat Island (UHI), is well documented in many cities around the world. Higher urban temperatures have a severe effect on the energy consumption of urban buildings while impacting the environmental quality of cities, urban health and survivability levels. Therefore, the design and implementation of advanced mitigation and adaptation policies in cities are crucial.

The sixth issue is social inequalities, poverty and ethical issues. The provision of healthy and adequate shelter for everyone is a difficult challenge for the building sector when there are more than 1 million people living in slums, and the number is constantly increasing. In parallel, more than 150 million people in developed countries cannot afford to cover their basic energy needs. Eradication of poverty and energy poverty requires the implementation of generous, well-designed housing programs to enhance resilience in the corresponding countries and amortise social inequalities.

All the issues summarised above can have dramatic consequences on a global scale and are also extremely relevant for the future of the EU. The coordinated updating of existing policies together with well-targeted and innovative EU, national and local initiatives are required to deliver the required reductions of GHG emissions from buildings in Europe to nearly zero, as discussed by Norton et al. [38]. Three key aspects are identified in the paper: (1) ensuring that measures to reduce energy and GHG reductions also enhance the health and well-being of building occupants, (2) integrating decarbonisation of electricity and heat supplies for buildings with the decarbonisation of industry and transport, (3) reusing and recycling to reduce embodied GHG emissions in building materials, components and processes used in both the construction of new buildings and in building renovations.

The decarbonisation of buildings is an opportunity to develop new products and services that have the potential to create new high-skilled jobs, and this has clear political implications and can be incorporated into a more ambitious view of the transition pathways towards a low-carbon world [39]. Obviously, decoupling global economic growth from carbon emissions remains an open question. In this regard, Kaya Identity provides a useful method for analysing the similarities and differences between nations in their carbon intensity. Recent research by Bigerna and Polinori [40] social, and technological targets, such as continuous prosperity, growth, and increases in energy production and reductions in fossil fuel (FOS, for instance, demonstrates the convergence of the Kaya Identity components for the EU Member States towards the ambitious 2050 decarbonisation targets. Comparative Kaya Identity studies conducted on a global scale could provide valid evidence and insights that can aid in guiding policies toward long-term carbon reduction goals.

3.2. LOCAL INNOVATION, PRODUCTIVITY AND ACCELERATION OF LOW CARBON TRANSITIONS

While many sustainability challenges are global, as discussed in Section 3.1, the majority of transitions research has focused on the emergence of innovations in small niches and, in general, on a scale where the interactions between multiple “helixes” (e.g. in a Quintuple Helix innovation model) can be empirically analysed. Further, most of the studies regarding the acceleration of innovation have focused on the immediate technological and economic drivers of acceleration (e.g. R&D investment, upscaling, taxes and subsidies), while substantial policy and research efforts are needed to address "acceleration challenges" [4].

Addressing the "acceleration challenges" may require new governance structures and more active policies aimed at steering and orchestrating change: «Ensuring that socio-technical systems move towards greater sustainability is a major challenge for governments, but also for civil society. At the core of such transitions is a shift in governance structures that not only allows change to occur but also directs and orchestrates some of the changes» [41].

As stated in Section 3.1, simple interventions are unlikely to be sufficient to generate the necessary dynamism to promote the technological and behavioural change required for low-carbon transitions. The ability to effectively utilise data and insights from bottom-up initiatives and pilot projects to steer policies in a dynamic manner appears crucial. On the other hand, the technological potential of automation, utilising Artificial Intelligence (AI), Machine Learning (ML), and digitalisation, has only been partially exploited, and future scenarios are quite open and not necessarily constrained by pre-defined trajectories [42].

GATO [43], a highly adaptable artificial intelligence model (a "generalist agent" that can perform over 600 distinct tasks, like operating a robot, captioning images, detecting objects in pictures, etc.), was recently unveiled by DeepMind, a division of technology conglomerate Alphabet. We can honestly claim that there are few technologies that stir the imagination as AI does, and the hype around artificial general intelligence (AGI) is tangible. GATO is likely one of the most advanced artificial intelligence systems on the globe that is not dedicated to a particular function.

The idea that AGI, unlike traditional AI, will learn a task by intuition and experience, akin to a human, rather than requiring a large quantity of data to do so (being pre-trained or programmed to solve a certain set of issues), makes it very intriguing. Nonetheless, contemporary AI technologies combining supervised, unsupervised and reinforcement learning have quickly revolutionised the machine learning field leading already, for example, to generative AI applications such as ChatGPT by OpenAI, launched recently.

More modestly, we could say that while Artificial Intelligence (AI) is frequently manifested today in the form of complex deep neural networks, simpler Machine Learning (ML) techniques, whose inner workings are understandable, might be useful to tackle small- and medium-sized statistical, data mining and automation problems. Despite not being as fashionable as deep learning/AI, simple, reliable and scalable ML approaches can have a positive economic (as well environmental) impact (in a positive sense) in many applications where accurate predictions and decisions are crucial.

The fractal, multi-level nature of innovation and the fact that there are multiple transition pathways and specific low-carbon innovations to reduce emissions in each (sub)sector, which must be identified, designed, and managed, indicate a wide range of relevant (potential) applications for data-driven ML methods. As discussed in Section 2.1, the existing limitations with respect to business models, when there exists a relevant technical potential for savings, could be mitigated by simple and effective digitalisation strategies and ML applications could help lower the entry-level barrier to knowledge-based growth.

It is difficult to say whether AI/ML evolution will help overcome economic stagnation and create future jobs and prosperity through grassroots innovation (Phelps, 2014) while providing solutions to the problems discussed in Section 3.1. However, the challenge of maintaining technical innovation with a "human in the loop" approach to automation, fostering data analytics literacy and education rather than merely stoking technology hype cycles [44], is definitely worth attention.

In recent years, there has been a proliferation of artificial intelligence (AI) strategies designed by different countries to maximise benefits while minimising risks. As indicated in comparative studies, the policy is fundamental, and the differences between, for instance, the EU and US are significant [45]there has been a proliferation of artificial intelligence (AI. Simultaneously, numerous organisations have launched a vast array of initiatives to establish ethical principles for the adoption of socially advantageous AI. Also in this instance, the proliferation of principles threatens to overwhelm and confound.

The problem is analysed by Floridi and Cowls [46], who propose five core principles to synthesise the plethora of emergent instances in this research field. To simplify as much as possible, four of them are fundamental bioethical principles: beneficence, nonmaleficence, autonomy, and justice. The fifth principle (specific to AI) is explicability, which includes both intelligibility (as an answer to the question "how does it work?") and accountability (as an answer to the question "who is responsible for the way it works?") in the epistemological and ethical senses, respectively.

Far from being generic, Floridi and Cowls' principle of "explicability" requires a clear commitment to the creation of AI/ML applications and technical aspects such as "explainability" (i.e. the extent to which the internal mechanics of a machine-learning algorithm can be explained in human terms) and "interpretability" (i.e. the extent to which a human can understand the rationale behind model output, given a change in input, and the algorithmic logic can be quickly inspected) are called into question. These two technical factors are essential to guarantee the possibility of inspecting, auditing and trusting the AI/ML model, contributing (at least partially) to minimise the risks outlined in Section 2.2.

This ethical dimension of AI/ML has direct implications for the construction industry in the context of increasing digitalisation. Emerging technological solutions for the digitalisation of design and construction processes, digitalisation of the supply chain of the construction industry, predictive control of energy demand, predictive maintenance of construction technologies, peer-to-peer energy trading within energy communities, and many other possible applications are heavily dependent on data-driven (AI/ML) models.

For this reason, the "explicability" principle must be considered (due to the use of AI/ML models) alongside the other decision-making principles discussed in Section 2.2: feasibility (e.g., external constraints determined by the use of natural resources [47]), viability (internal constraints, specific project factors), and desirability (e.g. compatibility with societal values, closely linked to behavioural change issue). At the same time, literacy can improve comprehension of new technologies and their effects and promote social acceptability and desirability for the wider public.

3.3. OPEN RESEARCH QUESTIONS RELATED TO INNOVATION AND KNOWLEDGE-BASED GROWTH

The growing awareness of the fundamental challenges humanity faces on a global scale, including climate change mitigation, the prevention of ecosystem degradation, and other major problems, necessitates an acceleration of innovation-supporting policies, as already discussed. The ability to grasp the dynamics of radical breakthroughs and to fight inertia is at the centre of a growing field of research dealing with "sustainable transitions" and "low carbon transitions" are part of it.

Most transition research has focused on the emergence of innovations in small niches and, in general, on scales where empirical analysis can be conducted effectively on the ground. As seen in Section 3.1, global scale problems associated with low carbon transitions for the built environment have direct (and frequently dramatic) implications at the local scale, and it is necessary to reconcile the grand visions (i.e. the top-down perspective) surrounding the aforementioned challenges with the implementation experiences on the ground (i.e. the bottom-up perspective).

The applications enabled by digitalisation and AI/ML techniques could, in principle, align (at least partially) with the benign vision of knowledge-based growth, whose critical assumptions and limitations were analysed in Section 2.1. Nonetheless, multiple technical and ethical issues must be considered, and ten research questions, deemed pertinent from a bottom-up perspective, are posed hereafter:

1. Are business models for knowledge-based growth appropriate for low carbon transitions in the built environment (e.g., are mechanisms and indicators used in decision-making processes fit for purpose, particularly in a long-term, whole life-cycle perspective?)?
2. Are accounting methods used transparently from a system perspective (e.g., do they consider the

potential shifting of impacts from one system to another?)?

3. Is the human dimension considered and correctly accounted for (e.g., all the aspects connected to behavioural change, which may have direct and indirect impacts on carbon emission)?
4. Are uncertainty and risk dimensions accounted for properly (e.g., in relation to energy pricing dynamics, behavioural change, etc.)?
5. Are low carbon transitions promoting innovation, digitalisation, productivity and competitiveness (i.e. do they actually foster innovation compared to the state-of-the-art? How can we measure it?)?
6. Is AI/ML "digital twin" paradigm suitable for low carbon transitions in the built environment (e.g. how can we design systems of interconnected AI/ML models able to deal with the multiplicity of aspects involved?)?
7. Are ethical principles considered with respect to digitalisation, automation and AI/ML use in projects?
8. Are literacy and analytics changing the perspectives in decision-making processes, or are other contingent factors more influential?
9. What job opportunities are generated in the low carbon transitions in the built environment, and is job polarisation a relevant problem?
10. What can be the role of small-scale projects in promoting skills development and regional ecosystems of innovation from a globalisation perspective?

These questions can be expanded upon and can lead to the formulation of hypotheses that can be then tested on the ground in small niches and bottom-up projects (for the reasons outlined previously), which can, in turn, generate policy-relevant insights if experiments are appropriately conducted, and research data is made available in open and accessible formats.

4. CONCLUSION

The fundamental challenges humanity faces on a global scale regarding climate change mitigation, sustainable water use, prevention of ecosystem degradation, reduction of waste production and disposal, and regenerative agriculture are the focus of "sustainability transitions" [1] research. Transition processes can be considered a "Great Reconfiguration" from a socio-technical perspective [3]. A "Great Reconfiguration" requires horizontal and vertical policy efforts to accelerate innovation policies under new inexperienced conditions. Socio-technical change can be seen as an opportunity for radical innovation (as part of paradigms like Quintuple Helix) and for entrepreneurial ecosystems at the local and regional levels.

One of the underlying assumptions in innovation paradigms such as Quintuple Helix is that knowledge-based growth can bring several advantages. Some of the "automatic" presuppositions behind innovation paradigms have been critically analysed in Section 3.1, and the problematic science-policy-society interaction and tensions have been discussed in Section 3.2 in relation to the development of policies. Addressing these tensions and increasing the level of literacy regarding energy and environmental themes (as well as their economic implications) appears crucial today, as indicated in Section 3.3, together with initiatives nudging behavioural changes, which may have a fundamental impact on low carbon transitions.

Further, traditionally innovation policies have focused on the immediate technological and economic drivers of acceleration (e.g. R&D investment, upscaling, taxes and subsidies). However, "traditional" policies are unlikely to deliver prosperity, social inclusion and competitive dynamism in and of themselves in a knowledge economy. Further, sustainability transitions research has focused on small niches and scales where empirical analysis can be done effectively. Insights from niches and bottom-up initiatives for low carbon transitions in the built environment can help adjust policies quickly and reconcile grand visions (top-down perspective) with ground implementation experiences (bottom-up perspective).

On the one hand, multiple factors can contribute to the creation of effective policies, including rethinking the role of information and knowledge from science to policy and society (i.e. science-policy-society interaction in a knowledge society) to promote literacy. On the other hand, digitalisation and AI/ML applications, in the context of increasing automation, can be an opportunity to create new prosperity in a knowledge-based growth perspective, acknowledging opportunities and threats. Emerging technological solutions for the digitalisation of design and construction processes, digitalisation of the supply chain of the construction industry, predictive control of energy demand, predictive maintenance of construction technologies, peer-to-peer energy trading within energy communities, and many other possible applications are relying heavily on data-driven (AI/ML) models.

Far from being a generic instance, Floridi and Cowls' ethical principle of "explicability" [46] implies a serious commitment in relation to "explainability" and "interpretability". These two technical aspects are essential to guarantee the possibility of inspecting, auditing and trusting AI/ML algorithmic logic and models, making them more "transparent" and contributing, at least partially, to reduce the risks of their application.

Considering ground implementation experiences, multiple research questions can be formulated, involving, for example, how business models are conceived (e.g., are decision-making mechanisms and indicators fit for purpose, especially in a long-term, whole life cycle perspective?) and what are the state-of-the-art advances (are digitalisation, productivity, and competitiveness dimensions addressed?) determined by low carbon transitions. Quantification of uncertainty and risk, transparency of modelling strategies, and suitability of AI/ML-based paradigms like "digital twins" are also crucial issues in combination with human factors.

Finally, Section 3.3 research questions aim to stimulate the development of hypotheses that can be tested in small niches and bottom-up projects, which can, in turn, generate policy-relevant insights if experiments are appropriately conducted and research data made available in open and accessible formats. Creating a knowledge society in a knowledge economy and promoting knowledge-based base growth strategies require targeted and thought efforts rather than grand visions inflated by rhetoric and hubris.

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