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Emerging Technologies for Decarbonization in Building Sector: Evidence From Patent Inventions

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ABSTRACT

According to the "Global Building Construction Industry Report" released by the United Nations Environment Programme, the carbon emissions generated by building operations alone have reached about 10 gigatonnes in 2021. With its rapid and large-scale urbanization, China is one of the main contributors to the global carbon emission. Decarbonization thus became the central task for China's building sector. Emerging technologies, especially digital technologies, provide the potential for building decarbonization, which is possibly realized through the full life cycle of buildings. Yet, understanding towards a localized innovation of these technologies and how they engage carbon reduction remains far from clear. Moreover, due to the large scale and massive nature of buildings, threshold of business applications of these emerging technologies is high thus discussed insufficiently. Draws on literature and expert review, this research discloses the linkage of 14 specific emerging technologies and building decarbonization in a full life-cycle (the planning, construction, use/operation and demolition phases) of buildings. Yangtze River Delta, one of the fastest urbanizing and largest market for building sector in China, is selected for observation. With an OT-matrix and over thousand sorted patent inventions, it identifies that contribution of the emerging technologies to building decarbonization is most secondary. Quite a few general-purpose technologies (e.g., blockchain, IoT), which possibly disrupt the industry fundamentally, are almost vacant. State owned enterprises are the main actors in the technology innovation, followed by university and public research institutions. There is a mixed location of downtown, periphery and outskirts characterizing the spatial pattern of these technologies. The findings help to recommend policy makers, firm managers, professionals and researchers in accessing and developing disruptive technologies for low carbon building industry, and promote business application in this field.

Keywords: Emerging technology, Building sector, Carbon reduction, Patent inventions, Yangtze river delta, China

INTRODUCTION

Released by the United Nations Environment Programme, the latest "2022 global status report for buildings and construction – toward a zero-emissions, efficient and resilient buildings and construction sector" indicated that construction activities have resumed to pre-pandemic levels in major economies. Carbon emissions from the building operation have surpassed the previous peak in 2019, reaching about 10 gigatonnes ($GtCO_2$) in 2021. The Paris Agreement were then reiterated at the 26th Conference of the Parties to the United Nations Framework Convention on Climate Change (UNEP, 2022). Lack of fundamental structural changes of the buildings sector to reduce energy demand and consumption was the main reason for the rebound of carbon emissions. Invention and application of the state-of-art technologies in building industry were in shortage due to the complexity to incorporate smart, often virtual and digital, technologies into physical environment (Opoku et al., 2021, Gawer, 2014). It is thus imperative to clarify how disruptive technologies can possibly be applied to building sector and assimilate advanced technology for building decarbonization throughout its full life cycle—planning and design (PD), construction (C), operation and maintenance (OM), and end of use or demolition of buildings (ED).

EMERGING TECHNOLOGIES AND DISRUPTIVE POTENTIAL FOR BUILDING DECARBONIZATION

Abiotic building projects generate substantial carbon emissions throughout its life cycle and their giant and weighty nature has raise substantial environmental concerns. Consulting database of Scopus and Web of Science, this research traces 14 emerging technologies of potential for building decarbonization and for reconciling negative environmental impacts of buildings. In the phase of planning and design, decarbonization can be achieved through the improvement of efficiency, accuracy and integration. Building information modelling (BIM) enhances design for saving material and supports the actualization of low-carbon idea (Charef and Emmitt, 2021). 3D BIM is possible to simulate energy consumption, thereby optimizing the design of space geometry and material use for energy-saving (Charef, 2022). To achieve this, designers shall incorporate computational modeling or algorithm and combine BIM and AI to promote efficiency of design and materials use (Salet and Wolfs, 2016, Lagaros and Plevris, 2022). Building design can also be assisted by IoT and blockchain that can speed up the flow and sharing of information (Teisserenc and Sepasgozar, 2021), and by AI that enables automatic adjustment and optimization of low-carbon scenario through data mining and machine learning.

Construction is a crucial phase for decarbonization, during which disposal of building debris is the key to minimize the environmental impacts. Drones (also known as unmanned aerial vehicles) can help a precise onsite aerial surveying and reduce carbon emission compared with traditional aerial photography (Li and Liu, 2019). Robotics enables automatic operation and improves the accuracy of on-site construction work. 3D printing is one of the most promising technologies for zero waste construction. It opens the potential to take advantage of state-of-art environmentally friendly materials such as biodegradable/biocompatible/natural polymer and to produce sophisticated structure and architectural model with lower cost and higher efficiency (Verma et al., 2022). Modular construction as an off-site production system is another technic method to achieve less resource wastage. Researchers found that off-site modular construction, especially off-site prefabrication, enables waste multiply reduced as the recycling system in a factory environment is much more robust than that on-site. Prefabrication can also be aided by 3D printing and prefabricated modular buildings are able to minimize noise, transport and disruption on environment(Loizou et al., 2021, Ferdous et al., 2019). There is also construction waste recycling robot help waste management (Wang et al., 2019). In mining industry, sensor-based sorting technique facilitates construction and demolition waste recycling.

In building operation and maintenance, electricity power supply relying on traditional fossil fuel is the main factor contributing to carbon emission, use of renewable energy thus is a critical step for nearly zero energy buildings (NZEB). Solar photovoltaics are most common technologies in NZEBs (Feng et al., 2019), often installed on rooftop and sometimes on facades in high-rise buildings. To utilize renewable energy and meet architectural requirements, professionals and researchers proposed building-integrated photovoltaic (BIPV) modules and systems to optimize buildings' energy-saving performance (Martín-Chivelet et al., 2022). There is also other renewable energy occasionally applied, e.g., wind and water. Integrating cyber physical technologies such as IoT and cloud computing into the application helps establish smart-building systems for accurate energy control. Building system's sensitivity on temperature, thermal comfort, humidity and danger can be enhanced by applying sensors and wireless in favour of automatic building maintenance (Cheung et al., 2018, Debrah et al., 2022). Performance of the system also benefits from AI that provides real-time feedback and regulation based on instant information transfer and exchange enabled by the IoT, cloud computing, and blockchain (Debrah et al., 2022, Won et al., 2022). An example would be automatic building diagnosis for abnormal operation monitoring and fault detection by which the 'black holes' of energy consumption caused by unexpected man-made defects or equipment defects in heating, ventilation, and air conditioning can be identified (Allen et al., 2015). Energy-saving and environmental protection materials such as polymer nanocomposites are also essential for building decarbonization.

Decarbonization in end-life maintenance or demolition of buildings is equally significant but often less noted. With the development of VR and AR, emulation technology makes remote repair possible, thus could indirectly reduce carbon consumption for building refixing or regeneration. Like construction, demolition work produces substantial architectural garbage, for which recycling robots and related control system will greatly help. Tearing down buildings is also dangerous that workplace injuries, illnesses, and fatalities shall be avoided. Technologies of sensors, wireless communication, cloud computing, AI with advanced machine learning, and BIM have created opportunities for establishing safety management systems of buildings (Asadzadeh et al., 2020), helping refrain work redundancy and loss of energy. The disruptive potential of blockchain technology can go beyond the life cycle of buildings, extending to the bid, deliver, and secure payment by connecting different technologies, devices, and stakeholders through peer-to-peer networks. Doing so, work delay or redundancy can be avoided and its collaboration with BIM is named 'Blockchain of Circular BIM things' (Teisserenc and Sepasgozar, 2021, Turk and Klinc, 2017) for energy saving.

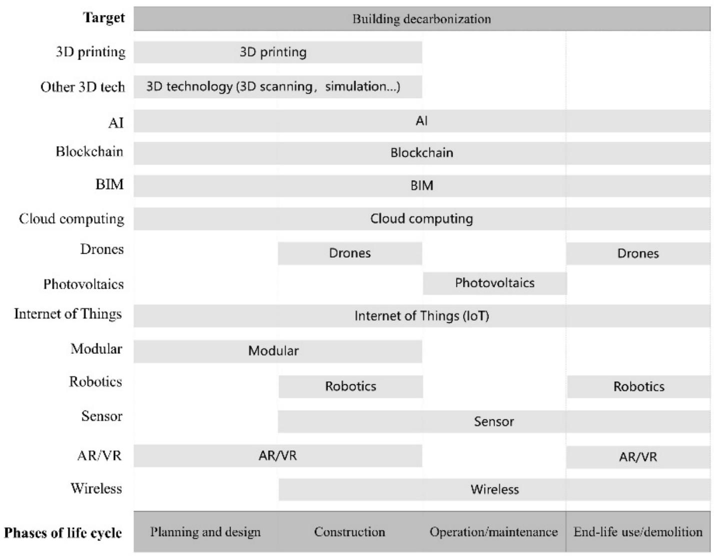

Figure 1: Potential of 14 technologies in building decarbonization.

PATENT INVENTIONS OF THE EMERGING TECHNOLOGIES IN BUILDING SECTOR

To understand how these technologies innovate, adjust or being applied in the local, this research focuses on Yangtze River Delta, one of the most urbanized and largest market for building industry in China, and collected patent data of each technology applied from this region. Initial collection encompasses over 7 million records and over 100 thousand records left after filtering valid patents in section E of building and fixed construction (Figure 2). With keywords search and data cleaning, the research sorts out around three thousand raw records of the 14 technologies.

Patent inventions of the 14 technologies have overall increased since 2010. Modular (1021, 33.84%), robotics (502, 16.71%), photovoltaics (490, 16.24%), wireless (274, 9.08%) and sensors (263, 8.72%) have most patent inventions, followed by 3D printing (149, 4.94%), IoT (136, 4.51%), BIM (62, 2.06%), other 3D technologies (58, 1.92%) and drones (34, 1.13%). AI, cloud computing, VR/AR and blockchain only have less than 10 records each (Figure 3).

Most technologies are applied in construction and operation phases, which generate most carbon emission in building sectors (Table 1). 3D printing is mainly applied to produce walls for architecture, or structures for infrastructures such as bridges or tunnels so that construction waste can be reduced. Most 3D printing technologies are used at the phase of construction, either on-site or off-site, but a few records show that it is also occasionally used in

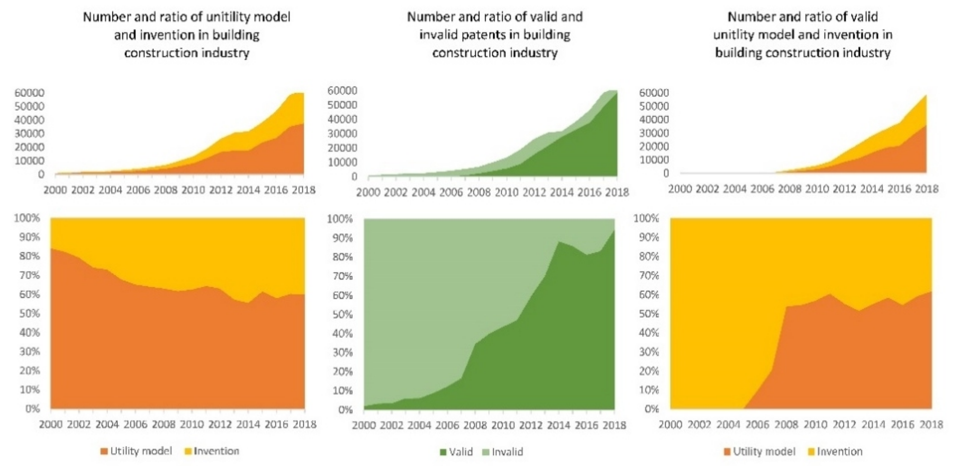

Figure 2: Number and ratio of patents applications in building sector in YRD (2000-2018).

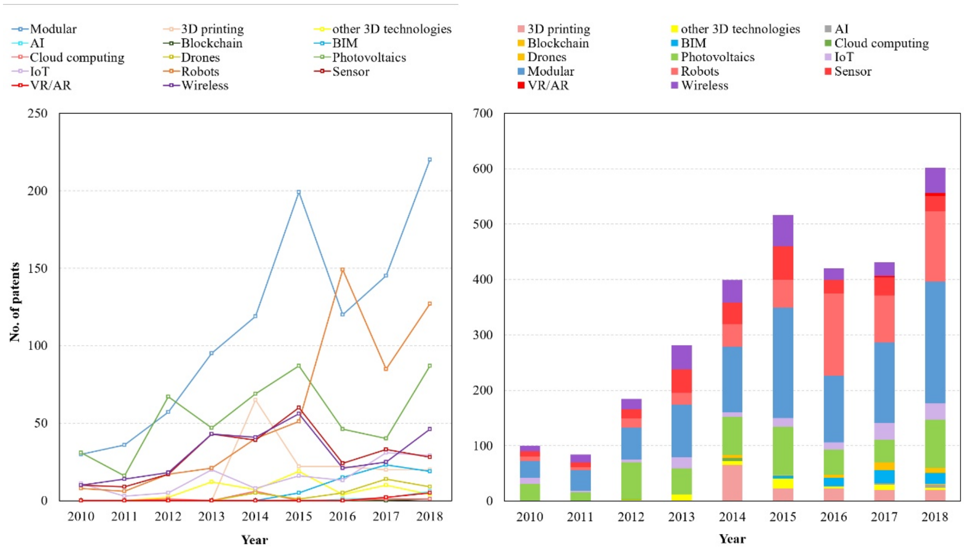

Figure 3: Trend for patent applications of the fourteen technologies during (2000-2018).

maintenance or renovation. 3D printing is occasionally mixed with sensors, wireless, robotics and intelligent technology (not AI). The most commonly mixed technologies with 3D printing are modular, which enables rapid construction with minimized waste on-site. Other 3D technologies primarily deploy 3D concept to simulate scenes or structures, help fix or better maintain buildings. 3D-related technologies are mostly employed to optimize use experiences or warn danger through simulation. Different from 3D printing, the role of other 3D applications in waste reduction is minimal. Other 3D technologies also mix with 3D printing and modular but are more often combined with sensors and VR/AR. AI, blockchain, cloud computing and VR are rarely applied to building sector. The limited inventions contribute to efficiency improvement of construction operation and maintenance but combination of AI, blockchain, and other technologies is inadequate. Though quite many records serve multiple, overlapping objectives and are designed to be as intelligent as possible, few are fused with AI. BIM is overwhelmingly used during construction for large scale buildings and sometimes bridges and infrastructures. Integrated modular technology, BIM is committed to reduce waste and environmental impacts through improving accuracy and efficiency of construction. Drones are mostly used to improve construction and maintenance efficiency of roads, bridges and recently architectures. Photovoltaics enables the use of renewable energy for energy-saving. Photovoltaics also combines modular assembly to avoid waste and speeds up installation. IoT often serves as platform technology for data sharing and information flows. Yet, most applications are small in scale, in windows or doors for anti-theft purpose. They also assist intelligent construction monitoring, operation and transportation management. As prefabricated constituent, modular primarily promotes work efficiency and reduces construction waste on site, thus contributes most to construction. Robotics mainly substitutes work once shall be conducted by human beings, especially those dangerous, environmental-unfriendly, and repetitive tasks, since automation improves precision, efficiency and reduces unnecessary resource consumption. Sensors often combine wireless technology for instant data and information transfer, thus enhance efficiency of building and construction operation. It is widely used to monitor operation status and to respond properly for energy and resource saving and supply (especially water supply). It also occasionally combines photovoltaics to utilize renewable resources. Wireless technology has similar application as sensors.

Table 1. Matrix analysis of emerging technologies in full life cycle.

Tech-life cycle matrix		**Applied Life cycle**			
		PD	**C**	**OM**	**ED**
Specific technology	3D printing	-	149	2	2
	Other 3D		24	31	
	AI			9	
	Blockchain			1	
	BIM	1	62	3	
	Cloud computing	1		8	
	Drones	2	3	20	
	Photovoltaics	57	109	324	
	IoT		7	129	
	Modular	10	829	56	3
	Robots	1	177	320	4
	Sensor		58	205	
	VR/AR	1	1	5	
	Wireless		29	250	
Total	73	1448	1363	9	

Among the top 15 applicants, state owned enterprises (SOEs) contribute most to patent inventions and are the main actor leading patents cooperation. Three central SOEs a municipal SOE produce 238 inventions. Tongji University (70), China University of Mining and Technology (41), Hohai University (32) and Southeast University (30) are the main contributors among universities, which are secondary significant constituents for patent invention network. Private firms such as Wenzhou Suiren Intelligent Technology Co., Ltd. (32) and Zhejiang Yasha Decoration Co., Ltd. (23) are active, but the share of each firm is not substantial. Their cooperation with universities and main SOEs for the bases for cooperative network (Table 2, Figure 4).

Table 2. Main applicants in identified fourteen technologies.

No.	Applicant name	No. of patents	Applicant type
1	China Metallurgical Group Corporation, MCC	78	Enterprise -SOE
2	Tongji University	70	University
	China State Construction Engineering Group Co., Ltd	70	Enterprise -SOE
3	Shanghai Construction Group Co., Ltd	69	Enterprise -SOE
4	China University of Mining and Technology	41	University
5	Hohai University	32	University
6	Wenzhou Suiren Intelligent Technology Co., Ltd	32	Enterprise - Private
7	Southeast University	30	University
8	Zhejiang Yasha Decoration Co., Ltd	23	Enterprise - Private
9	China Railway Group Limited	21	Enterprise -SOE
10	Ma **	19	Personal
11	Zhang **	17	Personal
12	Jieshou Shaoen Precision Machinery Co., Ltd	16	Enterprise - Private
13	Ningbo Polytechnic	16	University
14	Zhejiang Heda Solar Technology Co., Ltd	16	Enterprise - Private
15	Nanjing IOT Sensor Technology Co., Ltd	14	Enterprise - Private

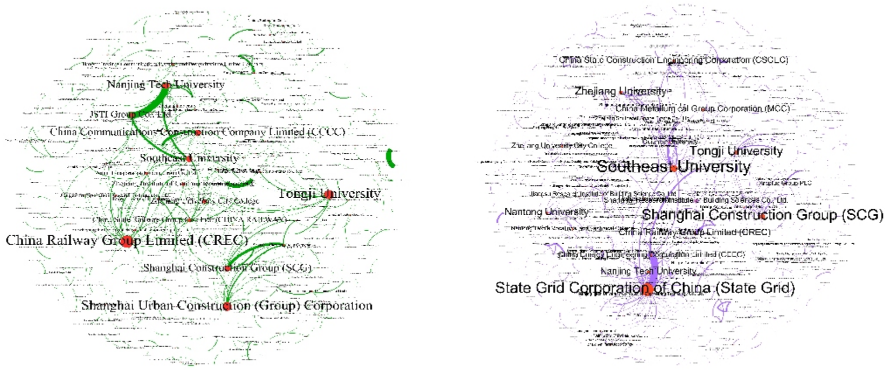

Figure 4: Cooperative patents in construction of roads and railways (left) and building (right).

Figure 5 shows the spatial distribution of each technology and the kernel density of all the patents, which mainly concentrated in Shanghai, south Jiangsu and north Zhejiang and distributed in regional center cities such Shanghai, Nanjing, Hangzhou, Suzhou, Hefei, Xuzhou, Wuxi and Changzhou as well as some county-level cities such as Taicang, Kunshan and Jiangyin along the highways and high-speed railways. A hybrid of monocentric and multi-nuclei spatial pattern characterized by gradient distribution came into being. In this hybrid pattern, Shanghai is the main kernel while Nanjing and Hangzhou are two sub-kernels, less intense than the kernel areas are Suzhou-Wuxi-Changzhou belts and Hefei-Xuzhou center, other places such as Nantong, Wenzhou, Anqing, Zhenjiang-Yangzhou, Ningbo Yinzhou-Beilun etc. have formed even lower-level agglomeration areas of innovation in the meanwhile. From the perspective of the spatial distribution of various types of technology patents, patents of 3D printing, BIM, VR/AR and drones mainly distributed in Shanghai and Nanjing. Patents of IoT, Sensor and Wireless mainly distributed in Hangzhou, Ningbo and cities along the Shanghai-Nanjing highway. Patents of other 3D technologies mainly distributed in cities along the Shanghai-Nanjing highway. Patents of modular, photovoltaics and robotics concentrated in Shanghai, southern Jiangsu, and northern Zhejiang. Patent distribution of AI, cloud computing and blockchain is sporadic.

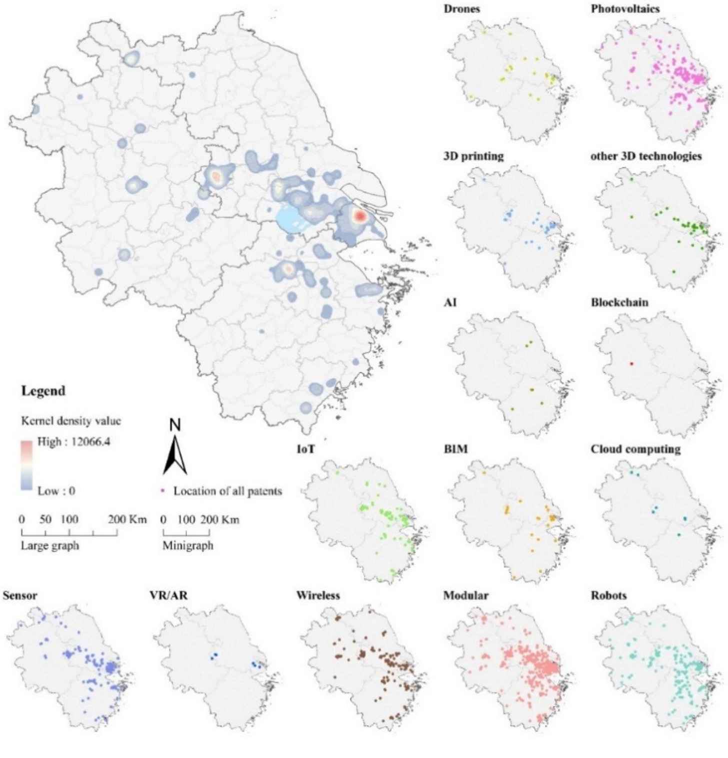

Figure 5: Mapping innovative activities of the fourteen technologies in YRD.

CONCLUSION

This research reveals the emergent technologies and their potential for building decarbonization. Observations from patent inventions in YRD suggest that contribution of the emerging technologies to building decarbonization is most secondary. The general-purpose technologies (e.g., blockchain, IoT), which possibly disrupt the industry fundamentally, are almost vacant. State owned enterprises are the main actors in the technology innovation, followed by university and public research institutions. A mixed location of downtown, periphery and outskirts characterizes the spatial pattern of these technologies. The findings help to recommend policy makers, firm managers, professionals and researchers in accessing and developing disruptive technologies for low carbon building industry, and promote business application in this field.

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