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Building Back Better: Lessons Learned from Sichuan Earthquake on Decarbonizing China's Construction Industry through Microalloying

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The construction industry bears a massive carbon footprint that is largely derived from the carbon-intensive nature of key structural materials. Microalloying of structural steel represents an underappreciated strategy for enabling greater economy of materials use and thus reducing carbon emissions. Policy implemented after the Sichuan Earthquake has mandated an increased use of vanadium steel, giving rise to an unintended (but welcome) benefit of substantial decarbonization of a major sector.

At 14:28 on May 12, 2008, an earthquake measuring 7.9 on the Richter scale struck Wenchuan county in the Sichuan province of the People's Republic of China (PRC). For hundreds of thousands of years, the Indian-Australian and Eurasian plates had inched toward each other, but in less than three minutes, their collision would unleash a devastating quake that would set in motion thousands of landslides, reroute rivulets, and cause an upheaval of the earth by up to 29 feet in some places, wreaking massive devastation across hundreds of villages and towns dotting the mostly mountainous region. When the dust settled, 90,000 people were dead, over 370,000 were injured, and more than 11 million homes had been destroyed.[1] The devastation wrought by the 2008 Sichuan earthquake in China forced a major rethink of building construction practices. The disproportionate number of crumbled schools and municipal buildings drew specific attention to corruption in public construction, lax enforcement of standards, and their inequitable enforcement (Figures 1A and 1B).[2] The selective devastation wrought on primary school buildings—thousands of students had been in attendance during the afternoon hours—led to heart-rending images juxtaposing the unequal consequences of the earthquake, perhaps most notably memorialized in the haunting art installations of Ai Weiwei (Figure 1A). Zhu Rongji, the Chinese Premier, coined the term "tofu dregs" denoting shoddy infrastructure—public projects that were poorly funded, used inferior building materials, and were erected with callous disregard of the most basic safety regulations.

The collective soul-searching that followed the earthquake led to policy interventions that have been massively consequential across all of China. In a "build back better" approach aimed at remedying infrastructure built on weak foundations, policy interventions during the aftermath of the quake first encouraged and then mandated improved seismic designs largely through the use of higher-grade reinforcement bar steels ("rebar"), which form the basis of reinforced concrete structures, a cornerstone of the construction industry. In this commentary, we attempt to capture the far-reaching effects of policy decisions during the aftermath of the 2008 Sichuan earthquake through the lens of micro-alloyed steel in China. We find that while addressing the urgent need for a paradigm shift in China's construction industry to mitigate catastrophe during natural disasters, increased reliance on structural materials that enable considerable economy of materials use has led to an impressive reduction in China's carbon footprint even while China has undergone an unprecedented construction boom in the same period.[3]

Micro-alloyed Steels in China

According to China's Iron & Steel Research Institute Group (CISRI), 227 million metric tons (MMt) of steel were used to produce concrete reinforcement bars in China in 2019, a large fraction of which utilized microalloying as the primary strengthening mechanism to create high-strength-low-alloy (HSLA) steels that offer superior yield strength (and thereby load-bearing ability), elongation performance, and ductility relative to conventional carbon steels.[4] The mechanical properties of micro-alloyed steels result from the combined effects of grain refinement and precipitation strengthening arising from the incorporation of trace elements such as vanadium, niobium, or titanium.[5] Increases in yield-strength as much as 15 MPa per 0.01 wt.% addition

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of microalloying elements have been reported.[5] Historically vanadium has been the microalloying element of choice for steel producers in China, owing to its superior solubility in austenitic steel at low-temperatures; which increases the ease of manufacturing and is paramount to the formation of the nanoscopic precipitates that underpin yield strength and seismic resilience. In subsequent sections, we explore how building code changes have created a strong demand for this unassuming element, vanadium, its disproportionate impact on global emissions, and the closely entangled impact on the market penetration of redox flow batteries, a major emerging alternative for grid-level storage.

Vanadium Markets after the Quake

Figure 1C charts vanadium consumption in rebar applications in China from 2005–2019 based on data provided by CISRI. In 2011, the introduction of building codes for seismic design (GB/T 50011-2010) that largely restricted the use of grade 2 (335 MPa) steels led to a massive surge in the consumption of vanadium. Between 2010 and 2014, China's vanadium consumption (Figure 1C, light blue) grew by ca. 225% and at more than twice the rate of steel production, evidencing a massive boost in the intensity of vanadium used in steel, in addition to large rebar volumes. Vanadium consumption decreased for the following two years as rebar suppliers discovered an inexpensive workaround, the utilization of quenching and self-tempering (QST) processes, which could meet the yield strengths specified in the standards but not the elongation requirements for seismic activity—QST steels are inherently brittle due to formation of martensite on the surface and are particularly vulnerable to fire damage often observed in the aftermath of earthquakes.[4] In response, the Standardization Administration of the People's Republic of China (SAC) released new standards for steel-reinforced concrete in 2018 (GB/T 1499.2.2018), banning the use of grade 2 (335 MPa) and QST steels altogether and authorizing three high-strength microalloying alternatives: grade 3 (400 MPa), grade 4 (500 MPa), and grade 5 (600 MPa), which require approximately 0.03%, 0.06%, and > 0.1% vanadium microalloying, respectively (among other alternatives). In the years leading up to the policy change, (2016—2017) vanadium consumption grew steadily as major steel producers increased inventories in anticipation of the new standards. A rapid increase in vanadium consumption combined with an inability of global vanadium production (Figure 1C, orange) to scale at commensurate rates drove vanadium pricing (Figure 1C, dark green) to a thirteen-year high of \$127/kgFeV in November 2018 according to the *Metal Bulletin*, eclipsing the previous high in 2005 that followed the introduction of grade 3 rebar. Notwithstanding the high prices, vanadium consumption rose by 28% in 2019 along with an increase in the intensity of vanadium used in steel from 0.046 kgV/ton of steel in 2018 to 0.053 kgV/ton of steel in 2019.

Despite an overwhelming preference in China for vanadium addition in rebar, the price spike in 2018 created cost incentives for steel manufacturers to substitute ferrovanadium with other early transition metal alternatives, which provide similar strengthening benefits despite some solubility limitations. Softening of ferrovanadium prices in the second half of 2019 allowed a substitution reversal, but the temporary shift in market shares demonstrates the sensitivity of the construction industry to the supply vagaries of one element, vanadium, with a relatively modest global production of 100,000 metric tons. While vanadium consumption has been historically anchored to steel (hence volatile pricing in a fluctuating steel market), vanadium redox flow batteries (VRFBs) are poised to take a significant share of the stationary storage market which is expected to grow at least 17-fold by 2030[6] and could create a step-change in vanadium demand. Some estimates indicate that an additional 80,000 metric tons V/year will be required if VRFBs occupy just 18% of the market by 2027; the supply and price stability of vanadium in response to the early onset demand from VRFB installments will be paramount to their commercial viability in the years to follow. Indeed, vanadium price fluctuations have been used to justify research in alternative flow battery chemistries; however, much of this alarm is unjustified considering substantial global reserves of vanadium exceeding 15 MMt.[7] Indeed, VRFBs will likely diversify the existing vanadium consumption portfolio, thus incentivizing new production (including substantial primary production), creating support at higher vanadium prices, and enabling a natural hedge against price elasticity demand. Furthermore, vanadium electrolyte producers are well-positioned to guard against price instabilities through supply chain agreements made possible by the impressive recyclability of vanadium-based electrolytes, which allows them to be reused in future energy storage applications.[6,8] The competing material demands and inevitable interrelationships between the established construction industry and the emerging electrochemical energy storage sector provide an interesting view of the impact of materials criticality on the energy transition, albeit in this instance perceived conflicts can be happily resolved with scaled-up production, increased emphasis on recycling across both sectors,[7] and the judicious use of policy and financial instruments that ensure stable demand.

Trending Skyward: High-Strength Rebar

Despite a large upheaval of the vanadium industry resulting from building code changes, a sharply upward

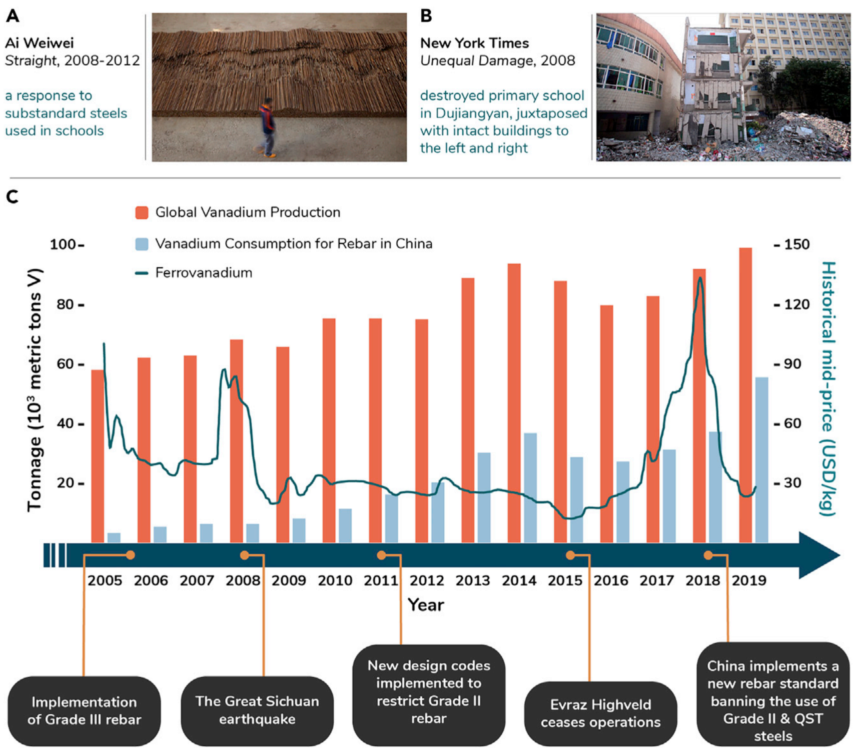

Figure 1. A Fluctuating Vanadium Market During China's Construction Boom

(A) An art installation entitled Straight by Chinese artist Ai Weiwei commemorating the victims of the Sichuan Earthquake and built from rebar recovered from damaged buildings, reproduced under a Creative Commons license.

(B) Photograph demonstrating a Xinjian primary school in Dujiangyan destroyed while another school, at left, and hotel, at right, remain intact. Photo by Du Bin for *The New York Times*.

(C) Total tonnage of global vanadium production, and vanadium consumption for rebar in China between 2005 and 2019 are plotted along the leftmost vertical-axis in metric tons of vanadium and depicted by light-blue, and orange colored column bars, respectively. Historical mid-point price of ferrovanadium for the same period is plotted along the rightmost vertical-axis and illustrated in dark green. Key events contributing to the fluctuation of the vanadium market are highlighted below the timeline. Vanadium production and consumption statistics were provided by China's Iron & Steel Research Institute Group (CISRI). Historical mid-point price of ferrovanadium is plotted along the rightmost vertical-axis and was taken from Metal Bulletin. Key historical events have been identified with the help of Vanitec, an international technical and scientific committee comprising companies engaged in the production, recycling, processing, and manufacturing of vanadium and associated products.

trajectory of vanadium used in construction applications (rebar grades and their corresponding yield-strengths, and vanadium percentages are shown in Figure 2A) has persisted. Figure 2B illustrates the relative weightings of different low- (2) and high-grade (3, 4, and 5) rebar steels produced between 2005 and 2019 in China according to CISRI. In 2008, low-grade (2) rebar represented ca. 68% of the total rebar production in China, whereas higher-grade alternatives such as grade 3 and grade 4 steels comprised a mere 25% (Figure 2B, red). The restriction of grade 2 steel in GB/T 50011-2010 in 2011 spurred a major shift in the production of high-grade steels, driving the percentage of high-strength rebar (grade 3 and above) to nearly 85% by 2014 (Figure 2B, red). Except for 2015, which marked the first annual decline of steel production in China in decades (and therefore rebar production as shown in the dark green line in Figure 2B), the production of high-strength rebar steels continued to increase, reaching an all-time high (ca. 91%) in 2019, surging in part, as a result of the authorization of GB/T 1499.2.2018 in 2018, which banned the use of grade 2 and QST in reinforced concrete structures.

An Unintended, but Welcome, Consequence of Microalloying

While the benefits of microalloying in enhancing the functional properties of steel are well documented, considerable economy of materials use can be gained from the widespread adoption of HSLAs in construction applications.[5] Since 2006, China has been the world's largest CO_2 producer with emissions estimated at 13,920 MMt of CO_2 in 2019 alone, a substantial portion of which can be traced to the construction industry.[9] The decarbonization of the construction industry represents an urgent imperative and has as its linchpins, process intensification, automation, and economy of materials use resulting from the deployment of lightweight but high-strength materials and additive manufacturing.[10] Formidable logistical challenges exist in the way of implementing many of these solutions at scales and rates that are commensurate with construction in China. The tremendous amount of embodied energy and carbon in construction materials such as cement and steel make dematerialization a key strategy that can be readily implemented.[5] The superior strength-to-weight ratio of HSLAs relative to mild steel, for example, implies that substantially less rebar (or concrete) is required to meet the performance demands of similar load-bearing applications. In subsequent sections, we calculate the potential reduction in the carbon footprint of steel reinforcement bars resulting from vanadium microalloying using PRC consumption statistics provided by CISRI.

Figure 3A shows a four-story (5×3) bay hypothetical building from which a structural modeling framework has

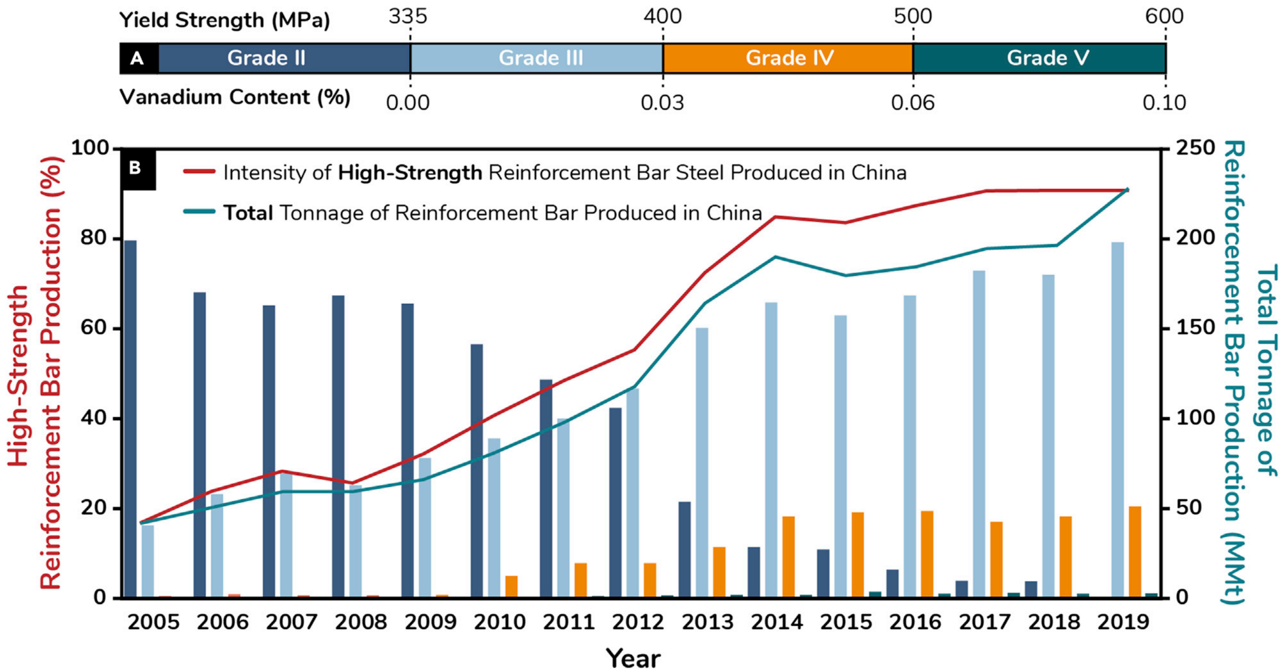

Figure 2. Changing Trends in High-Strength Rebar Use in China

(A) Illustrates the different low- and high-grade rebar steels used in China along with their corresponding yield-strengths and vanadium contents.
(B) The relative weighting of grade 2, grade 3, grade 4, and grade 5 steels (as shown in (A)) produced in China from 2005–2019 are plotted along the leftmost vertical-axis and are depicted by dark-blue, light-blue, orange, and dark-green bar columns, respectively. The cumulative fraction of high-strength rebar (grades 3, 4, and 5) relative to the total quantity of rebar produced in China is shown on the same axis and depicted in red. The total tonnage of reinforcement bar produced in China for between 2005 and 2019 is plotted along the rightmost vertical axis in million metric tons (MMt) and depicted in dark green. Rebar production statistics were provided by China's Iron & Steel Research Institute Group (CISRI).

been developed in ETABS v18 to calculate the quantity of steel required to achieve the same load-bearing capacity for different grades of rebar.[5] Relative to grade 2 (335 MPa) steel, approximately 14%, 30%, and 40% savings in steel are made possible with grade 3 (400 MPa), grade 4 (500 MPa), and grade 5 (600 MPa) steels, respectively. Savings in steel have been directly translated to carbon savings after accounting for the carbon cost of vanadium incorporation in Figure 3B. It is worth noting that most vanadium extractions come from recycled products (74% produced through co-production with steel and 11% recovered from waste products such as fly ash, petroleum residues, and spent catalysts), making the carbon costs associated with vanadium production relatively low.[8,11] The tonnage of CO_2 savings, by year, are shown in orange in Figure 3B relative to the total quantity of CO_2 emitted from industrial process in China (Figure 3, gray) from 2005–2019. For each year, the total quantity of rebar produced and the relative weightings of low- and high-grade rebar (Figure 2) are considered to account for the scaling relationship between yield strength, material savings, and carbon costs associated with vanadium incorporation.

From 2005–2019, even though CO_2 emissions from industrial process in China increased by 65%, the carbon savings afforded by microalloying of rebar increased by over 2000% (Figure 3B, orange) demonstrating that trace elements such as vanadium play a critical role in the decarbonization of some of the most challenging industrial sectors.[5] The estimated carbon savings made possible by supplanting grade 2 rebar with higher-grade alternatives totaled ca. 230 MMt of CO_2 (between 2005 and 2019); to place these savings into a global perspective, 230 MMt of CO_2 is equivalent to carbon emissions due to fossil fuels in Ukraine (225 MMt), oil in Indonesia (229 MMt), gas in Canada (229 MMt) and coal in Poland (206 MMt) in 2018 according to the *Global Carbon Atlas*. In 2019 alone, 31.5 MMt of CO_2 savings are directly attributable to microalloying, this equates to a 1.5% reduction in the carbon footprint of China's industrial processes (as shown in dark green in Figure 3B).[9] Notably, the largest year-on-year growth rates in carbon savings occurred between 2011 and 2014 (following the introduction of GB/T 50011-2010) and between 2018 and 2019 in response to the prohibition of grade 2 rebar in 2018 (outlined in GB/T 1499.2.2018) illustrating the direct impact of policy intervention on the decarbonization of a major sector.

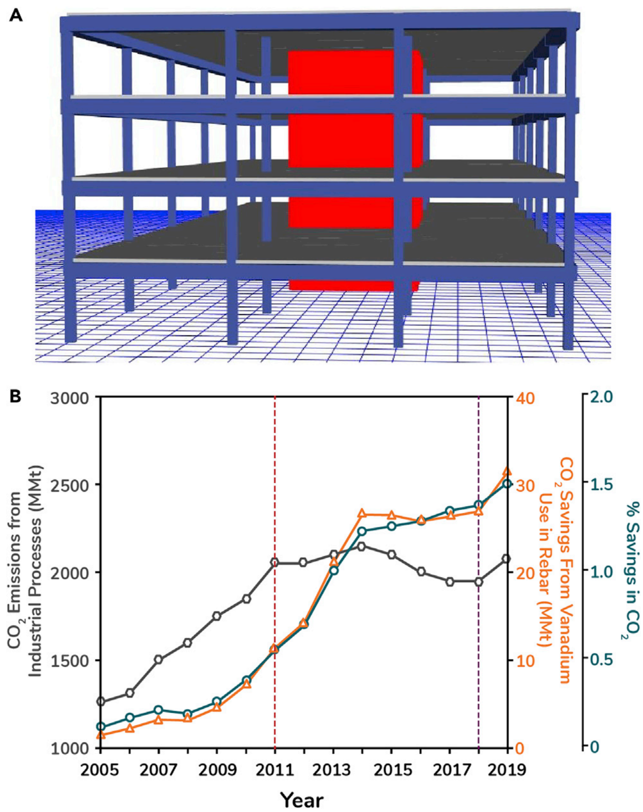

Figure 3. Estimating the Potential CO_2 Savings Resulting from Microalloying in Rebar

(A) A 3-dimensional rendering of a four-story (5×3) bay hypothetical building from which a structural modeling framework has been developed for analysis in ETABS v18 to calculate the quantity of steel required to achieve the same load-bearing capacity using different grades of rebar (more details provided in Pradeep Kumar et al).[5]

(B) Total CO_2 emissions from industrial processes in between 2005 and 2019 are plotted along the leftmost vertical axis (shown in gray) in million metric tons (MMt). Estimated CO_2 savings from vanadium microalloying in rebar are plotted along the right vertical-axis (shown in orange) in million metric tons (MMt). Savings were calculated using the structural framework introduced in (A) and rebar statistics shown in Figure 2B. Percent savings relative to total CO_2 emissions from industrial process in China are plotted along the rightmost vertical axis (shown in dark green). The red and purple dashed lines indicate the years in which major policy changes were implemented.

Implications for Policy

The construction industry exacts a rather heavy toll on limited natural resources, leaving a massive carbon footprint that is derived, primarily from the carbon-intensive nature of key structural materials such as steel and concrete. Dependency on fossil fuels is deeply embedded in steel/cement manufacturing processes, effectively locking construction to nonrenewable resources and leaving the carbon footprint from the so-called "hard-to-abate" sectors, substantial and undiminished. The perspective provided in this work demonstrates that the massive and seemingly rigid carbon footprint of construction materials can indeed be significantly reduced by supplanting low-grade materials with higher-value alternatives that offer considerable economy of materials use. While perhaps an unintended benefit, the implementation of new building codes limiting the use of low-grade structural materials in China, directly attributable to the 2008 Sichuan earthquake, has led to significant CO_2 savings in one of its leading carbon-emitting sectors. The far-reaching effects of building code changes after the Sichuan earthquake demonstrate the importance of embedding a life cycle assessment (LCA) to any policy decisions that will affect major industries. In addition, policy interventions seeking to decarbonize the built environment should consider the distinctive and likely underappreciated role of microalloying elements. The price fluctuations and ultimate tempering of price volatility illustrate the competing demands for critical materials in established and emerging sectors and point to the need for supply chain management and a long-term perspective for critical materials that have substantial consequences for clean energy and decarbonization.

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DECLARATION OF INTEREST

This work was funded in part by Vanitec, an international technical and scientific committee comprising companies engaged in the production, recycling, processing, and manufacturing of vanadium and associated products. The authors do not have any financial stakes in any of the industries noted in this work.

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