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Building materials such as concrete and steel are known to be significant contributors to greenhouse emissions and exact a toll on the environment. Judicious selection of materials is thus vital in reducing the total energy and carbon footprint of the construction industry. In this study, a cradle-to-gate life cycle assessment is carried out to examine the impact of vanadium microalloyed steel rebar in terms of material savings and embodied energy and carbon footprint reduction, thereby providing a rich global perspective of the (outsized) role of elements added in trace concentrations on the overall footprint of the construction industry. As such, the manuscript addresses an important and timely topic at the intersection of materials criticality, life cycle assessment, and policy interventions.

ARTICLE

Punching Above its Weight: Life Cycle Energy Accounting and Environmental Assessment of Vanadium Microalloying in Reinforcement Bar Steel

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Steel-reinforced concrete is ubiquitously used in construction across the world. The United Nations estimates that the worldwide energy consumption of buildings accounts for 30—40% of global energy production, underlining the importance of the judicious selection of construction materials. Much effort has focused on the use of high-strength low-alloy steels in reinforcement bars whose economy of materials use is predicated upon improved yield strengths in comparison to low-carbon steels. While microalloying is known to allow for reduced steel consumption, a sustainability analysis in terms of embodied energy and CO_2 has not thus far been performed. Here we calculate the impact of supplanting lower grade reinforcement bars with higher strength vanadium microalloyed steels on embodied energy and carbon footprint. We find that the increased strength of vanadium microalloyed steel translates into substantial material savings over mild steel, thereby reducing the total global fossil carbon footprint by as much as 0.385%. A more granular analysis pegs savings for China and the European Union at 1.01 and 0.19%, respectively, of their respective emissions. Our cradle-to-gate analysis provides an accounting of the role of microalloying in reducing the carbon footprint of the steel and construction industries and highlights the underappreciated role of alloying elements.

1. Introduction

The built environment represents a substantial source of greenhouse emissions and consumes an inordinate proportion of available energy and natural resources.[1–3] The United Nations estimates that the worldwide energy consumption of buildings accounts for 30—40% of the total global energy usage, which is equivalent to 2,500 million tonnes of oil equivalent (Mtoe) annually; notwithstanding improvements in sustainable building practices,[1] a sharply upwards trajectory is projected with increasing urbanization. The construction and operation of buildings consumes 16% of the total global water resources, 25% of the total harvested wood (virgin wood) supply, and 40% of the total supply of aggregates (raw stone, sand, and gravel supply), thereby considerably depleting ecosystems of natural resources.[4,5] Much recent effort has focused on reducing the carbon footprint of the built environment during construction, operation, and end-of-life disposal or reuse/recycling. Arguably one of the intrinsic difficulties associated with this effort is to simultaneously reduce values of both embodied energy and operational energy, which often have countervailing dependencies. Central to the adoption of sustainable building practices is the design and deployment of materials within structural elements, architectural facades, and functional components that either can be sourced with minimal impact on the environment and/or drastically reduce operational energy consumption.[6–8] Obtaining a rigorous accounting of materials across their life cycle is imperative to inform the selection of building materials and requires consideration of the embodied energy and CO_2 implications of materials production and transportation, quantities required to achieve specific functionality, constraints arising from use of the said material, and the often-entangled changes in the requirements for other materials or components. In this article, we focus on a mainstay of the construction industry, reinforcement bar steels, and examine the implications of vanadium microalloying, a ubiquitous strengthening mechanism,[9–12] from the perspective of the impact on material use, embodied energy, and carbon footprint arising from supplanting lower grade reinforcement bars with higher strength vanadium microalloyed steels.

1.1. Embodied Energy and Carbon Footprint of the Built Environment

While much research has focused on the identification of building elements that reduce operational energy consumption, recent publications have illustrated that embodied energy contributes significantly to the total energy use of the built environment across its life cycle.[13–15] Embodied energy over a life cycle of a building can be further divided into Initial

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Embodied Energy (IEE), Recurrent Embodied Energy (REE), and Demolition Energy (DE).[16] Building materials account for over 90% of the IEE, and their judicious selection is thus of paramount importance to reducing the enormous energy and environmental footprint of construction.[6,8,17] The choice and quantities of building materials are determined not just to minimize energy consumption but also from the need to incorporate design constraints necessary for structures to withstand hazards such as earthquakes, high wind, and tornadoes.[18,19] Notable LCA studies have illustrated the importance of these considerations in the cost of construction, maintenance, and repair.[18,19]

Building materials such as concrete and steel exact a heavy toll on natural resources. Considerable embodied and operational energy expenditures are furthermore incurred during production, manufacture, usage, construction, and maintenance on account of these key two structural materials. Indeed, some estimates suggest that the production of cements accounts for approximately 4% of global greenhouse emissions. However, the longevity, structural performance, and seismic resilience of reinforced concrete has few parallels and this combination of materials thus continues to find widespread use.[20] Similarly, steel is used as a means of reinforcement across large swathes of the construction industry but incurs a considerably larger energy and carbon emission burden as compared to other building materials given the traditionally energy intensive nature of steel production. About half of the steel produced each year goes towards the construction of buildings and infrastructure.[21,22] Increasing urbanization has led to a sharply upwards trajectory, which bodes poorly for the carbon footprint of the construction industry. Since 2000, global steel production has doubled, reaching a record high of 1700 million metric tons (mMT) in 2017.[16] Despite efficiencies gained by upcycling of by-products such as slag, a striking 2 tons of CO_2 are generated for every ton of steel produced; however, it is worth noting that there are notable differences depending on the nature of steel production, specifically the utilization of blast or electric arc furnaces or the use of clean hydrogen, which can somewhat reduce this number.[23] From a global perspective, over 9% of worldwide CO_2 emissions are directly attributable to steel production.[24] According to the International Energy Agency (IEA), the demand for steel will double by 2050, necessitating a sharp reduction in the emission of carbon per unit of steel production or the implementation of alternative construction approaches that enable reduced steel consumption.[24]

1.2. Vanadium Microalloyed Steels: Higher Strengths Enable Reduced Steel Consumption

High-strength-low-alloy (HSLA) steels have emerged as an attractive class of strengthened steels, which, by dint of their higher yield strength, offer considerable economy of materials use in structural applications in construction. In contrast to conventional low-carbon steels, HSLA steels offer higher yield strength, improved elongation performance, enhanced resistance to brittle fracture, and greater corrosion resistance, thereby satisfying ductility, weldability, and toughness criteria for structural applications.[25,26] HSLA steels are prepared through metallurgical processes that enable precise control over microstructure and dislocation density through alloying, refinement of grain size, the inclusion of nanoscopic precipitates, programmed tempering profiles, and thermomechanical treatments.[10,26–28] Micro-alloyed ferrite-pearlite steels are ubiquitously used in structural applications and typically contain relatively small additions (usually less than 0.10%) of carbide or nitride-forming elements.[28] Yield strengths as high as 1000 MPa are accessible from microalloying. While other alloys, such as stainless steels[29] and dual-phase steels[30] offer similar performance benefits, the increased cost to consumers and added complexity during processing have rendered HSLA steels the primary strengthening mechanism for most structural applications.[31]

In construction applications, the primary consideration for the selection of a specific ferrous alloy composition for reinforcement bars is the strength-to-weight ratio, often quantified by the yield strength. Indeed, the classification of reinforcing bars in accordance with British[32,33] and European[34] standards and the nomenclature denoted here directly reflect the minimum permissible yield strength.[32–34] A higher-grade reinforcement bar implies that substantially less steel can be used to achieve the same structural performance in load-bearing applications. However, there is a trade-off between yield strength and the ductility as well as fracture toughness of steel; as the yield strength increases, there is a concomitant decrease in ductility and fracture toughness.[35] Hence, it is pivotal to select a ferrous alloy for a specific structural application based on the desired combination of yield strength and toughness. Indeed, through grain refinement and precipitation strengthening mechanisms that will be discussed below, vanadium microalloying allows steel producers to achieve the desired combination of strength, ductility, and toughness specifications mandated by building codes. The advantages of high-strength steels have been notably demonstrated in the case of automotive frameworks by the American and International Iron and Steel Institutes through a light weighting initiative wherein weight savings from utilization of HSLA steels resulted in a 51% reduction in energy consumption over the life cycle of a vehicle.[36,37] A computational and experimental report directed by the United States Army Research -Laboratory (ARL) demonstrated up to 17% material savings resulting from the use of vanadium microalloyed HSLAs in long-span joists and girders.[38] A previous study also suggests that the addition of vanadium to steel reinforcing bars reduces the amount of carbon needed to attain a particular yield strength and enables processing at lower temperatures as compared to niobium steel.[39] While considerable economy of materials use derives from adoption of HSLAs in construction applications, an accurate assessment of how this translates to savings in energy and carbon remains to be determined.

In this article, we focus on analyzing the embodied energy and carbon footprint derived from microalloying with vanadium, a commonly used strengthening mechanism that has widespread global use. Microalloying with relatively small amounts of vanadium, ca. 0.02—0.2%, brings about considerable improvements in yield strength, ductility, and seismic performance.[40–43] Vanadium incorporation strengthens steel through formation of nanoscopic precipitates of vanadium nitrides, carbides, and carbonitrides during the austenite to ferrite transformation.[26,43–45] Additional benefits, often manifested as improved hardness, can be achieved through grain refinement of the resulting ferrite-pearlite microstructure. Unlike niobium-based alternatives that require specialized thermomechanical processes to realize the benefits of microstructure without sacrificing ductility, grain refinement in vanadium-microalloyed steels occurs upon cooling during the austenite to ferrite transformation.[46,47] The effectiveness of vanadium in improving yield strength stems from a fundamental thermodynamic property, the excellent solubility of the vanadium inclusions in the austenite phase as a result of favorable enthalpies of mixing.[45,46,48] In other words, a larger fraction of miscible vanadium in solution prior to rolling promotes a higher precipitation efficiency during the ferrite transformation.[49,50] The driving force for precipitation is increased even further by cooperative effects with nitrogen and manganese, which favor the formation of nitride precipitates, which are critical for increasing the yield strength of a ferrous alloy. Furthermore, the benefits of high solubility translate directly to improved ductility and lower requirements for rolling loads, which improves processing efficiencies and the overall energy use in comparison to alternative microalloying strategies. As such, grain refinement and precipitation strengthening imbued by vanadium microalloying allows steel producers to achieve the desired combination of strength, ductility, and toughness specifications mandated by building codes.

1.3. Energy and Carbon Costs Associated with Production of Vanadium Precursors

A rigorous life cycle accounting of embodied energy and carbon for vanadium-microalloyed steels requires consideration not just of the economy of materials use stemming from the increased yield strength accessible upon microalloying but also the quantitation of the energy and carbon expended in the production of vanadium precursors (which can be classified further as primary production, co-production, and recycling). In 2017, 74% of vanadium feedstock production occurred through co-production during steel-making operations, with the remaining balance coming from primary production directly from vanadium-bearing magnetite ores (14%), and secondary (12%) production from sedimentary vanadium largely found in oil residues or recovered from spent catalysts.[51] The proportion of co-production and recycling is distinctive and demarcates this element from other materials that require resource and energy intensive primary production. In a typical co-production process, vanadium-containing pig iron is processed in an electric arc furnace for the concomitant production of steel and vanadium-bearing slag. Subsequent processing converts extracted vanadium into ferrovanadium or nitrides, which are used as precursors for the preparation of different grades of HSLA steels.[52,53]

Quantities of energy use and CO_2 production from the vanadium production have been estimated in an extensive cradle-to-gate analysis published by Eckelman and colleagues.[54] Briefly, these authors have compiled an extensive life cycle inventory based on existing literature taking into account primary, secondary and co-production methods of vanadium extraction. Embodied energy and carbon values were estimated based on aggregated mining, concentration, melting, and transportation data. These authors arrive at the costs of 33.1 kg CO_2/kg V and 516 MJ/kg V for embodied carbon and energy, respectively. A recent life cycle analysis for a hypothetical vanadium redox flow battery estimates 39.1 kg CO_2/kg V_2O_5 based on the co-production of vanadium from a deposit in South Africa, which is in good agreement with the value reported by Eckelman and collegues, notably these values consider, to an extent, the savings resulting from vanadium recycling.[53] It is important to note that these numbers, nevertheless, reflect upper bounds since nearly all of the vanadium used in steel applications extraction comes from recycled products. Indeed, one of the distinctive benefits of vanadium-based steels is that the life cycle of most vanadium begins and ends with scrap steel thus promoting vanadium recycling and reuse in a closed-loop manner. Petranikova *et al*., have noted that given the low content of vanadium in HSLA steels (<1%), recovery of vanadium from scrap is not economically viable.[55] Inevitably, the embodied carbon and energy associated with incorporating vanadium into steel is subject to some variations stemming from variability in vanadium extraction processes, transportation distances, and reliance on renewable/non-renewable electricity sources. For example, vanadium suppliers such as BlackRock Metals are striving to further minimize environmental impacts from vanadium production through use of hydroelectricity predicting as much as 61% savings over traditional methodologies.[56] Nevertheless, as a result of the trace quantities of vanadium required to achieve significant improvements in yield-strength and the low carbon and energy impacts of vanadium production, variabilities in the carbon footprint of incorporating vanadium have only a minimal effect on the inferred carbon footprint reduction achieved as a result of microalloying.

1.4. Quantifying the Embodied Energy and Carbon Impact of Vanadium Microalloying

In 2017, approximately 235 mMT of steel were used to produce concrete reinforcing bars, a substantial proportion of which incorporated microalloying as the primary strengthening mechanism.[57] In 2017, the global average intensity of vanadium use in steel reached 0.053 kg V/MT steel.[51] While the benefits of vanadium microalloying in enhancing functional properties are well documented, a comprehensive carbon and energy accounting of the role of microalloying has not thus far been performed. Indeed, such a study is urgently needed as the construction industry seeks to directly address the costs of embodied energy and carbon footprint of construction, which have remained substantial and largely undiminished over the last several decades. Sustainable building practices require the design of load-bearing structural materials with reduced weight-to-strength ratios; microalloying provides a promising route to increased economy of materials use, which further has a knock-on effect in terms of reduced transportation costs, construction costs, and increased building resilience. A comprehensive accounting of the costs and benefits of vanadium microalloying, formulated in terms of embodied energy and carbon footprint, further considering historical data and future projections, is imperative to document the key (often underappreciated) role that vanadium plays in enhancing the sustainability of the steel manufacturing as well as construction industry.

2. Research Methods

In this article, our primary goal is to (1) estimate the embodied energy and carbon of vanadium-microalloyed high-strength reinforcement bars and (2) calculate potential savings with respect to mild steel. Life cycle assessment has been performed using the literature, data inventories, and market data collated from trade organizations in the steel and vanadium industry (World Steel Association and Vanitec, respectively). The study incorporates the process detailed in the sections below and further summarized in the flowchart sketched in Fig. 1: (1) Development of a structural equivalence model in order to determine the quantities of steel and concrete required to obtain the same load-bearing capacity when using reinforcement bars of different yield strengths. (2) development of a machine learning model using available literature data to relate yield strength to vanadium content; (3) creation of a life cycle assessment (LCA) model by gathering data pertaining to the embodied energy and carbon costs of steel, concrete, and vanadium from literature reports and LCA databases; (4) calculation and comparison of the embodied energy use and carbon footprint of vanadium micro-alloyed steels with respect to mild steel; and (5) estimation of the total carbon and energy benefits of microalloying around the world and by region by extrapolating unit benefits using geographically segmented market data gathered from trade organizations.

2.1. Data Sources

The following sub-sections briefly discuss the data sources used to develop the LCA model.

2.1.1. Structural modeling

For structural modeling the parameters for analysis are taken from and conform to the following structural design standards: (a) EN 1990: Structural design details;[58] (b) EN 1991-1-1: Dead and live load specifications for buildings;[59] (c) EN 1991-1-4: Wind load specifications;[60] (d) EN 1992-1-1: All analysis and design parameters for reinforced concrete structures;[34] (e) EN 1997-1: Geotechnical design details (foundation design);[61] (f) BS 4449:1997: Mild steel rebar grade details;[32] (g) BS 4449:2005: High strength steel rebar grade details;[33] (h) EN 206-1: Concrete specifications;[62] (i) EN 10080:2005 (E): Standard nominal bar sizes.[33] These codes are widely used for analysis and design of structures in European Union.

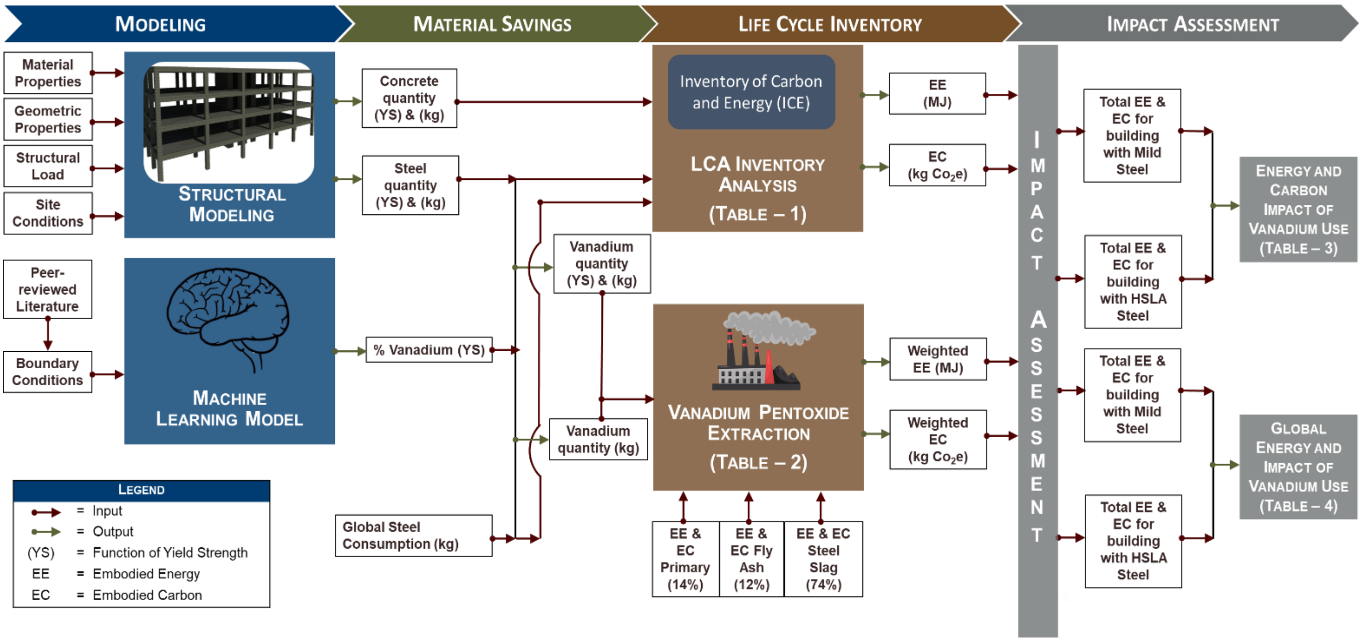

Fig. 1 Flow chart of methodology adopted for life cycle assessment. Structural modeling is used to determine equivalences in load bearing capacity between different grades of rebar, enabling quantitation of savings in steel consumption upon vanadium microalloying. A machine learning model is used to define the dependence of yield strength on vanadium content for specific alloy compositions aggregating a large number of trials mined from the published literature. Materials savings are translated to embodied energy and carbon savings using LCA databases in a life cycle inventory process subtracting the costs incurred in production of vanadium feedstock. Finally, an impact assessment is performed for different grades of steel utilizing vanadium consumption and steel production data to obtain realistic quantification of embodied energy and carbon benefits of microalloying on a global scale and for specific regions of the world.

2.1.2. Machine Learning Model of Yield Strength as a Function of Alloy Composition

The literature reports a wide range of yield strengths as a function of different alloying elements with varying concentrations processed using different thermal transformation profiles.[63–68] In order to arrive at aggregated data not specific to conditions of a single trial, yield strength dependences as a function of alloying element concentrations have been determined by considering the results of 67 different experiments mined from the literature by developing a statistical regression model curated to ensure fidelity with authentic construction practice.[63,64,66,67]

2.1.3. Life Cycle Inventory

In order to perform life cycle assessment, the Inventory of Carbon and Energy (ICE v2.0) has primarily been used to evaluate the embodied energy and embodied carbon derived from steel and concrete.[69] The methodology used to prepare the ICE database is consistent with ISO 14040 and 14044[70,71] recommendations.[72] ICE is a comprehensive open access embodied energy and carbon emissions database that includes cradle-to-site energy and carbon values associated with the construction industry. The embodied energy and carbon values of most construction materials can be found in this database. The embodied energy and carbon associated with extraction and co-production of vanadium is derived from the literature.[53,54] Specifically, the work of Eckelman and colleagues have estimated 33.1 kg CO_2/kg V and 516 MJ/kg V for embodied carbon and energy, respectively.[54] These results are consistent with calculations based on a recent life cycle analysis of a hypothetical vanadium redox flow battery (39.1 kg CO_2/kg V_2O_5). Collectively, a combination of primary, secondary, and co-production methods were considered.

2.2. Design Methodology

2.2.1. Structural Modeling

A structural modeling framework has been developed to calculate the quantities of steel and concrete required to achieve the same load-bearing capacity for different grades of reinforcement bars (corresponding to different vanadium concentrations). The structural codes used for this analysis are delineated in §2.1.1. Grade 250 MPa (~36 ksi) steel (mild steel) is taken as the baseline for evaluating savings in energy and carbon. Two distinct levels of structural modeling have been performed at the component and building level.

At the component level, individual structural components such as a reinforced concrete (RC) slab, RC beam, RC column and foundation are analyzed and the material quantities are calculated for different strengths of steel. All analysis and design parameters for reinforced components primarily conform to Eurocode 2.[34] Fig. 2 shows 3D renditions of (A) RC beam and (B) RC column analyzed in this exercise.

At the building level, a four-story – 5×3 bay hypothetical building has been modeled. Fig. 2C shows a 3D rendition of the building model. Each story has a height of 4 m; the bays span 7 m (5 bays) and 5.5 m (3 bays). Building Category C1 (schools,

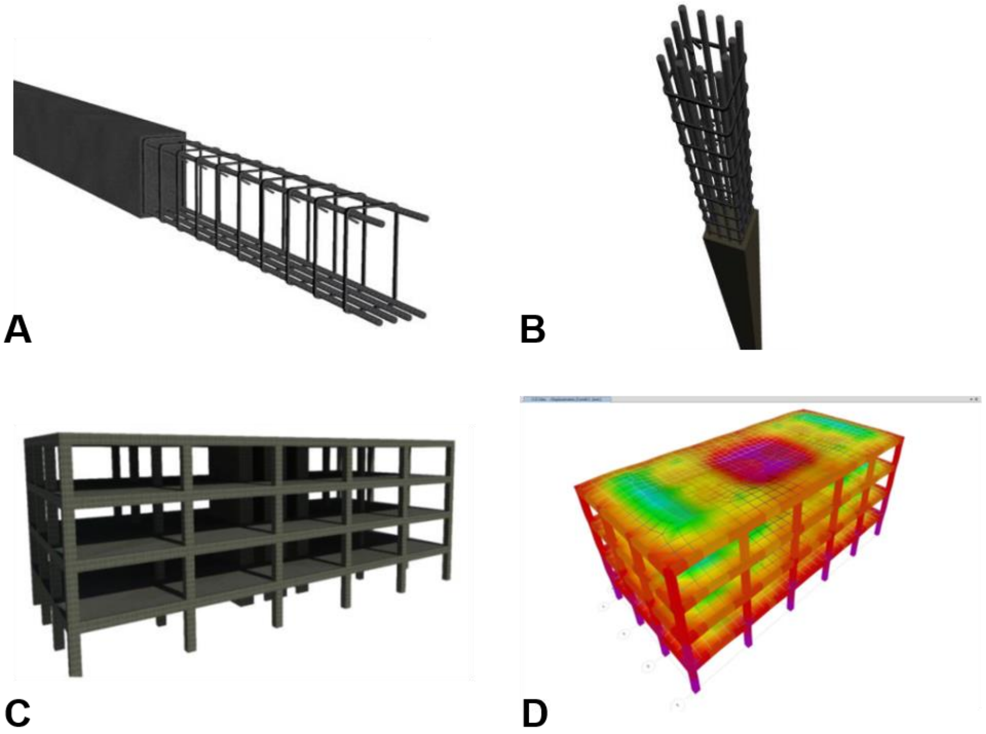

Fig. 2 3D renditions of structural components and hypothetical building model. (A). Reinforced concrete beam that illustrates the horizontal load bearing structural component with longitudinal and shear reinforcement to resist flexure and shear, respectively; (B). Reinforced concrete column that illustrates the vertical load bearing structural component with vertical reinforcing bars and stirrups to transfer the load from slabs and beams to the foundation; (C). Hypothetical building model developed using Revit that illustrates a typical reinforced concrete building, with RC slabs, RC beams and RC columns, which is subjected to standard loading and site conditions; and (D). ETABS model of the hypothetical building that illustrates the structural response after performing the structural analysis.

restaurants, etc - Table 6.1, EN 1991-1[59]) is used to develop the hypothetical building with roof type H (roof accessible only for maintenance and repair –as per Table 6.9, EN 1991-1[59]). The ETABS v18 structural software has been used to design and analyze the structure. Fig. 2D shows the analyzed hypothetical building model. Dead, live, and wind load values have been acquired from Eurocode 1991-1-1[59] and 1991-1-4[60], respectively. The total quantities of materials for structural beams and columns are derived from design results for different strengths of steel. Since, in the analysis, only superstructure is analyzed, approximately 70% of the total steel quantity within a building (beams, columns and slabs) is estimated to be in beams and columns. However, this value is dependent on the model– strength of steel, loading and geometric properties of structural components and it will be lower if the building foundation is further considered in the analysis. Eurocode 1992-1-1[34] specifications are used to design RC sections in the ETABS software.

For all models C30/37 MPa concrete (specifications taken from EN 206-1[62]) is used in conjunction with Grade 400 (400 MPa), Grade 500 (500 MPa), and Grade 600 (600 MPa) reinforcement bars, corresponding to different extents of vanadium alloying. Grade 250 (250 MPa) with no vanadium incorporation is used as the baseline to compare reduction in steel consumption accruing from vanadium incorporation. For foundation component design, the soil-bearing capacity is assumed to be 200 kN/m^2. The densities of steel and concrete are taken as 7850 and 2400 kg/m^3, respectively.

2.2.2. Developing a Machine Learning Model to Predict the Yield Strength of V-HSLA Steels

Given the multitude of variables that may affect yield strength in the steel, there exists considerable variability in the preparation of a reinforcement bar meeting certain structural specifications. For example, two identical grades of rebar might be prepared using distinct thermal conditions and chemical compositions. Nevertheless, efforts have been made to develop empirical models that predict the yield strength of a V-HSLA steels as a function of vanadium concentration. However, previous models have been limited to linear regression models.[45] Here, we have instead developed a machine learning model based on support vector machine (SVM) analysis in order to provide a robust method to delineate vanadium-derived strengthening effects in HSLA steels. SVM is a widely used technique for data classification and regression analysis of multivariate data; the details and applications behind SVM been discussed in detail elsewhere.[73,74] The e1071 R package version 1.6-8 was utilized to compute the support vector machine and regression.[74] SVM calculations were algorithmically tuned to pick the best performing cost and gamma terms for the radial basis function calculation using "leave-one-out" cross validation as a performance metric.

A total of 67 steel trials varying by composition and yield strength were mined from peer-reviewed publications to create a materials design space that considers (a) weight percent amounts of C, Si, Mn, V, and N in addition to (b) the bar diameter in order to correlate composition and yield strength.[63,64,66,67] Prior to the SVM computation, all samples were subject to a set of metallurgical constraints in order to better curate the dataset and obtain an unambiguous evaluation of the effects of vanadium addition. First, the steels considered for the model are free of other commonly used microalloying elements which are competitive for the formation of carbonitrides in HSLA steels including, Cu, Nb, and Ti. Secondly, the dataset was curated to include only "as-rolled" steels without any quench and self-tempering processes, which are known to greatly modify the microstructure and thus the yield strength. Features were ranked on how well individual variables correlated to yield strength by calculating correlation coefficients for a linear regression of each independent variable individually as delineated in Table 1.

The model identifies nitrogen, vanadium, and manganese content as the three most statistically significant descriptors for the prediction of yield strength. Given that the primary mechanisms of strength addition stems from the formation of vanadium carbonitrides, it is not surprising that vanadium and nitrogen are amongst the top descriptors of yield strength. Similarly, manganese content is known to contribute to the steel strength by solid-solution strengthening.[26] The visualization in Fig. 3 and Video S1 shows the model across the variables of vanadium, nitrogen, and manganese (temporal axis) weight percent while holding the carbon content constant at 0.22 wt.%, silicon content at 0.4 wt.%, and the bar diameter at 30 mm.

For the LCA calculations, a base steel composition comprised of 0.220 carbon, 0.008 nitrogen, and 1.24 manganese by wt.% was considered; vanadium weight percentages corresponding to 400, 500, and 600 MPa steels were calculated from the machine learning model, and are shown in Table 2. The SVM model provides yield-strength–vanadium content ratios that are indeed concordant with previous literature results.[28,51]

2.2.3. Life-Cycle Assessment

2.2.3.1. Functional Unit:

According to ISO recommendations, it is important to define a functional unit which provides a reference to which the results are standardized.[70,71] The main goal of this LCA study is to determine the savings in embodied energy and carbon due to the addition of vanadium in rebar steel. With this regard, the

Table 1. Features considered for the SVM model are ranked based on how individual variables are correlated to yield strength by calculating correlation coefficients for a linear regression of each independent variable individually

Variable	R^2
Vanadium content	0.578
Manganese content	0.224
Nitrogen Content	0.224
Carbon content	0.153
Phosphorus content	0.073
Sulfur Content	0.099
Silicon Content	0.068
Oxygen Content	0.047
Aluminum Content	0.027
Bar Diameter	0.025

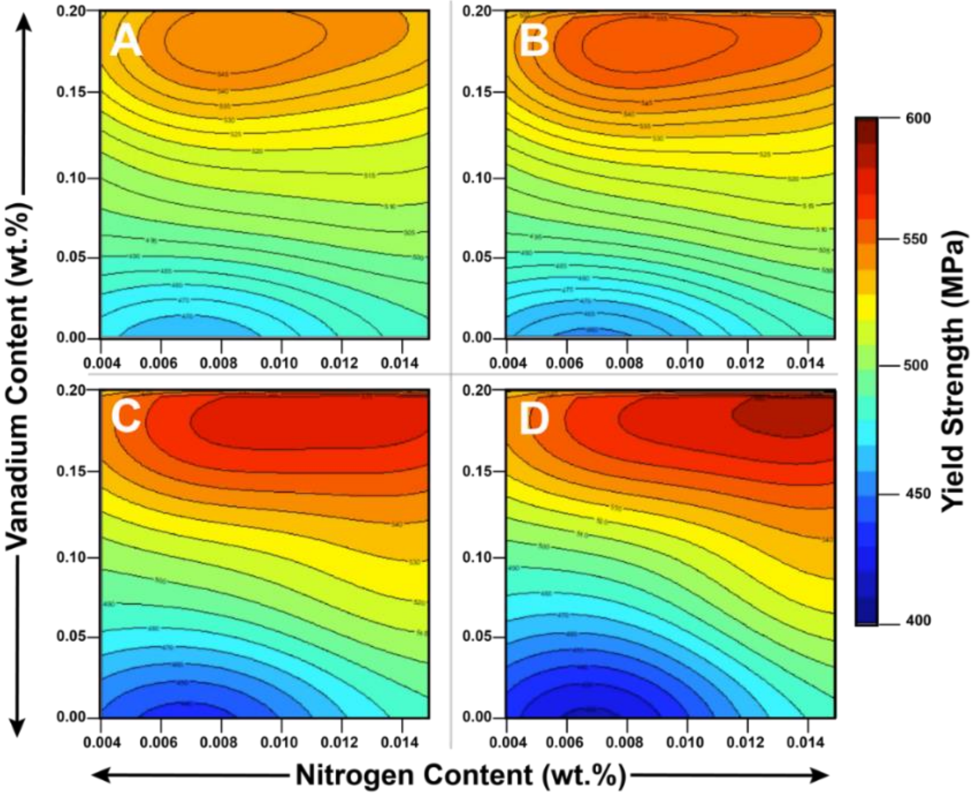

Fig. 3 Contour plot slices of the SVM regression showing the intersections of nitrogen and vanadium content at various manganese amounts (A) 1.100; (B) 1.124; (C) 1.172; and (D) 1.244 Mn wt.%. Video S1 shows the continuous evolution of the contours as a function of manganese content.

Table 2. Chemical composition corresponding to 400, 500, and 600 MPa steel calculated from the SVM model by fixing carbon, manganese, and nitrogen content allowing for variable vanadium content

Grade	Yield Strength (MPa)	Carbon (wt.%)	Manganese (wt.%)	Nitrogen (wt.%)	Vanadium (wt.%)
400	400	0.220	1.24	0.008	0.013
500	500	0.220	1.24	0.008	0.095
600	600	0.220	1.24	0.008	0.177

functional units considered for embodied energy and embodied carbon savings are MJ/m^3 and kg CO$_2$/m^3, respectively. The functional unit is primarily relevant for reporting the results from the LCA study; however, absolute units are used for the extrapolation of energy and carbon savings to the regional and global levels.

2.2.3.2. System Boundary:

System boundary defines the energy and non-energy inputs to different life cycle stages that are included in a LCA study. Fig. 4 illustrates a system boundary of different processes in a building's life cycle (cradle-to-grave).[75] As marked with the red box, the system boundary for this study is cradle-to-site, which covers the building material production stage and the transportation of finished materials to a construction site. The production stage involves raw material extraction and processing, primary production process, and finishing, packaging and storage including any associated transportation.

2.2.3.3. Approach:

As noted above, LCA is a tool to evaluate the cradle-to-grave environmental effects of an activity. Life-cycle assessment primarily deals with inventory analysis and impact assessment, and in some cases provides insight into avenues for process improvements. In this study, the goal is to develop a global view of the potential energy and carbon benefits of vanadium use in rebar steel and to then parse these benefits across different geographic regions where more granular data is available. The embodied environmental impacts of production encompass both direct and indirect components. The direct component represents the energy use and carbon emission of a plant manufacturing reinforcement bars, whereas the energy and carbon impacts of raw material used for rebar production constitute indirect impacts. Databases derived from hybrid LCA methods yield excellent coverage of the direct and indirect impacts of common construction materials and processes. Table 3 lists energy and carbon values for reinforcement bar

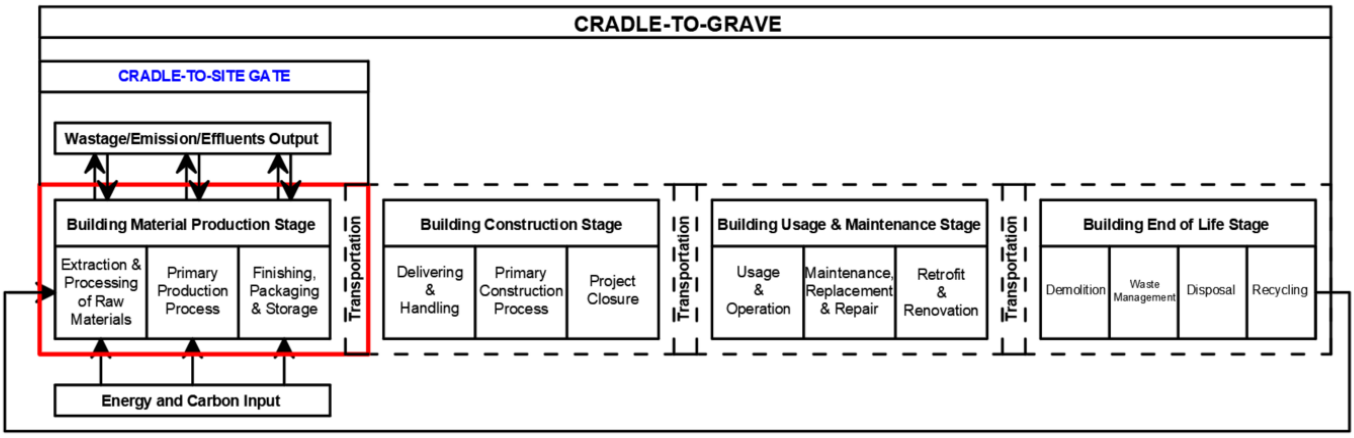

Fig. 4 System boundary for a building. Cradle-to-site gate (demarcated by the red box) is considered for this study

Table 3. Carbon and energy data for steel rebar, concrete and vanadium where the values for steel rebar extracted from ICE v2.0 for UK typical with EU 27 3-year average recycled content of 59% in steel production

	Embodied Energy (MJ/ kg)	Embodied Carbon (kg CO_2 e/kg)
Rebar	17.4[69]	1.4[69]
Concrete (30/37 MPa)	0.85[69]	0.126[69]
Vanadium	516 [54]	33.1[54] – 39.1[53]

steel and concrete extracted from ICE v2.0[69] and carried forward in our LCA calculations. Embodied energy and carbon values for vanadium production were taken from literature and are listed in Table 3.[53,54]

The limitations of the current model arise primarily from the availability and source of energy and carbon data. As mentioned in the previous section, the Inventory for Carbon and Energy (ICE) database is used for calculating the energy and carbon for steel and concrete materials. However, temporal and geographic limitations exist within the database based on when the database was prepared and source of data used for the preparation of ICE database. European and global averages were used to prepare the embodied energy database for different materials; however, for embodied carbon, UK sources were emphasized.[72] A similar limitation is applicable to the vanadium data based on the sources used to determine the embodied energy and carbon associated with the extraction and co-production of vanadium. However, the energy and carbon data for vanadium are notably from recent LCA studies.[53,54] Furthermore, it is notable that structural modeling presened here is limited to primarily steel savings in beams. However, if the section properties are varied, it could result in varying amounts of savings of concrete as well.

The impact assessment includes the environmental impact in terms of embodied energy and CO_2 emissions scaled using market data of global production supplied by Vanitec (Vanitec.org).[76] Vanitec, is a technical/scientific committee bringing together companies in the mining, processing, research of vanadium and vanadium-containing compounds. The embodied energy of the different types of rebar is computed in function unit (MJ/m^3), which represents the specific heat value per unit volume. The embodied carbon due to different types of rebar is computed in kgs of CO_2 emission per unit volume. The impact assessment category used for the carbon analysis is carbon emission excluding other greenhouse gases (GHG's) based on the carbon inventory used (ICE database).[72] The reduction in steel consumption derived from employing higher grades of reinforcement bars constituted from vanadium HSLA steels in comparison to baseline mild steel is translated to carbon and embodied energy metrics using the numbers in Table 3. The carbon and energy expenditure for production of vanadium is further determined and represents a debit to the energy and carbon benefits accrued from reduced steel consumption. The net results are scaled using global and regional market size and production data to determine the overall impact of vanadium microalloying in terms of energy and carbon savings.

3. Results

3.1. Quantification of the Embodied Energy and Carbon Impact of Reduction in Steel Consumption Derived from Structural Modeling

Structural analyses of RC structural components have been performed and the results are combined with machine learning models and an LCA inventory analysis to produce the embodied energy and carbon savings associated with each model. For component-level analysis, volume refers to the total volume of each component considered, whereas for building-level analysis, it is the total volume of the hypothetical RC structure that is considered. All results for the component and building level analysis were computed in terms of functional unit and the respective percentage savings were quantified and presented as shown in Tables 4(A, B) and 5. Table 4A delineates the energy and carbon savings for RC slab, beam and column, whereas Table 4B shows the results of analogous calculations for RC footing. An increase in energy and carbon savings with increasing strength of steel is observed for all structural components. Note that reduction in the amount of steel

Table 4. Results of energy and carbon savings for RC slab, beam, column, footing comparing V HSLA rebar grades to mild steel. EE: embodied energy; EC: embodied carbon (Yield strength shown in bold denotes mild steel bar as the baseline)

A	**RC Slab**		**RC Beam**		**RC Column**	
Yield Strength (MPa)	**% Savings**		**% Savings**		**% Savings**	
	EE	**EC**	**EE**	**EC**	**EE**	**EC**
250	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
400	0.81%	0.44%	33.66%	27.22%	4.52%	4.59%
500	1.06%	0.57%	43.50%	35.27%	6.67%	7.16%
600	1.22%	0.67%	49.78%	40.40%	8.83%	9.72%

B	**RC Footing**	
Yield Strength (MPa)	**% Savings**	
	EE	**EC**
250	0.00%	0.00%
500	12.09%	7.37%

Table 5. Results of energy and carbon savings for the hypothetical RC building depicted in Fig. 2(C, D) as calculated using the ETABS software (Yield strength shown in bold denotes mild steel bar as baseline)

Yield Strength (MPa)	**% Savings**	
	EE	**EC**
250	0.00%	0.00%
400	17.33%	12.26%
500	22.65%	16.16%
600	26.26%	18.83%

typically necessitates increased consumption of concrete; however, the relatively higher embodied energy and carbon associated with steel production (Table 3) implies an overall savings in both energy and carbon even after accounting for the increased amount of concrete that is needed.

The component level models have further been extrapolated to calculate the energy and carbon savings from a hypothetical reinforced concrete building, which has been modeled using the ETABS v18 structural software as described in §2.2.1. Table 5 shows the projected energy and carbon savings for the hypothetical building for different grades of vanadium microalloyed steel in comparison to a 250 MPa mild steel baseline.

3.2. Extrapolation of Embodied Energy and Carbon Savings to Regional and Global Impact

Some of the most granular data on vanadium consumption in steel for reinforcement bar applications comes from China, which has seen a large upheaval of the construction industry as a result of centrally mandated rebar standards[77] introduced in 2018. The elimination of rebar grade HRB335 and establishment of a new HRB600 grade to enhance the resilience of buildings to earthquakes, spurred in large measure by the devastation wrought by the 2008 Sichuan earthquake, has prompted a significant increase in vanadium consumption.[78,79]

Grade 3 (400MPa), Grade 4 (500MPa), and Grade 5 (600MPa) reinforcement bars manufactured in China are estimated to require 0.03%, 0.06%, and more than 0.1% V, respectively, which is generally consistent with expectations from the machine learning model in Fig. 3 and Table 2.

Based on data from the China Iron & Steel Research Institute (CISRI), the research and development base for metals and the authoritative agency for metallurgical analysis in China, in 2018, the total amount of vanadium consumed in rebar applications in China was 29,000 metric tons (MT)[51] of which 20,300 MT is assumed to be used in beams and columns. Table 6 extrapolates these numbers to two scenarios accounting for the entire vanadium consumption being utilized in either 400 MPa or 600 MPa rebar based on vanadium content required to achieve these yield strengths derived from the machine learning model in Fig. 3. Considering Table 6, if all 20,300 MT of vanadium is considered to have gone into the manufacture of 400 MPa

Table 6. Energy and carbon savings using vanadium in rebar market data (China) and assuming vanadium amounts quantified using the machine learning model. The steel column denotes the total steel consumption. The EE and EC columns denote the net savings in embodied energy and carbon for 400 and 600 MPa rebar. (Yield strength shown in bold denotes mild steel bar as baseline)

Yield Strength (MPa)	**Steel (t)**	**Vanadium (t)**	**EE**	**EC**	**Savings**		**China Carbon Savings**	
			(x10^9 MJ)	**(Gt CO$_2$e)**	**EE**	**EC**	**(Gt CO$_2$e)**	**%**
250	237,160,414	0	4,127	0.3320	0.00%	0.00%	0.000	0.00%
400	156,153,846	20,300	2,728	0.2193	33.90%	33.95%	0.113	1.15%

Yield Strength (MPa)	**Steel (t)**	**Vanadium (t)**	**EE**	**EC**	**Savings**		**China Carbon Savings**	
			(x10^9 MJ)	**(Gt CO$_2$e)**	**EE**	**EC**	**(Gt CO$_2$e)**	**%**
250	24,668,709	0	429	0.0345	0.00%	0.00%	0.000	0.00%
600	11,468,927	20,300	210	0.0167	51.07%	51.56%	0.018	0.18%

rebar, this accounts for 156,153,846 MT of rebar with vanadium microalloying. Based on the structural modeling results delineated in Table 5, the above mentioned quantity of rebar translates to an 81 mMT reduction of steel consumption in comparison to 250 MPa steel having the same loading and geometric parameters. The steel savings can be directly translated to embodied energy and carbon savings after debiting the costs of vanadium incorporation (from Table 2); embodied energy savings of 1,399×10^9 Mega Joules (MJ) and CO_2 savings of 0.1127 Giga tons (Gt) CO_2 emissions can be thus directly attributed to supplanting 250 MPa rebar with 400 MPa rebar. Using China's total fossil fuel-related carbon emission figures as 9.8 Gt,[80] this equates to a 1.15% reduction in the carbon footprint as a result of reduced steel consumption directly attributable to microalloying. The lower half of Table 6 represents corresponding numbers if all of the vanadium was used for production of 600 MPa and sets a lower bound for savings in embodied energy and carbon at 0.18%.

A more detailed assessment of the market data segmented by rebar grade allows for further refinement of the embodied carbon and steel numbers and provides a perspective of the role of vanadium in vastly different construction industries. In 2017, 130 mMT of 400 MPa reinforcement bars were produced in China, whereas the production of 500 MPa and 600 MPa reinforcement bars were 40 mMT and 0.9 mMT, respectively.[51] Extrapolating these numbers to steel used in beams and columns and based on vanadium consumption data, 9,800 MT of vanadium was used for production of 400 MPa and 500 MPa rebars, and 700 MT for production of 600 MPa rebar. Table 7 delineates the embodied energy and carbon savings with these quantities of rebar. Summing the savings from each grade of rebar allows us to arrive at a more granular estimate of 1.01% reduction in the total fossil carbon footprint of China because of reduced steel consumption directly attributable to microalloying in 2017.

The European Union (EU) has a vastly different construction industry that relies more extensively on tempering treatments. A growing perception of increased vanadium criticality combined and different constrction practices in the EU have diverted attention to alternative solutions – nevertheless, the fundamental materials properties that have garnered massive savings in China persist and remain active in decarbonizing construction in the EU.[55] Vanadium consumption in the EU in 2017 was 12,700 MT but only 30% of the vanadium goes towards reinforcement bar applications,[51,81] representing a total of 3,810 MT (of which 2,667 MT are used for RC beams and columns). Assuming this entire amount goes towards the production of 400 MPa reinforcement bars yields 20.5 mMT of steel, which represents steel savings of 10.6 mMT over baseline 250 MPa reinforcement bars (Table 8).

Table 7. Energy and carbon savings using vanadium in rebar market data (China) and taking vanadium and steel amounts for each grade of steel from available China rebar break up. The steel column denotes the total steel consumption. The EE and EC columns denote the net savings in embodied energy and carbon for 400, 500, and 600 MPa rebar. (Yield strength shown in bold denotes mild steel bar as the baseline)

Yield Strength (MPa)	Steel (t)	Vanadium (t)	EE	EC	Savings		China Carbon Savings	
			($x10^9$ MJ)	(Gt CO_2e)	EE	EC	(Gt CO_2e)	%
250	138,207,275	0	2,405	0.1935	0.00%	0.00%	0.000	0.00%
400	91,000,000	9,800	1,588	0.1277	33.95%	33.99%	0.066	0.67%

Yield Strength (MPa)	Steel (t)	Vanadium (t)	EE	EC	Savings		China Carbon Savings	
			($x10^9$ MJ)	(Gt CO_2e)	EE	EC	(Gt CO_2e)	%
250	51,570,772	0	897	0.0722	0.00%	0.00%	0.000	0.00%
500	28,000,000	9,800	492	0.0395	45.14%	45.26%	0.033	0.33%

Yield Strength (MPa)	Steel (t)	Vanadium (t)	EE	EC	Savings		China Carbon Savings	
			($x10^9$ MJ)	(Gt CO_2e)	EE	EC	(Gt CO_2e)	%
250	1,355,078	0	24	0.0019	0.00%	0.00%	0.000	0.00%
600	630,000	700	11	0.0009	51.98%	52.29%	0.001	0.01%
Total 1.01% savings in China's Carbon emissions								

Table 8. Energy and carbon savings using vanadium in rebar market data (EU) and assuming vanadium amounts quantified using the machine learning model. The steel column denotes the total steel consumption. The EE and EC columns denote the net savings in embodied energy and carbon for 400 and 600 MPa rebar. (Yield strength shown in bold denotes mild steel bar as the baseline)

Yield Strength (MPa)	Steel (t)	Vanadium (t)	EE	EC	Savings		EU Carbon Savings	
			($x10^9$ MJ)	(Gt CO_2e)	EE	EC	(Gt CO_2e)	%
250	31,157,972	0	542	0.0436	0.00%	0.00%	0.000	0.00%
400	20,515,385	2,667	358	0.0288	33.90%	33.95%	0.015	0.42%

Yield Strength (MPa)	Steel (t)	Vanadium (t)	EE	EC	Savings		EU Carbon Savings	
			($x10^9$ MJ)	(Gt CO_2e)	EE	EC	(Gt CO_2e)	%
250	3,240,958	0	56	0.0045	0.00%	0.00%	0.000	0.00%
600	1,506,780	2,667	28	0.0022	51.07%	51.56%	0.002	0.07%

Based on the embodied energy and carbon values delineated in §2.2.3, the utilization of 400 MPa reinforcement bars brings about a cumulative embodied energy savings of 184 ×10^9 MJ and embodied carbon savings of 0.015 Gt CO_2. A similar analysis is presented with the assumption that the entire vanadium amount of 2,667 MT goes towards production of 600 MPa reinforcement bars in the lower half of Table 8 to establish a lower bound. Fossil carbon emissions in the EU totaled 3.5 Gt[80] in 2017; Table 8 suggests a 0.07—0.42% reduction in the carbon footprint of the EU as a result of reduced steel consumption directly attributable to microalloying in 2018. More granular analysis necessitates segmented market size information on different grades of V HSLA rebar.

One approach to developing a more granular analysis is based on a dataset that indicates that the 2016 production of reinforcement bars in the EU was 11 mMT;[57] assuming that ca. 70% of this goes towards beams and columns, this yields a number of 7.7 mMT of steel, which incorporates 2,667 MT of vanadium in total.[81] Assuming a simplified two-grade system using total steel (7.7 mMT) and vanadium (2,667 MT) quantities and steel-vanadium relationship using machine learning model results (Table 2), 33% of consumed vanadium or ca. 869 MT goes into 400 MPa steel and 67% or ca. 1,798 MT goes into 600 MPa steel, whereas 87% or ca. 6.7 mMT of steel goes into 400 MPa and 13% or ca. 1 mMT steel into 600 MPa. Table 9 plots the proportionately scaled embodied energy and carbon savings, which translates to a cumulative 0.19% reduction in the total fossil fuel-related carbon footprint of the EU as a result of reduced steel consumption directly attributable to microalloying.

We next turn our attention to developing a global perspective. In 2017, World Steel Association estimates that 235 mMT of steel was used globally for reinforcement bars.[51,57] An estimated 164 mMT was used for beams and columns. One approach to calculate the energy and carbon savings is by extrapolating from China data that represents an upper bound of vanadium use in rebar, yields a total global utilization of vanadium in beams and columns as 43,720 MT. A rebar break-up similar to the one provided in the China data is used to extrapolate the steel rebar quantities the goes into each grade of steel. Table 10 shows the associated embodied energy and carbon savings. Considering global CO_2 emissions of 36.2 Gt in 2017, this analysis yields an upper bound for reduction in total global fossil carbon footprint of 0.377% as a result of reduced steel consumption directly attributable to microalloying.[82] These savings equate to the those gained, annually, by planting approximately two hundred sixty million trees.[83]

Another approach is by extrapolating from EU data that represents a lower bound of vanadium intensity of use in rebar, yields a total global utilization of vanadium in beams and columns as 19,945 MT. Steel rebar quantities are extrapolated similar to EU steel break-up for each grade of steel. Table 11 shows the associated embodied energy and carbon savings. The analysis yields a lower bound for reduction in total global fossil

Table 9. Energy and carbon savings using vanadium in rebar market data (EU) and vanadium amounts weighted by proportion of steel. The steel column denotes the total steel consumption. The EE and EC columns denote the net savings in embodied energy and carbon for 400 and 600 MPa rebar. (Yield strength shown in bold denotes mild steel bar as the baseline)

Yield Strength (MPa)	Steel (t)	Vanadium (t)	EE	EC	Savings		EU Carbon Savings	
			(x10^9 MJ)	(Gt CO_2e)	EE	EC	(Gt CO_2e)	%
250	10,151,623	0	177	0.0142	0.00%	0.00%	0.000	0.00%
400	6,684,146	869	117	0.0094	33.90%	33.95%	0.005	0.14%
Yield Strength (MPa)	**Steel (t)**	**Vanadium (t)**	**EE**	**EC**	**Savings**		**EU Carbon Savings**	
			(x10^9 MJ)	**(Gt CO_2e)**	**EE**	**EC**	**(Gt CO_2e)**	**%**
250	2,185,017	0	38	0.0031	0.00%	0.00%	0.000	0.00%
600	1,015,854	1,798	19	0.0015	51.07%	51.56%	0.0016	0.05%
Total 0.19% savings in EU's Carbon emissions								

Table 10. Energy and carbon savings using vanadium in rebar market data (Global) and vanadium amounts weighted by proportion of total steel for each grade. The steel column denotes the total steel consumption. Both vanadium and steel interpolated using China data. The EE and EC columns denote the net savings in embodied energy and carbon for 400, 500 and 600 MPa rebar. (Yield strength shown in bold denotes mild steel bar as the baseline)

Yield Strength (MPa)	Steel (t)	Vanadium (t)	EE	EC	Savings		Global Carbon Savings	
			(x10^9 MJ)	(Gt CO_2e)	EE	EC	(Gt CO_2e)	%
250	189,853,450	0	3,303	0.2658	0.00%	0.00%	0.000	0.00%
400	125,005,459	21,106	2,186	0.1757	33.83%	33.89%	0.090	0.25%
Yield Strength (MPa)	**Steel (t)**	**Vanadium (t)**	**EE**	**EC**	**Savings**		**Global Carbon Savings**	
			(x10^9 MJ)	**(Gt CO_2e)**	**EE**	**EC**	**(Gt CO_2e)**	**%**
250	70,842,066	0	1,233	0.0992	0.00%	0.00%	0.000	0.00%
500	38,463,218	21,106	680	0.0545	44.82%	45.00%	0.045	0.123%
Yield Strength (MPa)	**Steel (t)**	**Vanadium (t)**	**EE**	**EC**	**Savings**		**Global Carbon Savings**	
			(x10^9 MJ)	**(Gt CO_2e)**	**EE**	**EC**	**(Gt CO_2e)**	**%**
250	1,861,452	0	32	0.0026	0.00%	0.00%	0.000	0.00%
600	865,422	1,508	16	0.0013	51.11%	51.59%	0.001	0.004%
Total 0.377% savings in global carbon emissions								

Table 11. Energy and carbon savings using vanadium in rebar market data (Global) and vanadium amounts weighted by proportion of steel. The steel column denotes the total steel consumption. Both vanadium and steel interpolated using EU data. The EE and EC columns denote the net savings in embodied energy and carbon for 400 and 600 MPa rebar. (Yield strength shown in bold denotes mild steel bar as the baseline)

Yield Strength (MPa)	Steel (t)	Vanadium (t)	EE	EC	Savings		Global Carbon Savings	
			(x10^9 MJ)	(Gt CO$_2$e)	EE	EC	(Gt CO$_2$e)	%
250	216,656,852	0	3,770	0.3033	0.00%	0.00%	0.000	0.00%
400	142,653,659	6,498	2,486	0.1999	34.07%	34.09%	0.103	0.29%
Yield Strength (MPa)	Steel (t)	Vanadium (t)	EE	EC	Savings		Global Carbon Savings	
			(x10^9 MJ)	(Gt CO$_2$e)	EE	EC	(Gt CO$_2$e)	%
250	46,632,828	0	811	0.0653	0.00%	0.00%	0.000	0.00%
600	21,680,441	13,447	384	0.0308	52.65%	52.83%	0.034	0.095
Total 0.385% savings in global carbon emissions								

carbon footprint of 0.385% as a result of reduced steel consumption directly attributable to microalloying.[82] Fig. 5 illustrates the carbon savings in megatons (Mt) for the World, China, and EU regions and as a percentage of their respective emissions as shown in Table 10, Table 7, and Table 9. The economy of material use offered by vanadium microalloying is identical for the three regions – the difference in magnitude of CO$_2$ savings stems directly from the specific intensity of vanadium used in steel and regional market size.

4. Discussion

The steel industry is a leading contributor to global carbon emissions with a carbon footprint that is not readily amenable to reduction through technology innovations. It is estimated that ca. 22.5% of global steel production goes towards reinforcement bars used in the construction industry.[84] In this article, we have investigated the reduction of the embodied energy and carbon footprint of steel reinforcement bars resulting from vanadium microalloying. The incorporation of

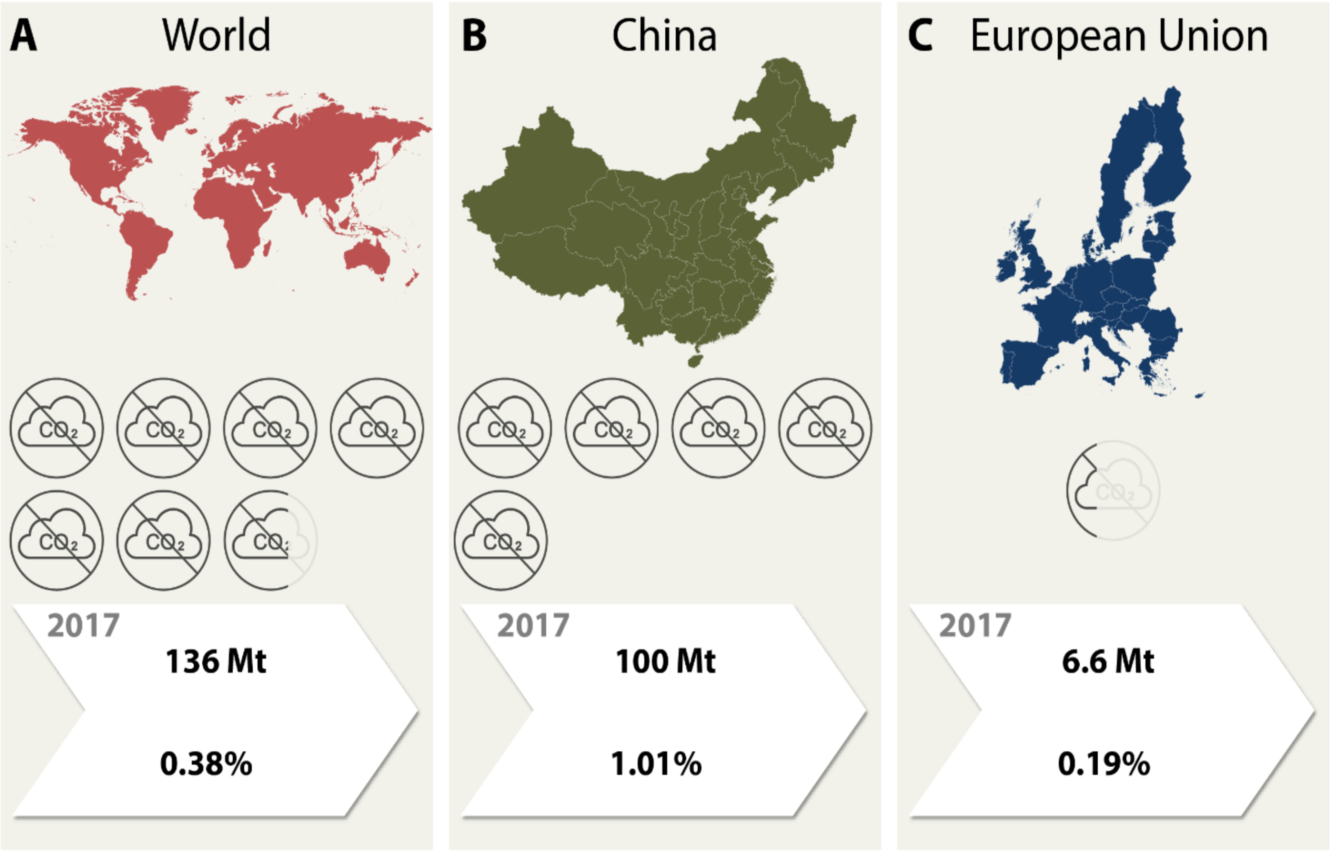

Fig. 5 2017 carbon savings directly attributable to vanadium microalloying for (A) World, (B) China, and (C) EU regions are shown in megatons (Mt) and as a percentage of the total region-specific carbon emissions in 2017. The calculations are weighted by a proportion of total steel for each grade as shown in Table 10, Table 7, and Table 9 for World, China and EU regions, respectively. Each full-size CO$_2$-savings icon represents 20 Mt of CO$_2$ saved, and partial representations of the icon reflect a percentage of 20 Mt of CO$_2$, i.e. 16 Mt and 6.6 Mt of CO$_2$ in (A) and (C).

small quantities of vanadium effects large increases in yield strength. A machine learning model is developed to identify specific alloy compositions from aggregated data and provide an unambiguous view of the dependence of yield strength on vanadium concentration (Fig. 3 and Table 2). The increased strength of vanadium microalloyed steels translates to substantial material savings in comparison to lower grade rebar. Material savings in turn translate to a reduction in embodied carbon and embodied energy of individual reinforced concrete structural elements (from 0.67% reduction in the carbon footprint of a RC slab (600 MPa steel) to 40.40% reduction in the carbon footprint of a RC beam (600 MPa steel), Table 4) as well as entire buildings (26.26% reduction embodied energy and 18.83% reduction in embodied carbon for a hypothetical building (600 MPa steel), Table 5) after debiting the energy and carbon costs associated with vanadium incorporation. While this work has focused primarily on the cradle-to-gate carbon and energy savings directly attributable to microalloying, it is important to note that the benefits of vanadium incorporation in steel are likely to continue during the use-phase. In addition to maintaining or surpassing the corrosion performance of comparable vanadium-free steels, vanadium-containing steels have shown greater resistance to hydrogen embrittlement, which is becoming increasingly relevant with growing trends of construction utilizing higher-strength rebar (>700 MPa).[85,86] In addition, vanadium steels are better suited than quenched and self-tempered (QST) alternatives to prevent failure and thus necessary replacement upon seismic loading.[42]

The reduction in carbon footprint deduced from the life-cycle assessment of the compositions with different vanadium content can be extrapolated using vanadium consumption data to obtain cumulative metrics on the role of microalloying in reducing regional and global greenhouse emissions. Granular and segmented market data is available for China given the recent adoption of new reinforcement bar standards. Impact assessment suggests that vanadium microalloying results in a ca. 1.01% reduction of total fossil carbon footprint (range of 0.18%—1.15%) in China. The EU market is considerably more diverse in terms of rebar grades and has a much lower consumption of vanadium. Nevertheless, ca. 0.19% reduction of total fossil carbon footprint (range of 0.07—0.42%) is estimated in the EU. Global figures extrapolated from worldwide vanadium consumption with China and EU intensity of vanadium use in rebar as boundary conditions denote 0.377—0.385% reduction of total global fossil carbon footprint, attesting to the significant role that vanadium plays in enhancing the sustainability of the steel industry.

Conclusions and Policy Implications

The construction industry represents a substantial burden on limited natural resources and has a massive global carbon footprint that derives in large measure from the embodied energy and carbon costs of building materials. Steel reinforcement bars are ubiquitous in reinforced concrete structures, and indeed half of global steel production goes towards the construction of buildings and infrastructure. Methods to increase the strength-to-weight ratio of steel through control of microstructure achieved through alloying or grain refinement hold considerable promise for reducing the amount of steel required to attain a specific load-bearing capacity. In this study, we have evaluated the carbon footprint of vanadium-microalloyed steel of different grades with respect to mild steel in terms of both embodied energy and carbon. A comprehensive accounting of the costs and benefits of vanadium microalloying demonstrates the critical (often underappreciated) role that vanadium plays in enhancing the sustainability of the steel industry as well as the construction industry. The impact of vanadium microalloying is estimated to be 0.377—0.385% of the total global fossil carbon footprint.

This work demonstrates that the impact of construction materials can be dramatically reduced by supplanting lower grade products with higher value alternatives. A life cycle focus is imperative for decisions that occur at the intersection of policy, energy, and the environment. The efficacy of vanadium in reducing embodied energy and carbon footprint is directly traceable to two specific attributes. First, as a result of the co-production of vanadium with steel and the substantial amount of vanadium extracted from recycled slag and spent catalysts, waste materials with minimal economic value, the energy and carbon costs associated with vanadium production are relatively low (Table 3); future projections suggest as much as a threefold reduction in the embodied carbon costs of vanadium production may be attainable with adoption of specific technology improvements such as utilization of hydroelectric power.[56] Notably, the geographically dispersed nature of vanadium deposits with considerable current or emerging commercial extraction across South Africa, China, Russia, Brazil, and Australia ensures that transportation costs are low. Second, vanadium addition increases yield strength at relatively low concentrations (e.g., as compared to niobium) and at low processing temperatures as a result of the intrinsic miscibility of the two elements in the Fe-V phase diagram, mitigating the need for complex thermomechanical treatments. As such, policy interventions seeking to reduce the carbon footprint of the steel and construction industries must consider the distinctive and often outsized role of microalloying elements. The potential for carbon and energy savings from microalloying is especially promising for rapidly growing economies such as India, which recently surpassed Japan as the second-largest steel producing country with an estimated steel output target of 300 mMT by 2030.[87] In 2017, the intensity of vanadium use in India was 0.035 kgV/Mt steel, lagging substantially behind the world average vanadium consumption of 0.053 kgV/Mt in part owing to a greater reliance on mild steel rebar strengthened by cold-working or heat-treat processes.[51] Improving India's specific vanadium from consumption from 0.035 kgV/Mt to 0.053 kgV/Mt by 2030 would require ca. 6,000 additional metric tons of vanadium per annum with carbon savings that are likely to scale commensurately.

The framework developed here informed by machine learning of data aggregated from the published literature, structural modeling in concordance with established building codes, life cycle assessment based on databases, and tonnage data obtained from trade organizations provides a blueprint for assessing the role of specific alloying elements in enhancing the sustainability of the steel industry.

Conflicts of interest

This work was funded in part by VANITEC. The authors have no conflicts of interest to declare.

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References

1 P. Huovila, Buildings and Climate Change: Current Status , Challenges and Opportunities, *United Nation Environ. Program.*, 2007, 1–88.

2 USDOE, Manufacturing Energy Consumption Survey (MECS), https://www.eia.gov/consumption/manufacturing/data/2014/.

3 U.S. Energy Information Administration (EIA), How much energy is consumed in residential and commercial buildings in the United States?, https://www.eia.gov/tools/faqs/faq.php?id=86&t=1.

4 G. K. C. Ding, The development of a multi-criteria approach for the measurement of sustainable performance for built projects and facilities, *PhD Thesis, Univ. Technol. Sydney*, 2004, 404.

5 M. K. Dixit, Embodied Energy Calculation: Method and Guidelines for a Building and Its Constituent Materials, *PhD Diss. Texas A&M Univ. USA*.

6 A. Bajpayee, M. Farahbakhsh, U. Zakira, A. Pandey, L. A. Ennab, Z. Rybkowski, M. K. Dixit, P. A. Schwab, N. Kalantar, B. Birgisson and S. Banerjee, In situ Resource Utilization and Reconfiguration of Soils Into Construction Materials for the Additive Manufacturing of Buildings, *Front. Mater.*, 2020, **7**, 1–12.

7 M. Bechthold and J. C. Weaver, Materials science and architecture, *Nat. Rev. Mater.*, , DOI:10.1038/natrevmats.2017.82.

8 A. Hasanbeigi, L. Price and E. Lin, *Renew. Sustain. Energy Rev.*, 2012.

9 A. Babakhani, A. R. Kiani-Rashid and S. M. R. Ziaei, The microstructure and mechanical properties of hot forged vanadium microalloyed steel, *Mater. Manuf. Process.*, 2012, **27**, 135–139.

10 T. N. Baker, Microalloyed steels, *Ironmak. Steelmak.*, 2016, **43**, 264–307.

11 M. Korchynsky and J. R. Paules, Microalloyed forging steels-A state of the art review, *SAE Tech. Pap.*, , DOI:10.4271/890801.

12 S. Zajac, T. Siwecki, W. B. Hutchinson and R. Lagneborg, Strengthening Mechanisms in Vanadium Microalloyed Steels Intended for Long Products., *ISIJ Int.*, 1998, **38**, 1130–1139.

13 S. Copiello, Economic implications of the energy issue : Evidence for a positive non-linear relation between embodied energy and construction cost, *Energy Build.*, 2016, **123**, 59–70.

14 P. J. Davies, S. Emmitt and S. K. Firth, Challenges for capturing and assessing initial embodied energy : a contractor ' s perspective Challenges for capturing and assessing initial embodied energy : a contractor ' s perspective, *Constr. Manag. Econ.*, 2014, **32**, 290–308.

15 R. Plank, The principles of sustainable construction, *IES J. Part A Civ. Struct. Eng.*, 2008, **1**, 301–307.

16 M. K. Dixit, Life cycle recurrent embodied energy calculation of buildings : A review, *J. Clean. Prod.*, 2019, **209**, 731–754.

17 M. K. Dixit, Life cycle embodied energy analysis of residential buildings : A review of literature to investigate embodied energy parameters, *Renew. Sustain. Energy Rev.*, 2017, **79**, 390–413.

18 H. Mahmoud and G. Cheng, Framework for Lifecycle Cost Assessment of Steel Buildings under Seismic and Wind Hazards, *J. Struct. Eng.*, 2017, **143**, 04016186-1–15.

19 P. Adhikari, H. Mahmoud, A. Xie, K. Simonen and B. Ellingwood, Life-cycle cost and carbon footprint analysis for light-framed residential buildings subjected to tornado hazard, *J. Build. Eng.*, 2020, **32**, 101657.

20 L. Guardigli, *Comparing the environmental impact of reinforced concrete and wooden structures*, 2014.

21 AISI, Profile 2016, *Am. Iron Steel Inst.*

22 L. Nakoryakova, D. Kasatkin and Y. Afanasyeva, *Overview of the steel and iron ore market*, 2019.

23 World Steel Association, *World Steel in Figures 2018*, 2018.

24 M. C. Moynihan and J. M. Allwood, Resources , Conservation and Recycling The flow of steel into the construction sector, *"Resources, Conserv. Recycl.*, 2012, **68**, 88–95.

25 C. Y. Chen, H. W. Yen, F. H. Kao, W. C. Li, C. Y. Huang, J. R. Yang and S. H. Wang, Precipitation hardening of high-strength low-alloy steels by nanometer-sized carbides, *Mater. Sci. Eng. A*, 2009, **499**, 162–166.

26 C. I. Garcia, *High strength low alloyed (HSLA) steels*, Elsevier Ltd, 2016.

27 T. W. Montemarano, B. P. Sack, J. P. Gudas, M. G. Vassilaros and H. H. Vanderveldt, High Strength Low Alloy Steels in Naval Construction., *J. Sh. Prod.*, 1986, **2**, 145–162.

28 D. A. Skobir, High-strength low-alloy (HSLA) steels: Visokotrdna malolegirana (HSLA) konstrukcijska jekla, *Mater. Tehnol.*, 2011, **45**, 295–301.

29 J. F. McGurn, in *PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON CORROSION AND REHABILITATION OF REINFORCED CONCRETE STRUCTURES HELD 7-11 DECEMB 1998, ORLANDO, FLORIDA, USA*, 1999.

30 R. Aiuti, C. Ascanio, S. Caprili, M. Dolšek, W. Salvatore, R. Valentini and J. Žižmond, in *COMPDYN 2017 - Proceedings of the 6th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*, 2017.

31 Z. J. Xie, Y. P. Fang, G. Han, H. Guo, R. D. K. Misra and C. J. Shang, Structure-property relationship in a 960MPa grade ultrahigh strength low carbon niobium-vanadium microalloyed steel: The significance of high frequency induction tempering, *Mater. Sci. Eng. A*, 2014, **618**, 112–117.

32 BS 4449:1997, *Specification for carbon steel bars for the reinforcement of concrete*, 1997.

33 BS EN 10080:2005, *Steel for the reinforcement of concrete - Weldable reinforcing steel - General*, 2005.

34 EN 1992-1-1, *Eurocode 2: Design of concrete structures - Part 1-1 : General rules and rules for buildings*, 2004.

35 R. W. Hertzberg, R. P. Vinci and J. L. Hertzberg, *Deformation and Fracture Mechanics of Engineering Materials*, John Wiley & Sons, Inc., 5th edn., 2013.

36 M. J. Crooks and R. E. Miner, The Ultralight Steel Auto Body program completes phase I, *JOM*, 1996, **48**, 13–15.

37 V. Smith, D. Gard and G. Keoleian, Ultra Light Steel Auto Body Advanced Vehicle Concepts Report No . CSS02-06.

38 J. Beatty, Vanadium Strong and Army Strong: Strength Matters!, *AMMTIAC Q.*, 2011, **6**, 3–14.

39 A. M. Sage, Vanadium in structural steels, 1984, **84**, 138–146.

40 R. G. Davies, The deformation behavior of a vanadium-strengthened dual phase steel, *Metall. Trans. A*, 1978, **9**, 41–52.

41 S. Gündüz and R. C. Cochrane, Influence of cooling rate and tempering on precipitation and hardness of vanadium microalloyed steel, *Mater. Des.*, 2005, **26**, 486–492.

42 D. Milbourn and L. Yu, Metallurgical Benefits of Vanadium Microalloying in Producing High Strength Seismic Grade Rebar, *Int. Semin. Prod. Appl. HIgh Strength Seism. Grade Rebar Contain. Vanadium*, 2010, 32–43.

43 B. K. Show, R. Veerababu, R. Balamuralikrishnan and G. Malakondaiah, Effect of vanadium and titanium modification on the microstructure and mechanical properties of a microalloyed HSLA steel, *Mater. Sci. Eng. A*, 2010, **527**, 1595–1604.

44 T. N. Baker, Processes, microstructure and properties of vanadium microalloyed steels, *Mater. Sci. Technol.*, , DOI:10.1179/174328409X453253.

45 R. J. Glodowski, *An Updated Prediction Model for Vanadium Precipitation Strengthening of Ferritic Steels*, 2014.

46 D. Rehder, The role of vanadium in microalloyed steels, *Metallomics*, 2015, **7**, 730–742.

47 P. Wang, Z. Li, G. Lin, S. Zhou, C. Yang and Q. Yong, Influence of vanadium on the microstructure and mechanical properties of medium-carbon steels for wheels, *Metals (Basel).*, 2018, **8**, 1–14.

48 A. Parija, G. R. Waetzig, J. L. Andrews and S. Banerjee, Traversing Energy Landscapes Away from Equilibrium: Strategies for Accessing and Utilizing Metastable Phase Space, *J. Phys. Chem. C*, 2018, **122**, 25709–25728.

49 Y. Li and D. Milbourn, The influence of vanadium microalloying on the production of thin slab casting and direct rolled steel strip, *7th Int. Conf. High Strength Low Alloy Steels, HSLA Steels 2015, Int. Conf. Microalloying 2015, Microalloying 2015 Int. Conf. Offshore Eng. Steels 2015, OES 2015*, 2015, **1**, 343–349.

50 K. A. Taylor, Solubility products for titanium-, vanadium-, and niobium-carbide in ferrite, *Scr. Metall. Mater.*, 1995, **32**, 7–12.

51 Bushveld, *Vanadium 101*, 2018.

52 G. Bauer, Vanadium and Vanadium Compounds, *Ullmanns Encycl. Ind. Chem.*, 2012, **37**, 425–474.

53 S. Weber, J. F. Peters, M. Baumann and M. Weil, Life Cycle Assessment of a Vanadium Redox Flow Battery, *Environ. Sci. Technol.*, 2018, **52**, 10864–10873.

54 P. Nuss and M. J. Eckelman, Life Cycle Assessment of Metals: A Scientific Synthesis, *PLoS One*, 2014, **9**, 1–12.

55 M. Petranikova, A. H. Tkaczyk, A. Bartl, A. Amato, V. Lapkovskis and C. Tunsu, *Waste Manag.*, 2020.

56 *BlackRock Metals: Life Cycle Assessment of Vanadium*, 2014.

57 World Steel Associaiton, *Steel Statistical Yearbook 2018*, 2018.

58 EN 1990:2002+A1, *Eurocode - Basis of structural design*, 2005.

59 EN 1991-1-1, *Eurocode 1: Actions on structures - Part 1-1: General actions - Densities, self-weight, imposed loads for buildings*, 2002.

60 EN 1991-1-4, *Eurocode 1: Actions on structures - Part 1-4: General actions - Wind actions*, 2010.

61 EN 1997-1, *Eurocode 7: Geotechnical design - Part 1: General rules*, 2004.

62 EN 206-1, *Concrete Part - 1: Specification, performance, production and conformity*, 2000.

63 G. Deping, H. Mingxing and L. Kaijin, *Application of VN Alloy in 400MPa Reinforcing Bar*, 2000.

64 Y. Lv, G. Sheng and Y. Jiao, Effect of V/N ratio on the high strain and low cycle fatigue behaviors of V–N microalloyed rebars, *Constr. Build. Mater.*, 2014, **69**, 18–25.

65 D. Milbourn, L. Yu, S. Copiello, P. J. Davies, S. Emmitt and S. K. Firth, Metallurgical Benefits of Vanadium Microalloying in Producing High Strength Seismic Grade Rebar, *Int. Semin. Prod. Appl. HIgh Strength Seism. Grade Rebar Contain. Vanadium*, 2010, **68**, 32–43.

66 A. M. Sage, Effect of V, N and Al on the Mechanical Properties of Reinforcing Bar Steels, *Met. Technol.*, 1976, **3**, 65–70.

67 S. Shihuai, W. Weiguo, Z. Ruoqiang, Z. Mingqi and W. Ying, The Commercial Trial - Production of HRB400 reinforced bar with V-N Microalloying, *Int. Symp. Res. Appl. High Strength Reinf. Bar*, 2003, 110–114.

68 Z. Yongquan, Y. Caifu and L. Shuping, *Study of V-N Microalloyed Steels for Reinforcing Bars*, 1998.

69 G. Hammond and C. Jones, *Inventory of Carbon & Energy (ICE) Version 2.0*, UK, 2011.

70 ISO 14040, Environmental management — Life cycle assessment — Principles and framework, 2006, 20.

71 ISO 14044, Environmental management — Life cycle assessment — Requirements and guidelines, 2006, 46.

72 G. P. Hammond and C. I. Jones, Embodied energy and carbon in construction materials, 2008, 87–98.

73 E. J. Braham, J. Cho, K. M. Forlano, D. F. Watson, R. Arròyave and S. Banerjee, Machine Learning-Directed Navigation of Synthetic Design Space: A Statistical Learning Approach to Controlling the Synthesis of Perovskite Halide Nanoplatelets in the Quantum-Confined Regime, *Chem. Mater.*, 2019, **31**, 3281–3292.

74 J. A. K. Suykens and J. Vandewalle, Least squares support vector machine classifiers, *Neural Process. Lett.*, , DOI:10.1023/A:1018628609742.

75 M. K. Dixit, C. H. Culp and J. L. Fernández-Solís, System boundary for embodied energy in buildings: A conceptual model for definition, *Renew. Sustain. Energy Rev.*, 2013, **21**, 153–164.

76 VANITEC, http://vanitec.org/.

77 China's inspections to speed up rebar standards rollout, https://www.argusmedia.com/en/news/1829554-chinas-inspections-to-speed-up-rebar-standards-rollout.

78 J. Patel, *China Steel Rebar : Market Overview and Latest Product Developments*, 2018.

79 Vanadium: New Chinese rebar standards positive for ferrovanadium demand, https://roskill.com/news/vanadium-new-chinese-rebar-standards-positive-ferrovanadium-demand/#:~:text=for ferrovanadium demand-,Vanadium%3A New Chinese rebar standards positive for ferrovanadium demand,of inferior steels in construction.&text=These will re.

80 Global Carbon Budget, Global Carbon Project, https://www.globalcarbonproject.org/carbonbudget/archive/2018/GCP_CarbonBudget_2018.pdf.

81 Vanitec, 2019.

82 K. Levin, New Global CO2 Emissions Numbers: They're Not Good, https://www.wri.org/blog/2018/12/new-global-co2-emissions-numbers-are-they-re-not-good.

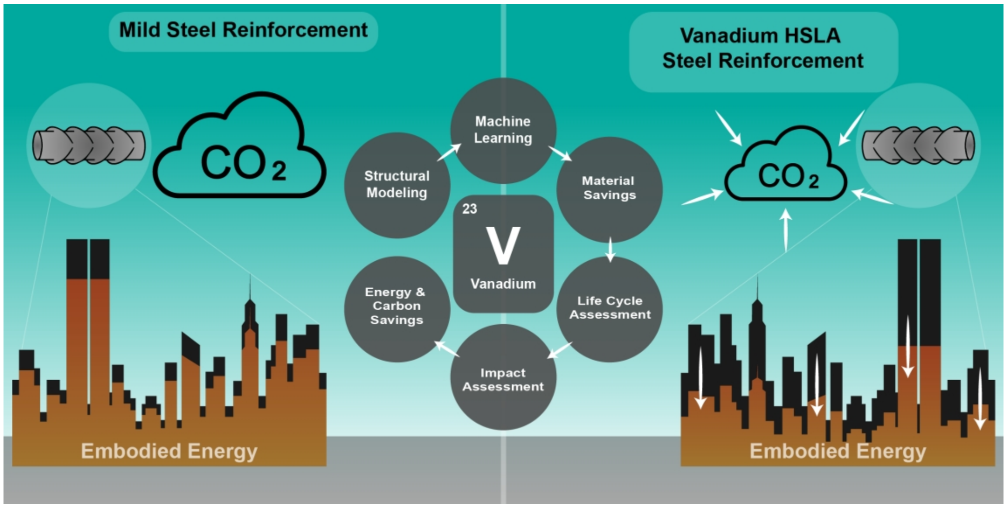
83 U.S. Forest Service, Trees, https://www.fs.usda.gov/learn/trees,(accessed 30 July 2020).

84 Steel In Buildings and Infrastructure, https://www.worldsteel.org/steel-by-topic/steel-markets/buildings-and-infrastructure.html, (accessed 6 April 2020).

85 L. Cho, E. J. Seo, D. H. Sulistiyo, K. R. Jo, S. W. Kim, J. K. Oh, Y. R. Cho and B. C. De Cooman, Influence of vanadium on the hydrogen embrittlement of aluminized ultra-high strength press hardening steel, *Mater. Sci. Eng. A*, 2018, **735**, 448–455.

86 L. Li, B. Song, B. Yang, L. Wang and W. Cheng, Effect of Tempering Temperature after Thermo-Mechanical Control Process on Microstructure Characteristics and Hydrogen-Induced Ductility Loss in High-Vanadium X80 Pipeline Steel, *Materials (Basel).*, 2020, **13**, 2839.

87 S. Salwan, India's Overwhelming Steel Projections?, https://www.metalbulletin.com/Article/3800977/Indias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