《工程科学学报》录用稿，https://doi.org/10.13374/j.issn2095-9389.2024.10.29.002 ©北京科技大学 2024

钢铁行业大气污染物排放清单、CO_2 排放清单的研究现状与未来展望

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摘　要　排放清单能够有效表征研究区域污染特征及温室气体排放情况，为制定污染物防控措施和协同减排策略提供科学依据.在全球推动绿色低碳发展的背景下，作为重要工业部门的钢铁行业，其低碳转型已成必然趋势，而低碳创新技术的不断发展与应用则对钢铁行业排放清单的精细化提出了新要求.因此，在查阅大量文献的基础上，本研究从钢铁行业大气污染物和温室气体(本研究以钢铁行业 CO_2 排放清单为准)的清单核算方法，全球、洲际、国家及城市/城市群的钢铁行业排放清单研究进展，清单的不确定性分析，局限性与未来展望 4 个方面对钢铁行业排放清单编制工作进行了汇总整理.发现了中国钢铁行业排放清单主要存在以下问题：，分别是清单数据种类和质量问题、无组织核算体系构建问题、CO_2 核算体系和方法问题、主要工序 VOCs 组分谱和颗粒物成分谱问题、基于 CEMS 的钢铁企业详细时间谱的问题、CO_2 核算体系和方法问题及清单应用问题等.建议未来丰富钢铁行业排放清单数据种类、，加强实测数据的收集与分析、，保证基础数据的准确性；，建立系统化的无组织排放核算体系、，统筹优化 CO_2 核算体系和核算方法、，提升排放清单的时间分辨率并拓展排放清单的应用方向，并加强学科间和国际合作，从而助力于全球大气污染物与温室气体协同控制.

关键词　钢铁工业；排放清单；排放核算；研究现状；未来展望

分类号　X51

Research sStatus and fFuture pProspects of– air pollutant emission inventory and CO_2 emission inventory Emission Inventories for Air Pollutants, CO_2 in the iIron and sSteel iIndustry

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收稿日期：

基金项目：国家自然科学基金项目(72174125);中央高校基本科研业务费资助(buctrc202133)

ABSTRACT The emission inventory can effectively characterize the pollution characteristics and greenhouse gas emissions in the study area, providing a scientific basis for the formulation of pollutant prevention and control measures as well as collaborative emission reduction strategies. In the context of global efforts to promote green and low-carbon development, as one of the key industrial sectors, the emissions of CO_2 and air pollutants from the iron and steel industry have attracted increasing attention. The low-carbon transformation of the iron and steel industry has become an inevitable trend. With the continuous development and application of low-carbon innovative technologies, the emission inventories of the iron and steel industry are evolving towards higher precision and greater comprehensiveness. The introduction of new technologies such as electric arc furnace steelmaking, hydrogen metallurgy, and carbon capture, utilization, and storage (CCUS) not only provides new solutions for reducing carbon emissions but also raises higher demands for the accuracy of emission inventories. Traditionally, emission inventories have relied on rough emission factors to estimate emissions. However, with the advancement of low-carbon technologies, the diversity of emission sources and the variation in emission characteristics make it essential to develop more refined emission inventories. Therefore, it is essential to carry out the research on the air pollutant emission inventory and CO_2 emission inventory in the iron and steel industry. Based on the extensive domestic and international literature, this study summarizes and organizes the compilation work of the emission inventory for the iron and steel industry across four key aspects: the accounting methods for air pollutants and greenhouse gases (this study primarily focuses on the CO_2 emission inventory of the iron and steel industry), global, intercontinental, national, and urban /urban agglomeration's emissions in the iron and steel industry, inventory distribution, and uncertainty analysis of the emission inventory in the iron and steel industry, along with limitations and future prospects. It identifies several significant issues within the iron and steel in China, including problems related to the variety and quality of emission inventory data, the issue of constructing an unorganized emission accounting system, shortcomings in CO_2 accounting systems and methodologies, challenges in characterizing VOCs component spectrum and particulate matter profiles in key processes, issues with developing detailed time series for steel enterprises based on CEMS, limitations in temporal resolution, and concerns regarding the application of emissions inventories. It is recommended that future efforts focus on diversifying the types of emission inventory data within the steel industry, strengthening the collection and analysis of measured data to ensure the accuracy of the underlying data. It is essential to establish a systematic unorganized emission accounting system and optimize the CO2 accounting framework and methods. Utilizing real-time CEMS monitoring data and incorporating VOCs composition profiles and particulate matter composition profiles from key processes helps to enhance the temporal resolution of the emission inventory. Additionally, expanding the applications of the emission inventory, strengthening interdisciplinary and international collaborations, and promoting the green and low-carbon development of the iron and steel industry contribute to achieving the synergistic control of global air pollutants and greenhouse gasesBased on an extensive review of the literature, this study summarizes and organizes the compilation work of the emission inventory for the iron and steel industry across four key aspects: the accounting methods for air pollutants and greenhouse gases (specifically adopting the CO_2 emission inventory of the iron and steel industry), global, intercontinental, national, and urban /urban agglomeration's emissions in the iron and steel industry, inventory distribution, and uncertainty analysis, along with limitations and future prospects. .It identifies several significant issues within the Chinese steel industry, including problems related to the variety and quality of emission inventory data, the lack of an organized accounting framework, challenges in characterizing VOCs component spectrum and particulate matter profiles in key processes, issues with developing detailed time series for steel enterprises based on CEMS, shortcomings in CO_2 accounting systems and methodologies, limitations in temporal resolution, and concerns regarding the application of emissions inventories. It is recommended that future efforts focus on diversifying the types of emission inventory data within the steel industry, strengthening the collection and analysis of measured data to ensure accuracy, and establishing a systematic and comprehensive emission accounting

system. Overall optimization of the CO_2 accounting system and methods is essential, along with expanding its application areas. Furthermore, interdisciplinary and international collaboration should be strengthened, ultimately contributing to the control of global air pollutants and greenhouse gases.

KEY WORDS iron and steel industry; emission inventory; emission accounting; research status; future prospects

根据《巴黎协定》，为将全球变暖控制在 1.5℃以内，必须在 2050 年实现净零排放目标[1, 2].作为能源消耗密集型的行业，钢铁行业约占全球能源系统总排放量的 8%，并占与能源相关的二氧化碳排放量的 7-10%[3].因此，降低钢铁行业二氧化碳排放对实现全球长期可持续发展至关重要(图 1).此外，钢铁生产过程涉及高温、高压冶炼以及复杂的化学反应[4]，会向大气环境释放多种污染物，包括 SO_2、NO_x、颗粒物(PM)、CO、重金属和 PCDD/Fs 等[5]，不仅对空气质量产生影响，还对全球气候变化、生态系统以及人类健康构成严重威胁.因此，有必要在不同时空尺度上深入探究钢铁行业 CO_2 等温室气体与多种大气污染物的排放情况及其潜在影响.

排放清单(即大气污染物排放清单、温室气体排放清单、融合排放清单等)是量化排放水平、识别典型污染源和特征污染物的重要工具，同时也是大气污染防治、碳减排等政策制定的关键支撑.先前的研究将钢铁行业作为重要工业源之一进行核算，而非将其作为单独部门开展大气污染物排放清单的研究[6-9].然而，低碳创新技术的更新和应用、向绿色钢铁生产的转型及超低排放技术的推广，对钢铁行业排放清单的精细化提出了新要求[10-12].钢铁生产工序包括烧结、球团造粒、炼铁、炼钢和轧钢等[13, 14]，涉及多种生产技术，从而导致不同工序和技术排放的大气污染物和 CO_2 等温室气体具有差异性.对于两种主要工艺路线，即高炉/碱性氧炉(BF/BOF)和电弧炉(EAF)，其在不同国家的市场份额、投入物结构及能源强度存在差异[15, 16].此外，随着向绿色钢铁生产过渡的清洁技术的实施和普及，如氢直接还原铁(DRI)技术[17-19]，其市场渗透率和替代率的差异也会影响钢铁行业的大气污染物与温室气体排放变化.因此，精细和全面的钢铁行业排放清单是准确量化排放变化的关键.与此同时，随着《巴黎协定》的减排承诺在全球范围内的加强，对大气污染物和温室气体融合排放清单的需求也日益增长，同时给协同效应研究带来了巨大挑战.钢铁行业协同效应研究涵盖了以排放水平或浓度的变化度量协同效应[20-22]、以健康水平的提高度量协同效应[23, 24]、以减排成本降低度量协同效应等[25, 26]，旨在分析其在实现气候目标的同时，对减少大气污染物的潜在共同效益.其中，精细化的钢铁行业融合排放清单是准确度量协同效应的关键.

排放清单的是表征钢铁行业 CO_2 等温室气体与多种大气污染物分布特征和演变规律的重要工具科学性、规范性和一致性也已成为政策制定与行业标准化管理的核心关注点.为此，国家和行业层面陆续发布了多项技术指南和标准，以规范排放清单的编制方法和核算框架，确保其科学性和可操作性..2014 年，原中国环境保护部先后发布了《大气污染源优先控制分级技术指南(试行)》和 8 个清单编制技术指南，规定了排放清单的定义，即指各种排放源在一定的时间跨度和空间区域内向大气中排放的大气污染物的量的集合.发展改革委办公厅于 2013 年 10 月 15 日发布的《国家发展改革委办公厅关于印发首批 10 个行业企业温室气体排放核算方法与报告指南(试行)的通知》中的《中国钢铁生产企业温室气体排放核算方法与报告指南(试行)》中对温室气体进行了定义，即指《京都议定书》中所规定的六种温室气体，分别为二氧化碳(CO_2)、甲烷(CH_4)、氧化亚氮(N_2O)、氢氟碳化物(HFCs)、全氟化碳(PFCs)和六氟化硫(SF_6)[27].2023 年 10 月 14 日，生态环境部办公厅发布《关于做好 2023—2025 年部分重点行业企业温室气体排放报告与核查工作的通知》(环办气候函〔2023〕332 号)，内附了(企业温室气体排放核算与报告填报说明 钢铁生产)[28]，文件中的温室气体特指 CO_2.此外，2024 年 1 月 30 日，生态环境部印发《大气污染物与温室气体融合排放清单编制技术指南(试行)》(环办大气函〔2024〕28 号)[29]，规定了大气污染物与温

室气体融合排放清单(简称融合清单)：指在一定时间跨度和空间区域内，按照一致的排放源分类分级体系、统一的排放量计算方法、共同的活动水平数据信息，逐源确定大气污染物和温室气体排放明细，在同一框架下汇总形成的排放数据集合.其中，大气污染物核算物质包括二氧化硫(SO_2)、氮氧化物(NO_x)、一氧化碳(CO)、挥发性有机物(VOCs)、氨(NH_3)、总悬浮颗粒物(TSP)、可吸入颗粒物(PM_{10})、细颗粒物($PM_{2.5}$)、黑碳(BC)和有机碳(OC)；温室气体核算物质包括二氧化碳(CO_2)、甲烷(CH_4)、氧化亚氮(N_2O)和氢氟碳化物(HFCs).在本研究中，钢铁行业排放清单主要指钢铁行业大气污染物排放清单、温室气体排放清单(本研究以钢铁行业 CO_2 排放清单为准)及融合排放清单(归纳排放清单研究进展时涉及).

排放清单(即大气污染物排放清单、温室气体清单、融合排放清单等)是量化排放水平、识别典型污染源和特征污染物的重要工具，同时也是大气污染防治、碳减排等政策制定的关键支撑.先前的研究将钢铁行业作为重要工业源之一进行核算，而非将其作为单独部门开展大气污染物排放清单的研究[9-12].然而，低碳创新技术的更新和应用、向绿色钢铁生产的转型及超低排放技术的推广，对钢铁行业排放清单的精细化提出了新要求[13-15].钢铁生产工序包括烧结、球团造粒、炼铁、炼钢和轧钢等[16，17]，涉及多种生产技术，从而导致不同工序和技术排放的大气污染物和 CO_2 等温室气体具有差异性.对于两种主要工艺路线，即高炉/碱性氧炉(BF/BOF)和电弧炉(EAF)，其在不同国家的市场份额、投入物结构及能源强度存在差异[18，19].此外，随着向绿色钢铁生产过渡的清洁技术的实施和普及，如氢直接还原铁(DRI)技术[20-22]，其市场渗透率和替代率的差异也会影响钢铁行业的大气污染物与温室气体排放变化.因此，精细和全面的钢铁行业排放清单是准确量化排放变化的关键.与此同时，随着《巴黎协定》的减排承诺在全球范围内的加强，对大气污染物和温室气体融合排放清单的需求也日益增长，同时给协同效应研究带来了巨大挑战.钢铁行业协同效应研究涵盖了以排放水平或浓度的变化度量协同效应[23-25]、以健康水平的提高度量协同效应[26，27]、以减排成本降低度量协同效应等[28，29]，旨在分析其在实现气候目标的同时，对减少大气污染物的潜在共同效益.其中，精细化的钢铁行业融合排放清单是准确度量协同效应的关键.

基于上述背景，本研究首先梳理了钢铁行业排放清单(大气污染物排放清单、温室气体排放清单(本研究以钢铁行业 CO_2 排放清单为准))的核算方法，其次系统综述了不同时空尺度钢铁行业排放清单(大气污染物排放清单、温室气体排放清单、融合排放清单等)的研究进展，再次总结了钢铁行业排放清单的不确定性分析方法，最后结合目前的研究进展讨论了钢铁行业排放清单发展的未来展望.通过阐述这些关键问题，本研究强调了全面、精确的钢铁行业排放清单在制定有效减排策略、推动钢铁行业绿色转型、促进国际合作、实现可持续发展及应对全球环境挑战中的重要性.

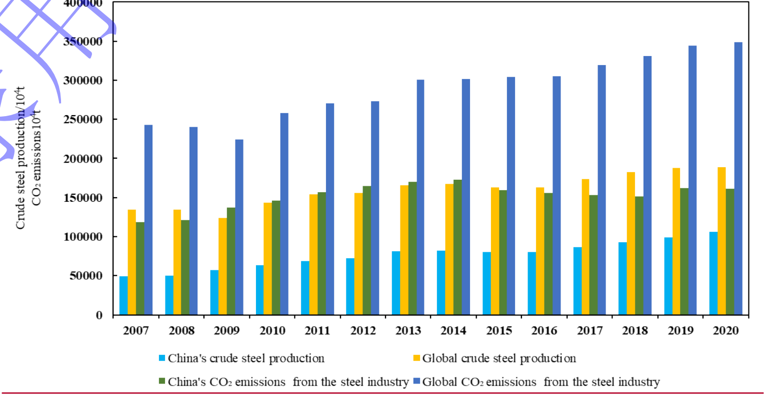


图 1 中国及全球钢铁行业粗钢产量及 CO_2 排放量的变化趋势[30]

Fig.1 Trends in crude steel production and CO_2 emissions in steel industry for China and the world[30].

1 钢铁行业大气污染物和温室气体(以 CO_2 为主)排放量的核算方法研究

1.1 大气污染物排放量的核算研究

钢铁行业大气污染物排放量核算方法排放清单建立方法主要包含污染源调查法、排放因子法、和在线监测法[30].本部分重点介绍了钢铁行业大气污染物排放量核算的方法.

1.1.1 污染源调查法

污染源调查方法主要依靠环境保护部门的现场调查及排查获得的数据，可反映钢铁企业的真实排放情况，核算的准确性相对较高.伯等[30]采用钢铁企业环评报告书中大气点源的相关信息，结合卫星遥感数据，构建了钢铁行业主要工艺解译库，获取了京津冀地区钢铁企业主要排污设施的地理信息，实现了对钢铁企业污染源的准确定位，并构建了京津冀地区钢铁行业高时空分辨率排放清单.然而，污染源调查法依赖于钢铁企业环评报告书等环保部门的现场调查及排查获得的数据，由于企业环评报告自我披露可能导致信息不完整，以及环境保护部门的调查资源和频率有限，无法全面覆盖所有污染源，进而影响对污染状况的准确评估.

1.1.2 排放因子法

排放因子法主要基于通过活动水平和排放因子进行核算(公式(1))[31]，是钢铁行业大气污染物排放量核算应用最广泛的方法.排放因子法被广泛用于核算 SO_2、NO_x 和 PM 等常规污染物的排放估计.其中，排放因子主要来自官方机构发布的权威文件，如从 1972 年开始出版并由美国环境保护署(Environmental Protection Agency，EPA)不断更新的大气污染物排放系数汇编 AP-42(Compilation of Air Pollutant Emission Factors，AP-42 大气污染物排放系数汇编)[32]，欧洲环境署(European Environment Agency，EEA)自 2006 年起向全社会公开发布并更新的 EMEP/EEA 空气污染物排放清单指南[33].此外，2007 年我国开展第一次全国污染源普查后编制的《第一次全国污染源普查工业污染源产排污系数手册》及 2017 年开展第二次全国污染源普查后编制的《第二次全国污染源普查产排污核算系数手册》也有效推动了钢铁行业排放清单编制工作的发展[34, 35].为实现全球对减排目标的共识和承诺，不同的钢铁生产国(组织)对钢铁行业不同生产过程的 SO_2、NO_x 和 PM 制定了不同的排放标准，如欧盟委员会发布的《钢铁生产最佳可用技术(BAT)参考文件》[36]及中国颁布并实施的一系列相关标准[37-41].随着逐步收紧钢铁行业大气污染物排放标准限值，我国钢铁行业不同工序的排放因子呈现降低的趋势(表 1).目前钢铁行业缺乏 PCDD/Fs 和重金属的实际监测数据.然而，工艺参数的变化(如温度和原料成分)、原料的质量和成分以及控制装置的效率等因素会导致污染物的实际排放量与估计排放量之间的差异.此外，就重金属而言，Wang 等参考先前的研究[42, 43]利用 S 型曲线预测有毒重金属的排放因子[44]，为编制排放清单提供了一种方法.然而，若要反映实际排放情况仍需要依靠实测数据以提高排放清单的准确性.上述研究采用的固定排放因子无法准确反映经济发展水平的差异以及不同国家间技术应用的进展.此外，排放因子的获取基于与操作条件和控制措施相关的各种假设或间接参数，进一步增加了不确定性.排放因子法的具体计算公式如下:

$$E=\sum_{n}\sum_{p}AC_{n,p,i}EF_{s,r,i,n}\times\left(1-\eta_{p,s,r,i}\right)\times 10^{-3} \quad (1)$$

式中，E 为排放量，t·a^{-1}；AC 为产品产量，t·a^{-1}；EF 为排放因子，g·kg^{-1} 产品；η 为来自 p 企业 i 工序的 r 排放源对污染物 s 的去除效率，%；n 为不同地区；p 为不同企业；i 为不同工序；s 为不同污染物；r 为不同排放源.

1.1.3 在线监测法

相比之下，基于烟气排放连续监测系统(CEMS)数据的方法具有显著优势.为获取实时、准确的排放数据，钢铁的主要生产国(组织)的钢铁企业都安装了连续排放监测系统(CEMS).在美国，根据《清洁空气法》，为~~以~~确保持续监测和定期报告排放情况，大型钢铁厂通常被要求安装 CEMS[45]；欧盟要求某些类型的设施根据《工业排放指令》(IED)配备在线监测设备，以提高透明度和监管效率[46]；为确保排放标准的全面实施，中国建立了在线排放监测系统(CEMS)，对工业企业的烟囱排放进行持续监测.伯等研究表明到 2018 年，CEMS 覆盖了中国 72%的钢铁厂，占钢铁产量的 91%，显著提高了排放数据的准确性和及时性[12]，能够提供高频次、精细化的监测数据(如污染物浓度、污染物排放量、烟气量、含氧量等)[12, 47]，能够准确反映不同时间段的污染源排放特征，显著提高了排放估计的准确性.为保证数据代表性和准确性,需要依据《固定污染源烟气(SO_2、NO_x、颗粒物)排放连续监测技术规范(HJ 75-2017)》对 CEMS 数据中出现的无效、零值和异常观测值进行规范处理[48].基于质控后的 CEMS 数据~~，基于~~及不同排污节点的污染物浓度(公式(2))~~(公式 2)~~，结合不同排污节点的理论烟气量，从而计算出不同企业的年均排放因子(公式(3))及各地区~~省份~~的年均排放因子(公式(4))~~，~~.结合不同工序的产量等参数，按照自下而上的方法计算得到不同企业各工序或不同地区~~省份~~的钢铁行业污染物排放量(公式(5))[12, 49, 50]~~[48]~~.相较于传统的基于固定排放因子的估算方法，在线监测法 ~~CEMS 网络的数据直接来源于实际操作中的监测结果，~~避免了基于假设或间接参数所带来的不确定性.然而,钢铁行业涉及的工序及排放源较多,在线监测系统有时无法覆盖钢铁企业所有的排放源(特别是无组织排放源).在线监测法的具体计算公式如下:

$$C_{AVG,s,r,i,m} = \sum_{h} C_{s,r,i,m,h} \Big/ \sum_{m} Oph_{m} \qquad (2)$$

$$EF_{s,r,i,m} = C_{AVG,s,r,i,m} V_{r,i} \times 10^{-6} \qquad (3)$$

$$EF_{s,r,i,n} = \sum_{m} EF_{s,r,i,m} \Big/ N_{s,r,i,n} \qquad (4)$$

$$E = \sum_{n} \sum_{p} AC_{n,p,i} EF_{s,r,i,n} \times 10^{-3} \qquad (5)$$

式中，C_{AVG}为排放浓度统计均值，mg·m-3；Oph为纳入分析的监测小时数；EF为排放因子，g·kg-1 产品；V为理论烟气量，m3·t-1 产品；N为样本个数；E为排放量，t·a-1；AC为产品产量，t·a-1；s为不同污染物；r为不同排放源；i为不同工序；m为不同排口；h为第h个运行小时；n为不同地区；p为不同企业.

表 1 2010-2020 年不同排放清单下中国钢铁行~~工~~业主要污染物排放因子的变化

Table 1 The variation of the emission factors of major pollutants in the Chinese iron and steel industry during 2010-2020 in different emission inventories

Pollutant	Emission factor (kg·ton-1 crude steel) 2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Reference
	-	-	2.19	-	-	0.47	-	-	0.31	-	-	[31]
	-	-	-	-	-	-	-	-	-	-	0.48	[24]
	3.31	3.25	2.96	2.76	2.38	1.89	-	-	-	-	-	[51]
SO_2	2.78	3.67	3.32	2.89	2.61	2.16	1.30	0.95	0.78	0.64	0.39	[52]
	3.45	3.37	-	-	-	-	-	-	-	-	-	[44]
	2.95	2.72	2.57	2.52	2.14	1.71	1.53	1.22	1.07	0.90	0.82	[53]
	0.002	0.002	0.002	-	-	-	-	-	-	-	-	[7]

	-	-	2.55	-	-	0.90	-	-	0.72	-	-	[31]
	-	-	-	-	-	-	-	-	-	-	0.91	[24]
NO_x	0.98	0.97	0.93	0.91	0.88	0.87	-	-	-	-	-	[51]
	1.56	1.39	1.34	1.23	1.23	1.30	1.68	1.65	1.45	1.16	0.87	[52]
	0.94	0.95	-	-	-	-	-	-	-	-	-	[44]
	2.50	2.51	2.48	2.26	2.26	2.23	2.26	2.11	1.96	1.75	1.41	[53]
	0.01	0.01	0.01	-	-	-	-	-	-	-	-	[7]
PM_{10}	-	-	0.94	-	-	0.42	-	-	0.31	-	-	[31]
	4.32	4.19	3.74	3.29	2.67	2.19	-	-	-	-	-	[51]
	2.58	3.01	2.50	2.38	5.20	4.44	2.21	1.49	1.26	1.00	0.46	[52]
	2.86	2.90	-	-	-	-	-	-	-	-	-	[44]
	2.82	2.76	2.68	2.19	1.93	1.64	1.46	1.23	1.17	1.08	0.98	[53]
	0.45	0.45	0.44	-	-	-	-	-	-	-	-	[7]

Notes: The emission factors are calculated based on the emissions from different emission inventories divided by the crude steel production data published by the National Bureau of Statistics of China during ~~for the years~~ 201~~2~~0-2020.

1.2 温室气体排放量(CO_2)的核算研究

本部分总结了国际和国内钢铁行业碳排放核算方法，涵盖了核算方法、核算边界、排放因子概述及适用范围(表 2).钢铁行业碳排放的核算方法主要包括以下几种：一是联合国政府间气候变化专门委员会国家温室气体特别工作组编写的《IPCC 国家温室气体清单指南》中的核算方法[54]；二是国际钢铁协会(World Steel Association，WSA)提出的 CO_2 排放计算方法[55]；三是世界资源研究所(World Resources Institute，WRI)与世界可持续发展工商理事会(World Business Council for Sustainable Development，WBCSD)共同开发的温室气体核算体系(Greenhouse Gas Protocol，GHG Protocol)，该体系包括了 CO_2 排放的计算方法 ~~CO_2 排放计算方法(温室气体协议 GHG Protocol)~~[56].此外，我国于 2011 年、2013 年和 2016 年分别发布了《省级温室气体清单编制指南》、《中国钢铁生产企业温室气体排放核算方法与报告指南》及《温室气体排放核算与报告要求》等温室气体核算指南[57]，为钢铁行业 CO_2 排放计算提供参考.2022 年美国钢铁学会发布的《钢铁生产温室气体排放计算指南》为研究钢铁生命周期的碳足迹和挖掘碳减排潜力提供重要工具[58].其中，IPCC 提供了钢铁企业典型工序的碳排放系数，适合宏观层面排放量的核算；国际钢铁协会提出的核算方法适用于研究钢铁生命周期碳足迹和减排潜力；温室气体核算体系(~~协议~~ GHG Protocol)则规定了不同的范围，为企业、项目提供温室气体核算的标准化方法，从而降低了核算成本.此外，《中国钢铁生产企业温室气体排放核算方法与报告指南(试行)》主要反映钢铁企业整体的 CO_2 排放情况，其排放因子的设定更符合我国的生产实际情况；而《省级温室气体清单编制指南(试行)》涵盖了更多的碳排放主体和区域，适用于钢铁行业层面 CO_2 排放的统计工作；《温室气体排放核算与报告要求》结合国内外现有计算方法推荐的排放因子和国内实际情况制定的各物料和能源的排放因子缺省值，适用于钢铁行业层面 CO_2 排放的统计工作.相比之下，美国钢铁学会的指南所推荐的排放因子缺省值是基于美国多家钢铁制造企业的排放因子平均值.综上，目前国内外钢铁行业碳排放核算方法在核算边界、适用范围和核算侧重点方面存在差异.在进行钢铁行业温室气体排放核算时，需要依据收集的数据及核算目标进行方法的选择.

表 2 国际和国内钢铁行业碳排放计算方法的比较

Table2 Comparison of carbon emission calculation methods in the international and domestic iron and steel industry

Year	Source of accounting methodology	Calculation methodology	Accounting boundaries	Overview of emission factors	Scope of applicability
Published in 2006	IPCC National Greenhouse Gas Inventory Guidelines,	Three calculation methods (the emission factor method, the	The accounting scope includes two components: emissions from fossil fuel	The method encompasses carbon emission factors typical for various	Greenhouse gas emissions are

and revised in 2019	prepared by the Intergovernmental Panel on Climate Change (IPCC) National Greenhouse Gas Inventory Task Force	mass balance method, and the direct measurement method) were provided	combustion and emissions from production processes. Notably, all combustion processes in steel production, except for coking, are categorized as industrial process emissions.	processes within steel enterprises.	accounted for by different entities, including national, corporate, and project levels.
First edition in 2009, and second edition in 2016	The CO_2 emission calculation methods proposed by the World Steel Association (WSA) include the first and second editions.	A lifecycle approach is employed, considering input and output at the process level, complemented by a comprehensive plant material balance.	The accounting scope includes direct emissions and indirect emissions, with consideration for carbon emission offsets from the recycling and reuse of by-products outside the steel plant.	The emission factors are based on weighted values from 160 global companies.	This approach is suitable for studying the carbon footprint of the steel lifecycle and exploring potential for low-carbon emission reductions.
1998	CO_2 emission calculation methods for the steel industry jointly developed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD)	Emissions are calculated using a material balance approach or stoichiometric method based on specific facilities or process flows.	The accounting scope includes direct carbon emissions (scope 1), indirect carbon emissions from electricity generation (scope 2), and other indirect carbon emissions (scope 3).	Scope 1 emissions are calculated using published emission factors based on the quantity of purchased commercial fuels; Scope 2 emissions are calculated using electricity consumption shown on meters and published emission factors from specific suppliers, local grids, or other entities; Scope 3 emissions are calculated using published or third-party emission factors based on activity data, such as fuel consumption or passenger miles.	The method is applicable for public reporting and participation in voluntary or mandatory greenhouse gas programs.
2011	Provincial Greenhouse Gas Inventory Compilation Guidelines (Trial Version)	The overall methodology follows the calculation methods outlined in the IPCC National Greenhouse Gas Inventory Guidelines.	The accounting scope primarily includes the steel production process, with CO_2 emissions arising from two main sources: the high-temperature decomposition of iron-making flux and the decarbonization process in steelmaking.	This method encompasses carbon emission factors typical for various processes within steel enterprises.	The method is applicable for accounting at the provincial level.
2013	Guidelines for the Accounting and Reporting of Greenhouse Gas Emissions for Steel Production Enterprises in China (Trial Version)	The method considers the inputs and outputs of materials and energy at the enterprise level.	The accounting scope includes emissions from fuel combustion, emissions from industrial production processes, emissions from net purchased electricity and heat, and emissions embedded in carbon-containing products.	The method is developed based on the actual conditions of Chinese steel enterprises.	The method is applicable to legally recognized production enterprises engaged in the production of steel products, as well as independent accounting units treated as legal entities.
2016	Guidelines for Greenhouse Gas Emission Accounting and Reporting Requirements.	Based on the input-output approach, without considering the internal flow of carbon within various processes, CO_2 emissions in the steel production process are accounted for from a macro perspective at the enterprise level.	The accounting scope includes emissions from fossil fuel combustion, emissions from externally purchased carbon-containing raw materials and the decomposition and oxidation of fluxes at various production stages, emissions from purchased electricity and heat, emissions from generated output electricity and heat, and emissions embedded in carbon-containing products.	Default emission factors for various materials and energy have been established by combining existing emission factors recommended by domestic and international calculation methods with actual conditions in China. Additionally, enterprises capable of self-measuring emission factors are encouraged to conduct their own measurements.	The method is applicable for the statistical work of CO_2 emissions at the steel industry level.
2022	Greenhouse Gas Emission Calculation Guidelines for Steel Production published by the American Iron and Steel Institute.	The method is based on the product level, analyzing the steel production process by each unit operation. It takes inputs and outputs into account at the process level, supplemented by comprehensive plant material balance calculations for verification.	The accounting scope includes direct emissions (from stationary sources, mobile sources, and direct fugitive emissions), indirect emissions from scope 2 (purchased electricity), and other indirect emissions from scope 3 (raw material extraction, fuel and energy-related activities not included in scope 1 or scope 2, upstream transportation, and distribution).	The recommended default emission factors in the method are based on the average values of emission factors from multiple steel manufacturing companies in the United States, and the use of Continuous Emission Monitoring Systems (CEMS) for direct measurement is encouraged.	The method is applicable for studying the carbon footprint of the steel lifecycle and exploring carbon reduction potential.

2 钢铁行业大气污染物和温室气体排放清单研究进展

本部分重点总结了不同空间尺度下钢铁行业排放清单的分辨率、物质类别、污染物排放特征、情景趋势预测及相关健康风险，旨在揭示钢铁行业在全球、区域(洲际、国家)和局地(城市、城市群)三个尺度上的污染物排放特征和环境影响，从而为钢铁行业改善钢铁行业的环境绩效、实现减污降碳目标提供有力支持.

2.1 全球尺度钢铁行业排放清单研究进展

目前，大多数全球钢铁行业排放清单的研究并未将钢铁行业作为独立部门进行核算，而是将其纳入在工业部门清单中进行分析(表 3).例如，Crippa 等[7]构建了 1970-—2012 年全球大气研究排放数据库(即 EDGAR v4.3.2 版本，目前更新到 EDGARv8.0)，涵盖全球人为排放的温室气体和污染物(SO_2、NO_x、CO、NMVOC、NH_3、PM_{10}、$PM_{2.5}$、BC 和 OC)，具有年度和月度的时间分辨率以及 0.1°×0.1°的空间分辨率，其中钢铁行业作为工业源之一进行核算.Janssens-Maenhout 等[8]编制的 HTAP_v2.2 数据集则提供了 2008 年和 2010 年的区域及全球排放网格，包括大气气态污染物(SO_2、NO_x、CO、NMVOC、NH_3)和碳质颗粒物(PM_{10}、$PM_{2.5}$、BC 和 OC)，其中钢铁行业作为重要的工业源被纳入核算.此外，Klimont 等[9]基于综合评估模型 GAINS 编制了 1990-2010 年全球人为颗粒物排放清单，明确了污染物来源和技术特征，其中钢铁行业被作为工业源的关键核算对象.尽管上述全球尺度的排放清单在大气化学和输送模型及管理决策中发挥了关键的作用，但是在编制方法、部门覆盖范围及时间和空间的一致性方面存在差异，而且很少包含不确定性估计.为此，Hoesly 等[59]构建了 1750—-2014 年历史人为化学反应气体和碳质气溶胶数据集，满足了全球大气模拟和其他研究对长期一致性排放趋势的需求，钢铁行业被纳入工业过程源核算.上述研究中，钢铁行业的排放估计被划分到工业部门进行核算研究，通常具有较大的空间覆盖范围和较粗的分辨率，适用于宏观趋势分析和全球性政策制定.其局限性在于忽略了钢铁行业特有的排放特征和影响，难以准确评估和制定有针对性的减排策略.

因此，系统开展聚焦于钢铁行业本身的排放清单研究是推动钢铁行业向绿色、低碳方向发展的关键.为深入理解钢铁行业历史排放趋势及驱动因素，Zhang 等[15]根据 1960—年至 2019 年各国钢铁行业特定的生产工艺和技术，对全球钢铁行业多种空气污染物排放进行核算，揭示了全球和区域钢铁行业排放时间变化的驱动因素(钢铁出口、国家环境政策、生产过程和末端控制技术).尽管在全球层面上讨论了钢铁行业发展的驱动因素和减排潜力，但特定于工厂的缓解潜力和技术驱动的途径仍不明确.为此，Lei 等[10]基于炼焦、烧结、球团、炼铁和炼钢等主要工序的全球钢铁行业设施级别基础信息，构建了 2019 年包含全球 4883 家钢铁厂，共计 19678 个生产机组的全球钢铁行业碳排放数据库，综合考虑设施特征、低碳技术发展、钢铁需求的变迁与相关气候目标，构建了全球钢铁行业工厂级脱碳策略，并制定全球钢铁行业减排路线.Xu 等[11]建立了 2019 年全球钢铁排放数据库(Global Iron and Steel Emission Database，GISD)，对设施级的 CO_2 的直接排放量进行了建模，利用厂龄与产量比率和排放强度两个指标进行成本效益分析，计算了三种主要的减排策略(淘汰多余产能、提高效率和向二次炼钢转型)下生产的减排潜力和相关成本，提出碳排放缓解措施，为精细化的排放估算和减排策略提供了强有力的工具.上述全球钢铁行业的排放清单对于理解钢铁生产对环境的影响、制定减排政策、以及推动技术创新具有重要意义.

综上所述，全球钢铁行业排放清单的发展历程是伴随着特定情景需求的变化而逐步演进的.早期的全球排放数据集通常将钢铁行业的排放纳入整体核算，缺乏对行业内具体排放源的细致划分.然而，随着全球气候变化的日益加剧，以及《巴黎气候协定》的签署和实施，国际社会对更为精细化的钢铁行业排放清单的需求日益增长.因此，近年来，全球钢铁行业排放清单逐渐向工厂级别精细化，能够详细反映各个工厂的排放特征，涵盖了从生产工艺、设备老化到产量等多方面的因素，从而为准确地量化排放源，支持政策制定，在全球范围内实现精准的减污降碳碳减排目标提供了科学依据.

表 3 不同年份全球尺度钢铁行业排放清单汇总

Table 3. Summary of global emission inventory of iron and steel industry in different years.

Emission inventory	Research year	Scales	Resolution and details	Type of material	References

EDGAR v4.3.2 (EDGARv8.0)	1970—2012 (2024)	Global	0.1° × 0.1° grid resolution	SO_2, NO_x, CO, NMVOC, NH_3, PM_{10}, $PM_{2.5}$, BC, and OC	[7]
HTAP_v2.2	2008, 2010	Global	annual and monthly gridded maps of anthropogenic air pollution emissions (0.1° × 0.1° grid resolution)	SO_2, NO_x, CO, $NMVOC_4$, NH_3 and PM_{10}, $PM_{2.5}$, BC, and OC	[8]
ECLIPSE V5a	1990—2010	Global	0.5° × 0.5° grid resolution	PM_{10}, $PM_{2.5}$, PM_1, BC, OC, and OM	[9]
CEDS	1750—2014	Global	emissions are provided annually by country and sector, and are gridded on a monthly seasonal basis	CO, CH_4, NH_3, NO_x, SO_2, NMVOCs, black carbon, organic carbon, and CO_2	[59]
/	1960—2019	Global	a total of 225 countries and regions are included	$PM_{2.5}$, PM_{10}, TSP, BC, OC, SO_2, NO_x, CO, PCDD/Fs, and heavy metals (Hg, Cd, Cr, Ni, As, Pb, Cu, Mn, Se, V, Zn)	[15]
CEADs-GSEI	2019	Global	point source (19,678 individual processing units located in 4,883 individual iron and steel plants)	CO_2	[10]
GISD	1990—2019	Global	it encompasses 116 countries or regions and all operating facilities that make iron and steel products as well as related intermittent products.	CO_2	[11]

2.2 洲际、国家尺度钢铁行业排放清单研究进展

洲际、国家尺度排放清单能够反映特定区域内的排放动态，评估区域内不同地区之间的排放差异及其对区域空气质量的影响，从而为制定更有针对性的环境治理策略提供了科学依据(表 4).尽管洲际尺度的排放清单中钢铁行业的排放尚未进行独立核算，但在亚洲层面，已有多项研究提供了重要的数据支持.Streets 等和 Zhang 等分别编制了 2000 年亚洲主要人为来源的污染物排放清单和 2006 年亚洲区域包含钢铁行业在内的人为源空气污染物排放清单 INTEX-B[60, 61]，为理解区域尺度上的空气污染物浓度及通量提供数据支撑.Klimont 等[62]构建的亚洲 SO_2、NO_x 和含碳气溶胶的排放清单，时间尺度涵盖 2000、2005、2010、2020 和 2030 年，提供了历史排放数据并预测了未来的排放趋势，为评估政策干预措施的影响提供了重要依据.Kurokawa 等[63]更新了亚洲区域排放清单(REAS)至 2.1 版本，涵盖 2000—2008 年亚洲地区(东亚、东南亚、南亚和中亚以及俄罗斯的亚洲部分)的大多数主要空气污染物和温室气体，并提供高分辨率(0.25°×0.25°)的逐月网格化数据，为亚洲各国空气质量变化及预测未来排放等提供重要参考.随着国际间合作和技术交流的不断深入，国内的研究者也参与到洲际排放清单的编制工作.Li 等[64]根据 MICS-Asia III 和半球空气污染运输工作队(TF HTAP)的基准年模拟并编制了 2008 年和 2010 年亚洲 29 个国家和地区所有主要人为源的大气污染物排放清单 MIX，为区域模拟提供一致的排放输入.Ohara 等[65]构建了亚洲 1980—2020 年期间的排放清单，也是第一个以统一的方法构建亚洲历史、现在和未来排放量的清单的研究，为理解和应对亚洲的空气污染问题奠定了坚实基础.上述亚洲尺度的排放清单为亚洲的空气污染传输研究和跨区域污染防治提供了关键数据支持，而钢铁行业包含在工业部门内进行核算.许多欧洲层面排放清单的研究也存在类似情况.例如，Klimont 等[66]编制的 1990-2010 年欧洲颗粒物排放清单及 Lee 等[67]基于生产和消费统计活动水平数据编制的欧洲工业排放清单均未对钢铁行业进行单独核算.上述研究表明洲际尺度的排放清单为理解空气污染传输和实施跨区域污染防治提供了关键数据支持，而钢铁行业并未作为独立的部门进行核算.

相比于洲际尺度的排放清单，国家尺度的排放清单能够更详细地反映出国家内部的排放源分布和排放强度，捕捉到区域差异和特定行业的排放特征.在国家尺度方面，Sugiyama 等[68]构建了 1990—2000 年日本高分辨率的 $PM_{2.5}$ 排放清单，涵盖了包含钢铁行业在内的 400 个部门.Alyuz 等[69]构建了 2010 年土耳其的 CO_2、PM、SO_x、CO、NO_x、VOC、NH_3

和 N_2O 排放清单，涵盖了 7 个主要类别和 53 个子部门，其中钢铁行业为重要的工业排放源，填补了土耳其排放清单中工业排放部分的空白.美国的 AP-42(Compilation of Air Pollutant Emission Factors, 大气污染物排放系数汇编)为美国大气污染物排放系数数据库[70]，涵盖了包含钢铁行业在内的各种工业过程和活动的空气污染物排放因子，为排放清单编制、空气质量模型模拟以及环境政策制定提供了重要依据.国内包含钢铁行业在内的全国尺度的多部门排放清单为钢铁行业的排放特征分析和影响贡献提供了重要的数据基础.例如，Zhang 等[71]建立的 2001 年中国颗粒物排放清单，首次实现了对中国钢铁行业颗粒物(TSP、PM_{10} 和 $PM_{2.5}$)排放的粒径分布和主要成分的核算.Lei 等[72]编制了我国 1990—-2005 年人为源颗粒物及关键化学组分排放清单，分析了钢铁行业颗粒物及其重要化学组分的排放历史变化趋势和地理分布特征[72].Streets 等和 Zhao 等分别构建了 2001 年中国的 CO 排放清单和 1995—-2010 年中国的 NO_x 排放清单[73, 74]，探究了包含钢铁行业在内的 CO 和 NO_x 排放的动态变化.Zhao 等[75]构建了 2005—-2010 年各省和全国的人为大气污染物和 CO_2 排放清单，揭示了控制措施对中国人为源排放的年际趋势、部门(包括钢铁行业)和空间分布的影响.Zheng 等[76]对 2010—-2017 年中国包含钢铁行业在内的人为排放趋势进行了量化，并进一步确定了排放趋势的主要驱动因素.此外，由清华大学开发并维护的中国多尺度排放清单模型(Multiresolution Emission Inventory for China, MEIC)是近年来我国区域大气污染研究中最为广泛应用的排放清单之一[77]，该模型涵盖了中国大陆地区全年和逐月的电力、工业、民用、交通和农业五个主要部门的 10 种大气污染物的排放数据，其中钢铁行业归属于工业部门.2015 年在原有的基础上升级到 MEIC v1.2，Li 等[78]基于 MEIC v1.2，综合考虑了排放源的多样性、技术组合的复杂性及可靠测量方法的不足，系统总结了涵盖钢铁行业在内的各类源的本地排放因子、源特征及分部门排放量估算结果.Gao 等[79]构建了 2018 年全国大气污染物与碳排放清单(China High Resolution Emission Database，CHRED 3.0A)，揭示了钢铁行业是 CO_2 及大多数空气污染物的主要排放源之一.相比于洲际排放清单，国家尺度的排放清单在捕捉行业的排放特征方面具有明显优势，然而，其在有效捕捉钢铁行业的具体排放特征和时空演变规律等方面仍存在局限性.

独立的钢铁行业排放清单够提供详尽的排放数据，还能揭示不同生产环节的排放特征，对于准确评估该行业的减排潜力和环境健康至关重要.在排放特征方面，王堃等[80]编制了 2011 年我国钢铁行业等 6 种有害重金属(Hg、Pb、Cd、As、Cr、Ni)的排放清单，揭示了钢铁行业不同工序的重金属排放特征.Gao 等[81]基于原料燃料投入、中间产品、生产设备、污染物控制技术和节能技术等信息，建立了 2015 年中国钢铁行业大气污染物的排放清单，分析了排放的时空特征，并对中国钢铁行业未来的大气污染物排放进行了预测.Wang 等[51]构建了第一个基于设施以单位为基础和特定源的中国钢铁行业 SO_2、NO_x、$PM_{2.5}$、PM_{10} 和 TSP 排放清单，时间跨度为 2010—-2015 年，分析了污染物排放的时间趋势以及不同控制措施对减排的影响.在减排潜力方面，Wu 等和赵等分别构建了 2012 年和 2013 年的中国钢铁行业主要工序的大气污染物排放清单[82, 83]，涵盖的污染物均包含了 SO_2、NO_x、VOCs、PCDD/Fs 和颗粒物，前者基于技术发展趋势和排放控制政策预测了 2030 年主要污染物(SO_2、NO_x、TSP)的未来排放量；后者考虑节能减排技术和末端治理技术，评估了不同减排情景下污染物的减排潜力成本.Chen 等[84]则以 2018 年为基准年，基于不同技术路线的能源消耗、创新技术的脱碳路径以及大气污染物的协同影响，探索基于最低成本方法的中国钢铁脱碳路径并致力于实现净零排放目标.随着研究的不断深入，将环境健康纳入协同减排的考虑因素.Wu 等[24]建立了中国 2020 年钢铁行业分工序 CO_2 排放和大气污染物(SO_2、NO_x、$PM_{2.5}$ 和 CO_2)融合排放清单，评估了不同省份与不同工序造成的 $PM_{2.5}$ 相关死亡，为环境健康影响和减污降碳协同控制提供重要支撑.不同于聚焦钢铁行业本身，杨[85]的研究将视角扩展至钢铁行业及其上下游产业，采用投入产出方法估算钢铁行

业上游行业的排放，建立了 2012 年基于点源的钢铁行业大气污染物($PM_{2.5}$、SO_2 和 NO_x)排放清单，评估了下游行业在消费和产出两个方面对钢铁行业污染排放的拉动作用，最后使用多目标优化模型分析了钢铁行业协同控制 CO_2、$PM_{2.5}$ 和成本的最优化减排方案.上述研究从钢铁行业层面开展了排放特征、减排潜力和环境健康研究.

然而，上述钢铁行业清单大多采用排放因子法开展中国钢铁行业污染物的排放量的估计，基于有限的钢铁工序排口的调研数据，排放因子的计算涉及多种假设和间接参数(如燃料中污染物含量、污染物防治技术和去除效率等)，无法反映钢铁行业工序间的排放差异及其随时间变化的特性，也无法反映最新的大气污染物排放水平及最新排放标准实施后的减排效果.

为克服上述问题，伯鑫等有机融合中国钢铁行业在线监测数据和环境统计数据，创新性地提出了一套新的时(各小时)-空(各排放源)高分辨率钢铁大气排放清单核算方法，分别构建了 2015 年[86]和 2018 年[49]中国高分辨率钢铁行业大气污染物排放清单，涵盖了中国钢铁企业主要生产工序的污染物排放量和活动水平(产量、空间位置、技术、规模等)信息，模拟现状和未来情景下的大气污染物排放对环境的影响贡献，研究结果为钢铁行业的减排政策制定、产业布局优化、空气质量达标规划以及大气区域联控提供了重要的科学数据支持.伯的团队在前期的研究基础上进一步探讨了 2012、2015 和 2018 年中国钢铁行业各工序和各地区的大气污染物的环境影响及未来发展趋势[31]，实现了高时间(小时级别的数据核算每个月份及全年的排放)和高空间分辨率(在空间上精确到具体企业的经纬度及单个点源).此外，Bo 等[12]基于构建的 2014—-2018 年中国钢铁厂时(每小时)-空(各设备)高精度污染物(PM、SO_2 和 NO_x)排放大数据库，发现中国钢铁行业在五年内污染物排放量下降了近一半，并指出在“碳达峰-碳中和”背景下，“减污降碳”协同治理应成为政府的主要政策方向.上述研究引入了实时动态的异质主体数据，有效克服了以往研究中参数假设较多、不确定性较高的问题，并通过多维度验证研究结果，提高了排放清单的准确性和可靠性.然而，本研究未纳入基于 CEMS 的时间谱分析，也未考虑钢铁行业无组织排放的相关问题本研究未考虑基于 CEMS 的时间谱，也未考虑钢铁行业无组织排放的问题.未来的研究应考虑纳入基于 CEMS 的时间谱分析，以便更好地捕捉钢铁行业排放动态变化，此外，亟需加强钢铁行业无组织排放的分析，从而建立更加全面的钢铁行业排放清单，从而为钢铁行业的减排策略提供更为科学的依据.

表 4 不同年份洲际、国家尺度钢铁行业排放清单汇总

Table 4. Summary of inventories of iron and steel industry emissions at the intercontinental and national scales in different years.

Emission inventory	Research year	Scales	Resolution and details	Type of material	References
/	2000	Asia	the majority of regional models are designed at a resolution of 1° × 1°, whereas studies focused on urban scales employ a finer resolution of 30"×30"	SO_2, NO_x, CO_2, CO, CH_4, NMVOC, BC, OC, and NH_3	[60]
INTEX-B	2006	Asia	spatial resolution:30 min×30 min seasonality: monthly	SO_2, NO_x, CO, NMVOC, PM_{10}, $PM_{2.5}$, BC, and OC	[61]
/	2000, 2005, 2010, 2020, and 2030	Asia	/	SO_2, NO_x, BC and OC	[62]
REAS 2.1	2000—2008	Asia	spatial resolution：0.25°×0.25°; temporal resolution：monthly	SO_2, NO_x, CO, NMVOC, PM_{10}, $PM_{2.5}$, BC, OC, NH_3, CH_4, N_2O, and CO_2	[63]
MIX	2008 and 2010	Asia	spatial resolution: 0.25°×0.25°; seasonality: monthly	SO_2, NO_x, CO, NMVOC, NH_3, PM_{10}, $PM_{2.5}$, BC, OC, and CO_2	[64]
REAS 1.1	1980—2020	Asia	0.5◦×0.5◦ resolution	SO_2, NO_x, CO, BC, OC, NMVOC, CO_2, N_2O, NH_3, and CH_4	[65]
/	1990—2010	Europe	/	SO_2, NO_x, VOC, NH_3, and primary PM	[66]

/	1991	Europe	50×50km	Ca	[67]
/	1990~2000	Japan	/	$PM_{2.5}$	[68]
/	2010	Turkey	/	CO_2, PM, SO_x, CO, NO_x, VOC, NH_3, and N_2O	[69]
/	2001	China	/	TSP, PM_{10}, $PM_{2.5}$, BC, OC, Ca, and Mg	[71]
/	1990~2005	China	30′×30′ resolution	TSP, PM_{10}, $PM_{2.5}$, BC, OC, Ca, and Mg	[72]
/	2001	China	30 min×30 min resolution	CO	[73]
/	1995~2010	China	/	NOx	[74]
/	2005~2010	China	/	SO_2, NO_x, CO, TSP, PM_{10}, $PM_{2.5}$, BC, OC, Ca, Mg, and CO_2	[75]
/	2010~2017	China	China's emissions by sector and year	SO_2, NO_x, NMVOC, NH_3, CO, TSP, PM_{10}, $PM_{2.5}$, BC, OC, and CO_2	[76]
/	2010	China	estimates of sector-based emissions for different species	SO_2, NO_x, NMVOC, NH_3, CO, PM_{10}, $PM_{2.5}$, BC, and OC	[87]
CHRED 3.0A	2018	China	10 km ×10 km	CO_2, CO, NO_x, VOCs, SO_2, $PM_{2.5}$, PM_{10}, NH_3, BC, and OC	[79]
/	1978~2011	China	0.5°×0.5° resolution	SO_2, NO_x, CO, PCDD/Fs, $PM_{2.5}$, PM_{10}, TSP, Pb, Cd, Hg, As, Cr, Ni, Cu, Mn, V, Se, and Zn	[44]
/	2011	China	0.5°×0.5°resolution	Hg, Pb, Cd, As, Cr, and Ni	[80]
/	2015	China	/	SO_2, NO_x, PM, $PM_{2.5}$, PM_{10}, and PCDD/Fs	[81]
/	2010~2015	China	/	SO_2, NO_x, $PM_{2.5}$, PM_{10}, and TSP	[51]
/	2012	China	/	SO_2, NO_x, VOCs, PCDD/Fs, $PM_{2.5}$, and TSP	[82]
/	2013	China	/	SO_2, NO_x, PM, PM_{10}, $PM_{2.5}$, and PCDD/Fs	[83]
/	2018	China	point source database records steel and cement plants under each ownership	CO_2, SO_2, NO_x, and $PM_{2.5}$	[84]
/	2020	China	811 steel enterprises across five major production processes	SO_2, NO_x, $PM_{2.5}$, and CO_2	[24]
/	2012	China	/	$PM_{2.5}$, SO_2, and NO_x	[85]
HSEC, 2015	2015	China	937 steel enterprises across different production processes	SO_2, NO_x, PM_{10}, $PM_{2.5}$, PCDD/Fs, VOCs, CO, BC, OC, EC, and F	[86]
HSEC, 2018	2018	China	996 steel enterprises across different production processes	SO_2, NO_x, PM_{10}, $PM_{2.5}$, PCDD/Fs, VOCs, CO, BC, OC, EC, and fluorides	[49]
/	2012, 2015, 2018	China	a high-resolution temporal (hourly) and spatial (by emission source)	SO_2, NO_x, PM_{10}, $PM_{2.5}$, BC, OC, EC, CO, and VOCs	[31]
CEAIS	2014~2018	China	a high-resolution temporal (hourly) and spatial (by equipment)	PM, SO_2, and NO_x	[12]

2.3 城市/城市群尺度钢铁行业排放清单研究进展

城市/城市群尺度的钢铁行业排放清单，有助于识别主要污染源和关键排放时段，为大气污染源解析、污染物传输扩散研究及大气污染防治提供重要的数据支持(表 5).在识别主要污染源和关键排放时段研究方面，Huang 等和 Zheng 等分别编制了 2007 年长三角地区主要的人为大气污染物及挥发性有机物排放清单及 2006 年珠江三角洲区域高分辨率的时空排放清单[88, 89]，揭示了包含钢铁行业在内的不同部门的排放特征，为制定有效的空气质量管理策略提供重要参考.吴等[90]基于 2010 年东亚地区背景的 MIX 排放清单和前期建立的 2012 年全国大气污染物高时空分辨率排放清单，识别出钢铁冶金行业为重点控制对象，为优化京津冀地区 $PM_{2.5}$ 污染治理的排放控制策略提供科学依据.

在污染物传输扩散和污染控制方面，伯鑫等[30]基于企业在线监测排放数据(CEMS)、污染源调查数据和钢铁行业调研数据，采用自下而上的方法，建立了 2012 年京津冀地区钢铁

行业高时空分辨率的排放清单(BTH-Steel version 1.0)，污染物涵盖了 SO_2、NO_x 和烟粉尘，并分析了不同控制情景下的污染物排放量.随后，伯鑫等[91]基于该高分辨率排放清单，结合淘汰产能设备名单，通过 CAMx 模式模拟分析了现状和化解产能情景下京津冀地区钢铁行业对 SO_2、NO_x 和 $PM_{2.5}$ 的影响.此外，伯鑫等[92]基于全国钢铁企业在线监测排放数据(CEMS)，建立了全国钢铁行业大气污染物排放清单管理系统，实现了排放清单的动态管理.上述研究通过构建高分辨率排放清单、分析污染物传输扩散及建立动态管理系统，为钢铁行业的环境治理和污染管控提供了科学依据.

综上所述，相比于全球尺度、洲际、国家尺度的钢铁行业排放清单，城市/城市群钢铁行业排放清单提供了更为精细的排放信息，为研究区域的污染源解析和污染防治提供了重要的科学依据.然而，目前仍缺少主要工序 VOCs 组分谱和颗粒物成分谱的研究，以及基于 CEMS 的钢铁企业详细时间谱的分析.未来应重点关注这些领域，进一步完善城市/城市群钢铁行业排放清单，从而制定更加精准的污染防治策略.

表 5 不同年份城市/城市群尺度钢铁行业排放清单汇总

Table 5. Summary of inventories of iron and steel industry emissions at the urban/urban agglomeration scale in different years.

Emission inventory	Research year	Scales	Resolution and details	Type of material	References
/	2007	Yangtze River Delta region	4km×4km	SO_2, NO_x, CO, PM_{10}, $PM_{2.5}$, VOCs, and NH_3	[88]
/	2006	Pearl River Delta region	3km×3km	SO_2, NO_x, VOCs, CO, PM_{10}, and $PM_{2.5}$	[89]
/	2012	Beijing-Tianjin-Hebei region	/	SO_2, NO_x, PM_{10}, $PM_{2.5}$, BC, OC, NMVOC, and NH_3	[90]
BTH-Steel Version1.0	2012	Beijing-Tianjin-Hebei region.	/	SO_2, NO_x, and PM	[30]
BTH-Steel Version2.0	2012	Beijing-Tianjin-Hebei region	239 steel enterprises were included, comprising 2,776 pollution emission outlets	SO_2, NO_x, and $PM_{2.5}$	[91]

3 钢铁行业排放清单的不确定性分析

排放清单不确定性分析研究旨在确定不确定因素的具体来源，并通过对不确定因素的定性和定量分析，最终提高排放清单的准确性.钢铁行业的排放清单的不确定性主要体现在活动水平和排放因子两个方面.在活动水平方面，钢铁生产涉及多种工艺和设施，每个生产单元的操作条件和工艺流程差异显著[93, 94].不同钢铁企业的操作条件，如炉温、燃料种类和用量等，都会影响活动水平的数据准确性[95, 96].此外，工艺流程的复杂性和多样性，例如高炉、转炉和电炉的使用比例差异，也增加了活动水平的不确定性[97-99].尽管已有大量研究收集了钢铁企业各生产单元的详细活动水平数据[12, 31, 49, 86, 100]，但若要精确反映实际排放情况，仍需进一步补充更多相关参数.

在排放因子方面，很少研究将单位级别的减排技术信息整合到排放清单中，从而导致单位层面的排放因子存在不确定性.研究者通常按工艺类别进行污染物排放计算，假设整个工艺统一采取减排措施[44, 82]，忽略了不同工艺可能需要不同的减排策略，尤其是每个工艺内部存在多个排放源的情况下.因此，未能充分反映减排技术所带来的潜在减排效果.进一步地，随着全球经济形势的变化以及政策的干预，推动了钢铁行业低碳和创新技术的发展和应用，特别是在巴黎协定签订之后，世界各国纷纷在钢铁行业内实施了多项政策.在政策方面，如欧盟通过了《欧洲绿色协议》[101]，提出到 2050 年实现碳中和目标，并推动低碳钢铁制造技术的发展.此外，欧盟资助低碳炼钢技术的研发与应用，促进技术创新和产业升级[102]；美国环保署通过实施《清洁空气法》和《清洁水法》严格监管钢铁企业的空气和水污染排放，要求企业采用先进的环保技术以减少污染.此外，政府通过《生产税收抵免》(PTC)和《投资税收抵免》(ITC)为使用清洁能源和减少碳排放的钢铁企业提供税收减免和

补贴[103, 104]；德国的碳税和补贴政策鼓励钢铁企业减少碳排放，投资低碳技术和工艺[105]；日本政府提供资金支持以升级设备和工艺，如国家与企业联合开展研发绿色技术项目，如COURSE50计划，旨在减少二氧化碳排放[106]；中国明确提出“碳达峰、碳中和”目标后，在政策层面，发布了针对钢铁行业的超低排放标准，要求企业大幅度减少污染物排放[37-41].在技术创新方面，作为传统高炉炼铁的低碳替代方案，氢基炼铁技术在欧盟和日本等国家受到重视[107-111].此外，碳捕获与封存技术(CCS)在钢铁行业逐步推广，美国和欧洲多家企业已开展试点项目以减少温室气体排放[112].中国钢铁行业在行业政策法规实施的推动下，陆续安装了新的烟气处理设施和集气装置，以提高排放控制效果[82].上述政策的干预和创新技术的应用推广对钢铁行业排放因子的准确性产生了显著影响.

评估排放清单不确定性的方法主要包括定性分析、半定量分析和定量分析.对于难以开展定量不确定性分析的污染物，可通过综合评估数据源的可靠性、估计方法的适用性以及排放因子相关不确定性来确定排放估计的不确定性[89].对于数据较为充足的污染物，则可开展排放估算的定量不确定性分析.蒙特卡洛模拟方法能够有效处理各参数之间复杂的相互作用及不确定性传递，尤其适用于需综合考虑多个不确定性的情景，因而应用广泛[113].目前，钢铁行业的排放清单大多采用蒙特卡洛模拟方法来量化排放清单的不确定性范围.随着钢铁行业排放清单估算方法的不断发展和完善，活动水平以及基于官方统计数据和现场实测的技术信息日益丰富~~基于授权统计和实地测量的技术数据日益丰富~~，使得相关排放的不确定性逐步降低.

在开展排放清单不确定分析之后，对排放清单校验也至关重要.除了与先前相同尺度下的排放量进行对比外[23, 31, 51, 83, 85]，研究者还利用空气质量监测站~~环境空气背景监测站~~数据、卫星遥感数据及模型反演技术等来核验污染物的排放量、时空排放特征及污染源贡献.例如，Bo等基于构建的钢铁行业排放清单，采用CAMx空气质量模型模拟污染物扩散，将模拟值与空气质量监测站的实测数据进行比较，验证了清单的准确性[12, 31].此外，Bo等还借助卫星数据等多种数据集对清单进行独立验证，以检验连续排放监测系统(CEMS)~~测量~~数据所揭示的减排效果对大气环境的实际影响[49].上述排放清单核验方法为提高排放清单的准确性提供了有效的方法支持和指导.

4 未来展望

本研究通过系统梳理钢铁行业排放清单的编制工作，结合全球推动绿色低碳发展的时代背景，展望了中国钢铁行业排放清单未来的核心发展方向，旨在强调通过提升数据的精确性和时效性，为我国钢铁行业制定科学减排政策和技术措施提供参考.具体的展望如下：

(1)中国本地化的参数对于排放清单的准确性至关重要.尽管实时监测技术能够提供比定期手动数据收集方法更为细致和及时的数据信息~~连续数据流~~，如何对其质控、核验和校准确保能够精准反映污染物的波动仍需进一步加强.在人工智能快速发展的背景下，基于历史数据、生产率和其他相关变量应用机器学习算法预测未来的排放量，将产生更有效的减排战略[114].此外，有必要整合新的监测技术对钢铁行业的新兴污染物进行监测，从而细化并丰富钢铁行业排放清单的污染物种类.此外，亟需加强基于CEMS的每个钢铁企业详细时间谱的深入分析，以提高排放清单的准确性和全面性.

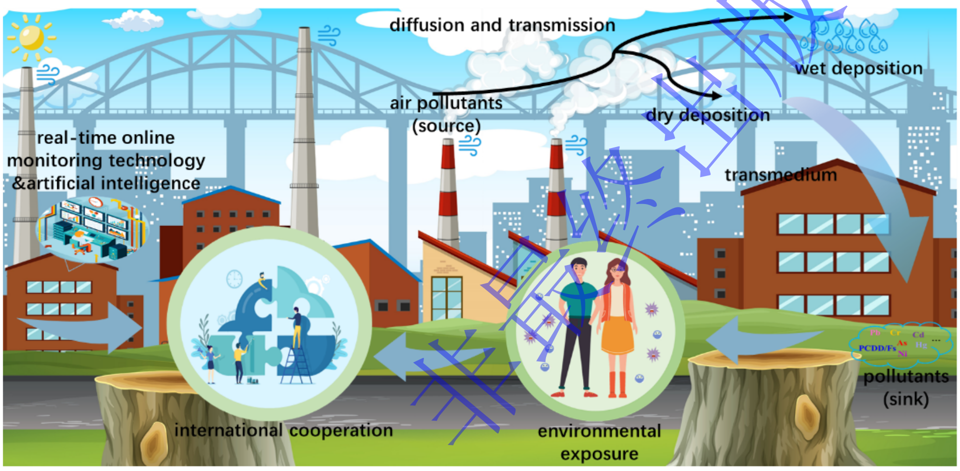
(2)针对钢铁行业主要工序大气污染物无组织排放核算体系问题，中国亟需建立系统化的无组织排放核算体系，并加强实测数据的收集与分析，以实现更加准确的排放评估和科学的环境治理策略.

(3)钢铁行业应积极开展有组织排放的VOCs的组分谱、颗粒物成分谱、重金属的实测数据以及二噁英的实测数据的研究，从而为控制钢铁行业~~内的~~污染物特征提供重要依据，助力于制定更科学的减排政策和环境管理措施.

(4)未来亟需建立钢铁企业的 CO_2 排放核算体系，构建钢铁企业 CO_2 实测排放因子库.同时，通过整合和分析不同企业和地区的钢铁行业 CO_2 排放因子，旨在形成统一的核算标准，增强数据的可比性.此外，将无组织排放的监测和新工艺(如氢冶炼)的纳入核算体系，从而促进对钢铁行业整体碳排放的科学评估和有效管理.

(5)为应对钢铁行业技术快速更新带来的挑战，排放清单的更新机制有待进一步优化.建议引入人工智能和大数据分析等先进数据处理技术，建立更加灵活高效的数据收集与处理系统，以确保能够及时反映新工艺、新设备及环保措施对排放状况的影响，从而提升排放清单的时效性.

(6)在全球气候政策和区域环境协作背景下，钢铁行业的排放清单将进一步向综合化、动态化方向发展，未来应增强国际合作，以应对全球大气污染物与温室气体协同控制的需求.同时，随着对钢铁行业污染物跨介质迁移及其健康影响的深入研究，排放清单将被更广泛地应用于污染物的跨介质迁移转化及其对公共健康的潜在威胁(图 12)，.此外，有必要进一步探索和确定空气质量模型中影响污染物跨介质迁移转化的关键参数，以支持长时间序列的精细化暴露评估，助力协同环境治理.



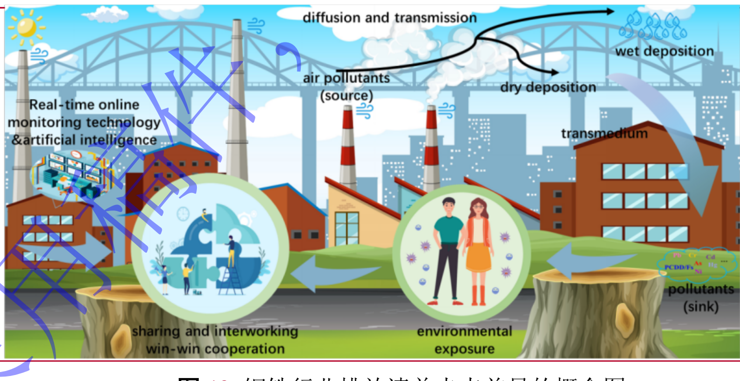


图 12 钢铁行业排放清单未来前景的概念图

Fig.2 1 The future prospects for emissions inventories in the iron and steel industry.

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