科技支撑碳中和目标实现的路径选择及政策研究

徐　俊*

中国科学技术部社会发展科技司

摘　要：中国提出碳中和目标，将深刻影响我国社会经济体系。碳中和对内将助推我国经济高质量发展、全面实现绿色转型，对外则可实现弯道超车，引领全球技术发展。然而，要实现这一目标，我国面临时间短、任务重、难度系数大的挑战。科技创新作为技术发展的动力引擎，在碳中和中扮演举足轻重的角色。没有科技创新，也就无从谈碳中和。然而，当前我国科技创新仍然存在整体水平较低、体制机制不健全、创新投入不足、基础条件薄弱等问题。碳中和愿景下，从技术端，要依靠“能源供给端”“能源消费端”“固碳端”三端共同发力。结合我国不同阶段能源消费结构、产业排碳特征，遵循各领域技术发展规律，提出各领域的科技创新路径，从而分阶段、分重点、分目标地推进技术发展。从政策端，也应从深化顶层设计、加强战略研究、加快技术发展、促进市场衔接、推动队伍建设等方面加大科技创新对碳中和的支撑作用。

关键词：碳中和　科技创新　技术路径　政策建议

JEL 分类号：Q55，P28

一、引言

工业革命以来，人类在使用化石能源/资源、从事工业生产以及改变土地利用方式等过程中向大气层排放了大量以二氧化碳（CO_2）为代表的温室气体，科学界普遍认为这是导致气候变化尤其是全球变暖的主要原因。这一观点在2021年8月联合国政府间气候变化专门委员会（IPCC）发布的关于气候变化物理科学的最新评估报告（Sixth Assessment Report，AR6）中得到再次明确（IPCC，2021）。

全球变暖将带来许多“不可预测”的环境影响。对欧洲而言，气温升高若引发北极冰川融化，大量淡水融入北大西洋，导致北大西洋暖流的补偿流减弱，进而使得洋流循环体系变慢，暖流动力减弱甚至消失[1]，欧洲或将迎来极寒时代。对我国而言，气候变暖在一定程度上可能是利大于弊。西北地区平均气温和降水量均呈上升趋势，出现了向暖湿转型的趋势，有可能出现重回汉唐时期的关中八百里沃野、八水绕长安、西北似江南的盛世景象（陈冰，2015；姚旭阳等，2022；张强等，2021）。但是从全球角度来看，如果任由气候变暖不断加速，人类生存环境总体将遭受极大负面影响，引发灾难性后果。

* 联系人：徐俊，邮箱：john_sheng1998@aliyun.com。

[1] 麦克斯韦的科学，2021，《科学家预警，大西洋洋流系统面临崩溃，欧洲或将迎来极寒时代？》https://baijiahao.baidu.com/s?id=1707808886327021297&wfr=spider&for=pc。

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当前欧洲等国积极推动碳减排倡议，一是基于其自身生存环境可能遭受极大威胁考虑；二是从政治方面出发，通过抢占道德制高点，稳固世界影响力；三是为了遏制经济衰退趋势，通过重塑世界发展规则，凭借技术优势，催生新的经济增长点，提高经济竞争力，推动欧洲经济复苏。

对比欧洲在气候变化问题上面临的困境，我国所面临的客观环境压力较小。且与发达国家相比，我国经济社会发展阶段还具有碳排放持续增长的刚性需求，但仍然以壮士断腕的勇气和决心多次向全世界提出碳达峰碳中和目标，彰显了我国对保护人类赖以共同生存的地球家园的负责任态度，彰显了对构建人类命运共同体的担当(习近平，2020)。

毫无疑问，碳中和的提出将会深刻影响政治经济文化和社会生活的方方面面。中国各部委、地方政府和大型企业也迅速响应，出台政策或制定工作计划，助力碳达峰碳中和目标(赖明，2021)。国内的专家学者、战略家和企业管理者也从国家战略、区域发展、产业布局甚至是企业管理角度，针对碳达峰碳中和工作面临的形势与挑战、碳排放路径、未来情景设计等方面提出自己的观点和想法，全国掀起了一股碳达峰碳中和研究热潮(王灿、张雅欣，2020；柴麒敏等，2020；王志刚，2021)。

笔者长期从事绿色低碳科技管理工作，近一年多的时间里围绕碳达峰碳中和，参与组织了与碳中和科技创新相关的研究与部署。本论文主要是基于笔者前期对科技创新之于碳中和的认识，集中分析了碳中和愿景下我国面临的机遇和挑战、科技创新所面临的现实问题，进一步聚焦和思考了科技创新支撑碳中和路径和政策方面的设计等，仅供读者参考。

二、碳中和愿景下机遇和挑战并存

2021年11月，第26届联合国气候变化缔约国大会达成了格拉斯哥气候协议一揽子决定，重申了《巴黎协定》提出的21世纪内“把全球平均气温升幅控制在工业化前水平以上低于2℃之内，并努力将气温升幅限制在工业化前水平以上1.5℃之内”，以及“公平、共同但有区别的责任和各自能力原则”，同时也明确提出削减煤炭、取消低效化石能源补贴[2]。煤炭等化石能源将进一步被加速替代，这对仍处于工业化、城市化发展阶段的中国而言，机遇与挑战并存。

从机遇来看，一是绿色能源、低碳技术将引发全球范围内一场深刻的科技革命和产业变革。我国作为世界上第二大经济体，需要抓住这次大变革的机遇，改变传统的发展方式，实现经济的高质量发展；二是碳达峰碳中和也是我国生态文明建设整体布局的内在要求，以降碳为重点战略方向，可以实现温室气体与污染物的协同减排，促进经济社会发展全面绿色转型；三是碳中和的现实表象是温室气体减排，实质是全球绿色低碳技术发展的竞争。当前绿色低碳技术在全球各国方兴未艾，各国间还基本处于同一起跑线上，我国应抢抓此次全球技术变革的窗口期，实现弯道超车，引领未来全球的技术发展。

从挑战来看，中国在2006年超过美国成为世界第一大碳排放国。IEA(2020a)的统计数据显示，2020年我

[2] 澎湃新闻，2021，《COP26峰会达成协议，发布《格拉斯哥气候公约》联合公报》，https://baijiahao.baidu.com/s?id=1716368873630146441&wfr=spider&for=pc。

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国二氧化碳排放量约112亿吨，约占全球排放总量的四分之一，是美国的2倍多、欧盟的3倍多；人均碳排放约为7.1吨CO_2/人，相当于世界平均水平1.6倍，同时超过欧盟和二十国集团的平均水平；单位GDP碳排放约为0.7千克CO_2/USD（2015年不变价），是世界平均水平的1.7倍、美国的3.5倍。我国碳达峰峰值水平预计在115亿吨以内，约是美国的2倍、欧盟的3倍。而从时间跨度上看，从碳达峰到碳中和，我国只有30年，而欧美则用了43~70年的时间，因此我国碳达峰碳中和面临的目标任务极其艰巨。另外，从经济社会发展阶段看，我国尚处于经济社会发展的上升期，碳排放总量和强度“双高”的情况仍将持续，经济发展与碳排放仍存在强耦合关系。在未来四十年，我国仍需要大力推进经济建设，提高城镇化水平，提升人民生活水平和质量，这其中都需要以大量能源消耗为前提。要实现经济社会发展与碳排放量脱钩，必须寻求一种可持续的经济发展模式。因此，无论从经济发展阶段、碳排放总量、人均碳排放量、碳中和实现周期，还是从技术发展水平来看，我国实现碳达峰尤其是碳中和目标需要付出更大努力（张贤等，2021）。

三、科技创新是实现碳中和的唯一选择

（一）科技创新是碳中和的唯一出路

碳中和表面上关注的是“碳”的问题，本质上是涉及能源、资源转化过程中尽量少排、不排甚至负排碳的问题。而能源、资源转化过程的实现都是以技术为载体实现。因此，碳中和的实现，技术是根本的落脚点。

据中国21世纪议程管理中心专家测算，若延续“十四五”期间低碳转型政策力度（即每五年碳强度下降率达18%，能源强度下降率达13.5%），保持现有技术发展水平，我国可实现在2030年前二氧化碳排放达峰，但峰值高达126亿吨，到2060年仍有约94亿吨碳排放，离2060年前实现碳中和目标有很大差距（见图1）。因此，现有技术发展水平不足以支撑碳中和目标实现。

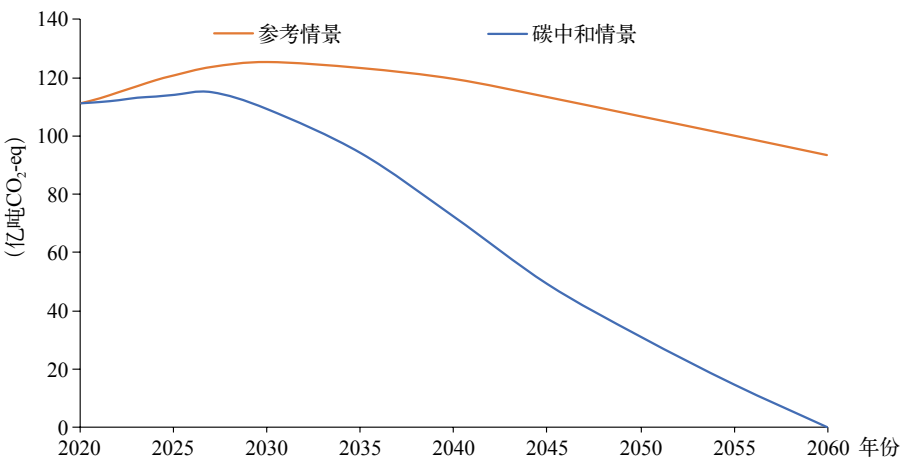

图1：不同情景下我国碳排放趋势分析

资料来源：《中国碳中和技术发展路线图》（征求意见稿）[3]。

[3] 由中国21世纪议程管理中心于2021年组织编写。

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为了提高技术水平，唯一能做的就是不断地进行科技创新，在理念创新、科学规律、技术发明、产业创新等各方面开展全新全方位的探索实践与创新变革。因此，科技创新是实现碳中和的唯一出路，也是碳中和目标实现的最终落脚点。

（二）世界各国的低碳科技竞赛

纵观全球，世界主要地区、发达国家和国际组织都基于碳中和目标对重点领域的碳减排技术路线进行了系统研究和战略部署，积极发展低碳技术，试图抢占低碳技术制高点。欧盟在2019年颁布的《欧洲绿色新政》提出“地平线欧洲”计划，35%的经费将用于支持应对气候变化研发，提出能源、工业、建筑、交通、消费等7个重点领域的关键政策、核心技术和实施计划[4]；并在2020年3月提交的《欧洲气候法（草案）》中提出将绿色经济作为未来经济、社会、外交等事务的重要抓手[5]。同时，欧盟也对一些关键技术提出了专门的发展战略。比如，2020年7月，欧盟委员会发布《欧盟氢能战略》，规划出欧盟氢能发展的三个阶段，提出到2050年的氢能发展目标，启动欧洲清洁氢联盟筹建，并预计到2050年，可再生氢能方面的累计投资将高达1800亿~4700亿欧元。英国《绿色工业革命十点计划》中提出将投入120亿英镑，加强海上风电、低碳氢、先进核电、零排放汽车、绿色建筑、CCUS等技术研发。[6]美国总统拜登将气候变化作为四大优先事项之一，在其《清洁能源革命和环境正义计划》中，拟确保美国在2035年前实现零碳发电，在2050年前达到“净零排放”，实现“100%清洁能源消费”。[7]在低碳技术方面，美国强调对液体燃料、低碳交通、可再生能源发电、储能技术等方面加大研究投入及技术支持。日本发布的《绿色增长战略》确定了海上风电、燃料电池、氢能、核能、交通物流和建筑等14个重点领域深度减排技术路线图和发展目标，旨在确保日本到2050年实现碳中和目标，构建“零碳社会”。[8]国际能源署长期开展减排技术评估并发布减排技术路线图，在《能源技术展望2020》中系统分析了解决能源行业各领域排放问题所需的清洁技术，如电气、氢能、生物能源以及碳捕获、利用和储存（Carbon Capture, Utilization and Storage, CCUS）技术等，强调要大力开发和部署清洁能源技术，才能在确保能源系统弹性和安全性的同时于2050年左右实现净零排放（IEA，2020b）。

（三）中国的低碳科技创新部署

中国政府已经充分认识到科技创新对碳达峰碳中和的重要意义。在《中共中央国务院关于完整准确全面贯彻新发展理念做好碳达峰碳中和工作的意见》中提出“政府和市场两手发力，构建新型举国体制，强化科技和制度创新，加快绿色低碳科技革命”。国务院《2030年前碳达峰行动方案》提出：“发挥科技创新的支撑引领作用，完善科技创新体制机制，强化创新能力，加快绿色低碳科技革命。”中央层面成立的碳达峰碳中和工作

[4] EUROPEAN COMMISSION. The European Green Deal[A/OL]. https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en, 2019-11-12.

[5] 资料来源：https://xw.qq.com/amphtml/20200401a0lx7o00。

[6] The Ten Point Plan for a Green Industrial Revolution, https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution/title,2020-11-18.

[7] 资料来源：https:// climatecrisis.house.gov/sites/climatecrisis.house.gov/files/ Climate%20Crisis%20Action%20Plan.pdf。

[8] 资料来源：https://www.meti.go.jp/english/ press/2020/1225_001.html。

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领导小组正在全面构建碳达峰碳中和“1+N”政策体系，“科技支撑”位列一系列保障方案的第一位。国务院国资委编制印发《关于推进中央企业高质量发展做好碳达峰碳中和工作的指导意见》，提出“着力科技和制度创新，加快中央企业绿色低碳转型和高质量发展”。

长期以来，中国在能源、建设、交通、废弃物资源化等相关领域持续支持绿色低碳关键核心技术的研发与示范，并取得了优异成果（刘仁厚等，2021）。碳达峰碳中和目标提出以来，科技部也在积极部署针对碳达峰碳中和科技创新的“碳达峰碳中和关键技术研究与示范”重点专项，以及“可再生能源技术”“氢能”“储能与智能电网”等10个与碳达峰碳中和强相关的重点专项和“绿色生物制造”“颠覆性技术创新”等16个弱相关重点专项。国家自然科学基金委部署了“面向国家碳中和的重大基础科学问题与对策”专项项目。中国科学院也在积极部署面向碳达峰碳中和的先导专项。上海、江苏、重庆等多地都在酝酿甚至已经推动设立相关研究项目。

四、中国科技创新存在的主要问题

然而，当前的技术储备与研发力度离支撑目标的实现还有很大差距，具体体现在：

（1）低碳科技总体水平参差不齐。目前我国在低碳科技创新基础研究方面投入少、能力不足，尚未形成技术源头。同时不同领域的发展水平差距大。以能源领域为例，我国的光伏、水电、煤化工、钢铁长流程等领域在全球处于领先地位，但是储能、氢能、钢铁短流程等技术发展相对滞后。推动技术系统化、工程化、产业化的高附加值能源科技装备国产化率低，高性能、高技术含量能源装备产品的设计、制造能力与国外差距较大，仍以引进、仿制为主。

（2）低碳科技创新体制机制仍不完善。碳中和提出以来，虽然社会各个层面就如何实现双碳目标掀起了一股思潮。但是总体来说，国家层面针对如何科技创新，未能发挥战略主导作用。各个领域各自为政，甚至各说各话，从国家层面尚未有一个统一、科学、公允的声音和态度。国家层面对碳中和相关的重大政策尚缺乏深入研究和论证，政策落地不确定、不稳定和不持续。碳中和是一个系统性问题，缺乏建立一个系统、高效且能够调动和融合各个领域协同创新的机制。同时，低碳科技推广与市场衔接力度不够，缺乏促进科技创新的财税金融政策，以及产业政策、法规保障，导致研发向应用转移的动力不足，创新价值链还未形成。

（3）低碳科技创新投入仍然不足。我国低碳科技投入不足。以能源领域为例，能源研发投入、政府研发投入占全国研发投入比例均在下降。能源企业更多地通过技术改造、技术引进和直接购买国外技术实现低水平技术升级。能源工业中用于消化吸收和再创新的经费极少，大部分经费用于自主创新含量不高的技术改造和技术引进。

（4）低碳科技创新基础条件薄弱。针对低碳科技创新产业总体规模在不断扩大，科技人员不断加入，基础创新能力不断增强，但离需求水平还相差甚远。以国家重点实验室、国家工程技术中心、国家认定企业技术中心、企业国家重点实验室为创新载体的数量少，缺乏整体的战略部署，创新载体的特色不明显，定位和侧重重复交叉，同时国家对创新载体缺乏持续稳定的支持。

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五、碳中和愿景下科技创新的路径思考

实现碳中和，需要从整个链条（包含源头替代—燃料和原料、过程削减—工业生产和建筑交通、末端处理—CCUS和碳汇三大部分）统筹加以考虑。通过对能源供给端和消费端的分析，碳中和需要“三端协同联动”，即“发电端”“能源消费端”和“固碳端”共同作用。[9]电力部门作为“发电端”，工业、建筑和交通等社会经济部门作为“能源消费端”，而碳汇、碳捕集利用与封存等负碳技术作为“固碳端”，不同发展阶段下不同部门实现碳减排的技术路径有所不同。科技创新应遵循各个领域技术发展规律，与时俱进、动态调整，分阶段、分重点、分目标推进技术创新。

（一）能源供给端科技创新路径

2020年，中国能源消费总量49.8亿吨标煤，煤炭消费占比56.8%。煤电装机占比49.1%，发电量占比60.8%。据苏健等（2021）测算，在“双碳”目标下，为满足我国经济和社会发展，中国能源消费总量还将继续增加，消费峰值在2030~2040年间达到60亿~64亿吨标准煤，随后稳步下降；到2025年、2030年、2060年我国能源消费总量将分别为58亿吨标准煤、60亿吨标准煤和56亿吨标准煤（见图2）。

从能源结构分析，降煤、稳油、增气、大力发展可再生能源是未来40年中国能源消费结构的总基调。我国煤炭生产“总体富余，供需基本平衡”，能满足每年40亿吨需求。然而为了实现碳中和，对于煤炭消费的压缩和限制首当其冲。最终煤炭在我国的能源消费体系内将起到压舱石的作用。中国原油、天然气生产长期不足。如果没有变革性技术，原油生产将稳定在2亿吨左右；天然气生产到2030年达到3000亿立方米峰值后，将努力保

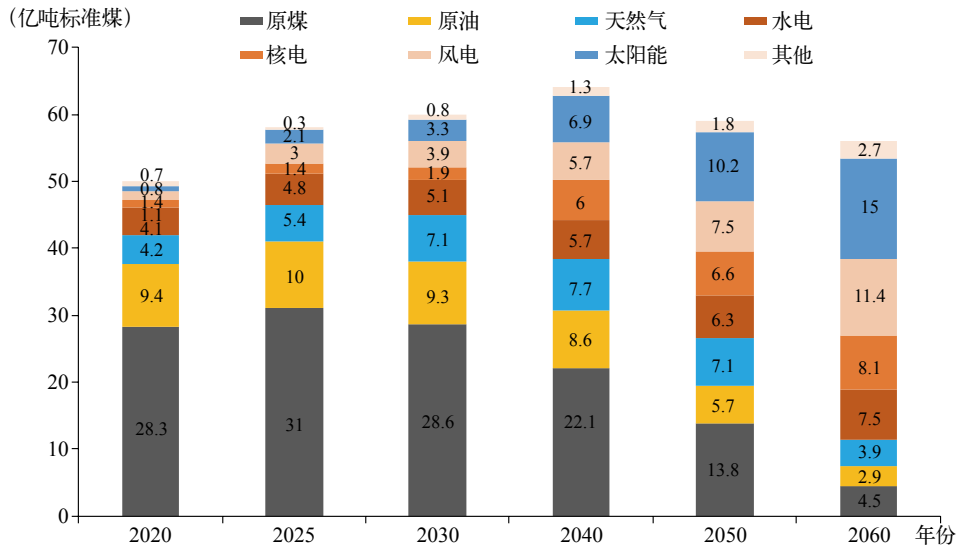

图2：中国能源消费总量与结构趋势预测

资料来源：苏健等（2021）。

[9] 资料来源：https://www.in-en.com/article/html/energy-2311652.shtml。

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持稳产。中国可再生能源资源丰富，尤其是西部地区风、光资源和东部沿海大陆架风力资源，资源潜力能够满足我国到2060年非化石能源占能源消费比重80%以上的需求。

中国未来能源趋势主要呈现以下几个特点：一是能源需求总体呈现先增长后降低的趋势；二是化石能源在2040年之前仍然在中国的能源消费体系中占主导地位；三是非化石燃料在一次能源需求总量中的比重不断提高，2040年替代化石能源成为能源供给主要形式，其在一次能源需求总量中的比重将从2025年的20%飞跃至2060年的80%左右；四是电能作为能源传输的主要形式，其重要性不断体现，其中又以绿电为主。2020年我国电能占终端能源消费比重约为27%，预计到2030年、2060年将分别提升到39%和70%。[10]

电力部门成为能源转化和供给的关键部门。①在碳达峰甚至2040之前，电力部门有可能仍以化石能源燃烧为主要的发电形式。针对煤电，主要创新手段是不断提升煤电机组效率，推广一次再热的超超临界机组、针对二次再热超超临界机组的高低位分轴布置技术、煤电的低负荷提效技术。同时，在我国储能技术没有大规模成熟之前，考虑以煤电的深度调峰技术作为提高可再生能源消纳的方式。稳步提高光电、风电的开发力度。②在达峰以后的深度减排阶段，推广应用原料脱碳技术，即以大规模掺烧甚至全烧生物质颗粒的方式，实现火电的零碳化。同时，实现高效优质光储能植物的创新研究，通过基因改良培育出高效光储能植物，如超级芦竹等植物，提供充足的生物基燃料，实现向“零碳生物质火电”转型。[11]与此同时，实现电力部门与CCUS技术的衔接，实现碳资源的部分转化利用。在可再生电力发展方面，实现高效低成本晶硅太阳能电池、新型薄膜电池的技术突破，大幅提高可再生电力的转化效率和储存能力。风电向远海高空、大型化、智能化、高可靠性发展。解决可再生能源制氢、智能电网等关键技术问题，利用大数据及新一代信息技术，构建出以光伏、风能、生物质和氢能等为主的一体化、智能化多能融合电力体系。在碳中和阶段，在零碳的火电技术基础上，得益于大规模的CCUS技术成熟，实现火电行业的负排放。同时积极推进四代裂变堆研发及聚变堆实验突破，推进核能安全高效应用，进一步提高电力系统的降碳能力。

（二）能源消费端科技创新路径

对能源消费端的低碳转型，一方面依托能源供给侧外部带来的系统性变革，另一方面也受益于其工业内部的技术革新带来的降碳。

工业部门是实现碳中和的重点领域。2020年工业部门碳排放约49亿吨，占比约44%，预计2025年前后达峰，峰值约55亿吨，2060年工业总体碳排放建议控制在3亿~5亿吨。①在碳达峰之前，工业部门依靠的降碳途径主要是生产工艺的进一步整合和优化实现能耗需求降低、提升产品的品质和延长使用寿命来减少产量规模、智能化生产以及提升产生过程中的二次资源的循环利用。对于钢铁和有色部门，主要通过产业全流程打通，冶金产品的质量提升，氢能冶炼、余热回收技术应用等途径，大幅降低碳排放。对于建材部门，主要走工业原料的低碳化，充分利用其他行业的固体废弃物，开发循环利用的建筑材料。对于化工行业，也是依靠工艺单元之间的系统优化和集成，主要耗能工序的流程再造，能量梯级利用的推广，物料循环利用提升以及低位热

[10] 资料来源：全国能源信息平台，https://baijiahao.baidu.com/s?id=1711103389482683034&wfr=spider&for=pc。
[11] 资料来源：http://xincailiao.com/news/news_detail.aspx?id=604161。

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能、灰渣等资源综合利用，大幅降低化工产业的能耗。对于新建项目，积极选用具有国际领先或国际先进水平的技术，提高产品收率，降低能源和资源消耗，推动行业低碳发展。比如，煤气化技术方面的水煤浆水冷壁废锅气化炉技术、第三代甲醇制烯烃（DMTO－III）技术、甲醇与石脑油耦合制低碳烯烃技术等。②在达峰以后的深度减排阶段，积极推广原料替代技术和短流程技术。对钢铁和有色部门，主要通过工业流程的转型，推广以废旧金属为原料的短流程冶金技术。水泥行业大规模推广低钙熟料、无熟料/少熟料等原料替代和氢能燃料替代技术。化工行业实现短流程节能低碳技术、低碳原料替代技术、CO_2资源化利用技术等的工业化应用，在具有较好条件的化工领域，优先推进CCUS技术的工业化应用，助力化工行业实现近零排放。③在碳中和阶段，人工CCUS/碳移除技术将在工业领域大规模应用，发挥关键性托底作用。

建筑部门是主要的能源消费端。2020年，我国建筑部门直接碳排放约6.2亿吨（不含村镇散煤供热和热水炊事等），占比约6%。中国建筑部门的碳排放总体开始进入平台期，且相关的零碳解决方案较为成熟，应率先进入去峰期并尽早实现近零排放。建筑部门实现低碳/零碳转型应以节能降耗建筑本体的开发建设以及全面普及电气化为落脚点。①在碳达峰之前，对存量建筑实行节能改造，对新建建筑推行超低能耗和近零能耗标准。通过高性能围护结构新材料、新产品和新工艺的应用，降低建筑的能耗需求。②在达峰以后的深度减排阶段，一是提高建筑的建设质量和品质，延长建筑的使用寿命；二是着力实现建筑用能全面电气化，推广夏热冬冷地区供暖、炊事、热水和蒸汽的电能与零排放替代技术和产品；三是加快推进热电协同技术创新，发展光储直柔技术，加强低碳建材和低碳建筑结构体系化应用，实现与电力和工业部门协同减排；四是推广光伏建筑一体化技术，最大限度挖掘建筑本体的可再生能源开发潜力。

交通部门作为油品和电力的主要消费端，碳减排潜力大，但难度高。对交通部门而言，2019年碳排放总量约11.5亿吨左右，占比约10%。争取将于2030年左右达峰，峰值控制在12.5亿~13.5亿吨。综合考虑交通运输的安全性、便捷性要求和减排技术与成本等因素，2060年碳排放将努力降至2亿吨以内。交通部门实现低碳需重点关注运输工具节能降碳和新能源替代。①在碳达峰之前，积极倡导公共交通、慢行交通，减少交通出行的能耗。积极开展燃油汽车的节能技术研发，包括提高发动机的效率、汽车车身的轻量化等技术。积极开发交通共享系统，提高交通出行的利用率。②在达峰以后的深度减排阶段，突破高性能电动和氢燃料电池车辆技术，全面推广新能源替代。打造智慧交通系统，重点突破智能感知、多元大数据融合处理、多元协同指挥调度等关键技术，提升综合交通运输整体效率。

（三）固碳端科技创新路径

碳汇、碳捕集利用与封存（CCUS）等负碳技术，是我国实现碳中和的兜底技术。①在碳达峰之前，未来针对森林、草原、湿地和海洋等生态系统，需加强碳汇机理研究，探索天空地一体化的碳汇精准监测技术，建立动态监测、报告和验证的核算体系，创新典型生态保护和修复技术，稳定并提高现有生态系统碳汇能力。积极开展CCUS技术领域的基础研究，适度推广CCUS技术的示范研究。②在达峰以后的深度减排阶段，加大针对碳捕集、分离、运输、利用、封存及监测等各个环节的技术攻关，加强新一代低能耗、低成本和高安全性CCUS技术研发和大规模全流程集成示范部署，探索建立与美国45Q税收法案类似的财税激励措施，为该技

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术的未来商业化应用奠定基础。积极推进CCUS技术在工业领域实现规模化应用。③在碳中和阶段，全面推广CCUS技术的商业化应用。

六、碳中和愿景下加大科技支撑作用的政策思考

一是深化跨技术、跨能源、跨领域的顶层设计。坚持全国一盘棋，建立科技部牵头的跨部门协作机制，充分发挥各领域战略科学家的群体智慧，广泛开展前瞻性的交叉学科研讨，准确把握未来碳达峰、碳中和领域的前沿科技发展方向，形成动态的碳中和科技创新顶层设计蓝图。

二是加强科技领域实现双碳目标的能源战略研究。在国家碳中和顶层方案的大前提下，依托科技计划五年实施周期，放眼长远做好中长期控碳、降碳、低碳和零碳能源科技战略规划，持续滚动推进非碳基能源技术迭代，深入研判经济性与生态友好性兼顾的多场景技术路径，保障国家能源安全。

三是加快新技术新模式试点示范应用。系统分析双碳目标下节能降碳技术需求，针对不同领域、不同场景积极开展试点示范，在试点中形成与推广成熟技术，形成在研一批、投产一批、储备一批的良性循环，促进新技术、新工艺、新模式的研发、转化和落地应用。

四是积极推动形成低碳技术市场化运作的体制机制。深入研究市场导向型的减排政策，开展净零技术经济学研究，深入研究碳中和对科技创新的倒逼和激发作用、科技创新对未来能源和工业体系的重塑功能，发挥有为政府和有效市场作用，有效协调技术政策与财税和投融资政策，建设低碳技术评估、交易体系，激发低碳技术创新，鼓励和引导低碳技术产业化应用，逐步提升净零技术在经济社会向碳中和转型发展中的重要作用。

五是推动碳中和人才队伍的系统和长远布局。针对“双碳”目标组建专门的技术创新和政策研究的人才队伍，加大对优势科研机构和团队支持力度，建立稳定支持机制，完善技术创新攻关主体布局，设立国家重点实验室和技术创新中心，建设科技信息资源平台，深入推进各个领域的交叉融合，特别要加强碳中和青年科技人才培养。

六是深化国际创新合作，推动技术交流合作共赢。促进多边机制与双边合作框架下碳中和科技创新，积极推动将碳中和技术创新纳入与主要国家双边科技合作框架的优先领域。推动和深化应对气候变化领域知识共享与技术转移，搭建技术转移平台和数据库，对接国际绿色低碳/脱碳转型技术需求与供给，促进绿色低碳技术双向流动。

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Path Selection and Policy Study for the Carbon Neutrality Required Technology

Xu Jun*

Department of Science and Technology for Social Development, Ministry of Science and Technology, Beijing, China

Abstract: *The carbon neutrality goal is of far-reaching influence to China's socio-economic systems. Domestically, carbon neutrality will promote China's high-quality economic development and green transition. Internationally, it represents an opportunity for China to lead the global low-carbon technology development. Yet daunting challenges lie ahead for this ambitious goal to be achieved in such a short time. As a driving force of technology progress, innovation plays a pivotal role in achieving carbon neutrality, but is faced with many obstacles in China, including the currently low level of innovation, institutional inadequacies, lack of innovation input, and inadequate fundamental conditions. Under the vision of carbon neutrality, we should identify technology innovation pathways on the three aspects of energy supply, energy consumption and carbon sink. Following those technology pathways, progress should be made in technology development in various stages with different priorities and objectives based on China's energy mix and industrial carbon emission characteristics. On the policy side, we should deepen top-down design, enhance strategic researches, expedite technology development and commercialization, and foster R&D talents to bring out the full potentials of technology innovation in supporting carbon neutrality.*

Keywords: *Carbon neutrality, technology innovation, technology pathways, policy recommendations*

JEL Classification Code: Q55, P28

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1. Introduction

Since the Industrial Revolution, carbon dioxide (CO_2) and other greenhouse gas emissions from mankind's consumption of fossil fuels and resources, industrial production and conversion of land use have been widely believed by the science community as the dominant driver for climate change and especially global warming. This assertion has been reaffirmed in the latest Sixth Assessment Report (AR6) published by the Intergovernmental Panel on Climate Change in August 2021 (IPCC, 2021).

Global warming will cause myriad unpredictable environmental impacts. Extreme weather and climate events will occur frequently and climate risks will continue to rise. Meanwhile, high-impact low-probability events have also received attention and consideration. Rising temperature may cause Arctic glaciers to melt into the North Atlantic Ocean and weaken the Atlantic Meridional Overturning Circulation (AMOC).[1] As a result, Europe may experience extremely low temperatures. For China, the benefits of global warming to some extent could outweigh the costs. Rising mean temperature and precipitation could be a boon to China's arid northwestern region, where humid weather in ancient times

* CONTACT: Xu Jun, e-mail: john_sheng1998@aliyun.com.

[1] Maxwell's Science. 2021. The Atlantic's overturning currents threaten to bring extreme cold to Europe. https://baijiahao.baidu.com/s?id=1707808886327021297&wfr=spider&for=pc.

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allowed the Han and Tang dynasties to thrive on fertile land and crisscrossing rivers (Chen, 2015; Yao, *et al.*, 2022; Zhang *et al.*, 2021). From a global perspective, however, unlimitedglobal warming will eventually wreak havoc on the environment with catastrophic consequences.

The motivations for countries in Europe and elsewhere to embrace low-carbon initiatives are threefold: First, environmental degradation poses a real threat to human survival; moreover, environmental protection gives them a moral high ground to cement their global influence; last but not least, green economy represents an opportunity to reshape the rules of world development, foster new growth drivers, and jumpstart European economic recovery.

China's environmental pressures are relatively small compared with the consequences of climate change facing Europe. As a developing country, China's economic and social development presents a growing demand for fossil fuel consumption. Yet on many occasions, China has reaffirmed its will to achieve carbon peak and carbon neutrality with the bravery of cutting one's one wrist, which shows its sense of responsibility for protecting mankind's common habitat and building a community with a shared future for mankind (Xi, 2020).

Without a doubt, carbon neutrality will influence every aspect of China's political, economic, cultural and social life. China's ministerial agencies, local governments and large enterprises have enacted policies or work plans towards carbon peak and carbon neutrality goals (Lai, 2021). Chinese experts, scholars, strategists and business executives have also shared their views on the current situation and challenges for carbon peak and carbon neutrality, carbon emission pathways and future scenarios, stirring a nationwide wave of research on those topics (Wang and Zhang, 2020; Chai *et al.*, 2020; Wang, 2021).

As a researcher in the field of green and low-carbon technology management, the author has focused on research and policy planning for carbon neutrality and innovation over the past year or so. This paper sheds light on the opportunities and challenges facedby China under the carbon neutrality vision and the pathways and policy design for innovation to support carbon neutrality.

2. Opportunities Coexisted with Challenges under the Carbon Neutrality Vision

On November 2021, the 26th UN Climate Change Conference of the Parties (COP26) reached the Glasgow Climate Pact and reaffirmed the commitment to mitigate greenhouse gas emissions in line with the provision "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" as originally stated in the Paris Agreement under the principle of "fair, common but differentiated responsibilities". It also called for cutting coal subsidies and phasing out inefficient fossil fuel subsidies.[2] Replacement of coal and other fossil fuels will be accelerated, which poses opportunities and challenges for China's ongoing industrial and urban development.

In terms of the opportunities, green energy and low-carbon technologies are poised to set off a profound technological and industrial revolution. As the world's second-largest economy, China should seize the opportunities from this great transformation and pursue high-quality economic development. Moreover, carbon peak and carbon neutrality are the intrinsic requirements of China's ecological civilization. Coordinated efforts to reduce both carbon emissions and pollution will help the green transformat. Behind the race for carbon neutrality is a global competition for green and low-carbon technologies, where countries remain at the same start line. China should take the opportunity of this global technological transition and lead future global technological development by overtaking on the

[2] COP26 Summit reached an agreement and released a joint communiqué on the Glasgow Climate Pact, ThePaper.cn. https://baijiahao.baidu.com/s?id=1716368873630146441&wfr=spider&for=pc. 2021.11.14.

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curve.

In terms of the challenges, China overtook the United States as the world's largest carbon emitter in 2006. According to the IEA (2020a), China emitted 11.2 billion tons of CO_2 in 2020, which were twice as much as those of the US and three times as much as those of the EU and accounted for over a quarter of global total emissions. China's per capita carbon emissions stood at 7.1 tCO_2/person, which was 1.6 times of the world average level and above the average levels of the European Union and G20. China's carbon emissions per unit of GDP was 0.7kg CO_2/USD (constant price of 2015), which was 1.7 times of the world average level and 3.5 times of the US level. China's carbon peak is expected to stay within 11.5 billion tons, which is twice the US level and three times that of the EU. While Europe and the United States promised to achieve carbon neutrality in 43 to 70 years after carbon peak, China only has three decades to do so. Achieving carbon peak and carbon neutrality in such a short time is an extremely arduous task. Moreover, there is a strong interconnection between China's economic development and carbon emissions. China remains on an upward trajectory of economic and social development, which entails high carbon emissions and carbon intensity. In the coming four decades, China needs to continue economic development, increase urbanization, and raise people's living standards, all of which require massive energy consumption. A sustainable mode of economic development, therefore, must be explored to decouple economic and social development from carbon emissions. In terms of economic development stage, aggregate and per capita carbon emissions, carbon neutrality cycle and technological development, China needs to make greater efforts to achieve carbon peak and in particular, carbon neutrality (Zhang *et al.*, 2021).

3. Technology Innovation: The Only choice towards Carbon Neutrality

3.1 Technology Innovation: The Only Path to Go Carbon Neutral

Carbon neutrality entails the reduction, avoidance and reversal of carbon emissions from the conversion of energy and resources, which cannot be achieved without technology. In this sense, technology is the fundamental pillar for carbon neutrality.

According to an estimate by the Administrative Center for China's Agenda 21 (ACCA21), China may see its CO_2 emissions peak before 2030 at the current level of technology development and the low-carbon policy intensity for the 14th Five-year Plan period (2021-2025) (i.e. carbon intensity and energy

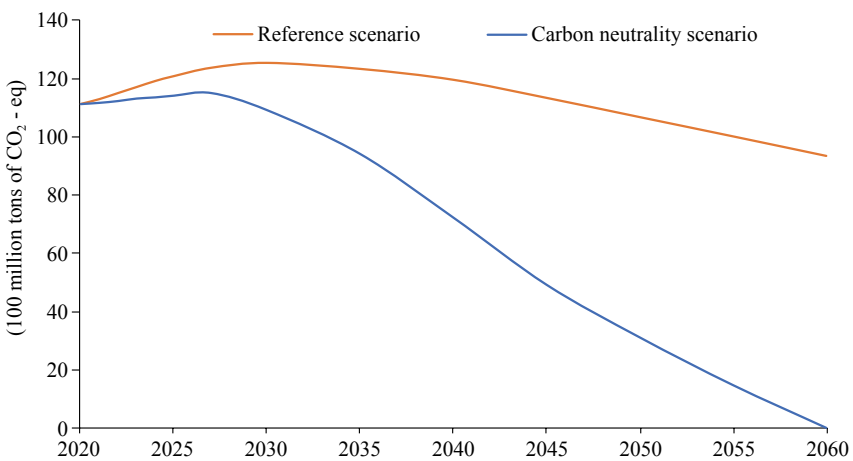

Figure 1: China's Carbon Emission Trends under Different Scenarios

Source: *China's Carbon Neutrality Technology Development Roadmap* (Consultation Draft).
Note: Drafted by the Administrative Center for China's Agenda 21 (ACCA21) in 2021.

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intensity drop by 18% and 13.5% every five years, respectively). Under this scenario, however, China's carbon peak will be as high as 12.6 billion tons with carbon emissions at 9.4 billion tons by 2060, which falls short of its carbon neutrality goal. That is to say, the current level of technology is insufficient to support the realization of carbon neutrality.

To raise the level of technology, the only thing we could do is to relentlessly innovate and make all-round progress in development philosophies, scientific research, technological inventions, and industrial innovation. Technology innovation is both the end and the means of carbon neutrality.

3.2 Global Race for Low-Carbon Technologies

Around the world, key regional blocs, advanced economies and international organizations have all carried out systematic research and strategic planning on the technology pathways for carbon emissions abatement in key sectors based on the carbon neutrality goal. The European Green New Deal enacted by the European Union in 2019 called for allocating 35% of the budget of the Horizon Europe program to support climate change research and proposed key policies, technologies and implementation plans in seven critical areas, including energy, industry, construction, transportation and consumption;[3] in the *European Climate Law (Draft)* submitted in March 2020, the EU identified green economy as a key pillar for future economic, social and diplomatic affairs.[4] Meanwhile, the EU also developed specific strategies on some key technologies. In July 2020, for instance, the European Commission published the EU hydrogen strategy, which identified three stages for hydrogen development in the EU and set targets for 2050, and announced the launch of the European Clean Hydrogen Alliance. By 2050, the EU's hydrogen energy investment is expected to reach 180 billion to 470 billion euros on a cumulative basis. In the Ten Point Plan for a Green Industrial Revolution, the British government vowed to invest 12 billion pounds on the research and development of offshore wind power, low-carbon hydrogen, advanced nuclear power, zero-emission vehicles, green buildings and carbon capture, utilization and storage (CCUS) technologies.[5] US President Joe Biden identified climate change as one of the top four priorities in his *Plan for a Clean Energy Revolution and Environmental Justice*, which aims to achieve zero-carbon power generation in the US by 2035 and net zero emissions and 100% clean energy consumption before 2050.[6] Regarding low-carbon technologies, the US vowed to ramp up research and technical support in such areas as liquid fuels, low-carbon transportation, renewable energy power generation, and energy storage technologies. Japan's *Green Growth Strategy* identified the technology roadmaps and development targets for carbon emissions reduction in 14 key areas, including offshore wind power, fuel cell, hydrogen energy, nuclear energy, transportation logistics and construction, with a view to achieving the carbon neutrality goal and creating a "zero-carbon society" by 2050.[7]

Based on its long-term assessment of carbon emissions technologies and publication of the carbon emissions technology roadmap, the International Energy Agency (IEA) has systematically reviewed clean technologies for reducing energy emissions in various energy sectors such as electric power, hydrogen energy, biofuels and CCUS technologies. It called for vigorously developing and deploying clean energy technologies to achieve net zero emissions by around 2050 while ensuring the resiliency and security of energy systems (IEA, 2020b).

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[3] EUROPEAN COMMISSION. The European Green Deal[A/OL]. https://ec.europa.eu/info/strategy/ priorities-2019-2024/european-green-deal_en. 2019.11.12.

[4] Source: https://xw.qq.com/amphtml/20200401a0lx7o00.

[5] The Ten Point Plan for a Green Industrial Revolution. https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution/title. 2020.11.18.

[6] Source: https:// climatecrisis.house.gov/sites/climatecrisis.house.gov/files/ Climate%20Crisis%20Action%20Plan.pdf.

[7] Source: https://www.meti.go.jp/english/press/2020/1225_001.html.

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3.3 China's Strategy for Low-Carbon Technology Innovation

The Chinese government has fully recognized the great significance of technology innovation to achieving carbon peak and carbon neutrality. In the *Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy*, the Chinese government vowed to "create a new-type whole-nation system leveraging both government and market forces to enhance technology and institutional innovation and speed up the green and low-carbon technology revolution". In its *Action Plan for Carbon Peak before 2030*, the State Council called for "giving play to the leading role of technology innovation and improving institutional mechanisms to enhance innovation capacity and accelerate the green and low-carbon technology revolution." The central steering group on carbon peak and carbon neutrality is creating a "1+N" policy system with a slew of assurances led by technology support. In the *Guiding Opinions on Advancing High-Quality Development of Central Enterprises and Work on Carbon Peak and Carbon Neutrality*, the State Assets Supervision and Administration Commission (SASAC) called for "expediting the green and low-carbon transition and high-quality development of central enterprises".

Over the years, China has supported the R&D and demonstration of critical green and low-carbon technologies in such areas as energy, construction, transportation and waste recycling with significant results (Liu *et al*., 2021). After adopting the carbon peak and carbon neutrality targets, the Ministry of Science and Technology has launched ten special key projects, including the Research and Demonstration Program for Critical Carbon Peak and Carbon Neutrality Technologies, renewable energy technologies, hydrogen energy and energy storage and smart grid, as well as 16 less related key projects such as green biological manufacturing and disruptive technology innovations. The National Natural Science Foundation of China (NSFC) has initiated the special project of "Major Fundamental Scientific Problems and Countermeasures for National Carbon Neutrality". The Chinese Academy of Sciences (CAS) is also planning to launch a special project on carbon peak and carbon neutrality. Many localities such as Shanghai, Jiangsu and Chongqing are deliberating or have already initiated relevant research programs.

4. Key Problems of Technology Innovation in China

However, China's current technological and R&D strengths fall short of supporting those goals.

(1) Uneven development of low-carbon technologies: China has yet to make sufficient investment in fundamental research, from which new technologies derive. Moreover, significant gaps exist in the level of technological development across various domains. In the energy sector, for instance, while China leads the world for photovoltaic energy, hydropower, coal chemicals and long-process steelmaking, it is also a laggard in energy storage, hydrogen power, and short-process steelmaking. China has yet to promote systematic R&D and commercialization and increase the localization ratio of high-value energy equipment. It still lags far behind internationally advanced levels in terms of high-performance and high-tech energy equipment, and relies on importation and imitation.

(2) Imperfect institutional mechanisms for low-carbon innovation: While the carbon neutrality goal has aroused broad public discussions, the government has yet to coordinate innovation programs in various sectors to bring about synergy and form a consistent, science-based and fair approach at the national level. Key national carbon neutrality policies have yet to be fully researched and implemented in a foreseeable, stable and sustained manner. Carbon neutrality is a systematic issue and requires a systematic and efficient mechanism to mobilize and coordinate innovation in various sectors. Moreover, the commercialization of low-carbon technologies calls for conducive fiscal, financial and industrial policies and legal assurances, the absence of which impedes the application of R&D results and the formation of innovation value chains.

(3) Underinvestment in low-carbon innovation: Take the energy sector for instance, China's energy

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R&D investment as a share of national total R&D input is decreasing in both public and private sectors. Energy companies rely on technology renovation, importation or domestic acquisition for technology upgrade at a low level. In the energy sector, less innovative technology upgrade and importation have received the bulk of R&D spending, leaving technology assimilation and re-innovation underfunded.

(4) Poor fundamentals for low-carbon innovation: Despite rapid growth, China's low-carbon industry, R&D workforce and innovation capacity fall short of demand. Few R&D programs have been carried out in partnership with innovation platforms such as state key laboratories, state engineering technology centers, state-designated corporate technology centers, and state key laboratories of enterprises. With overlapping priorities, those innovation platforms should be more focused on specific areas of research and receive more stable support from the state.

5. Reflections on Innovation Pathways under the Carbon Neutrality Vision

Carbon neutrality requires integrated efforts on the three fronts, of the substitution of fossil fuels and feedstocks, the emissions abatement of industrial, construction, transportation and terminal processing activities, as well as CCUS and carbon sink. In terms of energy supply and consumption, it takes the joint effects from power generation, energy consumption and carbon sink to achieve carbon neutrality.[8] Technology pathways for carbon emissions abatement vary across sectors, including the electric power sector as energy producer, industry, construction and other social and economic sectors as energy consumers, and negative carbon technologies such as carbon sink and CCUS on the carbon sequestration side. Technology innovation should proceed in a step-by-step manner with priorities and targets for each stage following the laws of technology development and latest trends in various domains.

5.1 Technology Innovation Pathways on the Energy Supply Side

In 2020, China consumed 4.98 billion tons of coal equivalent (tce), of which coal consumption accounted for 56.8%. China's coal-fired generation capacity made up 49.1% of total installed capacity and generated 60.8% of China's total electricity. According to Su *et al.* (2021), China's energy consumption will keep rising to meet the needs of the country's economic and social development and peak at 6 billion to 6.4 billion tce in 2030-2040 before decreasing gradually. By 2025, 2030 and 2060, China's total energy consumption is expected to reach 5.8 billion, 6 billion and 5.6 billion tce per year, respectively (see Figure 2).

As the keynote of its energy transition, China will reduce coal, stabilize oil, increase natural gas and scale up renewable energies in the coming four decades. With an overall surplus and basic supply-demand equilibrium, China's coal production is poised to meet its demand of 4 billion tons per year. Under the carbon neutrality goal, however, coal consumption is expected to shrink and ultimately serve as a ballast in China's energy consumption system. China's crude oil and natural gas shortages will persist. In the absence of revolutionary technologies, China will stabilize crude oil production at around 200 million tons, and try to keep natural gas production at the plateau after peaking at 300 billion cubic meters by 2030. China's abundant renewable resources, especially wind and solar in the western regions and offshore wind in the eastern coastal regions, will satisfy its goal to increase the share of non-fossil fuels to over 80% of total energy consumption by 2060.

We forecast the following trends of China's energy mix. First, China's overall energy demand will increase before decreasing in a later stage. Second, fossil fuels will continue to dominate China's energy consumption before 2040. Third, non-fossil fuels as a share of primary energy demand will keep rising and replace fossil fuels by 2040 to become a major energy source. Non-fossil fuels as a share of primary

[8] Source: https://www.in-en.com/article/html/energy-2311652.shtml.

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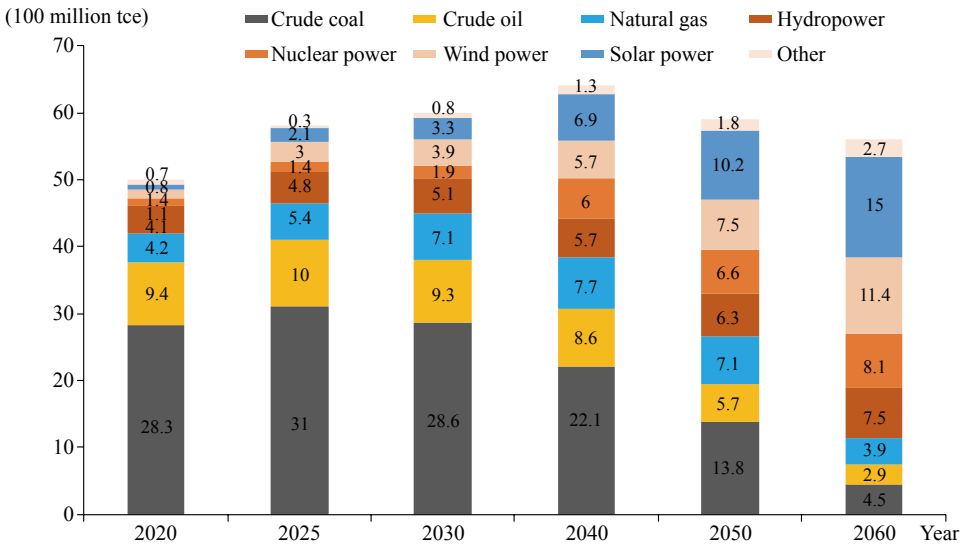

Figure 2: Forecast of China's Total Energy Consumption and Energy Mix

Source: Su *et al*. (2021).

energy demand will jump from 20% in 2025 to around 80% by 2060. Fourth, the importance of electric power primary fueled by renewables will come into greater play. In 2020, China's electric power as a share of terminal energy consumption stood at 27%. By 2030 and 2060, this share will rise to 39% and 70%, respectively.[9]

The electric power sector is vital for energy conversion and supply. It may still rely on fossil fuel combustion as the primary form of power generation in China before the goal of carbon peak is achieved or in a longer timeframe before 2040. Coal innovation is primarily driven by coal-fired power generation units. Priority should be given to deploying single reheat ultra-critical units, double reheat ultra-supercritical technology with cross-compound, high and low positioned steam turbo-unit, and efficiency enhancement technologies for the low-load operation of coal-fired power plants. Before energy storage technologies are ready for mass deployment, coal-fired power for peak-load regulation may facilitate the absorption of renewable energies. Steady progress should be made in the development of photovoltaic and wind power. After reaching the carbon peak, thermal power plants will decarbonize feedstock by mixing or completely adopting biomass pellets for zero-carbon thermal power generation. New botanical species such as giant reeds should be developed as photosynthetic energy storage devices through genetic engineering to provide sufficient biofuels for the transition towards "zero-carbon biomass thermal power".[10]

Meanwhile, the electric power sector should adopt CCUS technologies for the partial conversion and utilization of carbon resources. Regarding renewable power, technological breakthroughs should be made in high-efficiency and low-cost crystalline silicon photovoltaic (PV) cells to substantially increase the conversion efficiency and storage capacity of renewable power. Wind turbines should be deployed further offshore and become taller, larger, smarter and more reliable. We should acquire critical technologies such as renewable hydrogen production and smart grid, and create an integrated and smart multi-energy hybrid power system led by photovoltaic, wind, biomass and hydrogen power with the assistance of big data and new-generation information technology. In the carbon neutrality stage, we

[9] Source: National Energy Information Platform. https://baijiahao.baidu.com/s?id=1711103389482683034&wfr=spider&for=pc. 2021.09.17.
[10] Source: http://xincailiao.com/news/news_detail.aspx?id=604161.

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expect the thermal power sector to achieve negative emissions on the basis of zero-carbon thermal power technology as CCUS becomes ready for mass deployment. With progress in the Generation IV nuclear reactors and experimental fusion reactors, nuclear power will further contribute to decarbonization in the electric power system.

5.2 Technology Innovation Pathways on the Energy Consumption Side

On the energy consumption side, the low-carbon transition relies on both systematic supply-side change and industrial technology innovations.

The manufacturing industry is a key priority for achieving carbon neutrality. China's industrial carbon emissions reached 4.9 billion tons in 2020, accounting for 44% of total emissions, and are expected to peak by around 2025 at 5.5 billion tons and stand a suggested level of 300 million to 500 million tons by 2060.

(i) Before reaching carbon peak, the manufacturing industry may curb carbon emissions primarily by consuming less energy, improving product quality and durability, and reducing overall output through further production process integration and optimization. Smart manufacturing and secondary resource recycling may help, too. Steel and nonferrous metals sectors may slash carbon emissions by integrating production processes, improving the quality of metallurgical products, and adopting hydrogen smelting and residual heat recovery technologies. For the building materials sector, a key solution is the adoption of low-carbon industrial materials and the reuse of solid wastes from other sectors. For the chemical industry, carbon reduction solutions also include system optimization and integration between various production units, the re-engineering of key energy-consuming processes, the promotion of energy cascade use, material recycling, as well as the integrated use of low-grade heat energy, ash and slag. New industrial projects should embrace internationally advanced technologies, increase product yield, reduce energy and resource consumption, and promote low-carbon industry development. Such technologies include, for instance, coal-water slurry gasification technology with a cooling screen, the third-generation dimethyl ether/methanol to olefins (DMTO-III) process, and methanol-naphtha coupling for manufacturing light olefins.

(ii) In further reducing carbon emissions after reaching carbon peak, China should promote feedstock replacement and short-process technologies. Steel and nonferrous metals sectors should promote short-process smelting technologies with waste and used metals as feedstock through industrial process transformation. The cement sector should widely adopt low-calcium clinker and clinker-free or low-clinker feedstock, as well as hydrogen fuel substitution technology. The chemical sector should apply short-process energy-efficiency and low-carbon technology, low-carbon feedstock substitution technology, and CO_2 utilization technology. Some areas of the chemical sector with favorable conditions should apply CCUS technology and support the near-zero emissions of the chemical industry.

(iii) In the carbon neutrality stage, CCUS/carbon removal technologies will be deployed on a mass scale in the industrial sectors and play a critical role in achieving carbon neutrality.

The building sector is a key energy consumer. In 2020, China's building sector emitted 620 million tons of carbon dioxide (excluding rural bulk coal for heating and cooking), accounting for 6% of the total. Having entered a plateau with relatively mature zero-carbon solutions, China's building sector carbon emissions should take the lead in reducing carbon emissions and achieving near-zero emissions as early as possible. The realization of low-carbon/zero-carbon transition in the building sector should be predicated upon the development of energy-efficient buildings and all-round electrification.

(i) Before reaching the carbon peak, existing buildings should be retrofitted for energy efficiency, and new buildings should follow ultra-low energy consumption and near-zero energy consumption standards. Energy consumption of buildings should be reduced by adopting high-performance envelope structure and new materials, products and processes.

(ii) In further reducing carbon emissions after carbon peak, the building sector should first improve

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construction quality and durability; second, promote building electrification and electric and zero-emission alternative technologies and equipment for heating, cooking, water boiling and steam in hot-summer-frigid-winter regions; third, expedite technology innovations for combined heating and power, develop the photovoltaic-energy storage-direct current-flexibility (PEDF) technology, adopt low-carbon building materials and low-carbon building structure, and make coordinated carbon reductions in the electric power and industrial sectors; and fourth, promote building-integrated photovoltaics (BIPV) to maximize renewable potentials in buildings.

As a major consumer of oil and electricity, the transportation sector has great carbon reduction potentials, but the achievement of which is a tall order. In 2019, carbon emissions from China's transportation sector stood at some 1.15 billion tons, accounting for some 10% of total. The sector is expected to reach carbon peak by 2030 or so at 1.25 billion to 1.35 billion tons. Considering such factors as the safety and convenience of mobility and emissions reduction technologies and costs, the transportation sector will strive to reduce carbon emissions to less than 200 million tons by 2060. Priority should be given to vehicle energy efficiency, carbon reduction and new energy substitution. Before reaching carbon peak, we should proactively encourage public transportation and non-motorized transportation to reduce energy consumption. Priority should also be given to developing energy-efficiency technologies for fossil-fueled cars, including energy efficiency and lightweight bodywork technologies. Shared mobility systems should be encouraged to increase the utilization of mobility services and resources. In the further carbon production stage after reaching carbon peak, priority should be given to developing high-performance electric and hydrogen fuel cell vehicles for all-round new energy substitution. Smart mobility should focus on making breakthroughs in critical technologies, smart sensing, integrated big data processing and coordinated command and dispatch to increase overall transportation efficiency.

5.3 Technology Innovation Pathways for Carbon Sink

Negative carbon technologies such as carbon sink and CCUS are the underlying technologies for China to go carbon neutral. (i) Before reaching carbon peak, we should enhance research on the mechanism of carbon sink based on forest, pasture, wetland and maritime ecosystems, explore space-air-ground integrated carbon sink precise monitoring technologies, create an accounting system for dynamic monitoring, reporting and verification, adopt innovative typical ecosystem protection and repair technologies, and stabilize and enhance the carbon sink capacity of existing ecosystems. We should proactively carry out fundamental research on CCUS and demonstrative research for CCUS applications. (ii) In further reducing carbon emissions after reaching carbon peak, we should strengthen technological breakthroughs in various processes including carbon capture, separation, transportation, utilization, sequestration and monitoring, and ramp up the development and mass deployment of new-generation CCUS technologies featuring low energy consumption, low cost and high safety performance. Fiscal incentive similar to US 45Q tax credit should be offered to pave the way for the future commercialization of those technologies. Priority should be given to the mass deployment of CCUS technologies in the industrial sectors. (iii) In the carbon neutrality stage, the priority is to promote all-around commercial applications of CCUS technologies.

6. Reflections on Technology Innovation under the Carbon Neutrality Vision

The first is conducting top-down design for integrating technologies, energy sources and energy-consuming sectors. We should create a nationwide cross-departmental coordination mechanism led by the Ministry of Science and Technology to draw upon collective wisdom of strategic scientists, carry out extensive forward-looking cross-disciplinary research to identify future technology frontiers for carbon peak and carbon neutrality, and form a dynamic top-down design blueprint for carbon neutrality

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technologies.

The second is ramping up scientific research on energy strategy for achieving carbon peak and carbon neutrality goals. Under the premise of the national top-down scheme for carbon neutrality, we should formulate mid- and long-term strategic plans for carbon abatement, low-carbon and zero-carbon technologies on the basis of five-year plans for science and technology development, promote non-carbon-based energy technology iteration, and assess various technology pathways in terms of economic and environmental performance to safeguard national energy security.

The third is expediting the pilot demonstration applications of new technologies and business modes. Based on the assessment of demand for energy efficiency and carbon reduction technologies under the carbon peak and neutrality goals, pilot programs should be carried out in various sectors and use cases to roll out mature technologies. We should foster a virtuous cycle of technology research, commercialization and accumulation and encourage the development and deployment of new technologies, processes and business modes.

The fourth is establishing institutional mechanisms for the market-based operation of low-carbon technologies. The government should research market-oriented emissions reduction policies, carry out study on Net-Zero Techno-Eonomics, and investigate how efforts to achieve carbon neutrality may contribute to innovation and reshape future energy and industrial landscapes. The effective state and efficient market should be brought into play to coordinate technology, fiscal, investment and financing policies. Low-carbon technology evaluation and transaction systems should be put into place to inspire low-carbon innovation and apply low-carbon technologies in industrial sectors. Net-zero carbon technologies should play an important role in the economic and social transition towards carbon neutrality.

The fifth is cultivating carbon neutrality professionals. For the purpose of achieving carbon peak and carbon neutrality, the government should bring together scientists and policy researchers, scale up support to leading research institutions, and improve the layout of innovation entities by setting up key national laboratories and innovation centers. Moreover, it is also important to develop a technology information platform to integrate resources across various sectors, giving priority to fostering young scientists and engineers specialized in carbon neutrality.

The sixth is deepening international innovation cooperation for mutual benefit. We should promote carbon neutrality innovation with major countries. The two-way flow of green and low-carbon technologies should be encouraged by sharing climate change knowledge and technology and establishing technology transfer platforms and databases to match the international supply and demand of green and low-carbon/decarbonization technologies.

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