零碳创新：气候关联技术指南

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Advanced technologies are critical to stopping climate change—and the drive to develop and scale them is accelerating. Here are five themes that could attract $2 trillion of annual investment by 2025.

译文：先进技术是阻止气候变化的关键，同时开发这些技术并使之规模化的动力也正在加速。以下列出 5 个主题，这些技术到 2025 年每年可吸引 2 万亿美元的投资。

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New technologies represent a critical part of the world's decarbonization tool kit—and the world does not yet have all the technologies that it would need to solve the net-zero equation by balancing sources and sinks of greenhouse-gas (GHG) emissions. The good news: McKinsey research on Europe's net-zero pathway suggests that climate technologies that are already mature could, if deployed widely, deliver about 60 percent of the emissions abatement that will be needed to stabilize the climate by 2050. The challenge is that further abatement must come from climate technologies that aren't quite ready, including 25 to 30 percent from technologies that are demonstrated but not yet mature and another 10 to 15 percent from those still in R&D.

新技术代表着全球去碳化手段重要部分，全球仍不具备通过平衡资源并降低温室气体排放（GHG）解决净零排放方程全部技术。好消息是麦肯锡在欧洲净零排放路径的研究中推荐了已经成熟的气候关联技术，如果广泛采用，到 2050 年将可以带来约 60%的排放减少。挑战是将来的减少必须通过气候关联技术来实现，包括要通过那些仍在示范阶段仍未成熟的技术实现 25%-30%的排放，还有 10%~15%排放需要的技术仍处于研发阶段。

This need for innovation makes the pace of decarbonization difficult to predict. When, for example, will clean hydrogen cost $1 per kilogram: in 2025 or 2050? The answer will affect the speed at which industries from aviation to steel can decarbonize. Similarly, unless manufacturers of utility-scale batteries can make them at low cost, power producers will have to keep running fossil fleets to cope with the intermittency of renewables. Uncertainty about the availability of financing for innovation limits capital formation and slows scale-up. Integrating most climate technologies into existing infrastructure, hardware, software, and operational systems will be complicated, too.

这种对创新的需求使得脱碳的速度难以预测。 例如，何时清洁氢的成本将达到每公斤 1 美元:2025 年还是 2050 年? 答案将影响从航空到钢铁等行业脱碳的速度。 同样，除非公用事业规模的电池制造商能够以低成本生产电池，否则电力生产商将不得不继续使用化石电池以应对可再生能源的间歇性。 创新融资可用率的不确定性限制了资本筹集，并减缓了规模的扩大。将大多数气候技术整合到现有的基础设施、硬件、软件和操作系统中也将是复杂的。

Yet there are reasons to be optimistic. Recent history suggests that researchers and businesses can deliver the necessary advances and cost reductions (see sidebar, “Charting cost reductions for climate technologies”). Over the past decade, the cost of some renewable-energy projects came down by almost 90 percent, as did the costs of electric-vehicle (EV) batteries, LED lighting, and other energy-efficient hardware. Capital is increasingly plentiful, evidenced by the revaluation of cleantech stocks that began in June 2020, and by the growth in investments earmarked for sustainability and environmental, social, and corporate governance (ESG) objectives. Governments are lending strong fiscal support to low-carbon innovation. Pledges from big companies not only to cut emissions but also to decarbonize operations and product lines—to buy only renewable fuel or make only EVs—give confidence to entrepreneurs and their backers. Talk of regulatory mandates lends weight to these demand signals.

当然，我们有理由保持乐观。 最近的历史表明，研究人员和企业可以提速和成本削减。 在过去的十年里，一些可再生能源项目的成本下降了近 90%，电动汽车(EV)电池、LED 照明和其他节能硬件的成本也是如此。 从 2020 年 6 月开始

的清洁技术股重估，以及用于可持续发展、环境、社会和公司治理(ESG)目标的投资增长可以看出，资本越来越充足。 各国政府正在为低碳创新提供强有力的财政支持。 大公司的承诺不仅要减少排放，而且要使运营和产品线脱碳——只购买可再生燃料或只生产电动汽车——给企业家和他们的支持者带来信心。 有关监管授权的说法为这些需求信号增加了分量。

And, again, the need for climate technology is vast—which creates large potential markets and investment opportunities. Our estimates suggest that next-generation technologies could attract $1.5 trillion to $2 trillion of capital investment per year by 2025.[1] To enter these markets and navigate them successfully, established companies, start-ups, and investors will need a nuanced and ever-evolving understanding of technical advances, customer demands and commitments, and policy environments. In this article, we lay out five areas with considerable promise, along with potential obstacles along the path to scale (exhibit):

还有，对气候关联技术的需求巨大——这种需求创造了巨大的潜在市场以及投资机会。麦肯锡的预测显示下一代技术到 2050 年每年将吸引 1.5 万亿美元的资本投资。想进入这些市场并成功掌舵，经验丰富的公司、创业公司以及投资者都需要对技术的先进性、客户需求以及承诺还有政策环境有细致入微以及坚持不懈的理解。本文中，我们列出了 5 个关键领域以及潜在阻碍：

- 交通运输、建筑以及工业的电气化
- 下一个农业绿色革命
- 重新布置电网，提供清洁电力
- 履行氢能承诺
- 扩大碳捕获、使用及存储

五组技术，到2050年可吸引2万亿美元资本，同时减少40%的温室气体排放				
技术一览				
电气化	农业	电网	氢能	碳捕获
电动车电池	零排放农场设备	长久存储	低成本生产	前端和后端燃烧获取技术
电池控制软件	肉类替代品	先进控制	公路运输燃料	直接空气获取
高效的建筑系统	甲烷抑制剂	软件及通讯	氨气生产	与碳获取和存储一起的生物能
工业电气化	厌氧堆肥处理	交通工具到电网的整合	钢铁生产	生物炭
	生物工程	建筑到电网的整合	航空燃料	CO2浓缩混凝土
		下一代核能		
		高效材料		
到2025年的年度投资（单位：百万美元）				
电气化：700-1000	农业：400-600	电网：200-500	氢能：100-150	碳捕获：10-50
截止2050年每年减少的的CO2（单位：十亿吨）（1.5℃路径）				
电气：约5.0	农业：约10.0	电网：约5.0	氢能：约 2.5	碳捕获：约 3.0
数据来源：麦肯锡公司				

Electrifying transportation, buildings, and industry

运输、建筑及工业的电气化

Coal, oil, and gas have been the main fuels used to power buildings, industrial machines, and vehicles since the early 20th century. Getting to net-zero emissions will require electrifying most equipment and processes that now run on hydrocarbons and converting the electric-power system to renewable sources (see the next section). Many forms of electric gear, from EV batteries to heat pumps to industrial furnaces, remain expensive. Further innovation will be needed to reduce costs and increase uptake of the electric hardware that will drive a net-zero society.

自 20 世纪初以来，煤、石油和天然气一直是为建筑物、工业机器和车辆提供动力的主要燃料。要实现净零排放，需要对目前使用碳氢化合物的大部分设备和工艺进行电气化，并将电力系统转换为可再生能源(见下一节)。许多形式的电动齿轮，从电动电池到热泵到工业炉，仍然很昂贵。我们需要进一步的创新，以降低成本，增加电动硬件的使用量，从而推动一个净零社会。

Better EV batteries. Electrifying transportation requires cutting the cost of batteries, which can account for as much as half the cost of an EV. However, the lithium-ion batteries that are most common in EVs may never fall below the critical threshold of $100 per kilowatt-hour. To boost energy density and cut costs, battery chemistry will have to improve. Companies are working on anodes with high silicon content, which represent the next frontier. Beyond that, innovations in solid-state, gel, and foam electrolytes would turn ultra-high-capacity lithium metal anodes from a concept into a reality, and one that is safer than today's battery technology.

更好的电动汽车电池。电动运输需要降低电池成本，电池成本可占电动汽车成本的一半。然而，电动汽车中最常见的锂离子电池可能永远不会低于每千瓦时 100 美元的临界阈值。为了提高能量密度和降低成本，电池的化学性能必须改进。各公司正在研究高硅含量的阳极，这代表着下一个前沿。除此之外，固态、凝胶和泡沫电解质的创新将使超大容量锂金属阳极从一个概念变成现实，而且比现在的电池技术更安全。

Battery-control software. Hardware improvements aren't the only route to better batteries. Software control systems can also help, and even make up for shortfalls in chemistry. They can shorten charging times: imagine recharging an EV with a 300-mile range in ten minutes or less, instead of one hour at a supercharger or overnight on most home systems. They can prolong battery lives enough to match the life of the vehicle. And they could give EVs added pickup or hauling or towing capacity.

电池控制软件。硬件的改进并不是获得更好电池的唯一途径。软件控制系统也可以帮助，甚至弥补化学方面的不足。它们可以缩短充电时间:想象一下，在 10 分钟或更短的时间内给行驶了 300 英里的电动汽车充电，而不是在增压器上充电一小时或在大多数家庭系统上充电一晚上。它们可以延长电池的寿命，足以与车辆的寿命相匹配。它们还可以增加电动汽车的皮卡或拖曳能力。

Efficient building systems. Buildings account for about 7 percent of global CO_2 emissions. Cutting those emissions would require making buildings more energy efficient with technologies such as LED lighting, high-efficiency HVAC, and energy controls. But efficiency alone isn't enough. Buildings, like vehicles, have to go electric. Using heat pumps to keep buildings warm, instead of traditional boilers and furnaces, could cut global CO_2 emissions by 3 gigatons per year if implemented worldwide. Today's models are 2.2 to 4.5 times more efficient than gas furnaces, and recent advances, such as multiple or variable-speed compressors, let heat pumps work in cold conditions, In addition, energy-reactive windows and those with embedded solar cells could enable buildings to generate all the power they need.

高效的构建系统。建筑排放的二氧化碳约占全球的 7%。要想减少这些排放，就需要利用 LED 照明、高效暖通空调和能源控制等技术提高建筑的能效。但仅靠效率是不够的。建筑和交通工具一样，必须使用电力。使用热泵来保持建筑物的温暖，而不是传统的锅炉和熔炉，如果在全球范围内实施，每年可以减少全球二氧化碳排放量 30 亿吨。今天的模型是 2.2 到 4.5 倍的效率比天然气炉和最新进展,如多个或变速压缩机,让热泵在寒冷条件下工作,此外,energy-reactive windows 和嵌入式太阳能电池能使建筑物产生所需的所有权力。

Industrial electrification. As prices of renewable electricity and electric equipment drop, industrial companies could lower costs and emissions by electrifying their operations. The opportunity appears large. Industrial sectors such as cement, chemicals, and steel together consume more energy than other sectors (such as electric power and transportation), and only 20 percent of that energy is electricity. What's more, electrical equipment is less costly and more reliable for many industrial applications, though not all. Electric furnaces, for example, can make heat up to 350°C, but not the high heat of up to 1,000°C that many industrial processes need. Innovation will be needed to address these gaps. There is also the question of how to finance industrial electrification. Replacing long-lived equipment early can mean writing it off, and industrial products tend to have tight profit margins, which can discourage companies from making big capital outlays. New financial mechanisms could help companies cover the up-front cost of electric equipment even with the long payback period.

工业电气化。随着可再生电力和电力设备价格的下降，工业公司可以通过电气化来降低成本和排放。机会似乎很大。水泥、化工和钢铁等工业部门加起来消耗的能源比其他部门(如电力和交通)更多，而这些能源中只有 20%是电力。更重要的是，对于许多工业应用来说，电气设备更便宜，也更可靠，尽管不是全部。例如，

电炉可以产生高达 350°C 的热量，但不能产生许多工业过程所需要的高达 1000°C 的高温。需要创新来解决这些差距。还有一个问题是如何为工业电气化提供资金。过早更换长寿命设备可能意味着将其注销，而工业产品往往利润率较低，这可能会阻碍企业进行大规模资本支出。新的财务机制可以帮助企业支付电力设备的前期成本，即使是在较长的回收期。Launching

开启下一个农业革命

Agriculture accounts for about 20 percent of global GHG emissions. The most significant GHG from agriculture is methane, which has many times the warming power of CO_2. Reducing methane emissions from agriculture (and other sources) would require major changes to how society farms, eats, manages supplies and waste, and stewards cropland and forests. Many of the changes would be enabled by climate technologies, some of which are relatively mature while others need further development.

农业占全球温室气体排放的 20%左右。农业产生的最显著的温室气体是甲烷，其变暖能力是二氧化碳的许多倍。减少农业(和其他来源)的甲烷排放需要对社会耕作、食用、管理物资和废物以及管理农田和森林的方式做出重大改变。许多变化将由气候技术实现，其中一些技术相对成熟，而另一些需要进一步发展。

Bringing these technologies to the more than two billion people who work in agriculture will be one of the most difficult tasks on any path to 1.5°C of warming, requiring cost reductions, assistance programs, and infrastructure (such as distributed clean energy). These developments would amount to a new green revolution, one with the potential to surpass the gains that were realized as efficient farming practices were applied widely in the 1960s. These are some of the technologies that could decarbonize agriculture.

将这些技术带给 20 多亿从事农业工作的人，将是使气温上升 1.5 摄氏度的道路上最困难的任务之一，需要降低成本、开展援助项目和基础设施(如分布式清洁

能源)。这些发展将构成一场新的绿色革命，它有可能超越 20 世纪 60 年代广泛应用高效农业实践所实现的收益。这些技术可以使农业脱碳。

Zero-emissions farm equipment. The largest amount of on-farm emissions abatement could be achieved by shifting from traditional fossil-fuel equipment and machinery—such as tractors, harvesters, and dryers—to their zero-emissions counterparts. The economic potential is significant: deployment of zero-emissions equipment could produce cost savings of $229 per ton of carbon dioxide equivalent (tCO_2e). Nevertheless, uptake of zero-emissions farm equipment and machinery is far behind that of EVs; most varieties are still in the proof-of-concept or prototype phases. Cost reductions and supportive financing would accelerate adoption.

零排放的农用设备。从传统的化石燃料设备和机械(如拖拉机、收割机和干燥机)转向它们的零排放设备，可以最大程度地减少农场上的排放。这项技术的经济潜力是巨大的:零排放设备的部署可以为每吨二氧化碳当量节省 229 美元的成本。然而，零排放农业设备和机械的使用量远远落后于电动汽车;大多数品种仍处于概念验证或原型阶段。成本削减和支持性融资将加速采用。

Meat alternatives. Between one-quarter and one-third of global methane emissions are estimated to come from the digestive processes of cattle, sheep, and other ruminant animals. Those emissions will be difficult to abate unless consumers opt to change their diets. But some of the meat and dairy that people now eat could be healthfully, and cost-effectively, replaced with protein from crops such as legumes and pulses. This may require more land and different planting practices but could also reduce deforestation related to the clearing of land for pasture. Lab technology also points toward meat substitutes. Some are plant-based: Beyond Meat and Impossible Foods are two of the leading names in the field. Cultivated meats—those grown in bioreactors from animal cells—are also advancing. McKinsey research suggests that this could become a $25 billion global industry by 2030.

肉类替代品。据估计，全球四分之一到三分之一的甲烷排放来自牛、羊和其他反刍动物的消化过程。除非消费者选择改变他们的饮食，否则这些排放将很难减少。但人们现在食用的一些肉类和奶制品可以用豆类和豆类等作物的蛋白质来代替，

这既健康又经济。这可能需要更多的土地和不同的种植方式，但也可能减少与开垦土地用作牧场有关的森林砍伐。实验室技术也指向肉类替代品。有些是植物性的:Beyond Meat 和 Impossible Foods 是这一领域的两个领军人物。在生物反应器中从动物细胞中培养的肉类也在发展。麦肯锡的研究表明，到 2030 年，这可能成为一个价值 250 亿美元的全球产业。

Methane inhibitors. Companies are developing feed supplements and substitutes that inhibit methane production by altering an animal’s digestive processes. Trials have shown that these can reduce methane production by 30 to 50 percent. Propionate precursors—a class of free acids or salts, such as sodium acrylate or sodium fumarate—have been shown to inhibit methane emissions from cattle without affecting animals’ growth, and one of these has entered the EU approval process.

甲烷抑制剂。各家公司正在开发饲料补充剂和替代品，通过改变动物的消化过程来抑制甲烷的产生。试验表明，这些可以减少 30%到 50%的甲烷产量。丙酸前体——一类游离酸或盐，如丙烯酸钠或富马酸钠——已被证明可以在不影响动物生长的情况下抑制牛的甲烷排放，其中一种已进入欧盟的审批程序。

Anaerobic manure processing. Manure from cattle and hogs can release significant amounts of methane. Processing manure in anaerobic digesters can cut emissions and also generate biogas, a renewable form of natural gas that can be used on farms, sold to the grid, or fed into production of “gold hydrogen.” Such digesters are now used, though not widely, to control odor and pathogens. But companies are partnering with agriculture and landfill sites to produce biogas for various purposes, such as making compressed natural gas, which counts as a transport fuel under California’s low-carbon fuel standard.

厌氧堆肥处理。牛和猪的粪便可以释放大量的甲烷。在厌氧消化器中处理粪便可以减少排放，也可以产生沼气，这是一种可再生的天然气，可以在农场上使用，也可以卖给电网，或者用于生产“黄金氢气”。这种消化器现在被用来控制气味和

病原体，虽然不是很广泛。但一些公司正在与农业和垃圾填埋场合作，生产用于各种目的的沼气，比如生产压缩天然气，根据加州的低碳燃料标准，压缩天然气是一种运输燃料。

Bioengineering. Bioengineering advances agricultural productivity and carbon sequestration and thereby lowers the sector's emissions. Promising technologies include editing of plant genes to promote disease resistance and manage the soil microbiome.

生物工程。生物工程提高了农业生产力和碳封存，从而降低了该部门的排放。有希望的技术包括编辑植物基因以提高抗病能力和管理土壤微生物群。

Remaking the power grid to deliver clean electricity

重新布置电网，提供清洁电力

Almost everywhere, power grids are old, inefficient, unreliable—and carbon-intensive. They are nowhere near ready to handle the doubling of electricity demand that could take place by 2050 as electrification happens, let alone prevent a commensurate increase in carbon emissions. Modernizing and decarbonizing the grid involves three main tasks. One is speeding the installation of renewable-generation capacity; to achieve a 1.5°C pathway, we estimate that the global installation rate would need to increase from 3 gigawatts per week to 15 to 18 gigawatts. Another task is adding energy-storage capacity to manage the intermittency of solar and wind. Last is upgrading the transmission and distribution network to accommodate more front-of-the-meter and behind-the-meter assets.

几乎所有地方的电网都是旧的、低效的、不可靠的，而且是碳密集型的。随着电气化的实现，到 2050 年电力需求将翻倍，而这些国家还远远没有准备好应对这一局面，更不用说防止相应的碳排放增加了。电网现代化和脱碳涉及三项主要任务。其一是加快可再生能源发电能力的建设;为了达到 1.5°C 的目标，我们估计全球安装速率需要从每周 30 吉瓦增加到 15 到 18 吉瓦。另一项任务是增加能源

储存能力，以管理太阳能和风能的间歇性。最后是升级传输和配电网，以适应更多的表前和表后资产。

Few utilities are known as risk takers. For the most part, they are set up—and required by regulators—to deploy proven, mature technologies. These tendencies present limitations. But if innovators and grid operators work together (for example, on accelerating the scale-up of long-duration storage) and regulators send helpful signals (for example, by defining mechanisms to reward providers of battery storage and other services that help deal with intermittency), then the following technologies could help create a zero-carbon grid.

很少有公用事业公司被认为是冒险者。在很大程度上，它们是按照监管机构的要求建立的，以部署经过验证的成熟技术。这些趋势存在局限性。但是，如果创新者和电网运营商共同努力(例如，加速扩大长时间存储的规模)，并且监管者发出有益的信号(例如，通过定义奖励电池存储和其他帮助解决间歇性问题的服务提供商的机制)，接下来的技术可以帮助创建一个零碳排放的电网。

Long-duration storage. Even with falling solar and wind costs, as well as cheaper lithium-ion batteries, the intermittency of renewables makes these technologies impractical as the sole source of grid power. A solution is long-duration energy storage, which can store enough power to supply a network for two weeks or more (a typical period of limited renewable generation in many markets). In comparison, lithium-ion batteries can provide backup power cost-effectively for only four hours. At a levelized cost[3] of less than $20 per kilowatt-hour, long-duration storage would make 100 percent renewable systems cost-competitive in US states with ample wind and solar resources. Storage costs of $150 per kilowatt-hour would allow very high wind and solar penetration, provided that power systems also include strong demand-side management, backup gas turbines, or more integration of regional transmission networks.[4] Multiple storage technologies are emerging, including power-to-gas, flow batteries, and compressed or liquefied air. Big and small companies are active in this market, and start-ups are pioneering more advanced options such as mechanical systems and modular pumped hydro.

长期存储。尽管太阳能和风能的成本在下降，锂离子电池的价格也在下降，但可再生能源的间歇性使得这些技术无法成为电网电力的唯一来源。一个解决方案是长期能源储存，它可以储存足够的电力供应一个网络两周或两周以上(在许多市场中，这是可再生能源有限的典型时期)。相比之下，锂离子电池仅能提供 4 小时的备用电力。在每千瓦时不到 20 美元的水平成本下，长时间储能将使 100%的可再生能源系统在拥有充足风能和太阳能资源的美国各州具有成本竞争力。如果电力系统还包括强大的需求侧管理、备用燃气轮机或区域输电网络的更多整合，每千瓦时 150 美元的储存成本将允许非常高的风能和太阳能渗透多种存储技术正在兴起，包括电转气、流电池和压缩或液化空气。大大小小的公司在这一市场上都很活跃，初创企业正在开拓更先进的选择，如机械系统和模块化抽水蓄能。

Advanced controls. Today, grid utilization tends to average below 50 percent because the grid is built for times of peak demand and its performance worsens in extreme heat or cold. As more renewables and storage systems are deployed at the grid edge, in homes and commercial sites, they will make power grids more complicated to operate. Resilience, flexibility, safety, and efficiency can be improved with technologies such as solid-state transformers, advanced flexible AC controllers that allow more controlled grid flow, and high-voltage DC technologies for data centers.

先进的控制。如今，电网的平均利用率往往低于 50%，因为电网是在需求高峰时期建立的，在极热或极冷的情况下，其性能会恶化。随着越来越多的可再生能源和存储系统被部署在家庭和商业场所的电网边缘，它们将使电网的运行更加复杂。弹性、灵活性、安全性和效率可以通过固态变压器、允许更可控电网流量的先进灵活交流控制器以及用于数据中心的高压直流技术等技术得到提高。

Software and communications. Traditional electrical grids use idling power plants to maintain grid balance. These so-called spinning reserves are expensive to run but can respond quickly when demand fluctuates. Modern electric grids would rely on ultrafast communications to maintain grid balance by managing every device on the network. Software-defined inertial substitution (to maintain grid balance when there are fewer spinning reserves), advanced “volt-var” management (to maintain proper voltage over long transmission lines or in highly congested urban markets), and network-wide instrumentation for condition monitoring and fault isolation would help utilities spot issues and prevent interruptions. Distributed energy-management software can coordinate all these elements. Digitized grids will require better cybersecurity protection.

软件和通信。传统电网利用闲置发电厂来维持电网平衡。这些所谓的旋转储备运行起来很昂贵，但在需求波动时能够迅速做出反应。现代电网将依靠超快通信来管理网络上的每一个设备来维持电网平衡。软件定义的惯性替代(在旋转备用电量较少时维持电网平衡)，先进的“电压-无功”管理(在长距离输电线路或高度拥挤的城市市场上维持适当的电压)，而用于状态监测和故障隔离的网络范围内的仪器将帮助公用事业公司发现问题并防止中断。分布式能源管理软件可以协调所有这些元素。数字化的电网需要更好的网络安全保护。

Vehicle-to-grid integration. As more drivers switch to EVs, the big batteries in their driveways and garages could be hooked up to the grid to provide energy-storage capacity. One million typical EVs would offer about 75 gigawatts of storage, hundreds of times more than today’s single biggest utility-scale storage facility provides. Residential backup batteries add more. Accomplishing this integration requires technologies such as inverters that connect rooftop solar, wall batteries, EV batteries, and the grid, as well as fast chargers that buffer the grid from demand spikes while keeping EV batteries full.

汽车电网一体化。随着越来越多的司机改用电动汽车，车道和车库里的大电池可以与电网连接，以提供能量储存能力。100 万辆普通电动汽车可以提供约 750 亿瓦的存储能力，比目前最大的公用事业规模存储设施提供的存储能力高出数百倍。家用备用电池能增加更多电量。完成这一集成需要技术，如连接屋顶太阳能、

墙壁电池、电动汽车电池和电网的逆变器，以及快速充电器，以缓冲电网的需求峰值，同时保持电动汽车电池充满。

Building-to-grid integration. As buildings' energy controls improve, the buildings can be dispatched to the grid—that is, used to supply power—in ways that improve system performance. Buildings with energy storage or cogeneration could feed power onto the grid when called for, producing income for their owners. And if a utility could reduce power demand slightly in a central business district by signaling buildings to turn down lights, it could cope with demand spikes less expensively than by turning on a gas peaker plant.

建筑与电网的集成。随着建筑能源控制的改善，这些建筑可以被分配到电网——也就是用来供电的电网——以提高系统性能。有能源储存或热电联产的建筑可以在需要时将电力输送到电网，为业主创造收入。而且，如果一家公用事业公司能够通过向建筑物发出关灯信号来略微降低中央商务区的电力需求，那么它应对需求激增的成本就会低于启动天然气峰值电站。

Next-generation nuclear. Nuclear energy has an uneven history: from the 1950s' promise of "too cheap to meter" energy to construction-cost overruns in the 1970s to post-Fukushima fears. Now, the push to decarbonize power has lent new appeal to nuclear generation, which is emissions-free. Emerging technologies include the sodium-cooled, molten salt, and helium-cooled reactors known as "GenIV"; small, sealed, modular, factory-built reactors; and fusion energy, an area where new start-ups are pushing costs down and timelines forward to prototype devices in the mid-2020s, ahead of government-backed research programs.

新一代的核。核能的历史起伏不定:从 20 世纪 50 年代"便宜到无法计量"的能源承诺，到 70 年代的建筑成本超支，再到对后福岛的担忧。现在，能源脱碳的推动为零排放的核能发电提供了新的吸引力。新兴技术包括被称为"GenIV"的钠冷却、熔盐和氦冷却反应堆;小型、密封、模块化、工厂化反应堆;在聚变能源领域，

新的初创企业正在推动成本下降，并赶在政府支持的研究项目之前，将原型设备提前到本世纪 20 年代中期。

High-efficiency materials. Scientific advances could produce materials for a wide range of clean-energy applications. Solar cells made with perovskites, a special type of crystal, could outperform regular silicon solar cells—and cost less to make. Graphene, a single-atom-thick sheet of carbon, could revolutionize batteries (by enhancing conductivity and storage capacity), solar cells (by offering superior conductivity contacts with lower light blockage), and high-efficiency transmission lines to carry power from remote but productive renewable-generation sites.

高效的材料。科学的进步可以为广泛的清洁能源应用生产材料。由钙钛矿(一种特殊类型的晶体)制成的太阳能电池，性能优于普通的硅太阳能电池，而且成本更低。石墨烯是一种单原子厚度的碳，它可以彻底改变电池(通过提高电导率和存储容量)、太阳能电池(通过提供优良的电导率和较低的光阻)，以及从偏远但可再生能源发电厂传输电力的高效输电线路。

Scaling up the use of hydrogen

氢能使用规模化

Hydrogen could play a significant role in decarbonization, as a clean-energy carrier or fuel ingredient with many applications. High-energy density and zero-carbon combustion make hydrogen well suited to address the 30 percent of GHG emissions—across sectors as diverse as aviation and shipping, industry, buildings, and road transport—that would be hard to abate with electricity alone. Hydrogen could ultimately satisfy 15 to 20 percent of energy demand.

氢作为一种清洁能源载体或燃料成分，在脱碳过程中发挥着重要作用。高能量密度和零碳燃烧使氢气非常适合解决 30%的温室气体排放问题——涉及航空、航运、工业、建筑和公路运输等各个领域——仅靠电力是很难减少温室气体排放的。氢最终可以满足 15%到 20%的能源需求。

After a push in the early 2000s, innovation in hydrogen technologies stalled. Now it has new momentum. The Hydrogen Council identified 131 large-scale hydrogen projects announced between February and July 2021, bringing the total to more than 350. Direct investment in these projects, which would produce 11 million tons of hydrogen annually, is expected to top $130 billion.[5]

在 21 世纪初的推动下，氢技术的创新停滞不前。现在它有了新的动力。氢委员会确认了 2021 年 2 月至 7 月宣布的 131 个大型氢项目，使总数超过 350 个。对这些项目的直接投资预计将超过 1300 亿美元，这些项目每年将生产 1100 万吨氢气

Hydrogen has a long way to go to fulfill its potential. An entire infrastructure of pipes and storage facilities would have to be built, at great expense. Europe is responding with a plan, the EU Hydrogen Backbone,[6] to link low-cost supply centers with European demand centers. Other technologies integral to the hydrogen economy include the following.

氢要发挥其潜力还有很长的路要走。整个基础设施包括管道和储存设施，必须耗资巨大。欧洲正以一项计划作为回应，即欧盟氢支柱，将低成本的供应中心与欧洲的需求中心连接起来。氢经济中不可或缺的其他技术包括:

Low-cost production. If hydrogen could be made for less than $2 per kilogram in the European Union or $1 per kilogram in parts of the United States by 2030, major end uses would become economically viable. One production process is the electrolysis of water, whereby electricity is used to split water molecules into hydrogen and oxygen atoms. If electrolyzers run on renewable electricity, the resulting “green hydrogen” is carbon-free. (By comparison, “blue” hydrogen, made from natural gas, is carbon-intensive.) Estimates suggest that electrolyzer costs could fall 60 to 80 percent over the next decade.[7]

低成本的生产。如果到 2030 年，欧盟能以低于每公斤 2 美元的价格生产氢，美

国部分地区能以每公斤 1 美元的价格生产氢 ,那么主要的最终用途将在经济上可行。其中一个生产过程是电解水，利用电把水分子分解成氢原子和氧原子。如果电解槽使用可再生电力，产生的“绿色氢”是无碳的。(相比之下，由天然气制成的“蓝色”氢是碳密集型的。)据估计 ,未来十年电解槽的成本可能会下降 60%到 80%

Road-transport fuel. Hydrogen’s higher energy density makes hydrogen fu el-cell electric vehicles (FCEVs) suitable for long-haul or heavy road tran sport. For FCEVs to be adopted widely, they would need to become les s expensive, and fueling stations would need to be built.

公路运输燃料。氢较高的能量密度使氢燃料电池电动汽车(fevs)适合长途或重型公路运输。要想让氢燃料汽车得到广泛采用，就需要降低成本，还需要建立加油站。

Ammonia production. This is one of the most promising near-term uses f or low-carbon hydrogen. Green ammonia, made with green hydrogen, sh ould be the first variety to match the cost of conventional ammonia prod uction. Hydrogen is also relatively straightforward to integrate in ammonia production, so less supporting infrastructure is required. And ammonia c an be used as a fuel or as a “vector” for transporting hydrogen.

氨生产。这是低碳氢最有前途的近期用途之一。由绿氢制成的绿氨应是与传统氨生产成本相匹配的第一个品种。氢气在合成氨生产中也相对简单，所以不需要太多配套的基础设施。氨可以用作燃料或作为运输氢气的“载体”。

Steel production. The steel sector is one of the largest industrial emitters, producing about 7 to 9 percent of global emissions. The conventional bl ast furnace–basic oxygen furnace route for steel production emits approxi mately 1.8 tons of carbon per ton of steel. But using green hydrogen to power the direct reduction of iron as a feedstock for electric arc furnac es (which could also be powered by renewables) is one route to zero-carbon steel. Major steel producers in Europe are now piloting steel production with hydrogen.

钢铁生产。钢铁行业是最大的工业排放者之一，约占全球排放的 7%至 9%。传统的高炉-基础氧炉炼钢路线每吨钢铁排放约 1.8 吨碳。但使用绿色氢直接还原铁作为电弧炉的原料(也可以由可再生能源提供动力)是实现零碳钢的一条途径。欧洲的主要钢铁生产商现在正在尝试用氢气生产钢铁。

Aviation fuel. As the travel industry recovers from the COVID-19 pandemic, air travel is expected to produce 3 percent of global carbon emissions. These emissions will be hard to abate until planes are made to fly on fuels other than petroleum-based jet fuel. The best near-term alternative, according to the Clean Skies for Tomorrow Coalition, may be sustainable aviation fuels made from renewable feedstocks such as agricultural biomass. Within the next decade, hydrogen could provide electric power for smaller aircraft equipped with fuel cells. Eventually, hydrogen could be used for combustion in larger planes.

航空燃料。随着旅游业从 COVID-19 大流行中复苏，航空旅行的碳排放量预计将占全球的 3%。除非飞机能够使用石油以外的燃料飞行，否则这些排放很难减少。根据“明天清洁天空联盟”的说法，近期最好的替代方案可能是由农业生物质等可再生原料制成的可持续航空燃料。在未来十年内，氢可以为配备燃料电池的小型飞机提供电力。最终，氢可以在更大的飞机上用于燃烧。

Expanding carbon capture, use, and storage

扩大碳获取，使用和存储

Carbon capture, use, and storage (CCUS) is necessary to decarbonize hard-to-abate sectors and to remove CO_2 from the atmosphere (resulting in “negative emissions”). Presently, use of CCUS is minimal. Costs remain prohibitively high—typically \$50 to \$100 per ton of CO_2 (tCO_2)—and CCUS equipment consumes a lot of energy. Rollout of CCUS has generally stalled at second- or third-of-a-kind commercial-scale installations at coal or gas power plants, steel plants, and refineries.

碳捕获、使用和储存(CCUS)对于去除难以减少的部门的碳和从大气中去除二氧化碳(导致"负排放")是必要的。目前，CCUS 的使用很少。成本仍然高得令人望而却步——通常每吨二氧化碳(tCO2)要 50 到 100 美元——CCUS 设备消耗大量能源。在煤炭或天然气发电厂、钢铁厂和炼油厂的第二或第三种商业规模的安装中，CCUS 的推出通常处于停滞状态。

Moreover, innovation has been slow. Many existing CCUS plants employ 30-year-old solvent-based technologies for postcombustion carbon capture. But new technologies are emerging. Further R&D would be needed to reduce costs, and additional incentives will likely be required to make CCUS financially viable at commercial scale. But if the full cost of CCUS were to fall below \$50/tCO_2, it would make many applications economical. Here are some CCUS technologies that could help.

此外，创新一直很缓慢。许多现有的 CCUS 工厂采用了已有 30 年历史的基于溶剂的燃烧后碳捕获技术。但新技术正在涌现。进一步的研发将需要降低成本，并且可能需要额外的激励措施来使 CCUS 在商业规模上具有经济可行性。但如果 CCUS 的全部成本降至 50 美元/吨二氧化碳以下，它将使许多应用变得经济。以下是一些 CCUS 技术可能会有所帮助。

Pre- and postcombustion capture technologies. Precombustion technologies such as oxyfuel combustion represent promising ways to affordably capture CO_2 from point sources since they increase the concentration of CO_2 in flue gases. Development of new postcombustion technologies, such as second-generation solvent formulations, sorbents, and membranes, is helping bring down the cost of capture. Companies, governments, philan thropy, venture-capital, and growth-equity firms have all helped finance improvements in capture technology.

燃烧前和燃烧后捕获技术。氧燃料燃烧等预燃烧技术是从点源以负担得起的方式捕获二氧化碳的有希望的方法，因为它们增加了烟道气中的二氧化碳浓度。新燃烧后技术的发展，如第二代溶剂配方、吸附剂和膜，有助于降低捕获成本。公司、政府、慈善机构、风险投资公司和成长型股权投资公司都帮助资助了捕捉技术的改进。

Direct air capture (DAC). Withdrawing CO_2 from ambient air is difficult because air has, at most, one one-hundredth of the CO_2 concentration found in flue gases from industrial point sources. Nevertheless, DAC offers a way of removing CO_2 from the atmosphere—and the world is likely to need many different sources of negative emissions to achieve a 1.5°C pathway. To that end, several companies are investing in DAC, with the goal of achieving capture costs of $100/t$CO_2$ to $150/t$CO_2$ by 2030, 60 to 80 percent less than today's pilot projects. Low-cost DAC, coupled with low-cost hydrogen, could enable production of carbon-neutral e-fuels in the near to medium term.

直接空气捕捉(DAC)。从环境空气中提取二氧化碳是困难的，因为空气的二氧化碳浓度最多只有工业点源烟气中二氧化碳浓度的百分之一。然而，DAC 提供了一种从大气中消除二氧化碳的方法，而世界可能需要许多不同的负排放源来实现 1.5°C 的路径。为此，一些公司正在投资 DAC，目标是到 2030 年将捕获成本降低到 100 美元/吨二氧化碳至 150 美元/吨二氧化碳，比目前的试点项目减少 60% 至 80%。低成本的 DAC，加上低成本的氢气，可以在近期到中期生产碳中性的电子燃料。

Bioenergy with carbon capture and storage (BECCS). Many fossil-powered plants are nowhere near the end of their useful lives. Taking plants offline before they are due would burden utilities with stranded assets. But the value of these assets could be preserved by converting them to run on biomass, a renewable fuel. Adding CCS equipment to a bioenergy plant lets it produce negative emissions: biomass sequesters CO_2 as it grows, and when that biomass is burned, the CCS system keeps the CO_2 from entering the atmosphere.

具有碳捕获和储存(BECCS)的生物能源。许多化石能源发电厂离它们的使用寿命还很远。在电厂到期前将其关闭，会给公用事业公司带来搁浅资产的负担。但这些资产的价值可以通过将它们转化为生物质(一种可再生燃料)来保持。在生物能工厂中添加 CCS 设备会产生负排放:生物质在生长过程中会将二氧化碳隔离，当生物质被燃烧时，CCS 系统会阻止二氧化碳进入大气。

Biochar. Biochar is a stable, charcoal-like material made by processing waste biomass such as crop residues through pyrolysis or gasification.

生物炭。生物炭是一种稳定的类似木炭的材料，它是通过热解或气化处理农作物残渣等废弃生物质制成的。

Adding biochar to soil can improve soil health and agricultural productivity, opening the door for use in large-scale farming. This practice could sequester nearly 2 gigatons of CO_2 per year by 2050. Adoption rates will depend on the results of commercial-scale experiments over the next decade.

在土壤中添加生物炭可以改善土壤健康和农业生产力，为大规模农业生产打开大门。到 2050 年，这种做法每年可以吸收近 20 亿吨二氧化碳。采用率将取决于未来十年商业规模试验的结果。

CO_2-enriched concrete. Concrete has two main components: cement, which is the “glue” that holds concrete together; and aggregate, such as sand or crushed stone, which gives concrete most of its mass. Both have heavy

carbon footprints, but companies are working on solutions that would sequester CO_2 in concrete itself. Technologies for adding CO_2 as an ingredient in cement could reduce emissions by up to 70 percent and make cement stronger. Emerging processes might combine captured CO_2 with industrial-waste products such as fly ash, steel slag, and remediated cement to make artificial “rocks” for use in place of natural aggregate.

CO2-浓缩混凝土。混凝土有两种主要成分:水泥，它是将混凝土粘结在一起的“胶水”;还有骨料，比如沙子或碎石，这是混凝土的主要组成部分。两者都有很重的碳足迹，但有公司正在致力于解决方案，将二氧化碳封存在混凝土本身。在水泥中加入二氧化碳的技术可以减少多达 70%的排放，并使水泥更加坚固。新兴的工艺可能会将捕获的二氧化碳与工业废料(如粉煤灰、钢渣和修复水泥)结合起来，制造人工“岩石”，以取代天然骨料。

These climate technologies could contribute to solving the net-zero equation while creating growth potential for sectors and geographies. At present, the technologies exhibit varying levels of maturity, performance, market demand, and regulatory support. To bring them to commercial, climate-stabilizing scale would require companies, financial institutions, and governments to cooperate on investment and research programs as well as efforts to integrate technologies with existing industrial systems. This challenge is formidable, but the moment to devote creativity, capital, and conviction to addressing it is now.