实践出真知：

降低燃煤电厂CCUS项目成本前瞻

2019年11月

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降低燃煤电厂CCUS项目成本前瞻

煤炭工业咨询委员会向国际能源署递交的报告

2019年11月

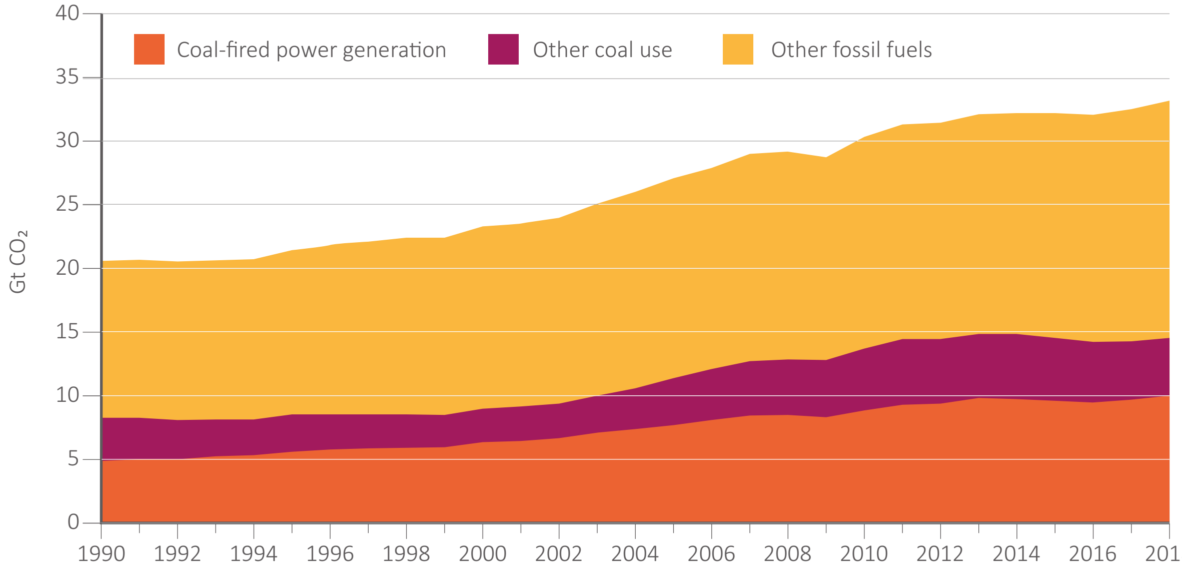
本文所表达的仅为国际能源署（IEA）煤炭工业咨询委员会（CIAB）的观点。本文的唯一目的是根据煤炭工业咨询委员会的角色, 为国际能源署秘书处提供建议。本文汲取了煤炭工业咨询委员会成员基于参与全球范围内CCUS项目和能源基础设施项目的设计，融资，建设和运营的经验。这些观点未必反映国际能源署秘书处及其成员国的观点或政策。

执行摘要

2015 年《联合国气候变化框架公约》（UNFCCC）巴黎协议，将全球平均温度上升幅度限制在较工业化前不超过 2°C 的水平。为了实现这一目标，大规模的排放密集型工业和发电过程必须大幅脱碳。在煤炭和天然气发电行业，以及钢铁和水泥制造等工业过程，化石燃料制氢，以及生物能源生产等领域，如果不加快推进各行业泛围内碳捕集，利用与封存（CCUS）的商业规模部署，就无法实现如此大规模的减排。按照《2018 年世界能源展望（WEO）》的最低成本情景，国际能源署（IEA）估计，CCUS 可以贡献 2060 年以前所需的累计减排量的 13%。政府间气候变化专家委员会（IPCC）第五次评估报告得出的结论是，没有 CCUS，实现温度上升不过 2°C 的上限目标将付出双倍以上开支，相当于 2100 年以前全球 GDP 累计增量的 3%。如果 CCUS 未能在全球范围内广泛应用于所有行业，则不太可能实现将温度升限控制在 2°C 以内。

根据 IEA 的《2018 年世界能源展望（WEO）》新政策情景，煤炭的贡献占全球二氧化碳排放量的很大一部分（见图解 1），预计到 2040 年煤炭将占一次能源总需求量的 22%。全球现役燃煤发电资产中三分之一以上服役不到 10 年，且至今仍在继续建造新的燃煤电厂。对投资经济回报的渴望将阻碍这些设施的过早淘汰。

图解 1：1990-2018 年全球能源二氧化碳排放源划分

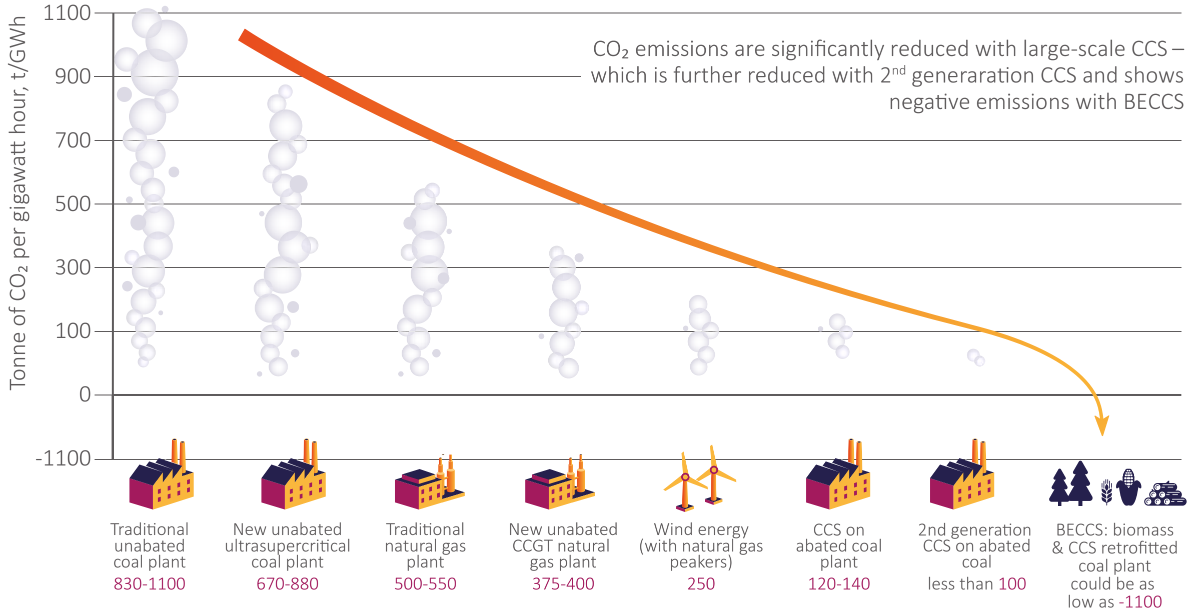


资料来源：国际能源署

近来，可再生能源技术（尤其是太阳能和风力发电）的成本和性能有了显著改善。使用可再生能源和替代能源的低排放或零排放发电，对于实现 2°C 温度增长限值至关重要。但是，我们简直无法放弃 CCUS 而不用。发展中国家人口和经济迅速增长，随之而来的难以缓解但必不可少的钢铁和水泥制造等工业发展，以及令人震惊的毁林面积和日益增加的农业生产活动，拉大了全球温室气体（GHG）减排的努力与实现 2°C 增温限值途径之间的差距。2060 年以前，整个能源行业总共需要减排约 7,600 亿吨二氧化碳，这相当于以 2017 年能源相关的排放为基准水平，持续 20 多年的排放量总和。因此，每项减排技术对于加快国际努力以减少大气中的二氧化碳水平都不可

忽略。此外，研究表明，通过与生物质混烧结合 CCUS（BECCS）的负排放策略，燃煤热电厂可以降低二氧化碳大气排放（见图解 2）。

图解 2：电厂大规模部署应用 CCUS 可减排二氧化碳



资料来源：碳捕集利用与封存知识国际中心

煤炭工业咨询委员会（CIAB）于 2016 年向国际能源署（IEA）递交的题为《CCS 的国际承诺：实现能源低碳未来的政策与激励措施》的报告中，鼓励各国政府推行政策，支持鼓励提高工业和电力行业 CCUS 部署应用进度，以实现 2°C 温度上限控制的目标。本文报告中再次强调这些建议，可以分为四个层面：

- 落实让资金投入能够获得市场回报率的政策，**刺激市场化采纳 CCUS**。
- **扶持项目开发，**以弥补早期项目的商业化短板并加快 CCUS 的采纳。
- **启用项目专用资金**，克服 CCUS 早期项目的财务风险。
- 提供资金扶持具备竞争优势潜力的技术与知识开发，**推进下一代 CCUS 技术。**

此外，在煤炭工业咨询委员会 2017 年度题为《CCS 的国际承诺：促进 CCS 部署应用的优先行动》的报告中，详细研究了美国，英国，澳大利亚和中华人民共和国的案例，为其它政府提供政策方面的经验教训，并充实了煤炭工业咨询委员会 2016 年度报告中的建议。

降低 CCUS 成本的机遇就在当下。本报告探讨了减少资本成本和运营成本的途径。尤其是对燃煤发电而言，降低成本将提高利用 CCUS 减排的经济可行性。迄今为止，在燃煤电站的第一代 CCUS 装置上所取得的卓越的工业化经验，已产生显著降低成本的成果。

事实上，与其它减排路径相比，燃煤电力行业的 CCUS 越来越具有成本比较优势。这里列举的若干实际范例，有助于制定适当的政策并形成其它驱动力，这对于按照必要的步骤推进 CCUS 的发展至关重要。范例主要有：

- 位于加拿大的**萨斯喀电力集团边界坝电站碳捕集利用与封存（CCUS）一体化设施**，是首例燃煤电站大规模燃烧后 CCUS 设施，于 2014 年开始运行。当时，据估计，根据该项目调试和早期运行的经验把握，建设并运营下一例规模类似的 CCUS 设施，可以至少节省成本 30%。

- 位于美国得克萨斯州的**佩特拉.诺瓦（Petra Nova）设施**，为工业化规模燃煤电站 CCUS 装置，于 2017 年开始运行。它使得人们对改善成本效益的驱动要素，有了更深入的掌握和更强的信心。

- **2018 年度尚德电厂碳捕集与封存（CCS）可行性研究**，依托位于边界坝设施附近的萨斯喀电力集团的 30 万千瓦单机燃煤电站，对实施燃烧后 CCUS 改造进行评价。据估计，该项目下一代 CCUS 运营，每吨二氧化碳的捕集成本可节省 60%以上。在此，将一一介绍这些成本优化源头的一系列考量，涉及节约项目资本成本，节约运营成本，优化商业论证，以及财务/政策选项。

迄今为止，大型 CCUS 设施大多数都在燃煤发电以外其它行业领域内。最为迫切的是必须将这些大型 CCUS 设施开发的机会扩展到燃煤发电行业领域。现已建成的项目为未来的 CCUS 项目设计和开发提供了重要的经验教训，且许多经验教训将势必大幅降低项目的资本性成本和运营成本。迄今为止的工作，已经成功地证明了规模经济性等有利因素能够降低二氧化碳捕集成本。技术的进步势必将进一步降低成本。因此，本文也突出列举了前景看好的新兴技术，包括膜捕集，富氧燃烧以及生物质能碳捕集与封存 (BECCS)等。CCUS 部署应用持续不断的进展将取决于以下几个方面：

- **加深理解并掌握相关专业知识**。必须继续融汇贯通专业技术知识，以更深入地理解降低二氧化碳捕集成本并改进设计的要素，促进技术进步。

- **降低共享运输和封存的不确定性**。为必要的投资提供便利，开发运输和封存系统等重大基础设施，包括制定更完备的物流规划。

- **强化政策上和财政扶持**。国际社会必须做出承诺，制定扶持性政策和支持创新的融资机制，以促使 CCUS 成长为稳固成熟的产业。

- **伴随投资 CCUS 商业化部署应用，继续投资于新技术的研究和试点项目**。在过去的几十年中，大量投入于研究，试点和示范的投资水平，不仅必须继续保持，恰恰必须增加，这有助于降低伴随煤电低排技术的投资风险，势必将加快技术开发周期。 为了加快新型燃煤电厂的设计，许可和运营，因地制宜地利用特有的黑煤和褐煤资源， 进行研究工作也是必不可少的，以获得独立和客观的分析，构建数据库并开发专业知识。

发电行业的 CCUS 技术应用是本报告的首要重点。到 2020 年，全球将有 20 多个商业化规模的 CCUS 项目投入运营，每年捕集并封存于地质构造内的工业源二氧化碳超过 3700 万吨。CCUS 并不算是一项新生事物，但在煤电行业中仍数罕见，迄今为止只有两个 CCUS 商业化装置在运行。为了兑现《巴黎协定》中的承诺，二十国集团成员国必须高度重视向 CCUS 大量投资，以实现全球能源相关的减排。鉴于缺乏可用的替代技术，许多基于化石燃料的排放密集型工业过程将需要应用 CCUS，来实现升温上限 2°C 的目标。CCUS 是促进向可再生能源和替代能源过渡的关键因素，而且在仍必需继续使用化石能源以保障经济运行的行业内，CCUS 亦绝对是关键组成部分。即使在全世界限碳的未来，CCUS 也将有利于在石油化工生产等那些我们别无选择的领域，继续使用现有的基于化石能源的基础设施和工业化操作。

最近，令人欢欣鼓舞的是，煤电与以能源为基础的相关产业联手开发 CCUS 商业化项目，加快了进步的步伐。率先实施的项目所获得的经验教训为后续项目节省了成本。

> 以可避免二氧化碳排放的每吨成本来衡量，煤电行业的CCUS较其它减排形式在成本上已经具备竞争力。

显然，需要明确而积极的担当，来扩展知识，深化理解和掌握关键性专业技术。这势必将促进煤电行业环境绩效的持续改善。保持，或更理想的情况是，加强 CCUS 商业化应用的发展势头，定将为实现《巴黎协定》的 2 度升温上限目标做出有意义的贡献。

碳捕集与封存一览

加速实现二氧化碳减排

1 工业设施或能源设施的二氧化碳排放源。通过碳捕集与封存（CCS），将捕集，回收并永久封存大量的二氧化碳。

2 以可能超过90%的捕集率捕集烟道气中二氧化碳，再压缩成浓相液态以便于运输。

3 二氧化碳经管道运输。二氧化碳也可以通过槽车，铁路或船舶运输，具体取决于CCS项目所在地的特定需求。

4 二氧化碳被送入地下深处的用途：

- **a** 增加石油采油率（EOR）—二氧化碳经回收再注，终将安全地永久封存在枯竭的油藏/天然气藏储层中。
- **b** 永久封存在多孔岩石层*的颗粒缝隙构造的微观空间内—深度超过1 千米，其上面质密而不渗透的“盖层”岩层，确保CO_2无限期地留存在那里。

5 测量，监控与验证（MMV）—部署严格而灵敏的MMV设备与程序，可以检测地下二氧化碳压力和浓度的变化，以确保其羽流的增长在可接受的合规范围内并在注入的储层内永久留存。同样，定期完成地表面监测，以确保注入操作或地面CO2操作过程中不会有CO_2泄漏到大气中，地下水系或土壤中。

* 深层砂岩在其岩石颗粒构造之间具有微观空间，即孔隙度，可容纳高盐度水份—其咸度是海水的10倍。由于存在这种非常咸的盐水，地质学家将这种类型的地层称为咸水层。

实践出真知：

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翻译
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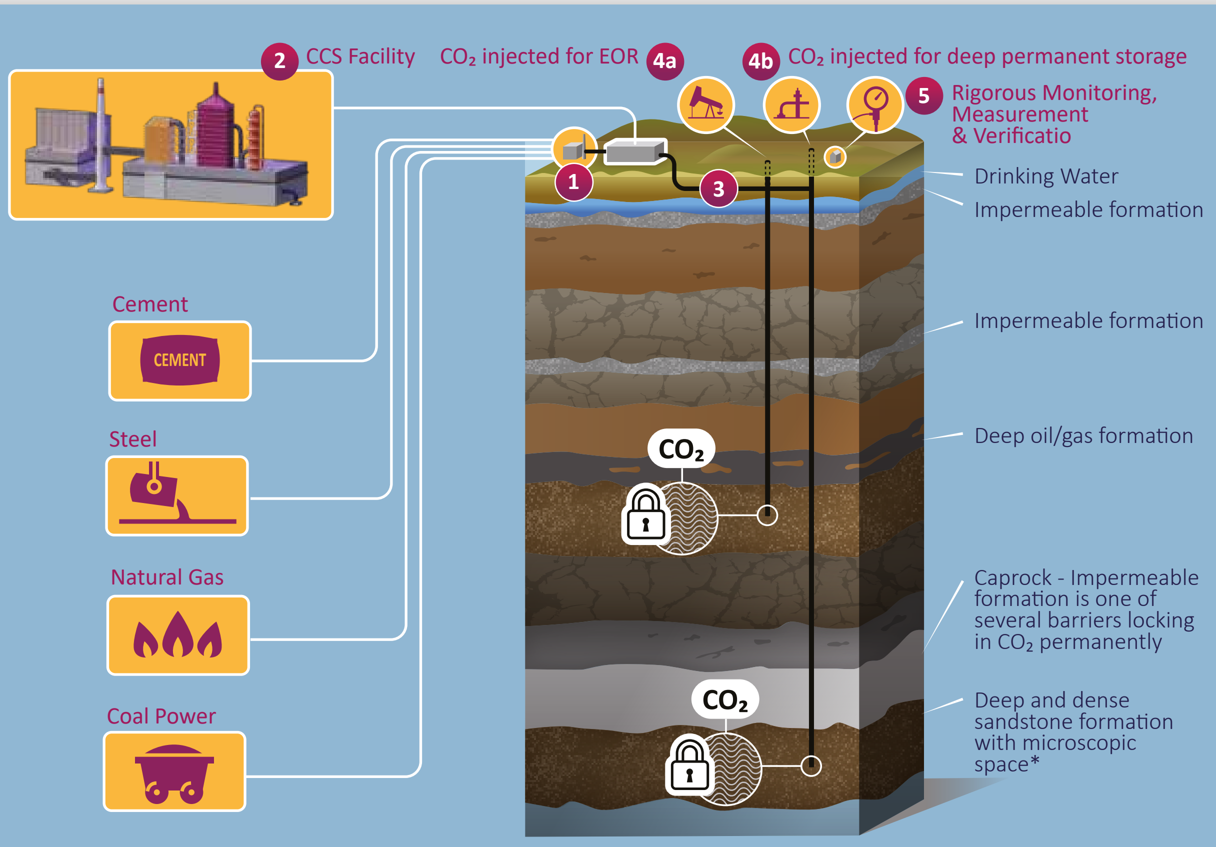


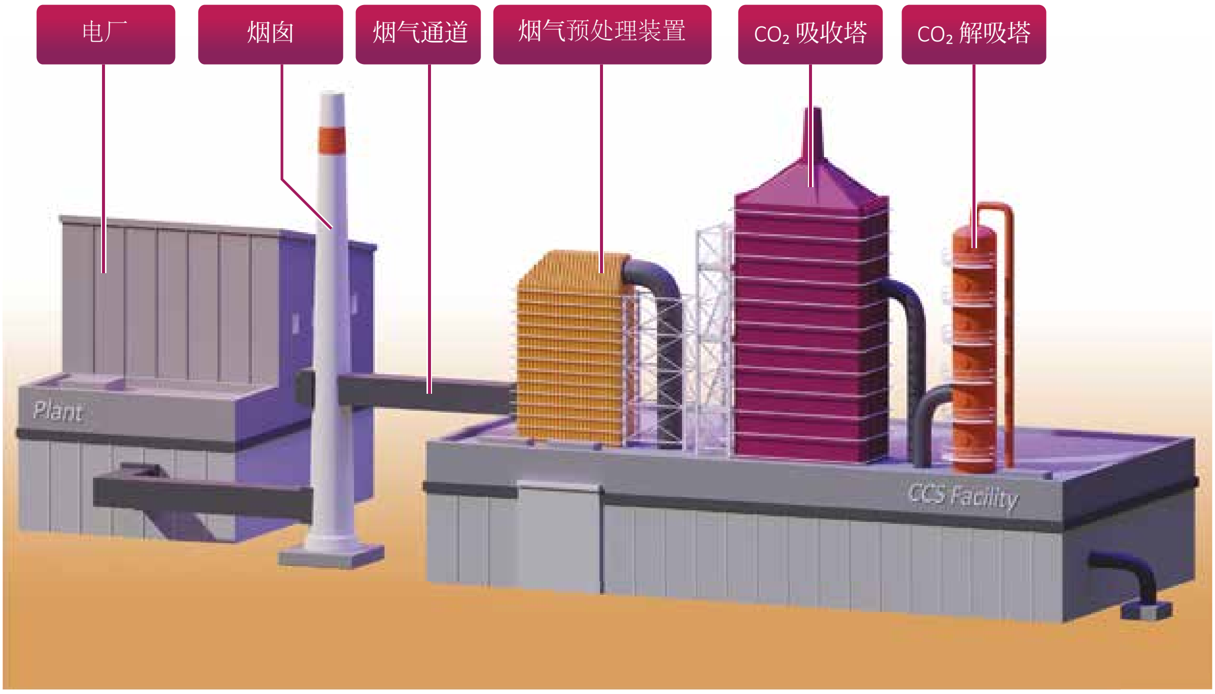
鸣谢与免责声明

本文经煤炭工业咨询委员会（CIAB）主席与执行委员会授权，由碳捕集与封存特别工作组撰写。除了工作组的作者们以外，本文还反映了其它多位供稿人对文章做出的贡献，煤炭工业咨询委员会谨此非常感谢。

煤炭工业咨询委员会的企业成员和独立组织成员旗下的诸多专家，对本文进行了技术性充实并予以审阅。作者向碳捕集利用与封存知识国际中心作出贡献的所有供稿人鸣谢。

煤炭工业咨询委员会（CIAB）是由若干煤炭相关企业的高管组成的团体，由国际能源署理事会成立于 1979 年 7 月，旨在从本行业角度就与煤炭有关的问题向国际能源署提供建议，其所表达的观点仅代表煤炭工业咨询委员会。本文的唯一目的是根据煤炭工业咨询委员会的角色，为国际能源署秘书处提供建议。本文集中体现了煤炭工业咨询委员会成员参与全球范围内 CCUS 项目和能源基础设施项目的设计，融资，建设和运营的经验。本文不一定代表国际能源署或已知的供稿人的观点。

工业设施或电厂的碳捕集设施构成



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图解

全球气候离不开碳捕集利用与封存

巴黎协定

2015 年 12 月，在联合国气候变化大会（COP21）2015 年度会议上， 197 个政府通过了《巴黎气候变化协定》[1]。《巴黎协定》的签署各方共同承诺：“将全球平均温度的上升幅度保持在比工业化前水平升高 2°C 以下，并努力将温度上升幅度限制在 1.5°C 以内……”。该协议旨在本世纪下半叶的温室气体（GHG）源与汇之间达到平衡，有效地实现温室气体净零排放。没有针对碳捕集，利用与封存（CCUS）的国际承诺，要实现该目标将面临巨大风险[2]。根据政府间气候变化专门委员会（IPCC）的估算，如果不启用 CCUS，则达到升温上限 2°C 目标的代价成本要高出一倍以上[3]。达到 1.5°C 上限期望值则需要大比例的净负排放，而这只能通过生物质能 CCUS（BECCS），直接空气捕集（DAC）以及生物化封存（例如造林）来实现。

在实现如此大幅度温室气体减排的作为方面，国际上尚未取得重大进展。必须以提供可靠便宜的能源的一定形式进行大量的碳减排，与此同时，特别是在发展中国家，必须支撑为维持和改善生活水平所必需的经济发展。加速努力，以实施提高能效并部署应用一揽子低排放能源技术与工业技术，也是必不可少的。

国际能源署的启示： CCUS 需求

为了实现《巴黎协定》的目标，CCUS 项目实施的步伐和频率，必须随着煤电领域的 CCUS 应用等清洁能源技术的商业化部署应用一起迅速加快。国际能源署（IEA）在 2017 年和 2018 年发布的《世界能源展望》（WEO）报告中对此予以充分阐述[4,5]。该报告模型清楚表明，到 2040 年，煤炭将继续满足全球能源需求的 12％至 22%。

特别是在发展中国家，对来自燃煤电厂的低成本且可靠的能源需求量将仍然很高。这些国家不断增长的能源需求，势必敦促继续使用现役的发电设施，并可能需要建设新一代的发电设施。全球现役煤电设施中，有三分之一以上的服役期不到 10 年。考虑到已经投入的金融资本规模，期望提前关停这些设施是不现实的。

那么，在现役的和新建的煤电设施大量增加 CCUS 系统装配，对于实现 2°C 升温上限目标将至关重要，这也是本报告的焦点。

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[1] United Nations Framework Convention on Climate Change. Paris Agreement. COP 21 Meeting. December, 2015. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

[2] For the purposes of this paper, CCUS is used to collectively refer to projects that utilize CO_2 to generate revenue, such as enhanced oil recovery (EOR), as well as projects that utilize dedicated geological storage of CO_2.

[3] IPCC (Intergovernmental Panel on Climate Change). Climate Change 2014 Mitigation of Climate Change. Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. UK: Cambridge University Press, 2014. https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_frontmatter.pdf .

[4] International Energy Agency. World Energy Outlook 2017 (WEO-2017). Paris: IEA, 2017. https://www.iea.org/weo2017/.

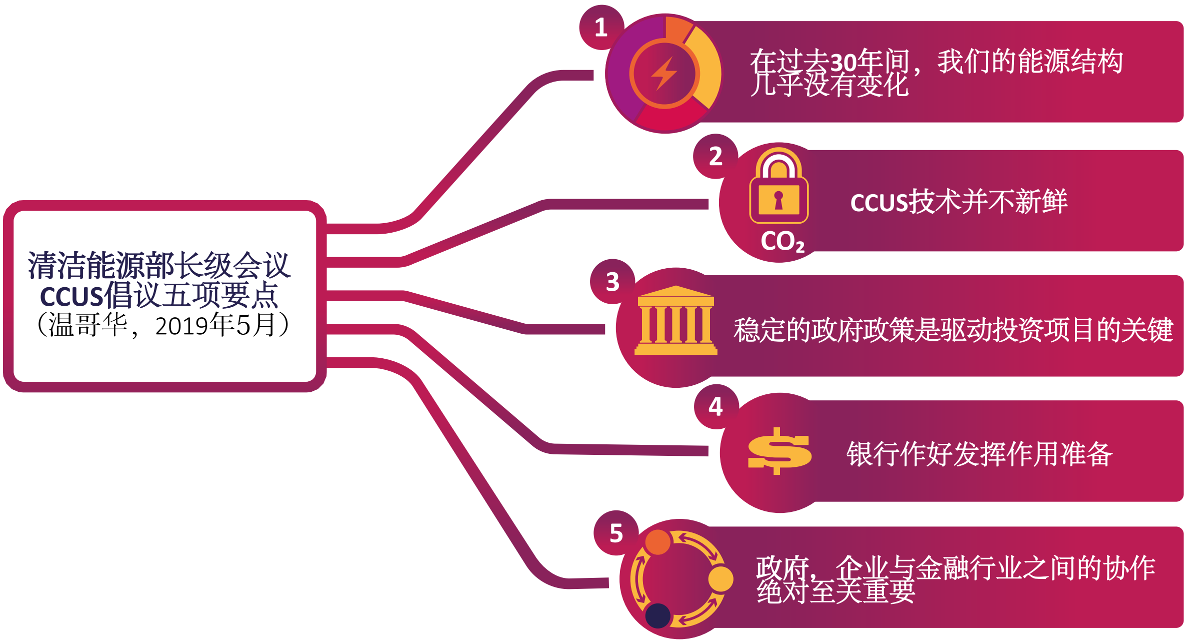
[5] International Energy Agency. World Energy Outlook 2018 (WEO-2018). Paris: IEA, 2018. https://www.iea.org/weo2018/.

据国际能源署 2012 年估计，要实现 2°C 升温上限目标，配备 CCUS 系统的电厂装机容量，到 2020 年需要达到 1,200 万千瓦，到 2030 年需要达到 2.15 亿千瓦，到 2050 年需要达到 6.64 亿千瓦[6]。但是，由于只有很少的项目进入规划阶段，到 2019 年为止还没有一个在建启用 CCUS 的电厂新项目，仅北美有两座已采用 CCUS 系统的在运行电厂。因此，甚至到 2024 年都不可能实现第一阶段目标。这样，在燃煤电厂部署 CCUS 改造项目的需求变得更加迫切。此外，要实现将气候升温限制在远低于 2°C 的更宏伟目标，将需要加大力度，更快加速 CCUS 部署应用步伐以及可再生能源和替代能源电力的装备使用。生物质能 CCUS（BECCS）等技术应用的快速增长，对于帮助实现该 CO_2 减排目标也一定必不可少。

CCUS 的国际承诺

目前，国际上对 CCUS 的承诺尚不协调。一些政府根据新的“清洁能源部长级会议 (CEM) CCUS 倡议”[7] (参见图解 3) 或借存在已久的“碳封存领导人论坛”[8] 聚会，而与此同时若干大公司和组织协作组成了诸如“石油和天然气产业气候倡议”[9]，在美国组成了”碳捕集联盟“[10] 和”碳利用研究委员会“[11] 等组织。这些努力的核心是促进 CCUS 发展这一共同使命。美国最近对 45Q 税收抵免规定进行了积极的调整，改善了实施 CCUS 的经济可行性，从而致使两党一致对 CCUS 大力支持。但是，国际上尚缺乏齐心协力启动激励措施和资金，来支持该技术更迅速地得以采用推广。

图解3: "清洁能源部长级会议CCUS倡议" 专题边会活动的主要信息， 共同加速CCUS: 为解开清洁能源谜底的关键环节融资 （2019年）



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6 International Energy Agency. Technology Roadmap: High-Efficiency, Low-Emissions Coal-Fired Power Generation. Paris: IEA, 2012. https://webstore.iea.org/technology-roadmap-high-efficiency-low-emissions-coal-fired-power-generation.

7 Clean Energy Ministerial CCUS Initiative. 2019. http://www.cleanenergyministerial.org/initiative-clean-energy-ministerial/carbon-captureutilization-and-storage-ccus-initiative

8 Carbon Sequestration Leadership Forum (CSLF). 2019. https://www.cslforum.org/cslf/

9 Oil and Gas Climate Initiative. 2019. https://oilandgasclimateinitiative.com/

10 Carbon Capture Coalition. 2019. http ://carboncapturecoalition.org/

11 Carbon Utilization Research Council. 2019. http:/ curc.net/

以适当的速率和规模部署应用 CCUS 技术是可行的，有助于实现《巴黎协定》的既定目标。这将需要有意义的公共政策提供激励和扶持，使部署应用轨迹与 2°C 升温上限目标接轨。必须迫切实施强有力的，精心设计的政策，以驱动有实际意义的行动步骤。

> CCUS没有其它低碳能源技术所享有的公共政策扶持与政治承诺。

政府与行业之间的协调，以及启动精心设计的政策，将扫除阻碍公有银行与私有银行为精心设计的 CCUS 项目提供融资的障碍，从而使 CCUS 项目能够以必要的步调部署到位，以实现意义深远的全球温室气体减排。

第一代燃煤电厂 CCUS 项目积累的经验

走向成功

CCUS 已经成为一种具有成本效益的减排技术，同时煤电行业的具体 CCUS 项目成本能够下降到远低于以前预期的水平。对与 CCUS 相关的各类成本以及促使成本降低的伴随因素的更深入掌握，定将使决策者和金融界更加充满信心，认识到 CCUS 可实现必要的温室气体减排的潜力。

如今的碳捕集技术基于波托姆斯（R.R. Bottoms）于 20 世纪 30 年代开发的天然气脱硫工艺[12]。近年来才开发出对该基本工艺的创造性革新，并在全球范围内部署应用到工业设施和煤电设施。

除用于天然气加工以外，CCUS 往往是首创或高附加值的小众技术应用，但碳捕集技术的技术可行性已得到明确示范验证。此外，CO_2强化采油（EOR）经过数十年工业化规模操作并取得丰富经验，CO_2运输产业已经成熟。在具备适当地质条件的地方，业已证明了能够将 CO_2安全地封存在地下，并且进行了必要的操作以及监控实践。这些关键要素验证了第一代 CCUS 技术是可靠的技术。不过，与任何新技术一样，在未来若干年内，由于 CCUS 商业化规模部署应用而产生的进一步创新，必将推动重大技术进步并相应地降低资本成本和运营成本。

两个工业化规模的燃煤电厂第一代燃烧后 CCUS 装置，提供了实践经验，积累了知识与感悟，进而从中得出了关系到降低资金成本和运营成本的结论。这两个在运行设施是：

- **萨斯喀电力集团（加拿大） 的边界坝 3 号电力机组碳捕集与封存设施** (边界坝 3 项目），为燃煤火力发电厂 CCUS 商业化规模装置，于 2014 年 10 月开始运行；
- **NRG 能源公司的佩特拉.诺瓦碳捕集与封存设施**（美国），为一个更大规模的燃煤电站 CCUS 装置， 2017 年开始商业运营。

燃煤电力设施 CCUS 工业化示范

萨斯喀电力的边界坝 3 号电力机组碳捕集与封存设施

位于加拿大萨斯喀彻温省的边界坝 3 项目，是电厂大规模应用二氧化碳捕集技术的先驱，为世界上首例燃煤电厂全规模一体化 CCUS 设施[13]。该设施的额定设计捕集容量为每年 100 万吨二氧化碳。 边界坝 3 项目设施包括二氧化碳捕集，压缩和运输等工序。边界坝 3 项目捕集设施与主电厂全容量集成，并从主电厂获取蒸汽和电力。 边界坝 3 项目设施运行产生的二氧化碳就近用于强化采油（EOR）作业，同时还为 Aquistore 项目提供二氧化碳，注入地质构造并永久封存。该项目现场对深咸水层中二氧化碳在 3,400 米深度运移进行实时测量，监测和验证 (MMV)。

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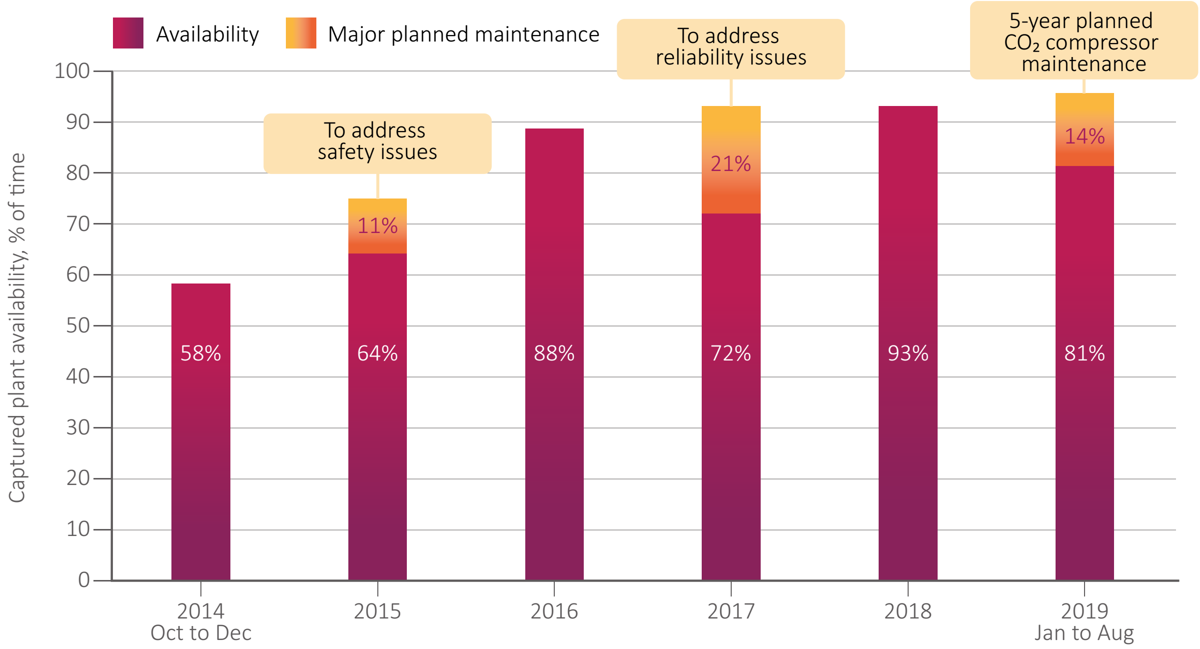
[12] Kohl, A. and Nielsen, R. Gas Purification (5th Edition). USA: Gulf Professional Publishing, 1997.

[13] Preston, C.K. The Integrated Carbon Capture and Storage Project at SaskPower's Boundary Dam Power Station. IEA Greenhouse Gas R&D Programme (IEAGHG) Technical Report 2015-06. UK: IEAGHG, 2015. https://ieaghg.org/publications/technical-reports.

图片说明：位于萨斯喀彻温省埃斯特湾市附近的萨斯喀电力边界坝电站3号机组碳捕集设施鸟瞰（碳捕集利用与封存知识国际中心供稿）。

边界坝 3 项目 CCUS 的经历是推动未来 CCUS 项目重大进步并呼唤灵感的一段佳话。这一成功运行的设施在提高效率的同时，为大幅降低资本成本和运营成本以及进一步改进下一代 CCUS 设施铺平了道路。此外，该设施在 2019 年跨越了一个重要的里程碑---自投运以来累计捕集和注入地下 300 万吨二氧化碳。随着实现稳定运行（见图解 4 和 5），边界坝 3 项目的下一个重点已锁定为提高运行效率和降低成本。

***图解4:** 边界坝3项目碳捕集设施的性能: 2014年10月启动至2019年7月依据年度利用时效的捕集设施可靠性*

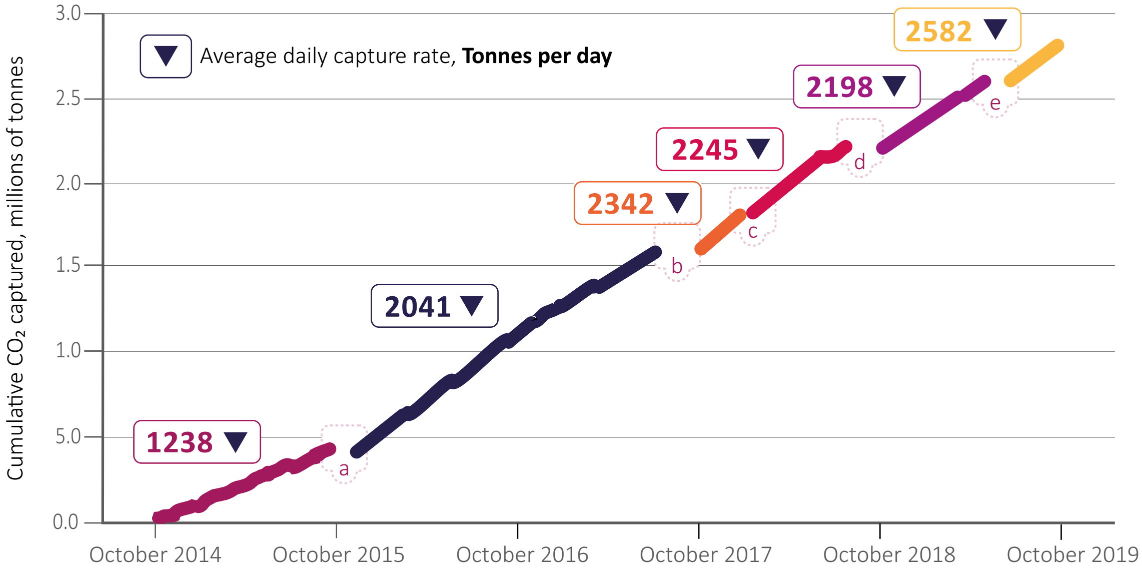


捕集岛的可用时效，是指在电厂至少以50%负荷运行时，捕集设施捕集二氧化碳的运行时间百分比。电厂 50%的负荷水平，为捕集系统运行的原设计最小预期负荷工况。

计算包括了计划内维护期以及任何计划外的延期。

资料来源： 碳捕集利用与封存知识国际中心

图解5: *边界坝3项目碳捕集设施的性能：2014年10月投运至2019年累计捕集CO_2*



停产与维护
a) 因安全原因计划内停机
b) 因可靠性原因计划内停机
c) 电力岛长时间停产导致CCS设施停运
d) 恶劣天气致汽轮机故障
e) 压缩机维护5年周期计划内停机

资料来源：碳捕集利用与封存知识国际中心

碳捕集利用与封存知识国际中心继续分享从边界坝 3 项目的实践经验中获得的知识感悟。中心的主要角色是基于经验体会提供导向，有助于未来 CCUS 设施项目显著地降低风险和成本 [14]。

NRG 能源公司的佩特拉.诺瓦设施

图片说明：位于WA 帕里什电站的佩特拉.诺瓦碳捕集设施鸟瞰（NRG 能源供稿）。

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[14] International CCUS Knowledge Centre. 2019. htt s://www.CCUSknowledge.com

2017 年初，位于美国德克萨斯州的佩特拉.诺瓦碳捕集与封存设施全面投运。它的设计捕集容量为 140 万吨 CO_2/年，通过管线将 CO_2 从位于帕里什县境内的燃煤电站输送到 130 公里外的油田，用于强化采油并封存[15]。

与边界坝 3 项目相似，佩特拉.诺瓦捕集装置使用专利胺溶剂，从燃煤主电厂的烟气中脱除 CO_2。但是，佩特拉.诺瓦设施仅从以往排放到大气中的烟道气中部分地而不是全规模捕集二氧化碳，并且利用专用的燃气轮机电厂为捕集过程提供所需的蒸汽和电力，而不像边界坝 3 项目那样由主电厂供应能耗[16]。

该项目采取了跨行业合资企业的途径，即直接将二氧化碳用于驱油生产并销售石油，而不是将二氧化碳出售给石油运营商。这样做既增加了项目风险成分，也增加了潜在收益。 佩特拉.诺瓦项目捕集的所有二氧化碳全部用于强化采油作业

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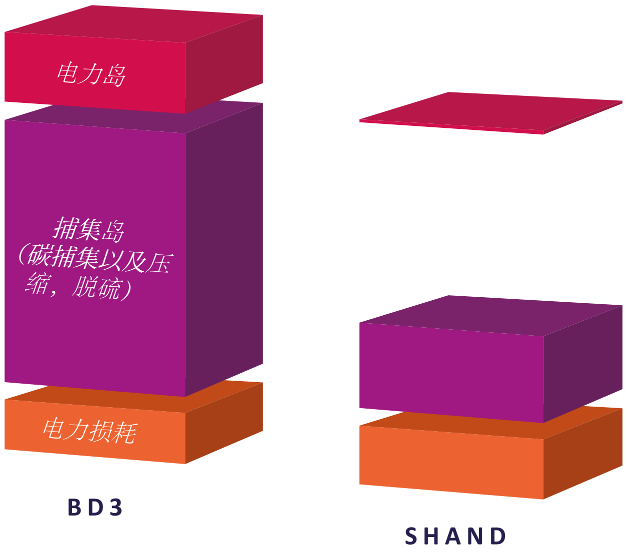
[15] US Department of Energy. Office of Scientific and Technical Information (OSTI). W.A. Parish Post-Combustion CO2 Capture and Sequestration Project Final Public Design Report. Report No. DOE-PNPH-0003311-2. February 2017. www.osti.gov/servlets/purl/1344080.

[16] Patel, S. Capturing Carbon and Seizing Innovation: Petra Nova is POWER's Plant of the Year. Power Magazine. August 2017. www.powermag.com/capturing-carbon-and-seizing-innovation-petra-nova-is-powers-plant-of-the-year/?pagenum=5.

降低 CCUS 成本

近年来，许多相关研究已经考虑到，基于迄今为止进行的 CCUS 项目积累了大量专业知识，CCUS 的成本下降指日可待[17,18]。例如，人们普遍认为，实现成本显著降低的首要驱动因素在于 CCUS 规模化部署应用[19]。尽管降低成本的早期策略是基于试点和研究项目所实现的渐进式技术改进，但如今，在商业规模部署应用实践基础上对于 CCUS 的理解把握越来越深入，可以更好地评价未来 CCUS 设施降低成本的潜力，并提高其性能效益。尽管如此，持续的试点和研究项目，对现有技术创新和新技术进一步开发所具有的潜力仍在增进了解。

图解6: 与第一代CCUS（边界坝3项目设施）相比，第二代CCUS（尚德电站可行性研究）捕集装置的资本成本降低了67％



资料来源：尚德电站 CCS可行性研究[20]

工业化技术进步的特点是，基于技术在早期运行中获得的经验教训，进而应用于改进下一代设备的设计和运行实践， 从而提高效率，降低资本成本和运营成本。运用从第一代技术项目早期运行中获得的专业知识和从经验教训中感悟的后见之明，如果重复建设第一代设计项目，通常可望节约成本 20-30％。碳捕集利用与封存知识国际中心针对萨斯喀电力集团尚德电站近期进行的 CCUS 改造可行性研究表明，若将边界坝 3 项目的知识经验应用于更大规模的项目，捕集 CO_2按每吨计算的资本成本最多可降低 67％[20]（请参见图解 6）。那么，随着未来一代代技术的部署应用，CCUS 的成本可能还要下降。

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[17] UK CCS Cost Reduction Task Force. Final report. The potential for reducing the costs of CCS in the UK. May 2013. https://www.gov.uk/government/publications/ccs-cost-reduction-task-force-final-report.

[18] UK CCUS Cost Challenge Taskforce. Delivering clean growth: CCUS Cost Challenge Taskforce report. July 2018. https://www.gov.uk/government/publications/delivering-clean-growth-ccus-cost-challenge-taskforce-report.

[19] MacDowell N., Fennell, P.S., Shah, N., and Maitland, G.C. The role of CO_2 capture and utilization in mitigating climate change. Nature Climate Change. 2017. 7, 243-249. https://www.nature.com/articles/nclimate3231 .

[20] International CCUS Knowledge Centre. The Shand CCS Feasibility Study Public Report. November, 2018. https://CCUSknowledge.com/pub/documents/publications/.Shand%20CCUS%20Feasibility%20Study%20Public%20Report_NOV2018.pdf

即使经过 CCUS 改造的设施无法精确复制，但深入了解与先前部署的 CCUS 设施所具有的共性，可能会为开发考量提供导向。 尚德电站可行性研究中的主要考虑因素包括，项目设施的选址定位，空间的可用性以及蒸汽循环设计。另外，诸如工程规模，撬装化，工程简化以及从边界坝 3 项目汲取的其它经验教训等因素，都将直接有助于降低估算成本。

CCUS 项目只有在具备足够的资金和政策扶持的情况下才会进行。令人信服的商业论证会助项目一臂之力，商业论证中列举的利好，可以包括现有和通用基础设施的充分利用，恰当评价可灵活调度的电力对电力系统的贡献，以及资本成本和运营成本的降低等。本报告的其余部分则概括总结有可能扩大煤电行业内 CCUS 项目部署的关键驱动因素。

降低资本成本

碳捕集设施的资本成本，占燃煤电厂第一代 CCUS 改造项目捕集总成本的一半以上。运用从这一代设施的设计与运营中获得的经验，定将有助于直接提高煤电行业推广未来 CCUS 设施的经济可行性。

扩大 CCUS 设施的规模

规模经济是推动公用事业电力产业发展的根本动力。大型设施通常比小型设施更具经济效益。边界坝 3 号燃煤发电机组在进行改造之前本来的额定功率为 15 万千瓦（毛容量），其容量适应局部电网需求。可是，按照全球通用规格，该机组很小。最大的现役燃煤发电机组通常额定功率达到 110 万千瓦或更高，具有更高的 CO_2 减排潜力。针对尚德电站的可行性研究，旨在以 30 万千瓦燃煤机组为依托设计第二代 CCUS 设施，其设计的年捕集能力为每年 200 万吨以上，为边界坝 3 项目捕集设施容量的两倍。 尚德电站可行性研究表明，由于电厂的规模更大，其二氧化碳捕集的单位成本可以显著降低。

发电厂的排放水平取决于其发电装机容量和效率，并直接影响与其匹配的捕集设施规模。大容量电力机组通常排放量更高。由于规模经济性，捕集能力翻一番未必导致捕集设施成本加倍。 尚德电站可行性研究表明，总体捕集能力增加，捕集设施的成本相应地略有增加，可以降低捕集成本。

场地布局与撬装化

新建 CCUS 设施的布局和可用空间是重要的设计考量要素，因为最低限占用面积可降低资本成本。捕集设施定位远离发电机组会增加连接的距离，增加材料成本和设备集成复杂性，也相应地会降低运营效率。 尚德电站现址原设计中还容纳了未曾建设的二号电力机组，这就为厂址预留了较宽松的空间（请参见图解 7）。采用这种定位策略可以在设计构思初期，就将高耗能工艺过程定位在发电机组旁边的最佳位置。将 CO_2 吸收塔安置于锅炉房侧面，或锅炉房/涡轮发电机房隔壁， CO_2 压缩机置于发电机侧面等理想位置，都成为可能。这种排列使烟道气管道，蒸汽管道和电气连接的长度最小化，从而大大降低了材料成本。此外，电力岛与捕集岛共享的电梯和楼梯天井，可以减少人员进出设施的成本。 边界坝 3 项目和佩特拉.诺瓦项目的开发场地较为紧密，使得捕集设施的定位变得复杂，从而导致成本增加，却减少设施性能升级的机会。

图解7: *安装碳捕集设施的尚德电站示意图*

资料来源: 尚德电站 CCS可行性研究[20]

大型基础设施项目的建设撬装化，已被业界广泛接受为可控制劳动成本和材料成本的有效手段。尽管未必总能撬装化施工，但事实证明，在施工现场外进行钢结构，设备，管道，电气和仪表的组装，可以显著提高生产率，降低差旅成本并缩短现场施工时间。通过这条途径，还有可能在全球范围内使用低成本的劳务资源，同时保证以低成本达标，并减少发电厂建设现场受到的干扰。

提高捕集率

CCUS 设施的 CO_2 捕集率，是指在捕集过程中从烟道气流的 CO_2 全部含量中分离或脱除的部分 CO_2。燃烧后捕集通常以 90%的捕集率为目标。但是，仅为了满足法规或其它要求，某些设施可能选择较低的捕集率。当边界坝 3 项目设施被批准动工兴建时，适用燃煤电厂的温室气体排放管控法规预计即将出台，但尚不确定。决定边界坝 3 项目选择 90%的设计捕集率，是基于技术上可实现的最佳的减排率，并相信该捕集率应符合即将出台的法规要求。

图片说明：边界坝3项目碳捕集设施位于萨斯喀彻温省埃斯特湾市附近的萨斯喀电力集团边界坝电站(碳捕集利用与封存知识国际中心供稿)。

最近的一项研究表明，即使采用最先进的技术，从烟气流中以低于 90%的比率捕集二氧化碳，可能会增加每吨捕集成本[21]。还有，对拟议中的尚德电站 CCUS 设计进行的敏感性研究表明，与 90%的捕集率相比，95%的捕集率提高了成本效益。对燃烧后捕集的研究也显示，超过 90%以上的捕集率具有成本效益，有助于降低成本[22]。当烟气上升经过吸收塔时，吸收剂会从烟气中将二氧化碳分子脱除。吸收塔身的顶部为烟气中 CO_2 浓度最低点。那里有个临界点，超过该临界点则吸收剂越来越难与烟气中的低浓度 CO_2 产生反应，捕集那里残留的 CO_2 会产生过分的额外成本（即，塔高增加和/或塔内表平面积增加相应增加成本），捕集设施的整体经济性将下降。为具体捕集设施更准确地找到特定捕集率的相应临界点，正在进行研究。

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[21] International CCUS Knowledge Centre. “Summary for Decision Makers on Second Generation CCUS Based on The Shand CCS Feasibility Study”. 2018 . https://CCUSknowledge.com/pub/documents/publications/Summary%20for%20Decision%20Makers%20on%20Second%20Generation.pdf

[22] Ferron, P., Cousins, A., Jiang, K., Zhai, R., Hia, S.S., Thiruvenkatachari, R., and Burnard, K. Towards Zero Emissions from Fossil Fuel Power Stations. International Journal of Greenhouse Gas Control. 2019. 87, 188-202.

提高主电厂的发电效率

火力发电厂的排放强度与电厂类型，寿命以及效率密切相关。例如，装备技术陈旧的燃煤电厂通常运行的主蒸汽压力和温度较低，受到其初始设计时经济可用的材料与技术的局限性所制约。这些老式机组的典型排放强度可能超过 1,200 吨 CO_2 / 百万千瓦时。 尚德电站是以褐煤为燃料的亚临界机组，排放强度约为 1,100 吨 CO_2 / 百万千瓦时。现代先进的超超临界电厂，即通常所谓高效低排或所谓 HELE 电厂，其排放强度可能低至 670 吨 CO_2 / 百万千瓦时[23]。新旧燃煤电厂之间的排放强度落差约三分之一，直接影响捕集设施规模要求，这一低排落差可降低电厂装配 CCUS 设施所产生的电力寄生性损耗以及资本性成本。

优化 CCUS 运行范围

火力发电厂对运行范围的可靠性和容量要求，较之与其匹配的碳捕集设施运行范围的要求迥然不同。火力发电厂必须在极端天气，燃料质量不稳定和设备出现问题等各种运行条件下，以高度可靠性和高容量保持供电的能力。

尽管以设备可用率高点水平进行长时间捕集是捕集设施的工作目标，但理想的工况是，具备在任何特定时间结点都能够完全或部分缩减 CO_2 捕集的能力，则可能有助于大幅度降低运营成本。确定捕集设施冷却系统的大小是一个值得考虑的实用例子 19。不以满足一年内最热到最冷的天数要求来设计冷却系统，而按照较窄的环境温度范围要求来设计，则可能会看好较小规模的冷却系统设计并相应节省开支。运用这种设计策略，可以通过限制二氧化碳的捕集量，以度过冷却能力不足的时间段。鉴于节省资本成本所带来的好处，这样做对年度捕集量的实际影响则可以忽略不计。

根据局域电网供需情况，具备能力以可变负荷供电的热电厂，具有很高的系统价值。捕集设施有能力跟踪火力发电厂负荷的变化波动，继续以最大容量捕集二氧化碳，是电厂全规模减排的关键。随着火力发电厂的负载降低，其效率降低，结果二氧化碳排放强度增加。在这种情况下，在烟气量降低的同时， 保持捕集设施运行的能力，能够降低电厂负荷起伏对排放强度的影响。通常根据满负荷的烟气量来设计捕集设施, 因此，在电厂负荷低下的情况下，捕集设施能够以更高的速率捕集二氧化碳。

培育 CCUS 供应链

成熟完善的供应链可增强竞争力，激励创新并降低技术成本，最终对资本成本产生积极影响。CCUS 供应链的发展将取决于建立有利于 CO_2 市场的格局，在这种格局下，项目供应商会对未来许多 CCUS 项目建设充满信心，促进供应链的发育成长。

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[23] Minerals Council of Australia, New Generation Coal Technology – Why HELE coal-fired power generation is a part of Australia's energy Solution. February 2017. http://www.newhopegroup.com.au/files/files/Why%20HELE%20is%20part%20of%20Australia%20s%20energy%20solution%20-%207%20February%202017.pdf

发育良好的供应链特征包括：

- 供应填料，热交换器，压缩机以及相关原材料等所有设备，在合理的时间范围内满足需求；
- 设备供应商之间存在适当的竞争，以提高效率，促进创新并最终降低成本；
- 供应商订单标准化并保持大批量，使制造商能够扩大生产以达到生产规模效益。

图片说明： WA 帕里什电站的佩特拉. 诺瓦碳捕集设施（NRG 能源供稿）。

降低运营成本

配备了 CCUS 的燃煤电厂的运营成本通常高于传统的热电厂，这有几个原因。首先，以边界坝 3 项目的全规模一体化集成设计为例，其捕集和压缩系统操作需要额外耗能，会降低电厂自身的电力净输出。而如果像佩特拉. 诺瓦项目那样加装独立的外接能源，则会产生额外的运营成本。其次，吸收溶剂，化学制剂，催化剂的消耗与废物处理，都会增加运营性开支。再者，需要额外的人手来操作和维护捕集设备。通过第一代 CCUS 设施已经深入理解掌握了真实运营的要素。这些设施早期所面临的挑战，恰恰突显了那些可以最大程度地降低运营成本的方方面面。

胺降解成本

现有的燃烧后捕集装置通常使用的是胺基溶剂，在低温下与 CO_2 选择性结合，并在加热时释放出纯的 CO_2。溶剂不断循环，反复捕集和释放 CO_2。胺溶剂分子在长时间使用过程中往往会分解或降解，从而降低捕集效率，并需要将其排出并用新鲜溶剂替代。更换降解胺溶剂的成本对运营成本有重大影响 [24]，并且反应了胺基捕集系统的基本运营风险特征。在起草制定 CCUS 项目的商务论证时，使用相同的烟道气和溶剂组合进行大量试点规模实验以量化胺降解的风险，被认为是恰当设计 CCUS 设施的标准实践 [25,26,27,28]，以确定胺溶剂维护的预期成本。不幸的是，这种降低风险的策略增加了 CCUS 部署应用的开发成本并延长开发时间表，从而迫使产业界启动大量研究，旨在确定胺降解加速的根源并探索潜在的减缓降解的策略 [29]。技术供应商已在重点关注降低胺降解的不利影响以及降低胺质量控制的相关成本。然而，工业化规模的设施项目方也必须进行额外的工作，以确保降低有关的成本。

图片说明：碳捕集技术验证设施位于萨斯喀彻温省埃斯特湾市附近的萨斯喀电力集团尚德电站(萨斯喀电力公司供稿)

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[24] Langenegger, S. “SaskPower spending more to capture carbon than expected”. CBC News. December 14, 2016. https://www.cbc.ca/news/canada/saskatchewan/saskpower-carbon-capture-1.3896487

[25] Gorset, O., Knudsen, J.N., Bade, O.M. and Askestad, I. Results from testing of Aker Solutions advanced amine solvents at CO_2 Technology Centre Mongstad. Energy Procedia. 2014. 63, 6267 – 6280.

[26] Wilson, M., Tontiwachwuthikul, P., Chakma, A., Idem, R., Veawab, A., Aroonwilas, A., Gelowitz D., Barrie, J. and Mariz, C. Test results from a CO_2 extraction pilot plant at Boundary Dam coal-fired power station. Energy. 2004. 29, 1259-1267.

[27] Hirata, T., Nagayasu, H., Yonekawa, T., Inui, M., Kamijo, T., Kubota, Y., Tsujiuchi, T., and Shimada, D. Current Status of MHI CO_2 Capture Plant technology, 500 TPD CCUS Demonstration of Test Results and Reliable Technologies Applied to Coal Fired Flue Gas. Energy Procedia. 2014. 63, 6120 – 6128.

[28] Wilson, M., Tontiwachwuthikul, P., Chakma, A., Idem, R., Veawab, A., Aroonwilas, A., Gelowitz D., Barrie, J. and Mariz, C. Test results from a CO_2 extraction pilot plant at Boundary Dam Coal-fired Power Station. Energy. 2004. 29, 1259-1267.

[29] Knudsen, J.N., Wærnes, O., Svendsen, H.F. and Graff, O. Highlights and main findings from the 8-year SOLVit R&D programme – Bringing solvents and technology from laboratory to industry. 13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 November 2016, Lausanne, Switzerland.

Maintenance Costs

First-generation CCUS facilities were built without the benefit of operational experience. Consequently, the maintenance requirements of the facility were not factored into design. A deeper understanding of the impact of maintenance on the design and operating cost of the newer facilities has been developed, based on actual operations, along with effective strategies to optimize operating equipment.

Maintenance costs are normally kept under tight control with advance planning. Emergency maintenance work carries a premium that may be many times higher than the cost of planned maintenance. Unplanned work often results in the need for CCUS plant shutdown with the associated reduction in overall capture rate. To avoid this, redundancy may be deployed at key pieces of equipment, such as key heat exchangers, to improve the operational reliability of the facility. This approach enables continued regular operations using the duplicate equipment while in-situ maintenance is performed on the affected equipment by existing plant staff during normal work hours rather than an emergency dispatch team, thereby significantly reducing CCUS facility operating costs.

Inside the BD3 Power Generator during scheduled maintenance *(Courtesy: International CCS Knowledge Centre).*

Optimization of Thermal Energy

Energy required to operate the CO_2 capture process includes: 1) thermal energy for solvent regeneration to release CO_2, and 2) electrical energy for CO_2 compression. A fully integrated capture facility draws its energy needs from the host power plant, as in the case of BD3. Alternatively, a purpose-built auxiliary power plant may be constructed to service the capture facility, which was deployed at Petra Nova.

One of the key challenges encountered by a fully integrated, post-combustion capture operation is minimizing the impacts of the capture facility's energy requirements on the host power facility. Sourcing energy for capture from the power plant imposes a power production penalty or "parasitic load" that reduces plant's net power output. The amount and the source of the required thermal energy are critical to the operational efficiency and flexibility of the power plant. A considerable amount of research and technological development has minimized the energy requirements of the CO_2 capture process, leading to commercial proprietary solvents, such as those used at BD3 and Petra Nova, that offer performance advantages reducing energy needs by as much as 30% compared to conventional amines.

The source of thermal energy has an impact on the overall capture costs. A comparison of BD3 and Petra Nova is useful to consider. If steam is extracted from the host thermal power plant, as in the case of BD3, the generation capacity of the unit decreases. Additionally, portions of the steam turbine may be replaced to optimize the steam extraction pressure without imposing throttling losses to enable provision of peak efficiency at full load[20]. Furthermore, the quantity of steam available, although not linearly related, will generally follow the demand of the CO_2 capture facility.

The kettle reboiler inside the Carbon Capture Test Facility at the SaskPower Shand Power Station *(Courtesy: SaskPower)*

In the case of Petra Nova, where an auxiliary, cogeneration, natural gas turbine supplies steam for CO_2 capture, it may be difficult to dispatch the two power units independently. Furthermore, a guarantee to meet demand from the grid for the new gas turbine cannot be made without compromising efficiency as the coal-fired power plant reduces its load to respond to daily dispatch variations. A benefit of this arrangement is that the lack of work in the power plant reduces down time of the host facility, and decreases the likelihood that the project will require the environmental permit to be updated.

The conclusion that may be drawn from this comparison is that extracting steam from the existing power plant would have the lowest impact and provide the most flexible and economic option for new CCUS facilities[20], however impacts on unit environmental permitting may need to be considered.

Water Consumption

Most commercial operations consider the environmental and cost impacts of water supply and use. A thermal power plant is sited accordingly. Lack of appropriate water supply may limit or halt expansion at a given site, and most power plant sites have been developed to the point that no additional water is available for cooling purposes. A CCUS system may be designed without the need for additional water to support the cooling requirements of the facility by sourcing it from flue gas condensation using a combination of dry and wet cooling[20]. This purposeful reuse of water reduces the volume of process waste from the power plant site, thereby decreasing associated treatment and disposal costs. This cost-saving opportunity is higher at power plants burning high-moisture fuels.

The evaporative cooling towers at the SaskPower Shand Power Station *(Courtesy: SaskPower).*

Compression Efficiency

CO_2 compression requires energy that imposes a substantial load on the power plant. Compression power at BD3 accounts for more than a third of the lost electricity output associated with the CCUS facility. The CO_2 capture plants at BD3 and Petra Nova were optimized for full load operation, and each employ a single, integrally-geared, CO_2 compressor that realizes the best efficiency at full load and has limited ability to accommodate lower flows of CO_2 without incurring significant efficiency losses. Compressor design improvements are required to maintain efficiency and operational flexibility to improve load following capability at the CCUS facility.

Digitalization

Digitalization can improve safety, increase productivity, and reduce costs in the coal and power industries. The potential impact and the associated barriers of these improvements varies considerably. However, overall savings could amount to 5% of the total annual power generation costs.

Digital data and analytical modeling could help achieve greater efficiencies and reduce power system operation and maintenance costs in several ways:

- Improved planning by reducing outages through better monitoring and predictive maintenance and limiting downtime by rapidly identifying points of failure,
- Improved efficiency of combustion in power plants that would lower loss rates in networks,
- Improved project design across the overall power system,
- Extend the operational lifetime of assets, and
- Increase the resilience and reliability of power supply.

CO_2 Transport and Storage Cost Reduction

The development of new CO_2 storage locations incurs significant costs. Additional costs, though comparatively lower, may be incurred due to enhanced requirements for monitoring as higher volumes of CO_2 are injected at established storage sites.

The UK CCS Cost Reduction Task Force[30] has estimated that *storage* costs for CCUS-equipped power plants may be reduced from £25/MWh for early CCUS projects to £5-10/MWh through investment in a CO_2 hub or common storage site with a capacity of up to 5 Mt of CO_2 per year. Should a storage cluster be developed to utilize several storage types and geologies, the reliability of CO_2 storage would increase, thereby reducing development risk. This approach will be vital to assure economically-scaled CCUS-enabled fossil-fired power generation projects can be delivered and financed at costs in line with industry norms.

Pipeline construction and installation costs increase at lower rates with increasing CO_2 transport capacity. This is due to the economies of scale achieved as the volume of transported gas grows. Consequently, with appropriate advance planning for surplus capacity, there is significant potential to decrease the cost of transporting CO_2 at higher volumes. Other fundamental drivers of transport costs include pipeline distance; crossing terrain, particularly onshore; and planning costs. Considering these variables, the lowest cost transport network would:

- Transport large volumes of CO_2 in appropriately-sized pipelines;
- Consider the sizing of trunk-line sections and feeder-line sections to ensure high utilization over the longest period of the asset lifetime;
- Minimize CO_2 transportation by accounting for terrain, shoreline crossings and planning constraints; and
- Minimize the need for constructing additional pipelines that would incur significant planning costs.

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[30] UK CCS Cost Reduction Taskforce. CCS Cost Reduction Task Force: Final Report. May 2013. https://www.gov.uk/government/publications/ccs-cost-reduction-task-force-final-report. [Costs quoted in 2012 British Pounds Sterling (£)].

The Task Force has anticipated that *transport* costs for CCUS-enabled power plants could drop from £21/MWh for early pipeline projects carrying 1-2 Mt CO_2 per year to £5-10/MWh for later projects with capacities between 5-10 Mt CO_2 per year.

A coal-fired power plant enabled with CCUS presents an ideal opportunity to anchor a CCUS industrial hub since, if suitably sized, it could capture millions of tonnes of CO_2 each year. Typically, other industrial operations are only able to supply up to hundreds of thousands of tonnes of CO_2 annually, making them ideal complementary partners on a growing CCUS industrial hub. Establishment of an interconnected, appropriately-sized network hub that combines higher volumes of CO_2 from several large capture plants could result in even lower per MWh transport costs over the long term than the Task Force has estimated. At increased transport volumes, increasing costs would be associated with larger diameter pipelines and longer pipeline lengths that would facilitate the development of the storage hubs or clusters. However, these increased costs would be outweighed by the significant advantages afforded by the increased availability of CO_2 for EOR and value-added chemicals or for storage at dedicated facilities with associated carbon offsets.

The Aquistore injection well during its installation *(Courtesy: Petroleum Technology Research Centre)*

Advancing the Business Case

The CCUS industry is in its infancy. Significant potential exists to establish key business drivers for implementing a CCUS project. Presently, CCUS deployment efforts have yielded two industrial-scale facilities at coal-fired thermal power stations, along with 17 other facilities that have applied CCUS to a range of industrial processes. The limited number of installations points to the challenging nature of developing a good business case for CCUS in conjunction with coal power. BD3 and Petra Nova each rely on a significant revenue stream from CO_2 EOR. To enable the widespread acceptance of CCUS, all challenging aspects of the value stream must be addressed and improved.

Grid Support and Ancillary Services

Large thermal power stations play an important role in overall power grid response, including frequency disruptions, power factor correction, diversity of fuel source, and dispatchability. Renewable generation sources are growing in number and will continue to climb over the next decades. Ancillary services, in the form of quickly dispatchable backup power, are critical to managing the inherent intermittency of renewable energy. Deregulated markets with low amounts of reserve power generation capacity may experience price spikes during periods of instability that may be many times above the normal market level[31,32]. Consequently, open-market utilities may receive additional compensation for providing backup power from sources such as CCUS-equipped, coal-fired power plants.

It is therefore important that integration of a capture facility with its host power unit(s) does not adversely affect the provision of reliable, stable power. Interestingly, the magnitude of the parasitic load associated with CCUS deployed at a power facility is an opportunity to enhance its business case in the situation where it is possible to shut down capture operations over a short period in order to accommodate peaks in power demand, thereby enabling the power plant to maximize output to the grid. The first generation of facilities have limited capabilities in this regard. Consequently, considerations for flexible curtailment of CCUS operations must be made in future facility designs.

Renewable Energy Integration

Maximizing low emissions electricity is essential to driving down global emissions; renewable energy sources are critical to this strategy. Reliable backup power supply is essential to managing power supply interruptions that are characteristic of renewable energy sources.

The Shand Feasibility Study identified an unexpected potential environmental benefit from utilizing a CCUS-retrofitted, coal-fired power plant, rather than a natural gas power plant, as the source of backup energy for variable renewable generation sources. If backup energy is sourced from a natural

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[31] Siddiqui, A.S. Price-Elastic Demand in Deregulated Electricity Markets. Lawrence Berkeley National Laboratory, LBNL-51533. 2003. https://eta.lbl.gov/publications/price-elastic-demand-deregulated.

[32] Trebing, H.M. A Critical Assessment of Electricity and Natural Gas Deregulation. Journal of Economic Issues. 2008. 42, 469-477.

gas plant, that power plant would be required to run at reduced loads to enable the integration of the maximum available power from renewable sources into the grid. However, a natural gas plant's efficiency decreases at reduced power output and its emission intensity profile increases accordingly if CCUS has not been deployed. Consequently, reducing the load of a natural gas plant to enable variable renewable generation effectively works against the non-emitting impact of variable renewable sources by increasing the emission intensity of the backup power supply.

In contrast, a CCUS-equipped, coal-fired power plant can increase its CO_2 capture rate when running at reduced load, thereby enhancing the environmental benefit of the renewable energy source by further reducing overall system emissions. This improvement may be achieved without any appreciable capital cost increases for the CCUS facility.

The Shand Feasibility Study estimated that the capture rate could increase from 90% at full load to 97% at the minimum power plant output level to support variable renewable energy sources which was determined to be 62% net output to the grid, at almost no additional capital cost. The integration of CCUS-equipped, coal-fired power generation with renewable energy is therefore an improved business case for CCUS retrofitting.

CO_2 Utilization Revenue & Storage Hubs

Key to the approval of the BD3 and Petra Nova projects was realizing value from the captured CO_2 that was utilized for EOR. However, sourcing CO_2 to meet the demand of an oil field from a single carbon capture plant is not without risk. An EOR operation requires a reliable supply of CO_2 to avoid interruptions in production. A single capture facility is prone to interruptions and trips from either the capture process or the associated power facility which prevents reliable supply of steady CO_2 volumes. Connecting two or more CO_2 sources to an EOR operation improves stability in CO_2 supply and reduces potential operating costs associated with CO_2 delivery challenges. As outlined above, when establishing a CO_2 hub under an appropriate CO_2-value regime, the business case for CCUS is improved, while its capital and operating costs are likely reduced, along with a reduction in the incremental cost of future transport and storage projects.

Surface monitoring equipment at the Aquistore CO_2 storage site. The BD3 Carbon Capture Facility (in background) sends CO_2 by pipeline for injection deep underground (3.4 km) and permanent storage *(Courtesy: Petroleum Technology Research Centre).*

An example of this CO_2 hub concept, the Alberta Carbon Trunk Line (ACTL), will be operational in Canada in late 2019[33]. The ACTL has been sized to transport 14.6 Mt of CO_2 per year in its 240 km pipeline that is expected to branch from a number of capture plants at different industrial facilities in a growing CO_2 hub. The transported CO_2 would be utilized for EOR and deep saline aquifer geological storage. At the present time, Wolf Energy has contracts in place to transport 4,400 tonnes per day of CO_2 captured at the North West Redwater Partnership's Sturgeon Refinery (1.2 $MtCO_2$/yr) and the Nutrien's Redwater Fertilizer production facility (0.3 $MtCO_2$/yr), both located northeast of Edmonton. The CO_2 will be utilized by Enhance Energy for EOR at its Clive oil field.

Similar CO_2 hub projects are emerging in the North Sea involving the UK, Norway and the Port of Rotterdam for the development of dedicated geological storage sites. The Port of Rotterdam may establish a CO_2 transport hub to serve The Netherlands' industrial facilities. It could expand to serve Belgium, Germany and/or the UK[34]. The proposed hub would, however, require an adequate carbon price or a significant subsidy for development to take place.

Impact of Technology Advancements on the Cost and Performance of CCUS

The economics of CCUS are steadily improving as a result of new technology development and associated innovations. Several decades of research, pilot, field, and commercial-scale projects have advanced various aspects of CCUS, leading to a dramatic reduction in costs. Currently, there are nearly 20 commercial CCUS installations operating in 9 nations, along with countless research and pilot projects on various aspects of CO_2 capture, utilization and storage ongoing around the world.

Capital and operating costs will continue to be whittled down through learning from commercial CCUS operations. However, technological progress has demonstrated that step changes in capital

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[33] Enhance Energy Inc. The ACTL Project. September 2019. https://actl.ca

[34] Simon, F. Meet Europe's two 'most exciting' CO_2 capture and storage projects. Euractiv. April 3, 2018. https://www.euractiv.com/section/energy/news/meet-europes-two-most-exciting-CO2-storage-projects/

and operating costs are made through research and development aimed at reducing the costs of subsequent generations of advanced, first-generation technologies. The greatest gains can be made in reducing capture costs since they represent by far the largest proportion of capture and storage capital and operating expenses. Nonetheless, gains continue to be made in transport and storage cost reduction through deployment of technology innovations resulting from operational experience and research that is normally associated with large-scale testing and validation studies typically conducted in conjunction with the growing number of commercial CCUS operations. Suitable carbon utilization technology development is at a much earlier stage and represents an ongoing priority and opportunity for the growing CCUS industry.

Many capture technologies are at various stages of maturity. A select few are considered herein to demonstrate not only the breadth of current research ideas, but also to emphasize the need for continued investment in research and pilot-scale technology development, along with the next essential step of commercial deployment of the most promising technologies.

Post-Combustion Capture Technologies

Coal-fired power plants fueled by pulverized coal must deploy post-combustion processes, such as aqueous amine scrubbing systems that have been installed at BD3 and Petra Nova. There will continue to be improvements in driving down the costs of amine capture systems as additional installations are deployed. However, other types of technologies that show some promise for future commercial operation are at various stages of development. Among these is CO_2 capture using membranes. Suitable membranes have been tested that can capture CO_2 at rates of 30-90% with costs as low as US$30-40 per tonne, however, the cost of capture at the high end of this range is currently steep[35]. In February 2018, the United States Department of Energy announced funding for seven engineering-scale tests of various advanced carbon capture technologies[36]. Two of these projects will evaluate membrane capture systems, including a 1 MW_e-scale project at the Technology Centre Mongstad in Norway. Other capture technology studies at various engineering scales based on aqueous and non-aqueous solvents, mixed salts and membrane-sorbent hybrids were granted funding. A key objective of ongoing work is to optimize energy consumption and consumables to decrease the costs of capture, in addition to reducing capital costs.

Negative Emissions: Biomass Co-firing with Coal-Fired Power Generation

The 5th IPCC report indicated that three of the four pathways that would enable achieving a global temperature increase significantly below 2°C require removal of CO_2 from the atmosphere. This may be accomplished by Bio-Energy with CCUS (BECCS) that entails combustion of a sustainably-produced bio-fuel for energy generation, followed by CO_2 capture and permanent geological storage. A BECCS retrofit of an existing coal-fired power plant could result in the ability to operate with negative emissions intensity equivalent to the power plant's emission intensity when operated utilizing coal since the CO_2 removed during biomass growth is not re-emitted to the atmosphere. The potential emission intensity of a lignite power plant converted to BECCS could be as low as -1,100 t/GWh. The most significant constraint on BECCS deployment is the availability of sustainable biomass. Co-firing of coal with biomass[37] (*see Figure 8*) in existing coal power plants that have been equipped with CCUS can have a positive impact on the development of biomass as a fuel source.

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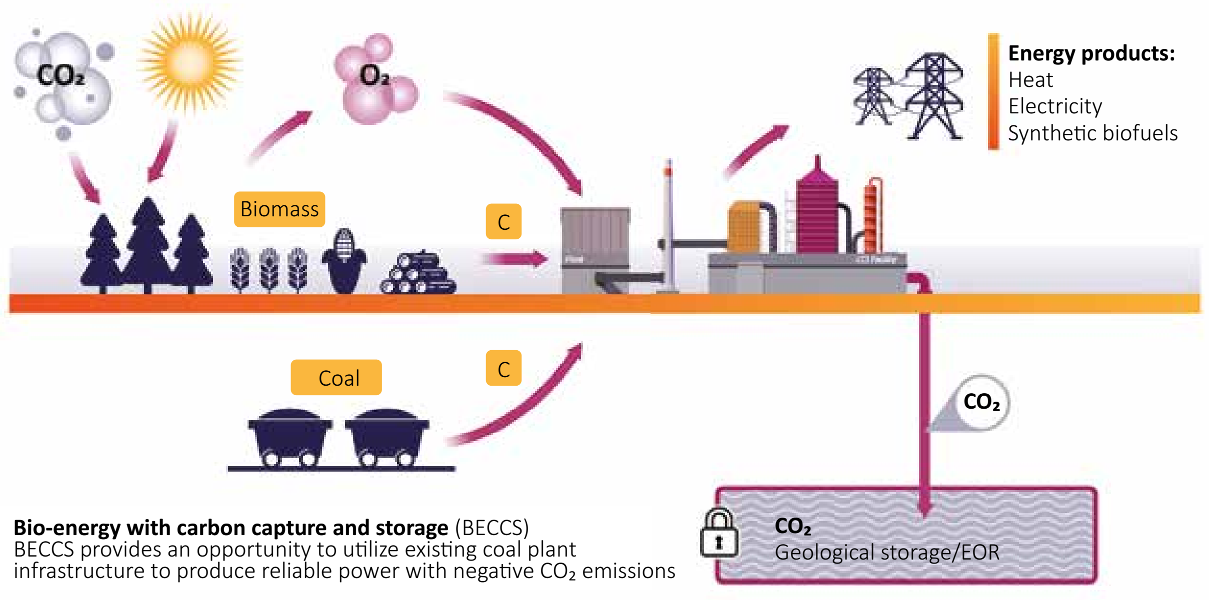
[35] Kniep, J. et al., Integrated Testing of a Membrane CO_2 Capture Process with a Coal-Fired Boiler. Presentation at the NETL CO_2 Capture Technology Review Meeting. August 8, 2016. www.netl.doe.gov/File%20Library/Events/2016/c02%20cap%20review/1-Monday/T-Merkel-MTR-Integrated-Membrane-Testing.pdf

[36] United States Department of Energy. News Release. February 2018. https://www.energy.gov/articles/energy-department-invests-44m-advanced-carbon-capture-technologies-projects

[37] CSIRO, Australia. Towards Zero Emissions CCS in Power Plants Using Higher Capture Rates or Biomass. IEA Greenhouse Gas R&D Programme (IEAGHG) Technical Report 2019-02. UK: IEAGHG, 2019. https://ieaghg.org/publications/technical-reports

Figure 8: *Bio-Energy Integration with Coal-Fired Power.*



Source: International CCS Knowledge Centre

Bio-energy typically comprises wood, woody waste and residue, crop waste, and purpose-grown biomass, including the growth of high-yield CO_2 crops that are suitable for marginal land and wastewater treatment. These fuel sources are often compressed into pellets that may be burned in a boiler, including a coal-fired boiler. Co-firing allows biomass to be blended with coal in varying amounts, depending on costs and biomass availability. For certain biomass types, blending with coal absorbs chlorine and other compounds from the biomass that would otherwise have a negative impact on emissions and air quality, as well as reliability of the boiler components and the carbon capture equipment. Some biomass sources can be effectively used without coal in existing facilities, supporting 100% biomass fuel, as has been successfully deployed at Drax power station in the UK.

BECCS experience is limited to date, with one commercial-scale installation capturing and geologically storing 1 Mt/y of CO_2 at a corn-to-ethanol plant in Illinois, United States[38,39]. Depending upon the sector, and whether or not a retrofit is possible versus new construction, it has been estimated that the cost of BECCS ranges from $15-400 per tonne of avoided CO_2, with bioethanol being the least expensive deployment option[40]. However, there are several factors that may encourage its development for power generation applications:

- A large number of coal-fired thermal power plants currently in existence could potentially be converted to fire biomass at reduced cost compared with constructing a new purpose built bio-energy facility. Appropriate timing is critical to assure conversion prior to anticipated power plant retirements and subsequent demolition by reusing exiting infrastructure and avoiding the significant capital cost associated with construction a new BECCS or biomass powered facility. For example, the newest coal-fired power plant in Canada is Keephills 3, a 450MW plant, that was commissioned in 2011, with an initial capital budget of $2B CAD. The cost to build a new, similar bioenergy thermal power facility, with or without CCUS, rather than retrofitting the existing facility, would delay development.

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[38] Archer Daniels Midland. ADM Begins Operations for Second Carbon Capture and Storage Project. 2017. https://www.adm.com/news/news-releases/adm-begins-operations-for-second-carbon-capture-and-storage-project-1.

[39] McDonald, S. Illinois. Industrial Carbon Capture & Storage Project. Presentation. Bioeconomy 2017. July 11, 2017. https://www.energy.gov/sites/prod/files/2017/10/f38/mcdonald_bioeconomy_2017.pdf

[40] Consoli, C. Bioenergy and Carbon Capture and Storage. Global CCS Institute. 2019. https://www.globalccsinstitute.com/wp-content/uploads/2019/03/BECCS-Perspective_FINAL_18-March.pdf.

- Existing coal fired power plants can be life extended almost indefinitely with a capital investment that is in the range of 10-15% of their replacement cost every 25-30 years.
- Experience with bio-energy at power stations would provide a suitable foundation upon which to build. Partial conversion of coal-fired power plants has taken place at several locations. The Drax power plant has achieved 100% biomass firing. This experience can be applied to subsequent biomass conversion of coal plants.
- The improvements in second-generation CCUS installations are key to making BECCS viable. The reduced capital and operating costs highlighted in the Shand CCS Feasibility Study are directly applicable to BECCS facilities.
- Biomass is generally sulfur-free thereby reducing the limestone consumption costs for SO_2 abatement and mitigating the impact of SO_2 slip into the CO_2 absorber with its negative impact on amine quality.
- BECCS conversions enable flexibility of energy supply. Conversion of power plants could maintain their ability to co-fire varying amounts of coal and biomass, matching seasonal and annual availability of biomass, including any supply disruptions.
- A staged launch of bio-energy power generation would support growth of feedstock supply. Biomass co-firing with coal would enable a gradual transition to increased biomass combustion, while the supply of biomass is established in regions with suitable growing conditions and in close proximity to coal-fired power station(s).
- An opportunity could emerge for agriculture and forestry operations located nearby a suitable coal-fired power plant by providing a new economic value stream from waste materials, such as straw and bark, in addition to new crops.
- Carbon offset credits from BECCS could have market value in certain regions. Negative emissions from BECCS could create a positive cash flow for the regions in which carbon credits are implemented to offset positive emissions elsewhere.

Oxy-Fuel Power Plant Technologies

In the future, capture at coal-fired power plants may be integrated into the power generation process either through pre-combustion or oxyfuel combustion[41]. Oxyfuel combustion is a coal-fired power technology that is promising and has been extensively explored at research and pilot scales over the past two decades. During oxyfuel combustion, coal is combusted in a process that uses pure oxygen instead of air. Fuel consumption is reduced due to the elimination of the other gaseous constituents in air, which comprises approximately 78% nitrogen. Pure oxygen is diluted with flue gas to avoid temperatures exceeding the specifications of commercial-scale boiler construction materials. The volume of flue gas produced during oxyfuel combustion is reduced approximately four-fold compared with thermal coal-fired power. Oxyfuel flue gas contains much higher concentrations of CO_2 due to the reduced volume of flue gas, along with a higher concentration of CO_2 compared with post-combustion flue gas (>60% vs 12-15%). Consequently, the capital and operating costs associated with purification and compression of the CO_2 can be significantly reduced. Oxyfuel combustion may also realize improved power plant efficiency due to increased coal utilization with an associated reduction in the parasitic power losses that are characteristic of post-combustion CO_2 capture power plant retrofits.

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[41] United States Department of Energy. Pre-Combustion Capture. 2019. https://www.energy.gov/fe/science-innovation/carbon-capture-and-storage-research/carbon-capture-rd/pre-combustion-carbon

Callide Oxyfuel Project

A useful example to consider is the joint Australian-Japanese Callide Oxyfuel CCUS Project conducted during 2012-2015[42]. The follow key features of the project included[43,44]:

- The fuel used in the project comprised Callide coal, an Australian medium-ash, semi-bituminous coal, mixed with up to 25% of three other coals with low to medium ash content and bituminous and anthracite ranks.
- Coal was combusted at a rate of 20,000 kg/hr in a 30 MWe oxyfuel boiler.
- Boiler reliability of 90% was achieved within one month of operation.
- The flue gas, containing 68-70% CO_2, was filtered and scrubbed in a caustic process, followed by cryogenic separation of the CO_2 at a production rate of 75 t/day and a purity of 99.9%.
- Capture of more than 95% of SO_x, NO_x, particulates and trace metals was achieved.

The capital cost of a similarly-equipped oxyfuel retrofit of a full-scale, 420 MW_e supercritical boiler with 2.8 Mtpa CO_2 capture was estimated to be AU$2000-2300/kW[45], including transport and storage. This cost represents a decrease by approximately one third compared with the investment in the pilot plant. The overall operating and maintenance costs for the 420 MW_e oxyfuel capture facility were determined to be 1.5 to 2.0 times those for an ultra-supercritical coal-fired power plant; costs were evaluated without CCUS in both cases. These observations clearly demonstrate the impact of scale on capital and operating costs and the additional costs incurred by deploying advanced, first-generation technologies.

Callide A Power Station in central Queensland, Australia which was the site of the Callide Oxyfuel Project *(Courtesy: CS Energy Ltd)*

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[42] Spero, C. and Yamada, T. Callide Oxyfuel Project – Final Results. Oxyfuel Technologies Pty Ltd. March 2018. https://www.globalccsinstitute.com/resources/publications-reports-research/callide-oxyfuel-project-final-results/

[43] Spero, C. Callide Oxyfuel Project – Lessons Learned. Global CCS Institute. May 2014.

[44] Spero, C. Callide Oxyfuel Project. Presentation to the IEAGHG Oxyfuel Combustion Network. October 27-30, 2015. https://ieaghg.org/docs/General_Docs/5oxy%20presentations/Keynote%20Address/K03%20-%20C.%20Spero%20(CS%20Energy).pdf

[45] Costs quoted in 2017 Australian Dollars (AU$).

Allam Cycle Pilot Project

The Allam Cycle is a novel power plant design that is based on pressurized, oxyfuel combustion technology. The steam used by conventional thermal power plants to generate electricity in a turbine is replaced with supercritical CO_2. Fuel combustion and power generation are integrated in the Allam Cycle. Like all oxyfuel combustion processes, the Allam Cycle uses oxygen for combustion and therefore requires an upstream air separation unit. Flue gas is produced during the cycle that is much higher in CO_2 than the flue gas generated by conventional combustion[42].

The Allam cycle is particularly promising since it produces CO_2, while generating power at a high efficiency, thereby potentially enabling electricity generation at rates that are competitive with conventional power plants without CO_2 capture capability. If CO_2 could be sold and/or incentives such as the US corporate tax code's Section 45Q tax credit were available, Allam Cycle power plants could be able to provide power at a significantly lower cost than unabated conventional plants. In other words, this system could result in the development of a power plant with negligible costs for CO_2 capture. The Allam cycle may be operated using natural gas, gasified coal, or biomass as its fuel source. A 50 MW_{th} demonstration of the natural gas-based cycle is located in La Porte, Texas, US[46]. Pilot-scale research is also being conducted on a 5 MW_{th}, lignite coal-based Allam Cycle at the Energy and Environmental Research Center, University of North Dakota[47,48].

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[46] NETPower. 2019. https://www.netpower.com

[47] North Dakota Senate. News release. February 2018. https://www.hoeven.senate.gov/news/news-releases/hoeven-announces-700000-in-doe-funding-for-energy-and-environmental-research-center-at-und-to-develop-allam-cycle

[48] Laumb, J. Advanced Coal-Fired Power Cycles. Presentation. 5 th Annual Minnesota Power Systems Conference. November 2018. https://www.ccaps.umn.edu/documents/CPE-Conferences/MIPSYCON-PowerPoints/2018/AdvancedCoalFiredPowerCycles.pdf

Enhancing Public Policy Support and Financing

Fulfilling the goals of the Paris Agreement requires an international commitment to the deployment of CCUS as a key climate change mitigation strategy. Governments and financing institutions view CCUS as costly and seek other, lower-cost, emission mitigation projects to incentivize or fund, thereby inhibiting the development of effective policies and financing in support of CCUS deployment.

A tour group at the BD3 Carbon Capture Facility *(Courtesy: International CCS Knowledge Centre).*

Paradoxically, these very mechanisms would drive down the costs of CCUS, thereby assuring the essential cost reductions to incentivize new projects.

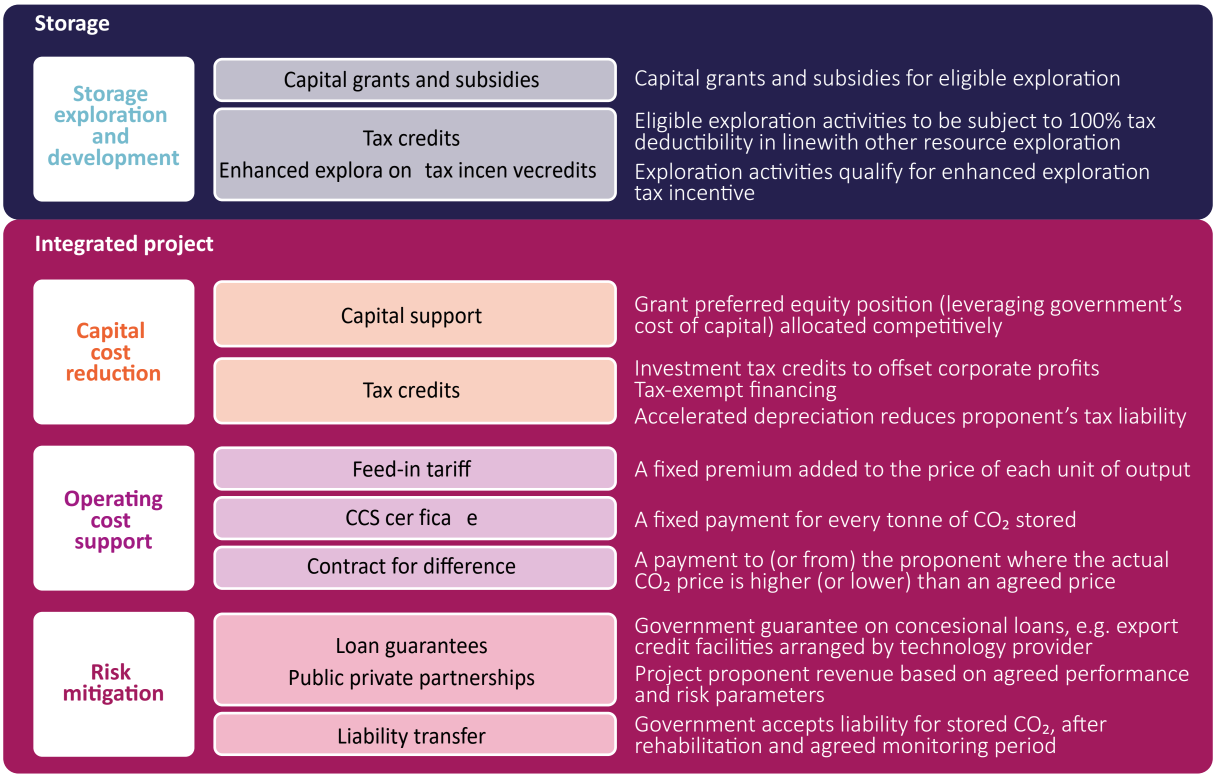
Although government policies must be tailored to a specific country, they may be grouped into the four broad categories as outlined in the 2016 CIAB report, namely:

- **STIMULATE CCUS MARKET UPTAKE** to substantially increase the level of CCUS deployment and investment capital. Policies must enable investment capital to earn a market-based rate of return and facilitate global CCUS deployment in energy and industrial markets while the technology matures.
- **SUPPORT PROJECT DEVELOPMENT.** The societal, emissions-reduction, and economic benefits of commercial-scale CCUS projects are immense. Applying lessons learned from existing projects and enacting policies to financially de-risk projects are both required to accelerate the CCUS project development process.
- **ENABLE PROJECT FUNDING.** Many countries have provided direct grant funding to CCUS projects. That approach continues to be important to improve project economics and strengthen access to investment capital that financially de-risks CCUS projects. Yet, that funding and investment are insufficient. Supportive public policy must be enacted. Low-carbon renewables have seen a global surge in market penetration due to similar policies. A parallel approach is essential for CCUS.

- **DEPLOY CCUS AND ADVANCE NEXT-GENERATION CCUS TECHNOLOGIES.** Traditional government focus on research and development is important. However, deployment of proven CCUS technology at large scale is critical to driving down costs and increasing deployment. Governments must continue to advance next-generation CCUS technologies and knowledge development that are pre-competitive or for which there are no identifiable market-based financial returns to assure future technology advancements.

Implementation of such policies would enable governments to achieve their commitments to the Paris Agreement at lower costs (*see Figure 9*).

Figure 9: *Policy Incentives to Improve the Economics of CCUS*



Storage	Storage exploration and development	Capital grants and subsidies	Capital grants and subsidies for eligible exploration
		Tax credits Enhanced exploration tax incentive credits	Eligible exploration activities to be subject to 100% tax deductibility in linewith other resource exploration Exploration activities qualify for enhanced exploration tax incentive
Integrated project	Capital cost reduction	Capital support	Grant preferred equity position (leveraging government's cost of capital) allocated competitively
		Tax credits	Investment tax credits to offset corporate profits Tax-exempt financing Accelerated depreciation reduces proponent's tax liability
	Operating cost support	Feed-in tariff	A fixed premium added to the price of each unit of output
		CCS certificate	A fixed payment for every tonne of CO_2 stored
		Contract for difference	A payment to (or from) the proponent where the actual CO_2 price is higher (or lower) than an agreed price
	Risk mitigation	Loan guarantees Public private partnerships	Government guarantee on concesional loans, e.g. export credit facilities arranged by technology provider Project proponent revenue based on agreed performance and risk parameters
		Liability transfer	Government accepts liability for stored CO_2, after rehabilitation and agreed monitoring period

Source: Greig, C. et al. Energy Security and Prosperity in Australia – A Roadmap for CCS.[49]

A useful example to consider here are the recent improvements to the existing 45Q tax credit in the United States to incentivize CCUS deployment, particularly for the "low-hanging fruit" in the industrial sector, such as ethanol production, natural gas processing, and ammonia production. CCUS advocates have a renewed sense of momentum in the US due to the passage of The FUTURE Act, which reformed the existing 45Q tax credit with a purpose to spur CCUS deployment. The reformed 45Q tax credit provides:

- \$35/tonne CO_2 for beneficial use, including EOR
- \$50/tonne CO_2 for saline aquifer storage
- 12-year window for receiving tax credits
- Construction must begin by Jan 1, 2024
- Minimum capture rate: 500,000 tpy for power plants and 100,000 tpy for industry
- Transferrable, which means that non-profits such as cooperatives can use the tax credit.

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[49] Reprinted by the International Energy Agency. Five Keys to Unlock CCS Investment. Paris: IEA, 2017. https://webstore.iea.org/five-keys-to-unlock-ccs-investment.

However, 45Q may require additional policy enhancement to spur CCUS deployment in the power sector[50]. While tax credits are a viable approach to incentivizing energy technologies in the United States, they are not the same as cash, which may result in some significant challenges for some power companies attempting to capitalize on the tax credit, including:

- An insufficient corporate tax base to utilize 45Q credits.
- United States tax rates have been reduced, so CCUS credits have also decreased.
- Monetization of tax credits may be lower than anticipated due to the decrease in tax credit value by at least 20% on transfer to a project partner or through monetization.
- Tax credits cannot fund project capital costs since they are only available annually as the project stores CO_2 over time rather that at project outset. Financing will likely be required for project capital costs.

To understand the remaining challenges for the United States' coal sector, the lessons learned from the NRG Petra Nova project may be considered. NRG managed to avoid the challenges of the United States' New Source Review (NSR) environmental regulation by adding cost and complexity to the project through construction of a natural gas turbine to provide the capture facility's steam and energy needs. The NSR regulation is not without risk for CCUS projects since it requires industrial emissions to be reduced using "best available technology". Consequently, an NSR for the most efficient CCUS integration of an existing facility may trigger plant modifications that are uneconomic and/or reduce the intended emissions reduction target.

According to NRG, incorporating the lessons learned from the project would reduce the cost of a similar project today by 10-20%[51]. Although the Petra Nova Project, by comparison, is often cited to have cost about $1 billion, this includes the pipeline and a capital project to prepare the oil field to receive CO_2, costs that would not necessarily be incurred by all projects. The capital for the carbon capture facility, by comparison, were approximately $635 million for Petra Nova.[52] A new 240MW project, similar to Petra Nova, capturing about 1.4Mt per year for CO_2-EOR could be eligible for 12-years of 45Q tax credits that would be worth approximately $588 million, thus improving the rate of return on investment and reducing financing risk.

In addition to the positive nature of the reformed 45Q tax credit, many other public policy proposals are currently in development or under consideration that will facilitate new CCUS projects in the power sector, especially for coal. Regardless of the challenges the coal-fired power sector faces for CCUS deployment, new projects are being considered in the United States today. It is certainly possible that the very real reductions discussed throughout this document could become reality in the United States in the near term, and lessons learned at each successive project will continue to reduce future deployment costs.

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[50] Energy Futures Initiative. Advancing Large Scale Carbon Management: Expansion of the 45Q Tax Credit. May 2018. www.energyfuturesinitiative.org/news/2018/5/22/efi-policy-paper-how-the-45q-credit-may-spur-carbon-capture-innovation.

[51] Richards, H. Carbon Dioxide from Coal Plants Has an Interested Buyer from Oil and Gas. If the Costs Come Down. Casper Star Tribune: October 2017. www.trib.com/business/energy/carbon-dioxide-from-coal-plants-has-an-interested-buyer-from/article_db13a06a-af61-52b5-858d-ff0330dc1e54.html.

[52] Petra Nova Parish Holdings, LLC, W.A. Parish Post-Combustion CO_2 Capture and Sequestration Project, www.osti.gov/servlets/purl/1344080

Conclusions

The objective of this report was to outline the long-term outlook for cost reductions from coal-fired power stations that capture and store CO_2 emissions using CCUS. *Figure 10* summarizes the key points outlined in this report. Existing projects provide significant lessons for future CCUS design and development; many will lead to dramatic capital and operating cost reductions. Work to date has successfully demonstrated the favorable economics of size and other factors to reduce the cost of CO_2 capture. Technological advancements will lead to further cost improvements. Promising new technological approaches, including membrane capture, oxyfuel combustion and BECCS have been highlighted accordingly.

Globally, there will be over 20 commercial-scale CCUS projects in operation by 2020, with more than 37 Mt of anthropogenic CO_2 being captured and geologically stored annually[53,54]. These projects serve to meet the 2010 G8 target set in Hokkaido in 2008[55], albeit a decade late. Only two of these projects involve CCUS-enabled, coal-fired power plants. A positive move forward in the deployment of industrial-scale, CO_2-utilization projects has taken place in the last few years that has significantly increased the number of commercially-viable technologies and the number of technology vendors that may be considered for upcoming projects. Furthermore, beyond the handful of nations that have undertaken large-scale CCUS, new pilot-scale CCUS projects and initiatives have been launched or are under development elsewhere.

In order to increase, or even maintain, the rate of CCUS deployment, a new commitment by G20 nations must be made to significantly increase CCUS installations. This is an essential next step in order to meet existing commitments under the Paris Agreement to increase CCUS deployment by 2030 and beyond. Continued progress will rely on the following:

- **IMPROVED UNDERSTANDING AND KNOWLEDGE.** Combining technical expertise to better understand the cost savings and design improvements for CO_2 capture must continue to facilitate progress.
- **REDUCED UNCERTAINTY ABOUT SHARED TRANSPORT AND STORAGE.** Facilitate necessary investment in the development of major infrastructure on transport and storage components, including better logistics planning.
- **STRENGTHENED POLICY AND FINANCIAL SUPPORT.** An international commitment must be made to establish supportive policy and innovative financing mechanisms to grow CCUS into a well-established industry.
- **CONTINUED INVESTMENT IN RESEARCH AND PILOT PROJECTS OF NEW TECHNOLOGIES, ALONG WITH COMMERCIAL CCUS DEPLOYMENTS.** The significant level of investment in research, piloting and demonstration over the past few decades must continue and, indeed, increase to help reduce investment risk associated with low emissions coal-fired power technologies. This will accelerate the technology development cycle. Research is also essential for independent and objective analysis, and generating data and developing expertise to accelerate design, permitting and operation of new coal power plants using specific black and brown coals in local conditions.

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[53] Zakkour, P. and Heidug, W. A Mechanism for CCS in the Post-Paris Era: Piloting Results-Based Finance and Supply Side Policy Under Article 6. Saudi Arabia: KAPSARC, 2019. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=24&ved=2ahUKEwjN84_9vPTkAhUTNn0KHefvBtA4FBAWMAN6BAgBEAI&url=https%3A%2F%2Fwww.kapsarc.org%2Ffile-download.php%3Fi%3D28368&usg=AOvVaw0QLVGqasyzuYweROMf3Dxp

[54] IEAGHG. Paris Climate Change Targets Cannot be Met Without CCS. Greenhouse News. Issue 128. December 2017. https://ieaghg.org/docs/General_Docs/Publications/December_2017_LR.pdf.

[55] Munk School of Global Affairs & Public Policy, University of Toronto. G8 Summits. Hokkaido Official Documents: Environment and Climate Change. Article 31. July 8, 2008. http://www.g8.utoronto.ca/summit/2008hokkaido/2008-climate.html.

Figure 10: *Summary of Cost Reduction Potential for CCUS at Coal-Fired Power Stations*

Storage

CO_2 Transport & Storage Cost Reduction

- Invest in CO_2 hubs and common user storage sites, ideally anchored by a large capture unit
- Plan for early phase surplus capacity in pipeline construction and installation to take advantage of the size-independent pipeline construction costs including trenching and securing of right of ways
- Plan trunk-line sections and feeder lines to maximize asset life
- Learn from others how to minimize infrastructure costs accounting for terrain, shoreline crossings & planning/environmental requirements

Integrated project

Capital & Commissioning Cost Reduction

- Build large facilities with higher capture rates to take advantage of economies of scale
- Choose site layouts to improve integration of the power and carbon capture plants and reduce interconnection and operation costs
- Include modular facility design to reduce on site construction costs and associated risks
- Balance complexity and efficiency based on local conditions and economic factors
- Choose high efficiency power plant hosts to reduce the relative impact of CCUS related parasitic load
- Develop CCUS supply chain for equipment to increase competition and spur innovation
- Stage and pre-plan power plant integration to reduce unit outage time during construction and commissioning

Operating Cost Reduction

- Reduce amine degradation costs by pre-validating the flue gas and amine compatibility
- Optimize maintenance tasks and scheduling to avoid unplanned work in order to reduce costs and production disruptions
- Re-use flue-gas produced water and waste water streams to reduce new water draws as well as disposal costs
- Improve digitalization and automation to maximize performance of the integrated operation
- Improve energy efficiency of capture (including compression), and source regeneration energy from lowest value heat source available
- Leverage operating knowledge of existing large-scale projects: e.g. health, safety, environment management, operating manuals and protocols

Advance the Business Case

- Appropriately value large coal generation units which provide grid security and ancillary services
- Enhance flexibility of coal-fired plants with CCUS to integrate with variable renewable generation sources
- Improve EOR operability and security by sourcing of CO_2 from multiple sources using transport hubs
- Invest in advanced technology research and pilot projects, along with commercial deployments
- Realize the potential value of negative emissions from biomass co-firing with CCUS to improve future economics and to allow a flexible expansion of biomass fuel sources
- Enhance policies and financing to enable private investors to realize benefits from expanded CCUS deployment

CCUS paired with coal-fired power generation is a global reality. While the application of CCUS in the power generation sector has been the primary emphasis of this report, applying the lessons learned from CCUS deployment at coal-fired power plants, as described herein, may be extended to other energy-intensive sectors as a CO_2 emissions reduction strategy and vice versa. Given the lack of available technology alternatives, many types of fossil fuel-based, emission-intensive processes will require CCUS to achieve the 2°C goal. Continued learning and knowledge from commercial CCUS installations at power plants will be directly transferable to energy-intensive industries, as will any policies and financial vehicles established to support rapid uptake of CCUS technology by the coal-fired power sector.

At the scale of emissions that may be captured from a single, large coal-fired power plant, these facilities present the unique opportunity to anchor CCUS hubs with additional, smaller industrial CO_2 sources supplementing supply for utilization and storage. The development of CCUS transport and storage infrastructure will be essential to increasing deployment of CCUS by fossil-energy-based sectors and must proceed in concert with any new CO_2 capture project development. Naturally, with the ability to rapidly build supply of CO_2, the number of end users in utilization and storage must also grow which will require appropriate government and financing levers to incentivize. Full-chain CCUS is vital to reducing global emissions in a growing world.

Recently, welcome and encouraging improvement in the pace and progress of commercial CCUS projects, undertaken in conjunction with coal-fired power and related energy-based industries, has been realized, thereby demonstrating the clear and positive commitment by industrial sectors to enhance knowledge, understanding, and critical know-how, that will inevitably lead to sustained improvement in the environmental performance of the coal power industry. Maintaining, or ideally increasing, momentum in commercial CCUS applications will make a meaningful contribution toward achieving the Paris Agreement’s 2-Degree goal.