UNIVERSITY OF WYOMING

SCHOOL OF ENERGY RESOURCES
CENTER FOR ENERGY REGULATION & POLICY ANALYSIS

WORKING PAPERS

NO. 3

Working Paper Title:

Evaluation of net zero scenarios for the Wyoming power system

Niall Mac Dowell, Yoga W. Pratama, Jada Fahy Garofalo, Kipp Coddington | 2021

CENTER FOR ENERGY REGULATION & POLICY ANALYSIS WORKING PAPERS

About the University of Wyoming School of Energy Resources' (SER) Center for Energy Regulation & Policy Analysis (CERPA) Working Paper Series

CERPA, which is one of SER's Centers of Excellence, draws upon interdisciplinary energy law, policy, technology and economic experts to conduct world-class energy analyses for the benefit of the State of Wyoming, the intermountain west region and the United States. CERPA was founded in 2020 specifically to respond to the energy challenges and opportunities facing the State of Wyoming.

The objective of the CERPA Working Paper Series is to share "works in progress". The authors of the papers are solely responsible for the content of their contributions. The working papers can be found at https://www.uwyo.edu/ser/research/centers-of-excellence/energy-regulation-policy/working-papers.html.

For more information about CERPA, please visit the CERPA web site at https://www.uwyo.edu/ser/research/centers-of-excellence/energy-regulation-policy/index.html.

University of Wyoming | School of Energy Resources
Center for Energy Regulation & Policy Analysis

Evaluation of net zero scenarios for the Wyoming power system

Niall Mac Dowell[1,2], Yoga W. Pratama[1], Jada Fahy Garofalo[2], Kipp Coddington[2]

[1] Centre for Environmental Policy, Imperial College London, London SW7 1NE, UK
[2] Center for Energy Regulation & Policy Analysis, University of Wyoming, WY 82071, USA

1 Abstract

This study presents a scenario-based techno-policy analysis of a range of pathways for Wyoming to transition to net zero. We first review the rapidly evolving policy landscape in the US, particularly in the context of policies specifically aimed at the deployment of CO_2 capture and storage (CCS) technologies applied to coal-, gas-, and biomass-fired power generation. Absent some targeted evolution of the policy landscape, the carbon intensity of Wyoming's electricity system is not anticipated to substantially reduce in the period to 2050. Beyond that, the adoption of a specific net zero emissions target for Wyoming, without further consideration of technology-specific policies, may increase costs by approximately 25% relative to a business-as-usual (BAU) scenario. The overarching conclusion of this work is that modest modifications of existing investment and production tax credits, in line with what is already being discussed, can deliver net zero emissions for Wyoming at a more than 20% cost reduction relative to a BAU scenario, and almost 50% less costly than an untargeted approach.

2 Introduction & Context

As of January 2021, 190 countries have ratified the Paris Agreement, confirming their commitment to limiting the global temperature increase to "well below 2°C" whilst pursuing efforts towards a 1.5°C limit. Achieving this goal implies reducing global greenhouse gas (GHG) emissions to net zero on average by between 2050 and 2070, and to net negative thereafter.

Since 2015, with a view to achieving this goal, there has been significant focus around the world on setting "Paris compliant" targets. In 2019, the UK made a legislative commitment to reduce its net emissions of greenhouse gases to zero by 2050. Since then, many other countries have followed suit, and, at the time of writing, approximately 61% of total CO_2 emissions, 68% of global GDP, and 56% of the global population are committed, to varying extents, to achieving net zero.[1] The vast majority of targets aim at achieving this net zero goal by 2050. Some, like China and Russia, are aiming to achieve these goals slightly later – by 2060. Others, like Sweden, are aiming to achieve net zero by 2045. The US, which recently re-joined the Paris Agreement, announced its Nationally Determined Contribution (NDC) to achieve a 50-52% reduction in economy-wide greenhouse gas emissions from 2005 levels by 2030 and a 100% carbon pollution-free electricity sector by 2035.[2]

---

[1] https://netzeroclimate.org/; https://eciu.net/analysis/reports/2021/taking-stock-assessment-net-zero-targets.
[2] https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-

As one of the leading energy-producing exporting states, Wyoming has also set a strategy for net-zero emissions by 2050; a strategy being further refined by the Wyoming Energy Authority.[3]

Achieving any net zero target is inherently complex, as the goal entails transitioning an entire economy in a relatively short space of time. Adding to this complexity is the need to create consistent policy to encourage action and increase investor confidence new technologies. In this context, it is revealing that only 44% of existing net zero commitments include a public plan, and only 20% meet the basic robustness criteria set out by the UN Race to Zero Campaign.[1] This is important as clarity on the detail of these commitments will be key to setting the interim targets that will be required to support investment in actual projects. Equally important are consistent laws and policies that encourage the use of important technologies and help to achieve net zero goals.

There is an abundance of evidence from, *inter alia*, the IPCC and IEA illustrating the uniquely important nature of carbon capture and storage (CCS) technologies in achieving a net zero outcome in a reliable and affordable way.[4] Moreover, there is a multidimensional benefit of using CCS technologies to achieve net zero outcomes. Not only are CCS technologies available for commercial scale deployment for the decarbonisation of electricity, but, once decarbonised, electricity has a compounding emissions-reduction effect in the electrification of other sectors such as heating, building, transportation, and industrial sectors.

This evidence notwithstanding, actual deployment of CCS technology has lagged substantially behind what is understood to be required in order to meet climate targets.[5] Thus, even though CCS technology is technically mature,[6] it remains immature from a commercial perspective.[7] Historically, the commercial deployment of CCS has been challenged on three distinct fronts; the large, up-front capital and ongoing operating costs associated with deploying and operating the CO_2 capture and compression equipment, and – perhaps most importantly – the challenge of accessing CO_2 transport and storage infrastructure. This latter point is particularly important for the development of strategic infrastructure. Absent policy incentives to overcome these barriers, investment in CCS technologies has been stymied.

Given the recognized benefits of, and growing interest in, using CCS technologies to achieve net zero goals, this study focuses on identifying and aligning policy and technology pathways towards a net zero electricity grid. Owing to a combination of federal and state government, US energy policy is distinct to that of other countries. In this context, there is the potential for tension between priorities at the federal and state level, should priorities and/or incentives become misaligned. This study focusses on the US in general, and on the state of

clean-energy-technologies/; https://sdg.iisd.org/news/us-sets-target-to-reduce-emissions-by-50-52-below-2005-levels-in-2030/.
[3] https://www.wyoenergy.org/energy-strategy/.
[4] IEA, Net Zero by 2050: A roadmap for the global energy sector, 2021; IPCC Fifth Assessment Synthesis Report, 2014.
[5] Global CCS Institute, Global Status of CCS 2021, 2021.
[6] Bui, M., et al, "CCS: the way forward", Energy & Environmental Science 11 (5), 1062-1176, 2018.
[7] Donovan, C., Hardy, J., Hindle, J., Mac Dowell, N., and Ostrovnaya, A., "Lending to low carbon technologies", HSBC Centre of Sustainable Finance, 2019.

Wyoming in particular, and evaluates how polices that support CCS can be more influential in delivering affordable and reliable power generation that is also aligned with a net zero outcome.

The study evaluates the interplay between federal- and state-level policies in the context of a broader net zero transition. As a state with a combination of substantial coal resources – both mineral resources and generating assets – and an objective to reach net zero by 2050 with focus on CCS technologies, Wyoming is a state with ample interest and ability to illustrate the combined impact of federal and state level policies and incentives for CCS technologies.[8]

3 Policy context – The US & Wyoming

In the US, the policy landscape is characterised by a combination of federal and state-level commitments running in tandem with the nation's renewed international commitment under the Paris Agreement. From 2005 to 2019 (fifteen years), the US reduced its greenhouse gas emissions by 12%.[9] At least 40% further reductions are necessary to achieve the 50-52% percent reduction by 2050 (in the next twenty-nine-years), and even more drastic reductions will be necessary from the electric power generation sector to achieve carbon pollution-free electricity by 2035 – a goal of the current federal administration. Though the US recently announced plans to "leverag[e] the carbon pollution-free energy potential of power plants retrofitted with carbon capture," historically the country has not seen commercial scale deployment of CCS technologies.

In the context of CCS, there are both federal- and state-level incentives for CCS technologies and infrastructure, but the full potential of incentive applicability to commercial-scale projects has not been realized. In part, this is due to the lack of system-wide infrastructure, which limits the connectivity of major CO_2 emitters to available geologic sequestration sites.

The recently passed SCALE Act begins to address the infrastructure quandary by providing funding for previously lacking yet integral infrastructure.[10] The SCALE Act creates a CO_2 Infrastructure Finance and Innovation Act (CIFIA) program, which awards the Department of Energy (DOE) $600 million in fiscal year (FY) 22 and FY 23, and $300 million in FY 24 through FY 26 for the administration of a low-interest loan, guarantee, and grant program to support CO_2 transportation, such as pipeline projects, in excess of initial demand to support growth in the transportation and sequestration industry.[11] The Act also expands the DOE's CarbonSAFE program, which develops and commercializes geologic sequestration and associated transportation infrastructure, prioritizing locations that have potential for large-scale storage as "hubs" for multiple-source storage. When CO_2 is injected and stored, "Class VI" wells, regulated by the EPA under the Underground Injection Control (UIC) Program, are used.[12] States may apply for and receive what is called "primacy", or the ability to

---

[8] https://www.wyoenergy.org/news/energy-opportunities-from-governor-gordons-2021-state-of-the-state/; https://subscriber.politicopro.com/article/eenews/1063727201.

[9] https://www.epa.gov/climate-indicators/climate-change-indicators-us-greenhouse-gas-emissions.

[10] https://www.congress.gov/bill/117th-congress/senate-bill/799/text.

[11] https://www.mayerbrown.com/en/perspectives-events/publications/2021/08/us-scale-act-of-2021-storing-co2-and-lowering-emissions-act#:~:text=The%20SCALE%20Act%20is%20intended,air%20capture%2C%20and%20must%20be

[12] *Id*.

administer the EPA's Class VI permitting system. To support efficient permitting, for FY 22 through FY 26, the SCALE Act provides $5 million for EPA permitting of Class VI wells and $50 million for state permitting of Class VI wells.[13] Finally, the SCALE Act supports the production of products made with captured CO_2 by appropriating between $41 million and $69 million from FY 22 through FY 26.[14]

The second component of the unrealized, yet potentially impactful, incentives for CCS commercial deployment are two federal tax credits -- Sections 48A and 45Q of the federal tax code. These provisions have significant potential to support the transition to net zero in the US, and particularly in Wyoming, but in their current form their applicability and impact are constricted.

Congress enacted section 48A of the Internal Revenue Code when it passed the Energy Policy Act of 2005.[15] The incentive is designed to reduce carbon dioxide emissions from coal-fired generation through efficiency upgrades.[16] Section 48A authorizes tax credits for integrated-gasification combined-cycle projects with a credit rate of 20%, qualifying advanced coal-based electricity generation technology (ACBGT) projects with a credit rate of 15%, and tax credits for non-electricity generating advanced coal-based technology projects with a credit rate of 30%.[17] Taxpayers have five years to place projects into service if tax credits are allocated under section 48A.[18]

However, as written, section 48A has limited applicability to CCS projects because it is not possible to simultaneously retrofit with CCS and improve the efficiency of the base plant.[19] Consequently, whilst approximately $1B has been awarded to "clean coal" projects, section 48A has never been applied to CCS projects. An additional feature of section 48A is the fact that the credit provides only limited funds for allocation.[20] Once these funds are distributed, the tax incentive is not available anymore.[21] Finally, the credit is only available to taxpaying entities, which limits availability of incentives to for-profit entities and excludes non-profit owned generation facilities, such as cooperatives.[22]

Modifications to section 48A that would increase its applicability across the electricity generation sector include removing the cap on funds for the incentive, reducing the efficiency requirement so the incentive would be available to CCS projects, and encouraging a direct pay option that would allow the incentive to be more easily used by non-taxable entities, like cooperatively-owned electricity generators (as is presently suggested in modifications to the section 45Q credit). Introduced in March 2021, the Carbon Capture Modernization Act sets out to amend the language of the tax incentive which would allow coal-fired power plants retrofitted with CCS

---

[13] *Id*.
[14] *Id*.
[15] Pub. L. 109-58, Title XIII, § 1307(b), Aug. 8, 2005, 119 Stat. 999 (as amended).
[16]https://www.iea.org/policies/11668-section-48a-qualifying-advanced-coal-project-credit ; 26 U.S.C. § 45A.
[17] https://fas.org/sgp/crs/misc/R43690.pdf at 6 (this has a bit about liability at 10); 26 U.S.C. 48A(d)(3).
[18] https://sgp.fas.org/crs/misc/R43690.pdf at 7.
[19] https://www.iea.org/policies/11668-section-48a-qualifying-advanced-coal-project-credit
[20] https://sgp.fas.org/crs/misc/R43690.pdf at 11-12.
[21] https://sgp.fas.org/crs/misc/R43690.pdf at 11-12.
[22] https://sgp.fas.org/crs/misc/R43690.pdf.

technology to benefit from the 30% tax credit.[23] It is noteworthy that the suggestion to modify section 48 of the tax code in this way was also identified as key by the NPC study to "meeting the dual challenge".[24]

Congress enacted section 45Q when it passed the Energy Improvement and Extension Act of 2008.[25] The section 45Q tax credit incentivizes CCS projects by allowing a tax credit for each metric ton of qualified carbon oxide[26] captured and sequestered in secure geologic storage, used for enhanced oil recovery (EOR), or used in another manner as specified by the law.[27] Congress has modified the section 45Q tax credit four times since it was initially created: in the American Recovery and Reinvestment Tax Act (ARRA) of 2009; in the Tax Increase Prevention Act of 2014; in the Bipartisan Budget Act (BBA) of 2018; and most recently, in 2020, with the Energy Act.[28] While each change to the tax credit has led to an increase in the credit's applicability to industry, the credit still contains provisions that constrain its ability to facilitate commercial-scale deployment of CCS technology.

Because the amount of the credit depends in part on the date carbon capture equipment is put into service,[29] equipment placed in service prior to the enactment of the BBA (February 9, 2018), is only awarded $20 per metric ton of carbon sequestered,[30] while equipment placed in service on or after the BBA of 2018 and for twelve years after the date of installation, is awarded up to $50 per metric ton of carbon sequestered.[31] Under current law, to calculate the credit amount for any taxable year after 2026, the credit should equal the "product of the respective credit per metric ton of carbon sequestered (values above).[32]

Despite the availability of section 45Q, the incentive has not been broadly used to attain commercial-scale deployment of CCUS technology. This is due to a myriad of reasons, some of which include the limited

---

[23] https://www.congress.gov/bill/117th-congress/senate-bill/661/text/is
[24] https://dualchallenge.npc.org/downloads.php
[25] Pub. Law. 110-343, 110th Congress, 122 Stat. 3765, Oct. 3, 2008
[26] "Qualified carbon oxide" is defined in the statute as:

> any carbon dioxide which-- **(i)** is captured from an industrial source by carbon capture equipment which is originally placed in service before the date of the enactment of the Bipartisan Budget Act of 2018, **(ii)** would otherwise be released into the atmosphere as industrial emission of greenhouse gas or lead to such release, and **(iii)** is measured at the source of capture and verified at the point of disposal, injection, or utilization[;] any carbon dioxide or other carbon oxide which--**(i)** is captured from an industrial source by carbon capture equipment which is originally placed in service on or after the date of the enactment of the Bipartisan Budget Act of 2018, **(ii)** would otherwise be released into the atmosphere as industrial emission of greenhouse gas or lead to such release, and **(iii)** is measured at the source of capture and verified at the point of disposal, injection, or utilization[;] or in the case of a direct air capture facility, any carbon dioxide which-- **(i)** is captured directly from the ambient air, and **(ii)** is measured at the source of capture and verified at the point of disposal, injection, or utilization. (26 U.S.C. § 45Q(c) (some internal numbering omitted).

[27] https://www.mayerbrown.com/en/perspectives-events/publications/2021/01/irs-issues-final-carbon-capture-regulations; 26 U.S.C. § 45Q.
[28] https://www.federalregister.gov/documents/2020/06/02/2020-11907/credit-for-carbon-oxide-sequestration; https://clearpath.org/our-take/energy-act-of-2020-could-reduce-co2-emissions-by-2500m-metric-tons/#:~:text=Elsewhere%20in%20the%20Energy%20Act,ton%20of%20CO2%20sequestered.
[29] https://www.federalregister.gov/documents/2020/06/02/2020-11907/credit-for-carbon-oxide-sequestration; https://clearpath.org/our-take/energy-act-of-2020-could-reduce-co2-emissions-by-2500m-metric-tons/#:~:text=Elsewhere%20in%20the%20Energy%20Act,ton%20of%20CO2%20sequestered.
[30] 26 U.S.C. § 45Q(a).
[31] 26 U.S.C. § 45Q(a)-(b). The actual amount of the credit is established by linear interpolation between $22.66 and $50.00 for geologic sequestration and between $12.83 and $35 for EOR and other beneficial uses. (*See* 26 U.S.C. § 45Q(b)).
[32] 26 U.S.C. § 45Q(b)(ii); see also: https://www.dgslaw.com/news-events/treasury-issues-final-regulations-on-section-45q-tax-credits-for-carbon-capture-and-sequestration.

applicability of tax incentives to non-profits, the time lag between the commence construction window in the statute and deployment ability of commercial scale technology,[33] the low value of the credit, and the annual capture thresholds in the statute that reduce the applicability of the credit.

At the time of writing, there are multiple federal bipartisan bills in play in the 117th Congress, aspiring to enhance the applicability of the section 45Q tax credit.[34] While this proposed legislation varies, certain trends have emerged, including provisions for direct pay, an extended commence construction deadline, an increase in the value of the credit, and a reduced eligibility threshold -- changes that could drastically impact the credit's ability to advance CCS projects. This study specifically evaluates the Build Back Better Act (BBBA),[35] which seeks to advance a variety of President Biden's domestic policies through the use of budget reconciliation procedures which should enable the U.S. Senate to pass it with only 50 votes, thus bypassing the filibuster. Early this fall, various committees in the U.S. House of Representatives passed relevant components of the BBBA. Thereafter, White House and Congressional negotiators have been working to reduce the legislation's size, which was originally $3.5T and, based on the most recent version released by the House Rules Committee on October 28, 2021, is now down to approximately $1.7T.

Under the current version of the BBBA, the bill would amend section 45Q to provide for an extension to the so-called "commence construction" window to Jan 1, 2032, allow for direct pay up to the full credit value over a twelve-year period, provide for an enhanced credit value up to $85/mt CO_2 for industry and power if the wage and apprenticeship requirements are met, and implement a facility-wide percentage capture requirement of 75% for power generation.[36]

Extending the 2026 commence construction deadline would allow for industry and technology to scale up to the extent needed to provide reliable electricity supply for electrification of the electricity sector by 2035 and other economic sectors by 2050.[37] Direct pay would alleviate burdensome tax equity transactions and allow non-profits, like cooperatively owned electricity generation facilities, to benefit from the incentive. With nearly 30% of residential electricity customers served by cooperatives, direct pay could drastically expand applicability of section 45Q.[38] Raising the credit value will drive capital investments in the commercial-scale deployment of the technology.[39]

---

[33] 26 U.S.C. § 45Q(d); https://home.kpmg/us/en/home/insights/2020/12/tnf-favorable-tax-provisions-renewable-energy-industry-enacted.html.

[34] https://carboncapturecoalition.org/wp-content/uploads/2021/09/Proposed-AJP-and-Infrastructure-Investments.pdf.

[35] https://www.congress.gov/bill/117th-congress/house-bill/5376.

[36] https://rules.house.gov/sites/democrats.rules.house.gov/files/BILLS-117HR5376RH-RCP117-17.pdf.

[37] https://www.electric.coop/nreca-to-congress-give-co-ops-direct-pay-incentives-for-clean-energy; (Carbon Capture Utilization and Storage Tax Credit Amendments Act of 2021, S. 986; Clean Energy for America Act, S. 1298; ACCESS 45Q Act, H.R. 1062; GREEN Act of 2021, H.R. 848; H.R. 2633).

[38] https://www.electric.coop/nreca-to-congress-give-co-ops-direct-pay-incentives-for-clean-energy; (*See* Carbon Capture Utilization and Storage Tax Credit Amendments Act of 2021, S. 986; Clean Energy for America Act, S. 1298; ACCESS 45Q Act, H.R. 1062; GREEN Act of 2021, H.R. 848; H.R. 2633).

[39] *See* Carbon Capture Utilization and Storage Tax Credit Amendments Act of 2021, S. 986; Clean Energy for America Act, S. 1298; CATCH Act, S. 2230; CATCH Act, H.R. 3538; H.R. 2633. *Id*.

These federal incentives apply concurrently with Wyoming laws that encourage CCS technology. The state of Wyoming, is an energy and a coal "hub." In terms of its raw resources, it is the top coal-producing state in the US, and holds more than one third of US coal reserves in producing mines.[40] In terms of electricity generation, in order of precedence, the state relies on coal-fired generation, renewable energy, natural gas, and hydroelectric generation.[41] Given the socio-economic importance of coal, both for its extraction and subsequent conversion to electric energy, it is unsurprising that the state has heavily encouraged the use of coal-fired generation and discouraged the retirement of coal assets.

At the state level and since 2017, Wyoming has taken broad steps to encourage CCS.[42] Primarily, House Bill 0200, now codified in at sections 37-18-101 through 102 of the Wyoming Statutes requires the Wyoming Public Service Commission (PSC) to develop rules (presently underway) that will set electricity generation portfolio standards that require use of "dispatchable," "reliable," and "low-carbon electricity."[43] The statutes encourage the use of CCS because the statute defines "dispatchable and reliable low carbon electricity" as using CCS technology and producing not greater than 650 pounds of CO_2/megawatt hour (MWh), averaged over a year.[44]

Wyoming Statutes, sections 37-3-117, 37-3-118, and 37-2-133 also encourage the continued operation of coal-fired generation. These statutes create a disincentive to retire and an incentive to sell coal-fired power plants starting in 2022. Every utility seeking to retire a coal-fired electric generation facility must first make a "good faith effort" to sell the facility for continued use as a coal fired electric generation facility, otherwise the utility will not be able to recover earnings on capital costs associated with new generation and there may be requirements to purchase electricity from the sold coal-fired plant.[45] Utilities retiring their coal-fired plants must also demonstrate that the retirement will not lead to added costs to ratepayers or less reliable service.[46]

In addition to overtly supporting coal-based generation and CCS, Wyoming also taxes the sale of electricity produced from wind at $1.00 per MWh and the sale of electricity produced from nuclear reactors at $5.00 per MWh.[47] The tax on nuclear-generated electricity was imposed in 2021 and does not apply to facilities owned by any arm of government or on demonstration-scale small nuclear reactors (SMRs).[48] While the Wyoming legislation did recently pass a law allowing any utility or person owning a coal or gas plant to apply to replace the plant with a SMR, it is unclear how this provision will interact with the above provisions disincentivizing the retiring of coal facilities.[49]

In recent years, the Wyoming Legislature has considered, but never enacted, a variety of bills that would disincentivize solar projects in the state. Although those bills have never advanced, the proposition has signalled

40 https://www.eia.gov/state/?sid=WY#tabs-4.
41 https://www.eia.gov/state/?sid=WY#tabs-4.
42 W.S. § 37-3-117, W.S. § 37-2-133; W.S. § 37-2-134; W.S. § 37-2-122; W.S. § 37-3-118; W.S. §§ 37-18-101–102.
43 W.S. §§ 37-18-101–102.
44 W.S. §§ 37-18-101–102.
45 W.S. § 37-3-117; W.S. § 37-3-118; W.S. 37-2-133.
46 WS § 37-2-134.
47 WS § 39-22-101; WS § 39-23-101 et. seq.
48 WS § 39-23-101 et. seq.
49 WS § 35-11-2101.

to solar project developers that the state may not provide a welcoming and economically favourable environment for such projects.

Despite the historic reticence toward commercial deployment of CCS technology, there is reason for optimism that deployment of CCS technology could accelerate due to recent legislative action and interest in CCS. In the study below, the authors evaluate the impact of these policies on Wyoming's generation profile to assess how the federal "carrot" incentives for CCS work with the state "stick" deterrents of other types of generation in Wyoming. The study examines a) an improved 48A; b) an improved 45Q based on the provisions in the BBBA; and c) Wyoming's wind and nuclear tax.

4 Approach & Methodology

This study uses the Electricity Systems Optimisation (ESO) framework[50,51] to identify and provide insight into least-cost pathways for the evolution of cost of electricity system transitions that can satisfy the electricity demand, system reliability, and CO_2 emissions requirements in relevant scenarios. As opposed to comparing individual technology costs, the ESO framework minimises total system cost by selecting the optimal capacity deployment and hourly dispatch schedules of each technology on the grid. Accordingly, the system integration cost of each technology and technology utilisation factor, *i.e.*, the actual capacity factor as opposed to expected capacity factor, including renewables curtailment, are explicitly accounted for. In this model, system reliability requirements are implemented *via* reserve and system inertia constraints. Here, we assume that wind and solar alone do not contribute to system inertia, and, therefore, synchronous compensator technology is included in the model.

One persistent challenge with energy systems modelling is ensuring that descriptions of projected capacity deployment is as faithful as possible to reality. Often, constant deployment rates are assumed, which does not reflect the increase in capacity deployment capability that has been observed in the context of sustained policy support. For example, as can be observed from **Error! Reference source not found.**, Germany's ability to deploy additonal onshore wind capacity approximately doubled in every five year period between 1995 and 2020.

[50] Heuberger, Rubin, *et al.*, 2017.
[51] Heuberger, Staffell, *et al.*, 2017.

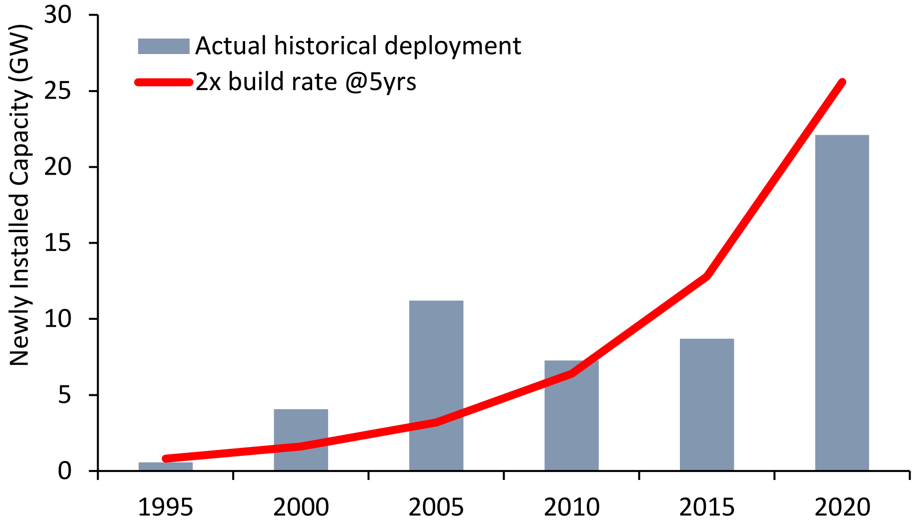

Figure 1. Historical onshore wind deployment in Germany. As can be observed, the grey bars reflect actual historical deployments of onshore wind between 1995 and 2020, whilst the red line shows projected additional capacity deployed until 2020 using the 1995 level as baseline, assuming a doubling period of five years.

Thus, in this study, we allow the deployment rate of renewable energy and energy storage technologies to exponentially increase, *i.e.*, build rates of renewable and storage technologies can double every 5 years. This assumption is consistent with what can be achieved under a supportive policy paradigm, and thus represents a reasonable best-case scenario for the deployment of renewable generating capacity. which demonstrates an extensive development of VRE capacity.

Mathematically, this is described as follows. To adopt and implement the assumption, build rates (b) of each technology (i) and period (a) are set as endogenous variables using build rate multiplier (BRM) of 2 and BR as the initial build rate of each technology, as shown in Equation (1). Equation (2) forces the binary variable bBR to 1 if the build rate of the previous period is greater than 0 which, in turn, forces $b_{i,a}$ to be a function of $b_{i,a-1}$. If $b_{i,a-1}$ is equal to 0, Equation (1) uses the initial build rate BR as the upper bound of $b_{i,a}$.

$$b_{i,a} \leq BRM_i \, MA_{i,a} \left(b_{i,a-1} + BR_i \left(1 - bBR_{i,a}\right) \Delta_a \, / \, BRM_i\right) \tag{1}$$

$$b_{i,a-1} \leq bBR_{i,a} \, M \tag{2}$$

Any net zero transition will be driven as much by policy considerations as by technical constraints. Thus, in order to reflect the various decarbonisation strategies that cover the emissions target, CCS capture rate, financial incentives, and policy drivers that may evolve in Wyoming, a scenario-based approach is adopted. In order to describe the rapidly evolving policy landscape, six distinct scenarios have been formulated to closely relate to current policy considerations and are set out in Table *1* below.

Table 1. Scenario definition. Here, CCS stands for "Carbon Capture and Storage", HELE stands for "High Efficiency, Low Emissions" power plants, and typically describes ultra-supercritical or integrated gasification combined cycle (IGCC) power plants.

Scenario	45Q			48A techs.	Tech. tax ($/MWh)		CCS capture rate (%)	2050 emissions target
	Deadline	Value ($/t)	Mechanism		Wind	Nuclear		
BAU	2026	50	Tax credit	HELE	-	-	70	N.A.
Net Zero Reference	2026	50	Tax credit	HELE			70	Net Zero
Enhanced 45Q	2032	85	Tax credit	HELE	-	-	70	Net Zero
Direct Pay 45Q	2032	85	Direct payment	HELE	-	-	70	Net Zero
Modified 48A	2032	85	Direct payment	CCS & HELE	-	-	70	Net Zero
WY Law	2032	85	Direct payment	CCS & HELE	1	5	70	Net Zero
90% CCS	2032	85	Direct payment	CCS & HELE	1	5	90	Net Zero

In the Business as Usual (BAU) scenario, the current policy paradigm is maintained, i*.e.*, 45Q is available at a maximum level of $50/t, 48A is not applicable to CCS, there is no binding emissions constraint, and all technologies are deployed in line with historical build rates for mature technologies, such as nuclear and thermal plants.

We first define and evaluate a Net Zero Reference scenario; wherein existing policies are unchanged, and no emission reduction target is imposed. Subsequently, we evaluate a set of scenarios with an end point constraint which requires that CO_2 emissions decline linearly to net zero by 2050. We then evaluate an Enhanced 45Q scenario where the level of the production tax credit is increased to $85/t, and the "commence construction" window is extended to 2032. Next, we evaluate a Direct Pay 45Q scenario where the 45Q tax credit is modified to reflect a direct pay option, allowing both for-profit and not-for-profit entities to benefit from it. Given the difficulty non-profit utilities often face to utilize tax credits, we assume that both the 45Q and the 48A tax credits are not available for non-profit utilities until direct pay options are available. Then, a Modified 48A scenario is evaluated wherein the 48A investment tax credit is assumed to be modified such that CCS projects – which decrease the power generation of the asset – qualify for the investment tax credit and direct pay is available. Following this, the impact of two key state-level policies, i.e., a production tax on wind and nuclear power, is evaluated. Finally, incumbent policies often assume that the facility-wide CO_2 capture level is approximately 75%. However, this results in a substantial amount of residual CO_2 emitted to atmosphere – and a potential opportunity cost in terms of lost revenue from tax credits. Thus, we also evaluate a 90% CCS scenario wherein the capture rate of all *units* is 90%.

5 Results & Discussion

First, we present the results of the reference BAU scenario. Here, as may be observed from Figure 2 below, absent any significant policy intervention, coal is anticipated to remain dominant in Wyoming's power system. As the existing coal fleet ages out, high efficiency, low emissions (HELE) coal-fired assets are deployed to fill the gap.

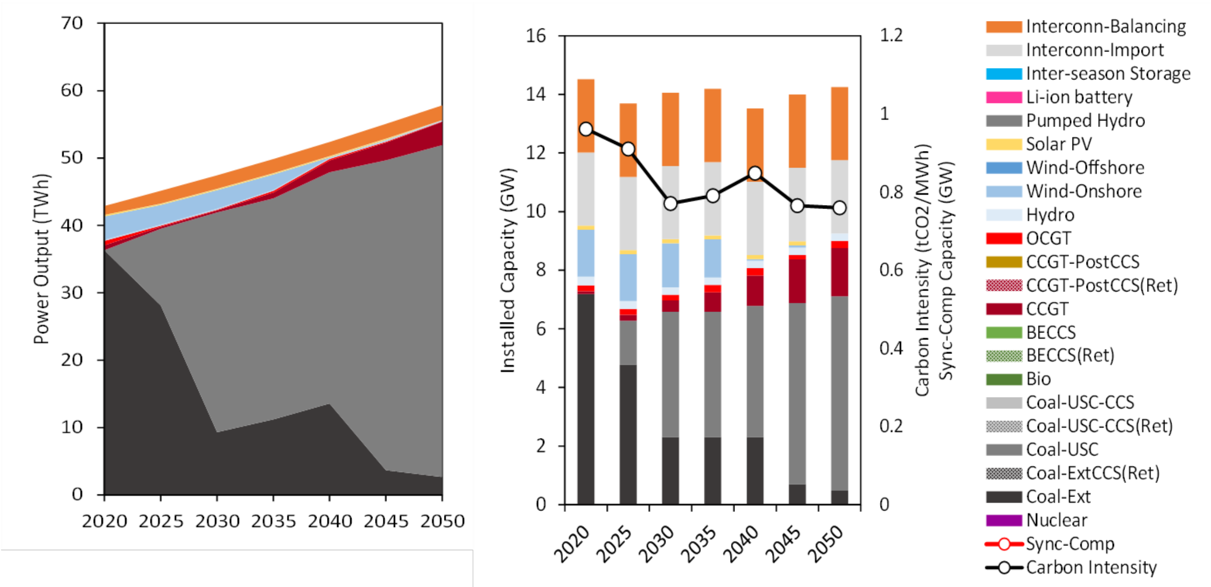

Figure 2: Electricity and capacity mix of Wyoming in the BAU scenario, i.e., 45Q remains at \$50/tCO2 and is exclusively available as a tax credit, i.e., not available to non-profit organisations such as Wyoming's co-ops. Similarly, 48A is assumed to require an efficiency improvement and is thus available only for high-efficiency, low-emissions (HELE) power plants, such as IGCC or USC coal. Moreover, to qualify for 45Q, construction must commence in 2026. Consequently, 75% of existing coal capacity will be retired by 2030, replaced by more efficient ultra-supercritical coal, reducing the carbon intensity of power generated in Wyoming from 0.95 t/MWh to 0.74 t/MWh.

If, as illustrated in Figure 3 below, Wyoming seeks to achieve a net zero emissions outcome in 2050 without further policy intervention, one can expect significant qualitative and quantitative changes to Wyoming's electricity system. In the Net Zero Reference scenario, for an intermediate period, the existing coal fleet will age out and will be replaced by HELE technology. In the near term, Wyoming may be anticipated to develop a capability to deploy more renewable power capacity (wind and solar power), which will be balanced by CCGT and, increasingly, CCGT-CCS technology, with nuclear power being deployed from the mid-2030s on to provide a supply of baseload energy. Concurrently, the total installed capacity increases from approximately 14 GW in 2050 in the BAU scenario to approximately 27 GW in this scenario. In terms of total system costs, this outcome is expected to be approximately 25% more costly than the BAU case.

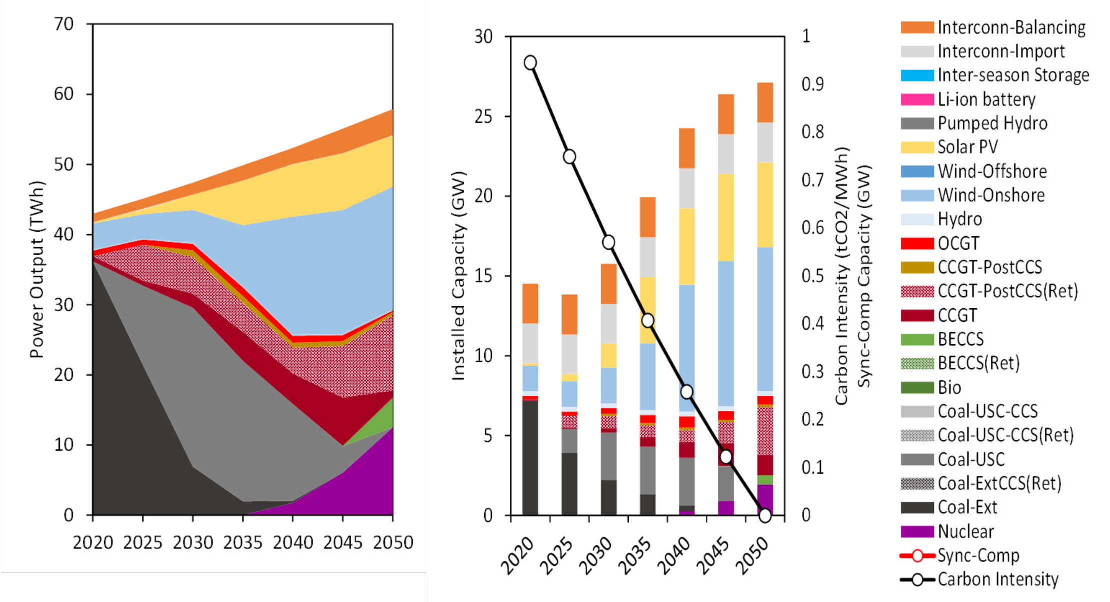

Figure 3: Electricity and capacity mix of Wyoming in the Net Zero Reference scenario, i.e., the BAU scenario but with net zero emissions target by 2050. Here, coal is largely phased out, initially by replacing the existing fleet by HELE options, and subsequently with nuclear power, as the CO_2 emission constraint becomes more pressing. When deployed, nuclear will play a significant role for providing baseload generation. Importantly, the role of onshore wind and solar PV significantly increases, which require flexible, low carbon capacity to balance it, leading to the deployment of CCGT-CCS.

At the time of writing, the US is considering increasing the level of 45Q to \$85/t CO_2 and extending the "commence construction" window to 2032. Thus, in the Enhanced 45Q scenario, we evaluated the impact of these modifications on Wyoming's electricity system in the context of a net zero target – the results are illustrated in Figure 4, below. This time, owing to the increased level of the 45Q tax credit, many of the privately-owned coal-fired power plants, which thus have sufficient tax liability to take advantage of the opportunity to retrofit CCS technology, are able to extend the economic lifetime of these facilities for the medium term. However, given that a substantial fraction of the Wyoming coal fleet is owned on a not-for-profit basis, it is not eligible to take advantage of the 45Q credit in its current guise as a tax credit. Natural gas is also observed to play an increasingly important role, with a combination of retrofit and new-build CCGT-CCS facilities appearing. However, in the longer term (post-2040), owing to the high level of residual emissions, coal – even with CCS – is phased out in favour of nuclear power, complemented with CCGT-CCS, where residual emissions are compensated for by a small amount of bioenergy with CCS (BECCS) and renewable energy.

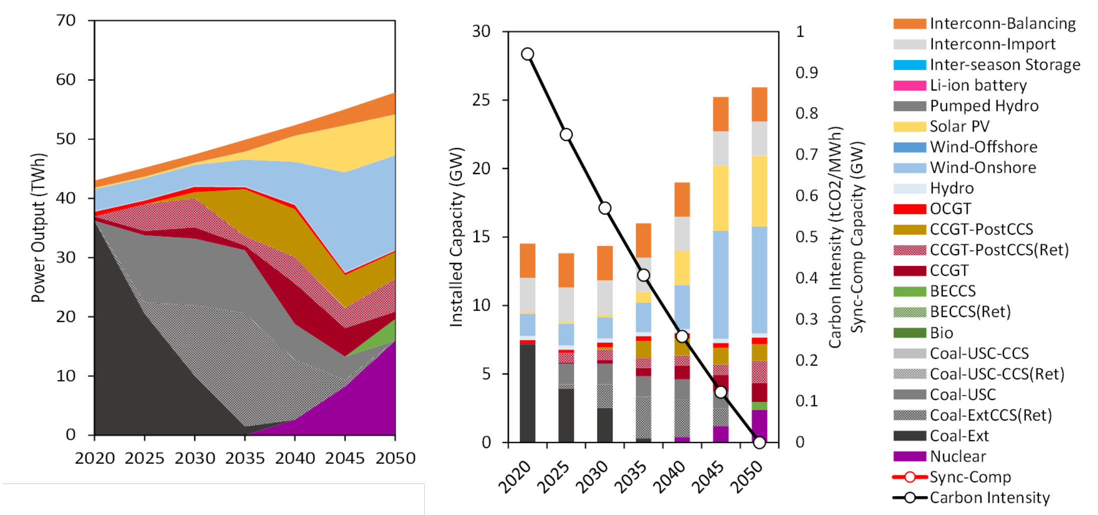

Figure 4: Electricity and capacity mix of Wyoming under the Enhanced 45Q scenario, i.e., a net zero scenario with an enhanced 45Q tax credit of 85 $/t and the "commence construction" window is extended from 2026 to 2032. Owing to the increased 45Q tax credit, the lifetime of a significant share of existing coal can be extended via CCS retrofit while the retiring coal is replaced by coal USC. Notwithstanding this, all coal needs to be decommissioned by 2050 for meeting the net zero target.

If 45Q is modified to a "direct pay" option, it becomes available to a greater number of Wyoming's coal plants. However, as illustrated in Figure 5, in the Direct Pay 45Q scenario the same long term emission constraints essentially eliminate coal, unless almost all the CO_2 is directly abated.

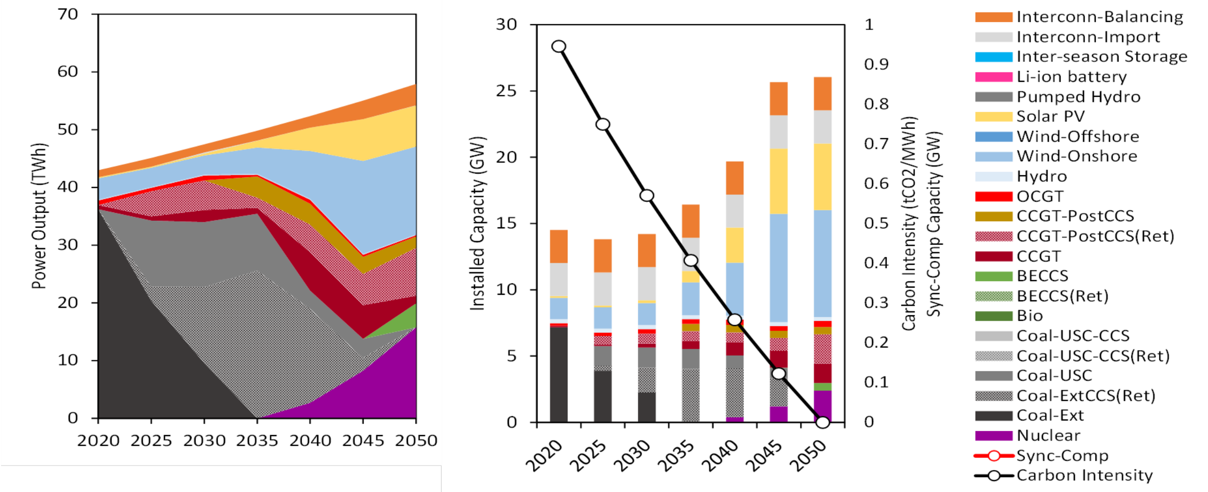

Figure 5: Electricity and capacity mix of Wyoming under the Direct Pay 45Q scenario, i.e., where 45Q is further modified to a "direct payment" option and is thus available to all stakeholders. As can be observed, the share of retrofitted coal-CCS between 2025 and 2045 increases, reducing the share of coal-USC and CCGT-CCS.

The next thought experiment evaluates the impact of modifying the language of 48A so as to make it available to CCS projects. Here, as illustrated in Figure 6 in the Modified 48A scenario, in the near term the amount of power generated by coal was observed to increase for the first time. However, once again, absent near-zero emissions from coal-CCS plants, coal is phased out in the longer term.

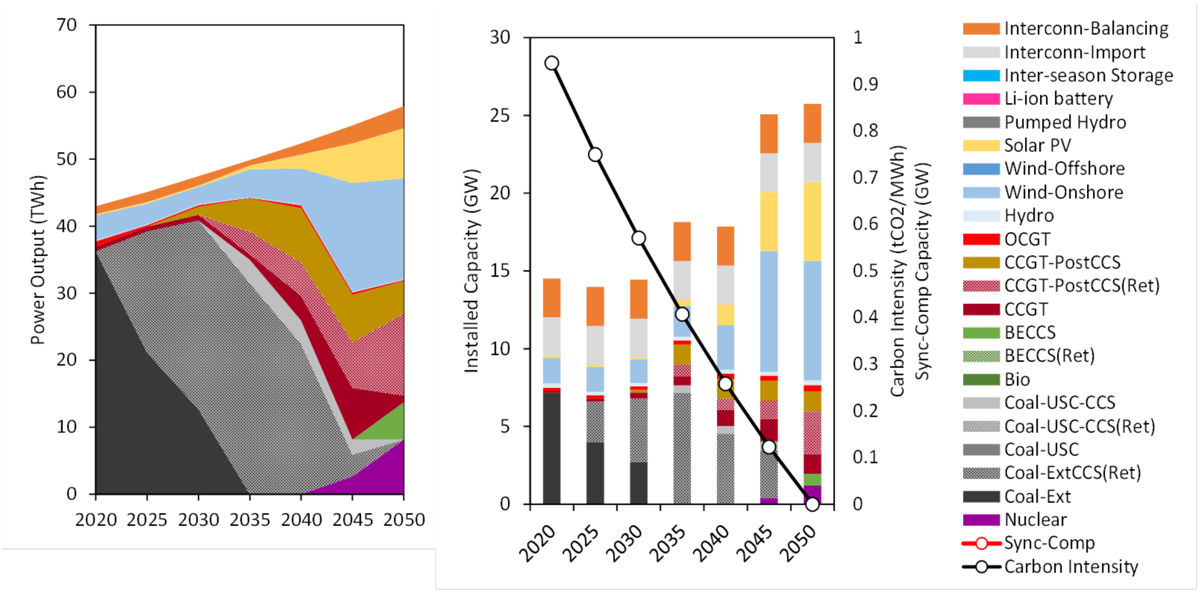

Figure 6: Electricity and capacity mix of Wyoming under Modified 48A scenario, i.e., where CCS is assumed to be eligible for the 48A credit. As shown, making CCS eligible for the 48A tax credit will significantly increase CCS retrofit on existing coal fleets in Wyoming while substantially decreasing the role of coal USC.

What is also observable from Figure 6 is that the modification to 48A substantially increases the role of CCGT-CCS, which has the impact of reducing the role of nuclear power in the longer term.

We next include the impact of Wyoming- specific legislation on Wyoming's generation profile, namely a tax on wind and nuclear generation of $1 and $5 per MWh, respectively. These results are illustrated in Figure 7 below, the WY Law scenario. Given that wind power is already a near zero marginal cost technology, this production tax does not have a noticeable impact on either the amount of wind capacity installed or on the contribution of wind to Wyoming's electricity system. The $5/MWh tax on nuclear power is meaningful, however, and has the impact of substantially reducing the role of nuclear power throughout the system.

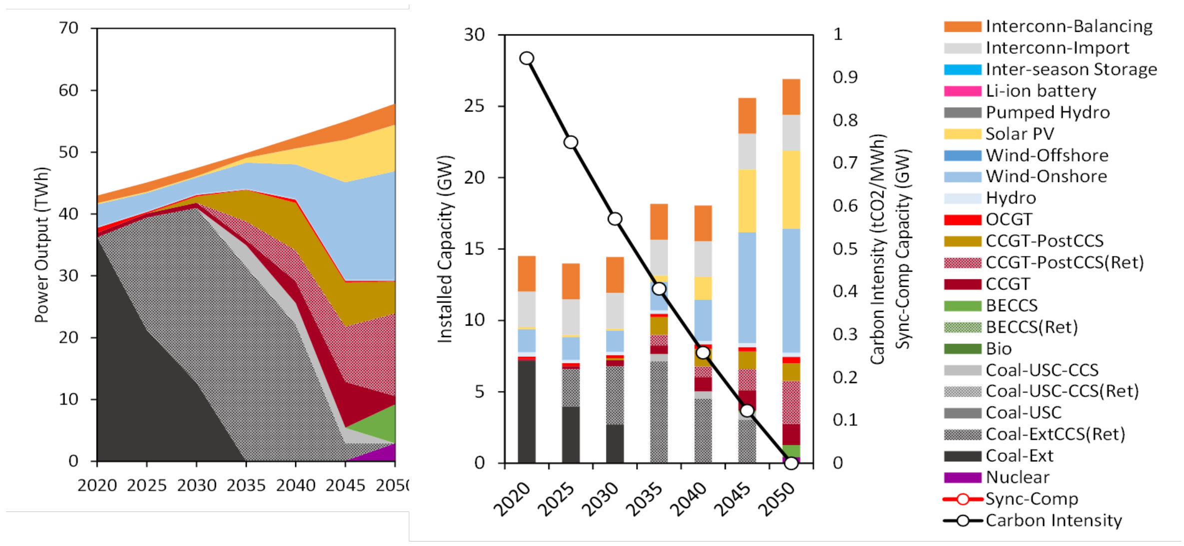

Figure 7: Electricity and capacity mix of Wyoming under the WY Law scenario, i.e., the inclusion of a $1/MWh and $5/MWh production tax for onshore wind and nuclear generation. It can be observed that the wind and

nuclear taxes lead to a significantly reduced share of nuclear, replaced by CCGT-CCS and BECCS. Similarl to the previous scenarios, all coal-based power plants are observed to be decommissioned by 2050.

The final scenario enables the coal- and gas-fired power plants to capture 90%, or more, of their CO_2 emissions. Importantly, this is eminently possible and has been demonstrated at operating facilities, such as the Boundary Dam facility in Canada, with a number of academic studies[52,53,54] indicating that the marginal cost of increasing the rate of capture is very low. The results of this thought experiment are presented in the 90% CCS scenario in Figure 8 below.

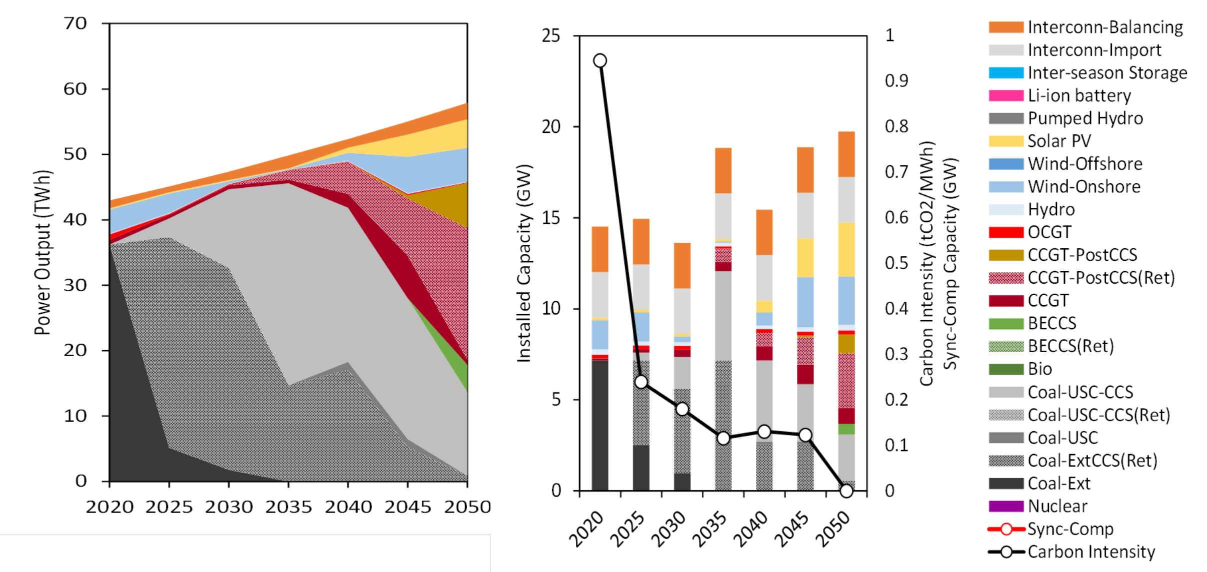

Figure 8: Electricity and capacity mix of Wyoming under the 90% CCS scenario. This figure shows that higher capture rate substantially increases the share of coal in the electricity system transition in Wyoming. The share of coal-CCS peaks in 2035 but gradually decreases afterward due to the end of the 45Q 12-year duration. However, 13 TWh/year of coal CCS generation in 2050 can be expected if the 90% capture rate CCS is adopted. Given that near zero emissions from coal-CCS are possible, a substantial role for coal in a net zero paradigm for Wyoming is therefore entirely possible.

Here, once the coal- and gas-fired power plants are able to capture the vast majority of their CO_2 and benefit from the improved production and investment tax credits, the future of Wyoming's generation profile is once again qualitatively and quantitatively altered. Here we see CCS playing a very significant role when applied to both coal- and natural gas-fired power plants in Wyoming. The existing coal fleet is first retrofitted with CCS, extending their lifetime, and the last of these units are not retired until 2050. There is a substantial addition of new HELE-coal-CCS capacity, with coal returning to a baseload power generation role, and displacing nuclear power. Owing to the finite duration of 45Q tax credits, fossil energy use appears to peak in the mid-2030s for coal and around 2040 for CCGT. Thereafter, renewable power plays an increasingly important role.

This study has evaluated the impact of a range of policy initiatives on the structure and operation of Wyoming's electricity system. It is instructive to finally consider the implications of each scenario on the total

---

[52] Feron, et al, Int. J GHG Con., 2019.
[53] Danaci, et al, Environ. Sci. & Technol., 2021.
[54] Brandl, et al, Int. J GHG Con., 2021.

system cost, which will inevitably be passed on to Wyoming's rate payers. These results are illustrated in Figure 9, below.

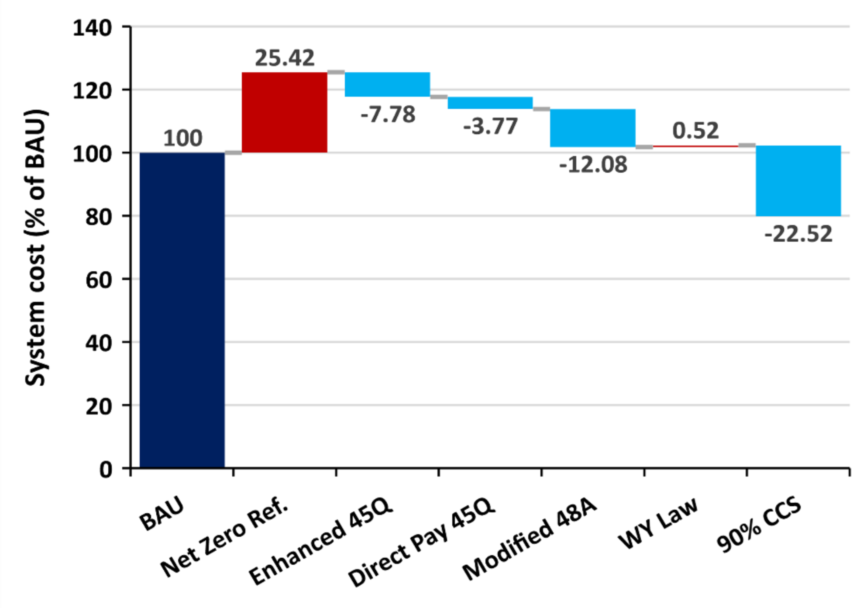

Figure 9: The figure presents a comparison of total system costs across the various scenarios described above relative to the BAU scenario. As can be observed, a net zero scenario for Wyoming in 2050 may, in fact, end up being significantly less costly to Wyoming rate payers than the BAU case. In achieving this, the most important levers were found to be amending 45Q to be a $85/t direct pay tax credit and maximising the rate of CO_2 capture across all assets in the state.

As can be observed, relative to a BAU scenario, the Net Zero Reference scenario was observed to significantly increase total system cost, implying that, absent any new policy, achieving net zero in this fashion might be anticipated to be very costly for Wyoming. Thereafter, the various policy measures evaluated here broadly had the impact of reducing system costs, partly by shifting the system costs to the federal level by taking advantage of federal tax credits. The exception to this rule is the application of WY Law, which imposed a production tax on wind and nuclear power. This was observed to have a very limited effect, though it did modestly increase the overall cost of the system through the lens of the model; however, the effect is so small so as to be negligible in the context of the accuracy of this modelling tool.

While state taxation on wind and nuclear generation did not seem to indicate much higher system-level costs (Figure 9), it should not be assumed that using state-based generation taxes do not impact the generation profile. A more detailed examination of the impact of state-based generation taxes would be needed to determine the specific impact of taxes on Wyoming's generation system.

Importantly, if all of the initiatives evaluated in this study are implemented, the end result is a net zero system costing approximately 22% less than the BAU and almost 50% cheaper than the Net Zero Reference scenario. In order to achieve this outcome, the most important steps were:

1. Increase 45Q to $85/t CO_2 and make it direct pay,
2. Modify 48A to make it applicable to CCS facilities as well as HELE power plants, and

3. Increase the rate of CO_2 capture to 90% or more.

6 Conclusions

This paper has presented a techno-policy study of a potential net zero transition for Wyoming. In the context of a broader US effort to decarbonise its economy and a consequently dynamic policy environment, particular focus was placed on the potential role of CCS technologies applied to Wyoming's fleet of coal-fired power generation assets. Wyoming is characterised by low energy prices and a relatively non-seasonal power demand that is not expected to increase significantly in the period to 2050. Evaluating the potential impact of 45Q and 48A on generation systems is a natural focus of the energy transition discussion in the US, more broadly, due to the country's demonstrated interest in rapidly reducing emissions and concomitantly revitalizing and expanding the nation's electricity infrastructure. For instance, the US recently passed the Infrastructure Investment and Jobs Act, which invests $1.2 trillion in infrastructure, investing over $12 billion over the next five years to support CCS technologies and infrastructure.[55] The law invests much of this funding into CO_2 transportation infrastructure, complimenting the SCALE Act and accentuating the importance of strengthening the 45Q and 48A federal tax credits. Taken together, these federal incentives provide a springboard for commercial deployment of CCS technologies.

This study starts by considering a perpetuation of the status quo, with the various production and investment tax credits in the current form. The conclusion was that, absent any change, coal will continue to play a dominant role in Wyoming's electricity grid, albeit with a substantial replacement of the existing fleet with more efficient assets – so-called "HELE" plants. As a consequence, the carbon intensity of Wyoming's power may be expected to decline by approximately 20% in the period to 2050. Alternative, non-coal power generation assets are unlikely to play a significant role.

In contrast, if a net zero target is adopted, without modification of the existing policy paradigm, coal will be entirely phased out by 2050, with nuclear power, CCGT-CCS, and intermittent renewable energy playing an increasingly important role. Owing to Wyoming's relative lack of seasonality, nuclear power provides a baseload supply, with the intermittent nature of wind and solar power complemented by the dispatchability of CCGT-CCS technology. In this scenario, the total installed power generation capacity was observed to increase from just under 15 GW today to approximately 27 GW by 2050.

We then stepwise modified the existing 45Q production tax credit to include a modification to direct pay, an uplift from its current level of \$50/t CO_2 to \$85/t CO_2, and an extension of the "commence construction" window to 2302. Similarly, the investment tax credit was modified so as to be available to CCS projects. CO_2 capture technology, where deployed, was assumed to capture no more than 70% of a given facilities emissions. Here, whilst this was observed to preserve the role of coal in Wyoming in the medium term, in the longer term, the requirement to meet a net zero emissions target largely constrained coal out of the mix.

[55] https://www.congress.gov/bill/117th-congress/house-bill/3684/text.

However, there are now several data points, both from the academic literature and from real-world plant operation, e.g., Boundary Dam and Petra Nova, that CO_2 capture rates that are substantially beyond 90% are eminently possible at a very low marginal cost. Moreover, technology vendors, such as Johnson Matthey are offering performance guarantees. Hence, we evaluated the impact of near-zero emissions from coal in Wyoming via a combination of high rates of point source capture and indirect compensation *via* BECCS. In this context, coal-fired power generation combined with CCS retained an important role in Wyoming's electricity grid, and, importantly, installed capacity was held to just under 20 GW. Finally, from an economic perspective, not only was the 90% CCS scenario observed to be almost 50% cheaper than the net zero reference case, but it was also observed to be over 20% cheaper for Wyoming's rate payers than the BAU scenario. Thus, this study recommends that 45Q be increased to \$85/t CO_2 for all power plants, that the "commence construction" window be extended to 2032, that 48A be made available to power CCS projects, and finally that the state's power fleet adopt a near-zero emissions target via the deployment of CCS technology with greater than 90% CO_2 capture rates.

7 Acknowledgements

The authors are grateful to Holly Krutka, Haibo Zhai, Abdallah Dindi, Melissa Firestone, and Selena Rose Gerace for helpful discussions and the provision of data during this project.

8 Appendices

8.1 Key techno-economic assumptions

Technology	Capital cost (\$/kW)	Fixed-OPEX (\$/kW.yr)	Efficiency (%)	Lifetime (years)
Nuclear	5100	103	100*	50
Coal-USC	2100	51	42	40
Coal-USC-CCS(Ret)	3800	115	32	40
Biomass	2500	77	42	40
BECCS(Ret)	3700	115	32	40
CCGT	725	13	50	40
CCGT-CCS(Ret)	2100	51	50	40
OCGT	1100	13	35	40
Coal-USC-CCS	5300	115	32	40
CCGT-CCS	2600	51	50	40
BECCS	5700	115	32	40
Onshore-Wind	1700	38	100*	30
Solar	1000	13	100*	30
Hydro	1600	64	100*	50
Battery	1500	38	85**	15

** Source of energy is already in kWh electricity*
*** Roundtrip efficiency*

Fuel	Fuel price ($/MWh)[*)]				CO_2 emissions factor, kg/MWh
	2020	2030	2040	2050	
Coal	5.5	5.5	5.5	5.5	322
Gas	8.2	10.2	10.6	11.3	184
Biomass	15.8	16.4	17.6	18.8	347 (110)[**)]
Uranium	6	6	6	6	0