CCUS Deployment Under the U.S. 45Q Tax Credit and Adaptation by Other North American Governments: MARKAL Modeling Results

Abstract

In 2018, U.S. Congress passed the Bipartisan Budget Act, known as 45Q [H.R. 3761], expanding the corporate income tax credit for carbon capture utilization and storage (CCUS). 45Q provides a performance-based tax credit for carbon capture projects of $30/ton of carbon dioxide (CO_2) (tCO_2) for anthropogenic CO_2 going to enhanced oil recovery (EOR), and $50/$tCO_2$ if going to straight storage. There are several conditions; for example, there is a 12-year time limit on tax credits for a new plant that commences construction before 2024 [H.R. 3761].

This study aims to test the incremental impact of the 45Q tax credits on CCUS deployment, CO_2-EOR, and power generation technological changes for North American (the United States, Canada, and Mexico) long-term energy system development. The scenario results show that offering a 12-year CO_2 storage subsidy provides the motivation needed for CCUS investment during the 12-year subsidy period, and the benefits of such investment can be sustained over the 40-year lifetime under CO_2 taxation. The modeling results show that carbon capture generation replaces uncontrolled fossil-fueled power, not new or existing renewables, so power generation and corresponding emission reductions from renewables remain unaffected by the availability of 45Q in the United States. Our scenario with CCUS technological learning indicates that CCUS could play a very important role under stringent environmental constraints. Thus, accelerated support and funding for the large-scale CCUS demonstrations is important for the execution of both short- and long-term climate mitigation goals.

Given the significant role of the United States, Canada, and Mexico on the world energy system, our results represent an important contribution to the study of global energy trends.

1. Introduction

CCUS technology development can accelerate deployment of viable options for reducing CO_2 emissions while increasing oil production. Despite its importance, the deployment status of CCUS technology is still at the earliest stage. The investment cost of CCUS is high and there is also a lack of effective government incentive policies. U.S. Congress approved a significant pro-CCUS national policy in February 2018, namely a revised tax credit for CO_2 utilization and storage known as 45Q.[1] The new 45Q tax credit includes no cap on the storage, thereby providing more flexibility for projects that may take years to plan and develop. The new 45Q tax credit increases the subsidy values for geological storage to \$50/tCO_2 and for CO_2-EOR utilization to \$35/tCO_2.

In 2019, there were 43 large-scale integrated carbon capture and storage (CCS) or CCUS facilities all over the world (18 projects are operating, 5 are under construction, and 20 projects are at the development stage) [Global CCS Institute, 2019]. Those projects are located in several countries, but the majority are in the United States (12) and Canada (7). Most captured carbon is used for CO_2-EOR that injects CO_2 into oil fields to produce additional oil.

CO_2-EOR is a tertiary oil production process that is used after the primary and secondary oil production phases have been completed and it represents the process of CO_2 injection into depleted or depleting oil and gas fields that causes the oil to run more freely to the producing well. During this process, the injected CO_2 is produced with oil, separated and reinjected, and nearly all of the purchased CO_2 remains securely trapped within the deep geologic formation [NETL, 2010; Melzer, 2012]. The volume of original oil in place (OOIP) is a key variable in determining the CO_2-EOR potential of a reservoir and it is used to

[1] The U.S. tax credit for carbon capture activities, known as 45Q, was enacted in 2008 [26 U.S. Code § 45Q] and provided \$US10 per ton for CO_2 stored through EOR operations and \$20 for CO_2 stored in deep saline formations. However, 45Q was not very effective once oil prices collapsed. In addition, \$10/tCO_2 was not a motivator for investment in large-scale CCUS. In 2016, the Carbon Capture Utilization and Storage Act was introduced; it would increase the credits to \$35/tCO_2 for oil recovery and \$50/tCO_2 for permanent sequestration. It would also allow more types of facilities to qualify and lift the cap, granting the credit to anyone starting a CCUS project in the next 12 years. On February 1, 2018, a bipartisan group of House lawmakers were pressing for a key CCUS tax credit to be included in a tax extenders package. The bill [H.R. 3761], sponsored by Mike Conaway, revised the existing Section 45Q CCUS tax break; on February 9, 2018, President Trump signed a CCUS credits bill into a law. The bill allows certain new industrial or direct air capture facilities to qualify for the credit if construction begins before January 1, 2024; it also allows qualified projects to claim the credit for 12 years, beginning on the date the equipment was originally placed in service. The bill increases the separate credit amounts, with respect to projects placed in service upon or after the enactment of this bill.

estimate how much oil remains as a target for the application of CO_2-EOR. In the United States, OOIP for CO_2-EOR is estimated at 400 billion barrels (Bbbl) and technically recoverable resource (TRR) for CO_2-EOR is estimated at 84.8 Bbbl [NETL, 2010]. In Canada, large field OOIP for CO_2-EOR is estimated at 37.6 Bbbl and large field TRR for CO_2-EOR is estimated at 5.7 Bbbl [IEA, 2009; Ahmed and Meehan, 2016]. Mexico's large field OOIP for CO_2-EOR is estimated at 92.6 Bbbl and large field TRR for CO_2-EOR is estimated at 14.1 Bbbl, most of which is concentrated in the Gulf of Mexico region [IEA, 2009]. However, many factors are important for economics of CO_2-EOR applications, not the least of which are the price of oil and the cost and availability of CO_2.

Lack of current CO_2-EOR projects is largely because anthropogenic CO_2 sources are not available or economically feasible in Canada and Mexico. For instance, there are a few small anthropogenic CO_2 fields existing in the southwest corner of Saskatchewan in Canada. The CO_2 deliverability from these fields would be inadequate for CO_2-EOR projects [Brown et al., 2016]. In Mexico, the amount of CO_2 available from industrial sources within a 100-kilometer radius of the Villahermosa basin is estimated at about 1% of the CO_2 required for CO_2-EOR; while in the Tampico-Misantla basin, it is it still insufficient at 11% [Godec, 2011a, Godec, 2011 b]. In Mexico, non-anthropogenic CO_2 sources for CO_2-EOR projects were identified as existing industrial and power plants that emit CO_2 [Lacy et al., 2013], and also possible new natural gas-fired power plants in the Gulf of Mexico [González-Díaz et al., 2017].

Until recently (November 2021), there was little pre-existing research on 45Q modeling available in peer review journals. In [Fan et al., 2018 and Fan et al., 2019], 45Q tax credit incentives are considered in China as a mechanism to encourage CO_2 emission reductions in the absence of a sufficient CO_2 price. The modeling results show that CCUS capacity expansion is limited to 3 gigawatts (GW) of coal power capacity retrofit that result in an annual sequestration of only 27 million tons of CO_2 ($MtCO_2$) [Fan et al., 2019]. The results in [Fan et al., 2018] show that if the allocation ratio of the CO_2 storage subsidy for coal power plants is zero, the full government subsidy for the initial CCS investment cost and clean electricity tariff in China are not sufficiently attractive for the coal power plants to invest in CCUS. Few studies emphasize the need for subsidies or other incentives to stimulate initial commercial use and large-scale deployment [Fan et al., 2019; Beck, 2020; Bui et al., 2018]. The modeling results presented in [Edmonds et al., 2020] show that a variety of CCUS applications could be induced by 45Q tax credits: several models project CCUS retrofits deployments and an additional 20–65 $MtCO_2$ sequestration per year could be expected to come online under 45Q.

The objectives of this study are to evaluate the impact of the CO_2-EOR and 45Q tax credit on CCUS investment decision-making in North America, 45Q and carbon taxes interaction, and 45Q budget costs. The following sections describe the North America CO_2-EOR potential, MARKAL model and scenario definitions, modeling results, discussion, and conclusions.

2. MARKAL Model and Scenario Definitions

MARKet ALlocation (MARKAL) is an integrated energy systems model that can be used to analyze energy, economic, and environmental issues at the global, national, and regional levels [Loulou et al., 2004]. MARKAL is a bottom-up, dynamic, linear programming optimization model used to find the cost-optimal pathway within the context of the entire energy system. MARKAL represents energy imports and exports, domestic production of fuels, fuel processing, infrastructures, secondary energy carriers, end-use technologies, and energy service demands of the entire economy. MARKAL does not contain an in-built database, so the user is obliged to enter input parameters. In this study, the publicly available EPAUS9r2017 database for the U.S. energy system had been adopted and modified. EPAUS9r2017 with U.S. Census regions representation was created by the Environmental Protection Agency (EPA) in 2017 to model changes in the U.S. energy sector through 2055; the time horizon extends from 2005 to 2055, divided into 5-year periods [Lenox et al., 2013; Loughlin, Benjey, and Nolte, 2011; Babaee and Loughlin, 2017].

We re-calibrated the EPAUS9r2017 reference scenario consistent with the U.S. Energy Information Administration (EIA) Annual Energy Outlook's (AEO) 2018 reference [EIA, 2018]. We extended

EPAUS9r2017 to include Canadian and Mexican energy systems as two additional new regions. Each of the 11 regions (nine of the U.S. Census regions, Canada, and Mexico) was modeled as an independent energy system with different regional costs, resource availability, existing capacity, and end-use demands. Regions are connected through a trade network that allows transmission of electricity and transport of gas and fuels. Electricity transmission is constrained to reflect existing regional connections between North American Electric Reliability Corporation (NERC) regions as closely as possible.

In the EPAUS9r2017 database, CO_2 capture for existing and new fossil-fuel generation sources is achieved with a removal efficiency of up to 90%. CO_2 capture is available for centralized production technologies including natural gas steam methane reform, coal gasification, and biomass gasification systems. In the EPAUS9r2017 database, CCUS technology representation focuses on CO_2 capture, while incorporating CO_2 sequestration (underground injection) as a single cost term. CO_2 capture from power plants may take place along one of two generic technology pathways: post-combustion capture and pre-combustion capture [Lenox et al., 2013]. The EPAUS9r2017 database represents each of these CCUS technology pathways as part of its electric sector module and the additional power needed to run the CCUS technologies is represented as an energy penalty. This shows up in the model as a decrease in the efficiencies of the technologies as compared to conventional power plants without CCUS. CO_2 capture retrofit options for all new coal steam technologies, existing coal plants, as well as new integrated gasification combined cycle (IGCC) and new natural gas combined cycle (NGCC) capacity. These retrofits sit as process technologies on the fuel chain upstream from their corresponding generating technologies. Similar to the new CCUS plants representation, the retrofit power requirements are interpreted here as an energy penalty.

We also included CO_2-EOR technology in the model's database with the following assumptions and limitations:

- CO_2-EOR potential estimates are based on TRR.

- CO_2-EOR potential estimates are presented at the regional levels (not at the projects or reservoirs levels).
- The volume of CO_2 recycled for injection was not included. Instead, “fresh” CO_2 usage rates were applied (fresh CO_2 and oil produced ratio). Fresh CO_2 usage rates can be calculated as CO_2 Purchased and Oil Produced ratio or CO_2 Injected minus CO_2 Recycled and Oil Produced ratio (see details on fresh vs. injected CO_2 in [Melzer, 2012]).
- The difference between the volume of CO_2 Injected and CO_2 Produced represents the volume of CO_2 permanently stored in the reservoir.
- Natural sources of CO_2 and industrial sources from gas processing plants, a host of nitrogen, hydrogen, and fertilizer, etc., were included into the model. However, to the knowledge of the authors, there is no published work in the literature regarding potential of Canadian natural CO_2 sources, so natural sources of CO_2 in Canada were not included in the model. There are a few small CO_2 fields that exist in the southwest corner of Saskatchewan. The CO_2 deliverability from these fields would be inadequate for CO_2-EOR projects [Brown, et al., 2017].
- CO_2 storage areas have been identified by the North American Carbon Storage Atlas [NETL, 2015].

Figure 1 shows a simplified CO_2-EOR module that we developed for our study in MARKAL (marked by grey) and its relationship with other technologies groups in the model. During CO_2-EOR, a large percentage of the originally injected CO_2 gets trapped in the geologic formation and the trapping continues as long as the CO_2 is injected. As the result of this “incidental” sequestration, the CO_2 that is produced should be recycled (captured, compressed, and continuously added to newly purchased “fresh” CO_2) for EOR operations to continue. Because of the effective “closed loop,” the experience of the industry to date is that 90–95% of the purchased CO_2 remains securely trapped within the deep geologic formation. As naturally occurring CO_2 can be permanently trapped safely in many geologic situations, CO_2 from EOR can be permanently trapped as well.

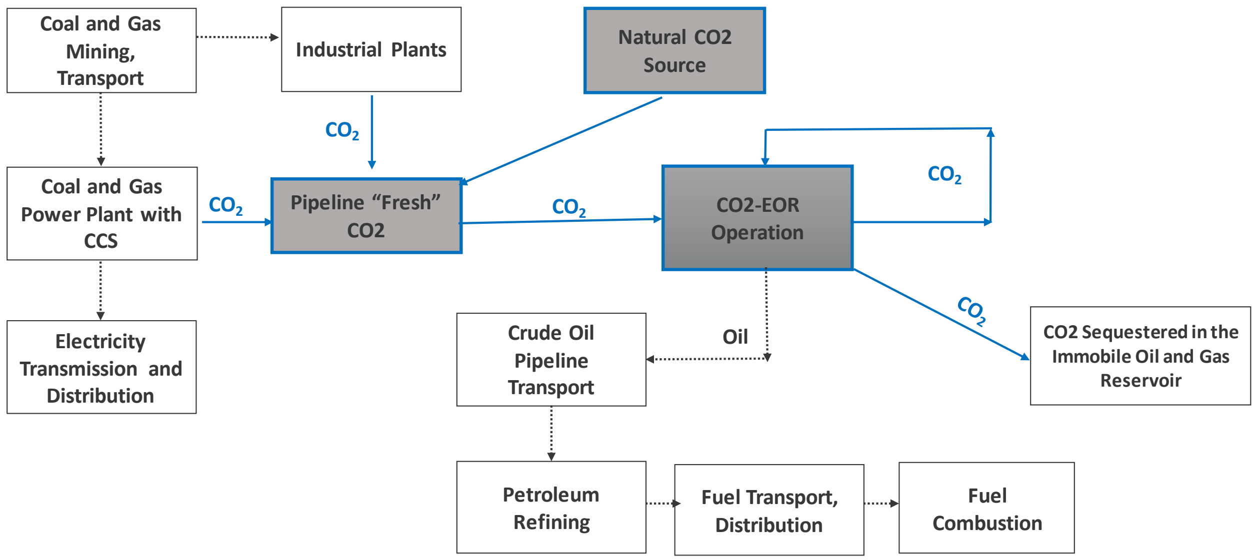

Figure 1: CO_2-EOR module in MARKAL and relationship with technology groups

MARKAL includes a representation of 45Q sequestration tax credits. In MARKAL, the time horizon is divided into 5-year periods, so additional revenue for new and retrofit electricity generators and industrial facilities using CCUS start in 2020. Credit payments are made to qualified generators during the first 15 years of operation or up to 2035. MARKAL permits power and industrial plants with CCUS to reduce or stop capturing if it is not economically attractive.

We examined CO_2 emissions and energy system technologies deployments under the six scenarios (see Table 1 for scenario names and definitions).

Table 1. Scenario definitions

Scenario Name	Scenario Definition	Tax credit ($/tCO$_2$)		Policy availability	Receipt of credit
		EOR	Storage		
Reference	AEO 2018 reference scenario	None	None	None	None

Carbon_All	Carbon taxes at $US 35/tonne starting 2020 and increasing at 5% per year until 2050. CO_2-EOR in North America	None	None	None	None
CCUS 45Q law + carbon price	Carbon price starts 2030; 45Q starts 2024 in the U.S. Tax credit of $30 per tonne of CO_2 for anthropogenic CO_2 going to EOR, and $50 per tonne if going to straight storage; CO_2-EOR option in Canada and Mexico	35	50	2024	12 years
CCUS 45Q law + carbon price + learning	CCUS 45Q law + carbon price scenarios with CCUS technological learning	35	50	2024	12 years
CCUS 45Q + carbon price	Carbon price case = 45Q 2024	35	50	2024	12 years
CCUS indef life + carbon price	Carbon policy scenario: carbon taxes at $US 35/tonne starting 2020 and increasing at 5% per year until 2055. This scenario includes a CO_2-EOR option in Canada and Mexico, and 45Q tax credit option in the United States	35	50	indefinite	12 years

We included scenarios with representation of technological learning in CCUS technologies that are consistent with the U.S. Department of Energy (DOE) research and development (R&D) goals. CCUS technological learning in the "CCUS 45Q law + carbon price + learning" scenario is reflected the DOE study [NETL, 2014]. DOE is conducting R&D activities on second-generation and transformational

CCUS technologies that have the potential to provide step-change reductions in both the cost of CCUS and the energy penalty imposed by its operation, as compared to currently available first-generation technologies [NETL, 2014]. The depiction of CCUS in this scenario reflects the cost and performance expectations based on DOE R&D program goals and detailed techno-economic studies of baseline and advanced technologies. Improvements in other energy conversion technologies were left in the default values. For the CCUS 45Q law + carbon price + learning run, this additional learning is a function of the actual technology deployment. Table A1 in Appendix A shows cost and performance characteristics of new power generation technologies.

3. Modeling Results

3.1 CO_2-EOR: Production and Storage Projections

Currently, CO_2-EOR is an important component of U.S. oil production, accounting for 0.3 million barrels (MMbbl) a day [EIA, 2018]. The modeling results show that 45Q leads to an increase in CO_2-EOR production of 400,000 bbl a day in 2030 in all scenarios (Table 2). However, with 45Q ending, CO_2-EOR production decreases. CO_2-EOR production in Canada and Mexico continuously increases, and by 2050, reaches about 50 thousand barrels (Mbbl) a day in Canada and 685–780 Mbbl a day in Mexico.

Table 2. CO_2-EOR production by scenarios (in MMbbl per day)

Scenarios	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
	United States			**Canada**			**Mexico**		
Carbon_All	0.21	0.15	0.10	0.01	0.01	0.06	0.31	0.52	0.77
CCUS 45Q law + carbon price	0.34	0.19	0.12	0.01	0.01	0.05	0.31	0.52	0.69

CCUS 45Q law + carbon price + learning	0.34	0.19	0.15	0.01	0.01	0.04	0.32	0.52	0.78
CCUS 45Q + carbon price	0.34	0.19	0.12	0.01	0.01	0.05	0.31	0.52	0.69
CCUS indef + carbon price	0.34	0.19	0.14	0.01	0.01	0.06	0.32	0.52	0.69

The scenario results demonstrate significant CO_2 emissions stored through CO_2-EOR projects: approximately 88–90 $MtCO_2$ in the United States, 1.4–1.6 $MtCO_2$ in Canada, and 39 $MtCO_2$ in Mexico by 2030 (see Table 3). However, in the United States, after 45Q tax credit expiration, CO_2 capturing and storing gradually decreases, reaching 32–40 $MtCO_2$ by 2050. In Canada and Mexico, where 45Q was not implemented, CO_2 capturing and storing keep increasing, reaching 6–7 $MtCO_2$ and 85–96 $MtCO_2$, respectively. The highest level of CO_2 storage by 2050 is observed in the CCUS 45Q law + carbon price + learning scenario in the United States and Mexico. In Canada, the highest level of CO_2 storage is in the CCUS indef + carbon price scenario.

Table 3. CO_2-EOR storage of CO_2 emissions by scenarios (in $MtCO_2$)

Scenarios	2030	2040	2050	2030	2040	2050	2030	2040	2050
	United States			Canada			Mexico		
Carbon_All	53.4	37.4	26.0	1.4	1.6	6.6	38.2	63.6	94.5
CCUS 45Q law + carbon price	87.8	48.6	31.6	1.4	1.6	5.5	38.2	63.6	84.5
CCUS 45Q law + carbon price + learning	89.8	50.6	40.8	1.6	1.6	4.6	39.1	64.6	95.8

CCUS 45Q + carbon price	89.8	50.7	32.9	1.4	1.6	6.0	38.1	63.5	84.4
CCUS indef + carbon price	87.8	48.5	35.5	1.6	1.6	6.7	39.1	64.6	84.5

3.2 CO_2 Abatement, Budget Costs of 45Q, and System Costs Scenarios Results

Figure 2 shows cumulative CO_2 emissions abatements (size of the bubble) by 2050 with total system costs difference to the Reference scenario versus cumulative budget costs by the end of the projected period. In all scenarios, cumulative budget costs are negative as cumulative revenue from CO_2 taxes are higher than cumulative subsidies by 1.2–2 trillion $US (see Appendix C for details). The highest cumulative revenue from CO_2 taxation is in the Carbon_All scenario that also shows the lowest cumulative system costs because in this scenario there is lower CCUS deployment, higher CO_2 emissions, and no 45Q budget costs. Including 45Q tax credits results in an increase of cumulative system costs of 40–85% in comparison to the Carbon_All scenario.

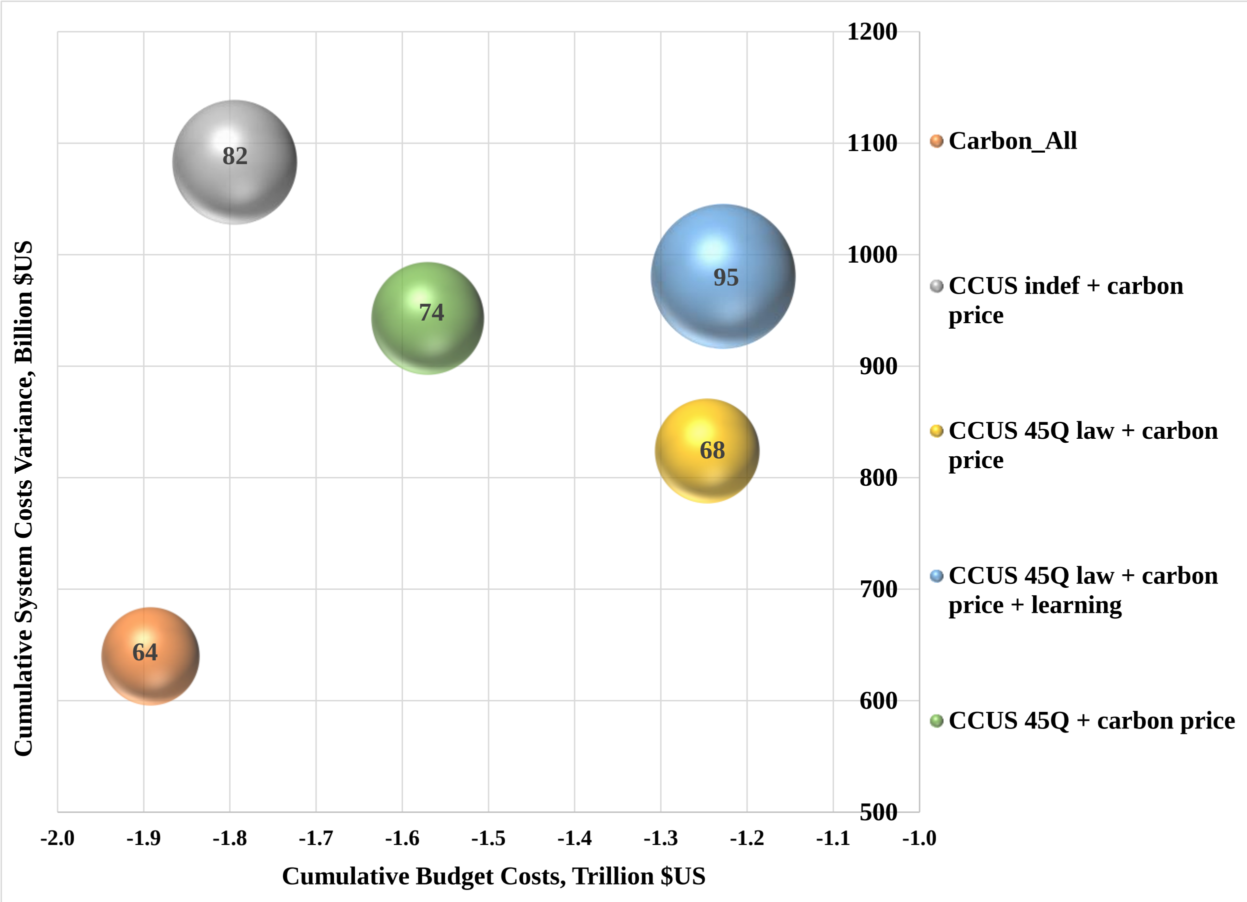

Figure 2. U.S. cumulative system costs variance versus cumulative budget costs for cumulative CO_2 emissions abatement by 2050. Cumulative CO_2 abatements in gigatons of CO_2 ($GtCO_2$) are estimated as a difference between cumulative CO_2 emissions in the Reference scenario and cumulative CO_2 emissions in other scenarios by 2050. Cumulative system costs variances are estimated as a difference between cumulative system costs in the CCUS scenarios and the Reference scenario by 2050. Cumulative budget costs are estimated as a difference between cumulative budget income from CO_2 taxation and cumulative costs of subsidies by 2050.

The highest CO_2 abatement, 95 $GtCO_2$ by 2050, can be observed in the CCUS 45Q law + carbon price + learning scenario. In the CCUS indef + carbon price scenario, cumulative CO_2 abatement is 82 $GtCO_2$, or 14% lower, and system costs are 10% higher than in the CCUS 45Q law + carbon price + learning scenario. The lowest CO_2 abatement across scenarios with 45Q (68 $GtCO_2$), can be observed in the CCUS

45Q law + carbon price scenario; therefore, delay in CO_2 taxation results in lower CO_2 abatement. In the CCUS 45Q + carbon price scenario, cumulative CO_2 abatement is about the same as in the Carbon_All scenario; thus, 45Q doesn't affect CO_2 abatement much if CO_2 taxes and 45Q implementations start at the same year. The CO_2 abatement in the CCUS indef + carbon price scenario is higher than in the CCUS 45Q law + carbon price and CCUS 45Q + carbon price scenarios, so indefinite 45Q policy availability results in higher CO_2 reduction through higher level of CCUS deployment (see CCUS deployment in Table B1, Appendix B).

Figure 2 illustrates that with the exclusion of the CCUS 45Q law + carbon price + learning scenario, higher CO_2 abatement is associated with higher cumulative system costs and lower cumulative budget costs in all scenarios with 45Q. In the CCUS 45Q law + carbon price + learning scenario, in comparison to the scenario without CCUS learning, cumulative CO_2 abatement is 38% higher, cumulative system costs are 19% higher, and cumulative budget costs are about the same as in the CCUS 45Q law + carbon price scenario.

Figure 3 presents cumulative CO_2 emissions abatements in the electricity generation sector (size of the bubble in $GtCO_2$) with total system costs difference to the Reference scenario versus cumulative budget costs by 2050. A high level of electricity sector CO_2 abatement presents in all scenarios: cumulative CO_2 abatements are with 89–94% of cumulative energy-wide CO_2 abatement. The highest level of CO_2 abatement in sectors, other than the power sector, is in the CCUS 45Q law + carbon price + learning scenario (about 10 $GtCO_2$) and the lowest level is about 6 $GtCO_2$ in the Carbon_All scenario. Thus, the result of CCUS "learning" assumptions is not only a higher level of CCUS deployment, but also a higher level of electricity production and higher end-use sector electrification (see electricity production details in next section).

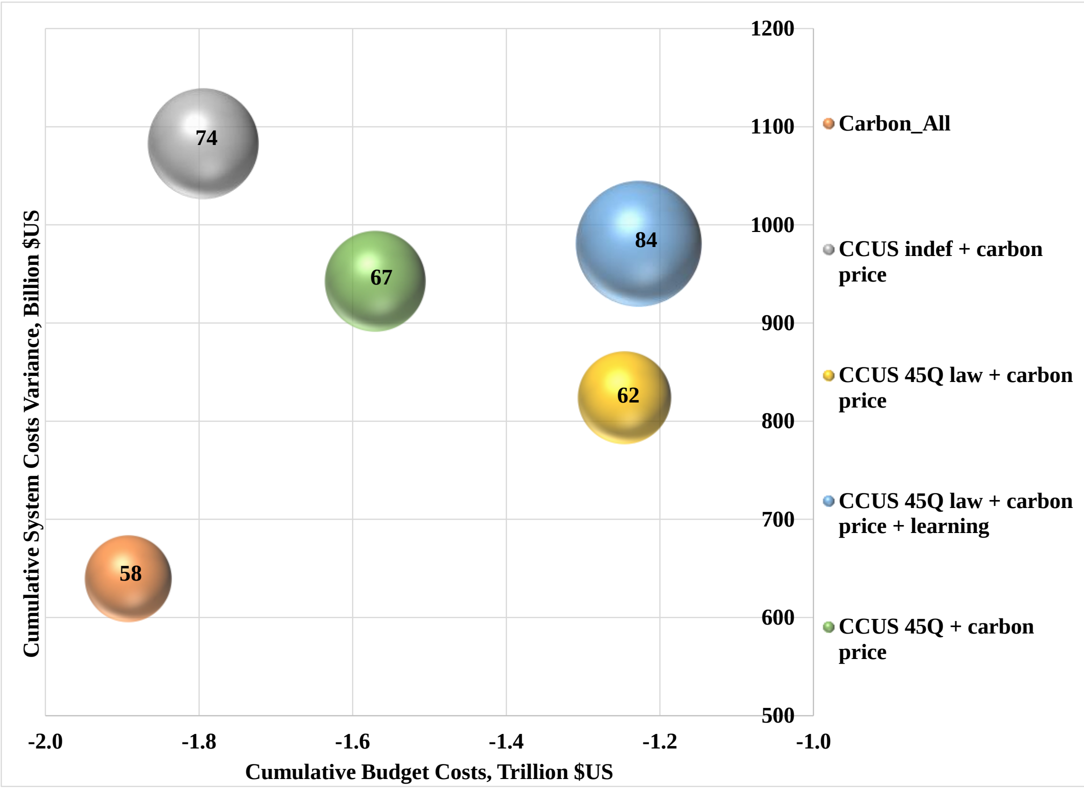

Figure 3. U.S. cumulative system costs variance versus cumulative budget costs for cumulative CO_2 emissions abatement in the power generation sector by 2050.

The modeling results show that, on the one hand, a price on CO_2 causes each individual generator to endure a cost that is proportional to its CO_2 emissions rate, and consequently provides the motivation for generators to take steps to reduce CO_2 emissions intensity in order to reduce costs. On the other hand, the 45Q tax credit encourages CCUS deployments, an important CO_2 emissions reduction technology. A delay in CO_2 taxation implementation results in lower CO_2 abatement by 2050 (the CCUS 45Q + carbon price scenario versus the CCUS 45Q law + carbon price scenario), as a result of delay in CCUS deployment.

3.3 Electricity Mix Projections: United States

In the United States, fossil fuels are the largest source of energy for electricity generation: natural gas and coal were about 33% each in total electricity production in 2015. Nuclear energy provided one-fifth of

U.S. electricity or about 19.6% of U.S. power generation. Renewables provided 17% of U.S. electricity in 2015: hydropower plants produced about 6%, wind about 5%, and solar energy about 1% [EIA, 2019].

In the U.S. Reference scenario (see Figure 4a), most conventional coal plants remained active through 2050 though their share in total electricity generation is decreasing. By 2050, about 43% of the electricity generated is from natural gas, 24% from coal, and 17% from renewables. There is no CCUS deployment in the Reference scenario. In all non-reference scenarios, deployment of CCUS starts by 2025, including biomass IGCC with CCS (the only CCUS technology that is associated with negative CO_2 emissions).

In all scenarios with 45Q tax credits, new coal IGCC plants are taking the larger share of the power generation mix by 2050. The lowest CCUS deployment (new and retrofit) can be observed in the Carbon_All scenario (the scenario with CO_2 taxes without 45Q). The share of NGCC plants without CCS in the Carbon_All scenario is higher than any other power source in 2025–2050 (see Figures 4a-4c).

Results show that CCUS technological learning assumptions significantly affect total power generation and the U.S. power generation mix: electricity production in the CCUS 45Q law + carbon price + learning scenario is about 25% higher than all other scenarios by 2050 (Figure 4b).

By 2050, total CCUS capacity (retrofits and new plants) is about 580 gigawatts electric (GWe) in the CCUS 45Q law + carbon price + learning scenario, or the highest CCUS capacity level across all scenarios (see Table B1 in Appendix B). Total CCUS (primarily retrofit) capacity steadily increases in the Carbon_All scenario, reaching about 86 GWe by 2050 or the lowest level across all scenarios. Interestingly, in all other 45Q scenarios (CCUS 45Q law + carbon price, CCUS 45Q + carbon price, and CCUS indef + carbon price) total CCUS capacity by 2050 is lower than by 2040.

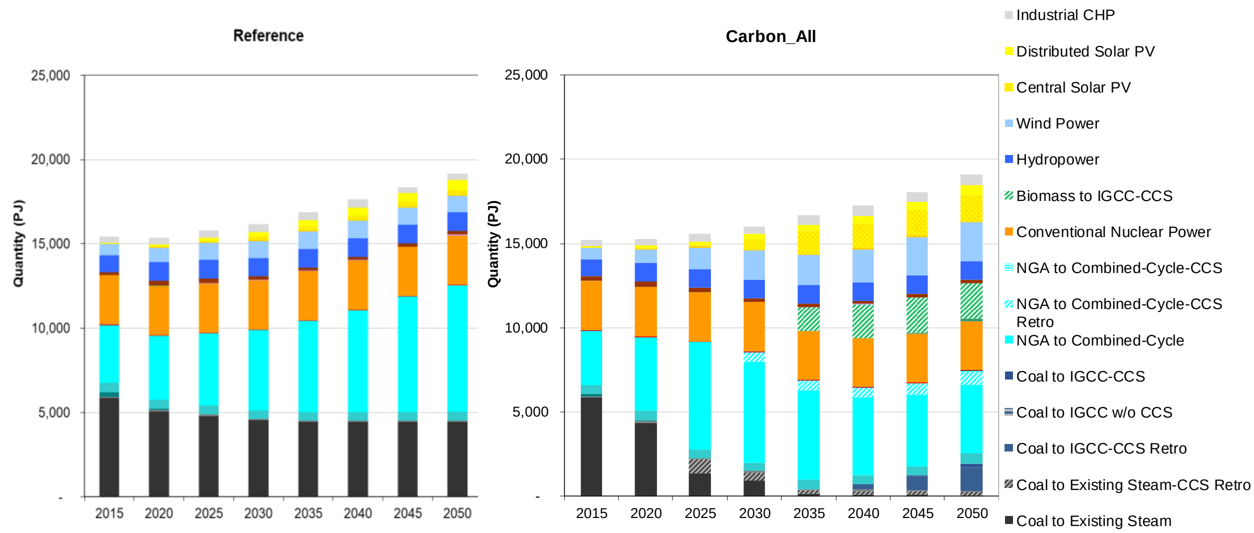

Figure 4a. U.S. electricity generation mix: Reference and Carbon_All scenarios

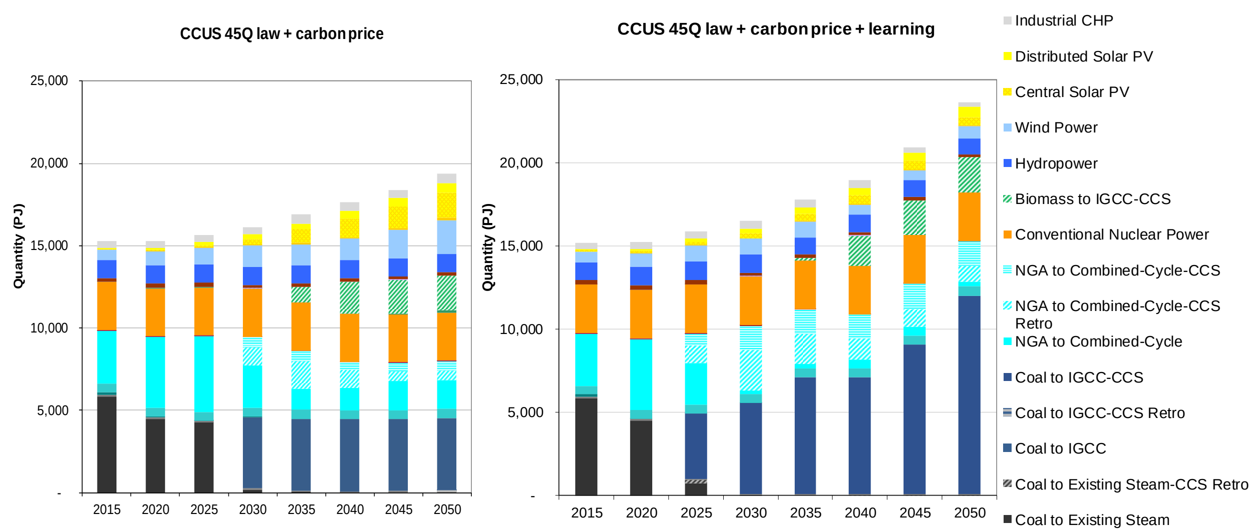

Figure 4b. U.S. electricity generation mix: CCUS 45Q law + Carbon Price and CCUS 45Q Law + Carbon Price + Learning scenarios

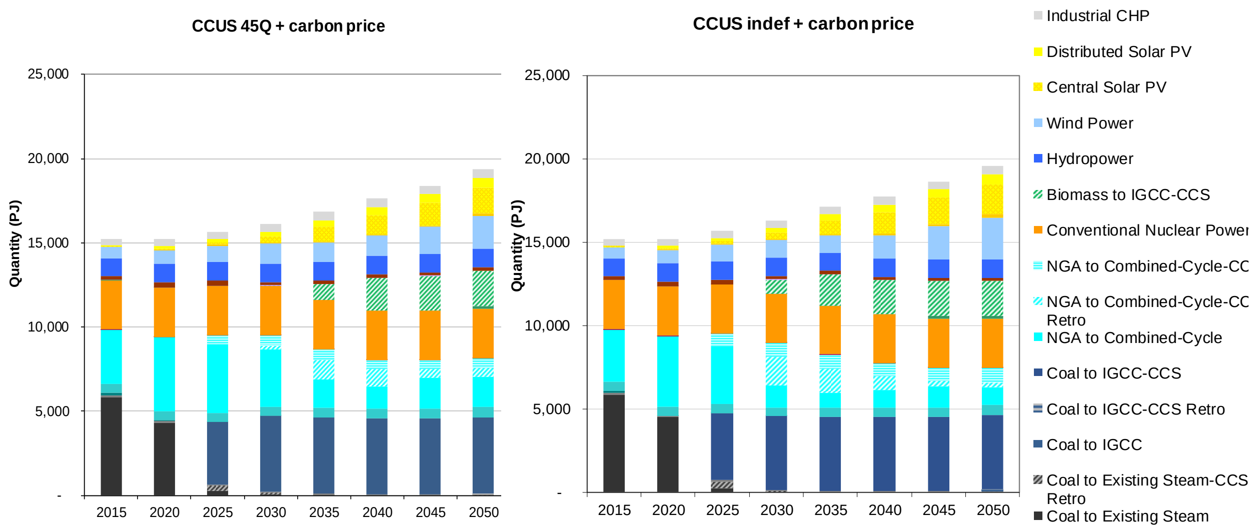

Figure 4c. U.S. electricity generation mix: CCUS 45Q + Carbon Price and CCUS Indef Life + Carbon Price scenarios

3.4 Electricity Mix Projections: Canada

Electricity in Canada is generated from a less diversified mix of sources than in the United States. The majority of supply comes from hydropower (more than 50%), while nuclear, coal and, to a lesser extent, natural gas provide the remaining electricity production (Figures 5a-5c). In 2015, coal, nuclear power, and natural gas contributed about 14% each. Small volumes of electricity were produced from renewables and waste—about 5%. The Canadian electricity system is part of an integrated North American electricity grid. Canada is a net exporter of electricity to the United States and in 2015, net exports of electricity to the United States were about 60 terawatt hours (TWh) [NEB, 2019].

The scenario projections show that electricity sources do not vary greatly in all scenarios (excluding CCUS 45Q law + carbon price + learning). Hydro keeps its importance in the power generation mix and total hydropower production is about 43% in total electricity generation by 2050. Electricity generation from natural gas increases significantly and is about 40% in the Reference scenario by 2050. Electricity production from coal makes a negligible contribution after 2020 in all scenarios (excluding CCUS 45Q law + carbon price + learning). In the CCUS 45Q law + carbon price + learning scenario, CCUS becomes affordable, so NGCC and IGCC with CCS can be observed by 2025; by 2040, all fossil fuels plants are equipped with CCUS. In two scenarios (Carbon_All; CCUS indef + carbon price), total electricity generation is about 15% lower than in the Reference scenario by 2050.

By 2050, total CCUS capacity (retrofits and new plants) is only about 35 GWe in the CCUS 45Q law + carbon price + learning scenario, and it is the highest capacity level across all scenarios (see Table B1 in Appendix B). In all other scenarios, total CCUS capacity is relatively low, reaching about 4–16 GWe by 2050.

3.5 Electricity Mix Projections: Mexico

Mexico generated 310 TWh of electricity in 2015, an increase of 21% from 2005. Fossil-fuel power plants provided 72% of Mexico's electricity capacity and 80% of electricity generation in 2015 [EIA, 2016]. In 2015, the share of electricity generation from nuclear was 3.8%, from hydro 10.4%, and from other renewables 3.5% (see Figures 6a). The United States-Mexico electricity trade is small in comparison to the electricity trade between the United States and Canada. Natural gas used for electricity generation in Mexico has risen rapidly since 2005 as price and availability have made it a more economic fuel source. Coal represents only 7% of total electricity generation and Mexico is a net importer of coal, supplying about 80% of its coal demand domestically.

According to scenario projections, fossil fuels will play an important role in power generation in Mexico in all scenarios, though their share will decrease from 80% to about 60% by 2050. In all scenarios (Figures 6a-6c), most conventional coal plants remain active through 2050 and the majority of them are retrofitted with CCS by 2030–2035. There is new NGCC CCS deployment by 2040 in the CCUS 45Q law + carbon price + learning scenario. By 2025–2030, CCUS deployment can be observed in the CCUS 45Q law + carbon price, CCUS 45Q law + carbon price + learning, CCUS 45Q + carbon price, and CCUS indef + carbon price scenarios to support CO_2-EOR projects even without implementation of 45Q policy in Mexico.

By 2050, total CCUS capacity (retrofits and new plants) is about 40 GWe in the CCUS 45Q law + carbon price + learning scenario, and it is the highest capacity level across all scenarios (see Table B1 in Appendix B). Total CCUS capacities in all other scenarios are about 25 GWe by 2050. Most of these CCUS capacities are natural gas power plants with CCS retrofits, and only in the CCUS 45Q law + carbon price + learning scenario can new NGCC with CCS deployment can be observed.

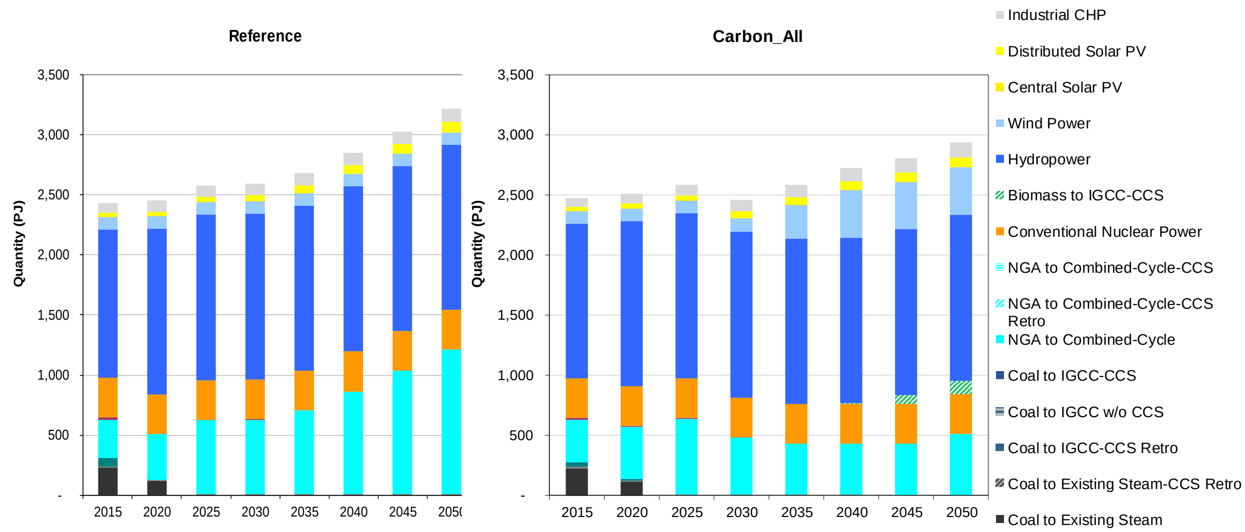

Figure 5a. Canada electricity generation mix: Reference and Carbon_All scenarios

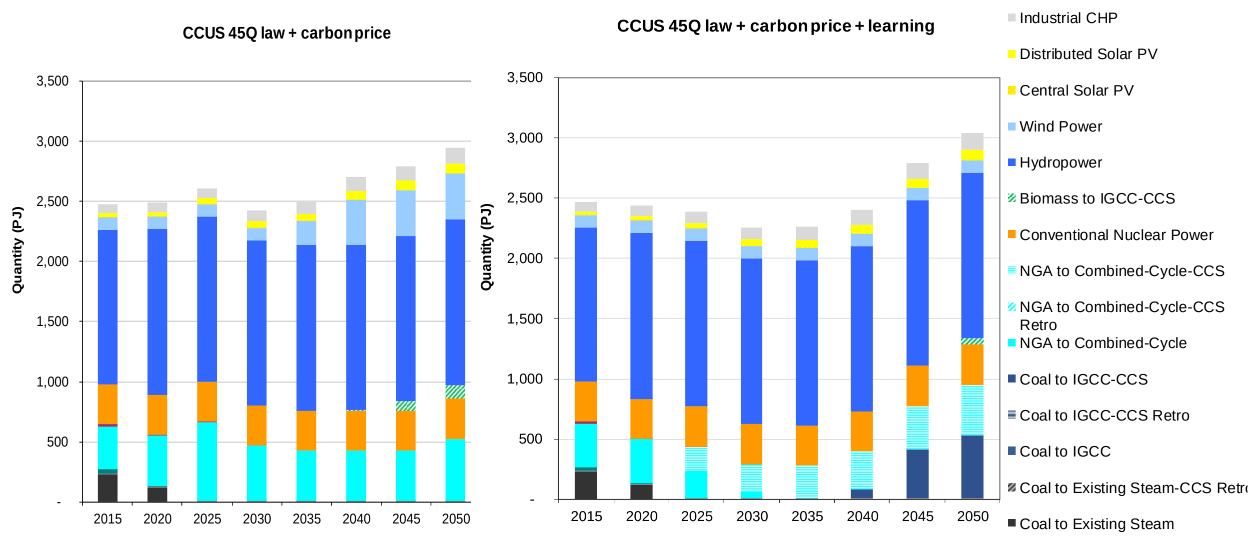

Figure 5b. Canada electricity generation mix: CCUS 45Q law + Carbon Price and CCUS 45Q Law + Carbon Price + Learning scenarios

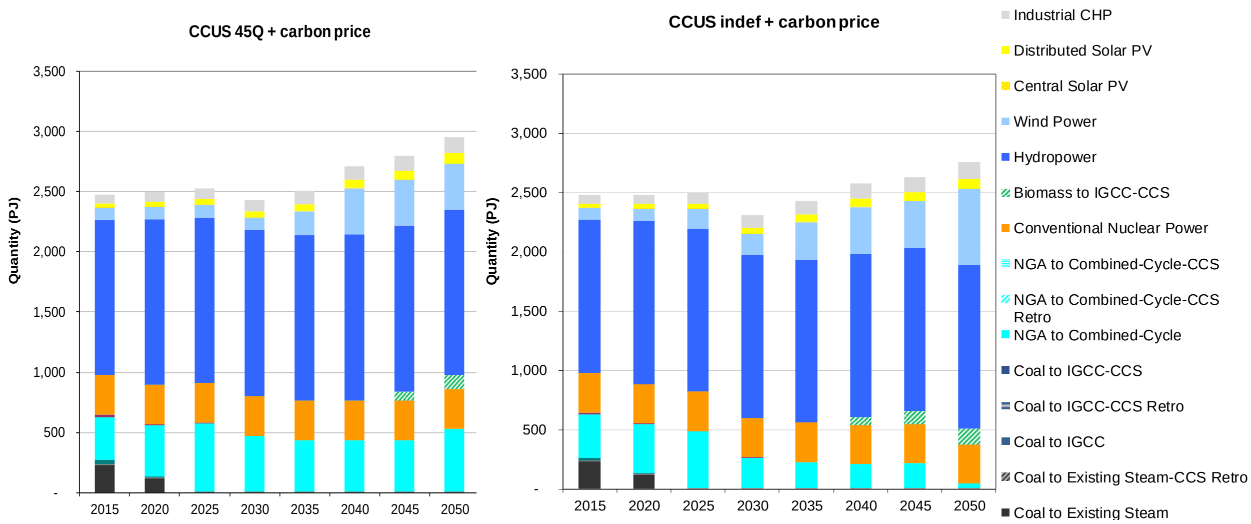

Figure 5c. Canada electricity generation mix: CCUS 45Q + Carbon Price and CCUS Indef Life + Carbon Price scenarios

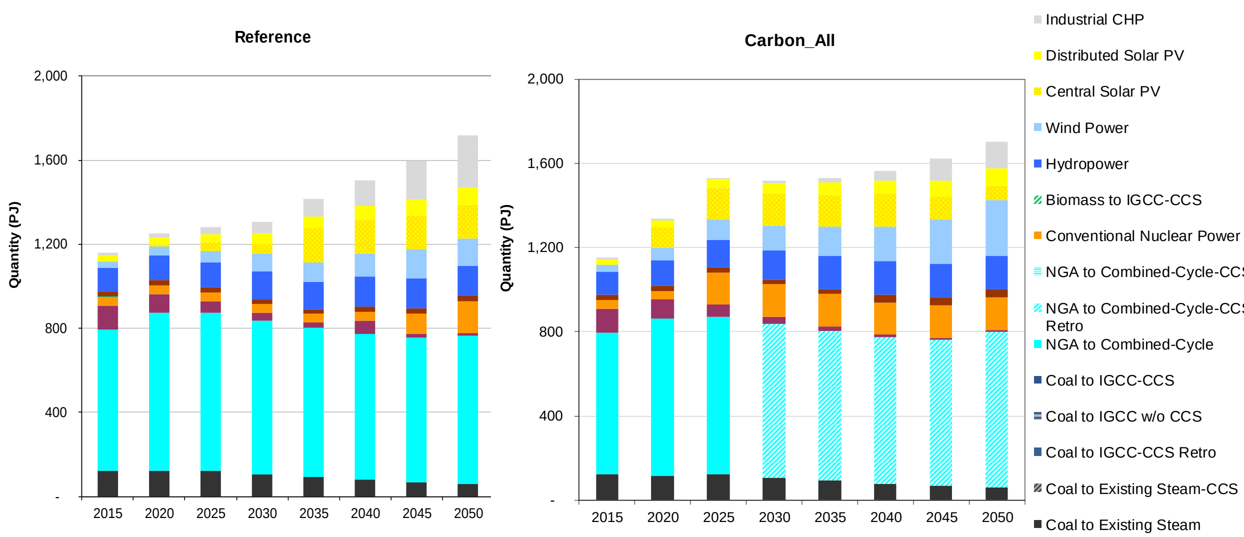

Figure 6a. Mexico electricity generation mix: Reference and Carbon_All scenarios

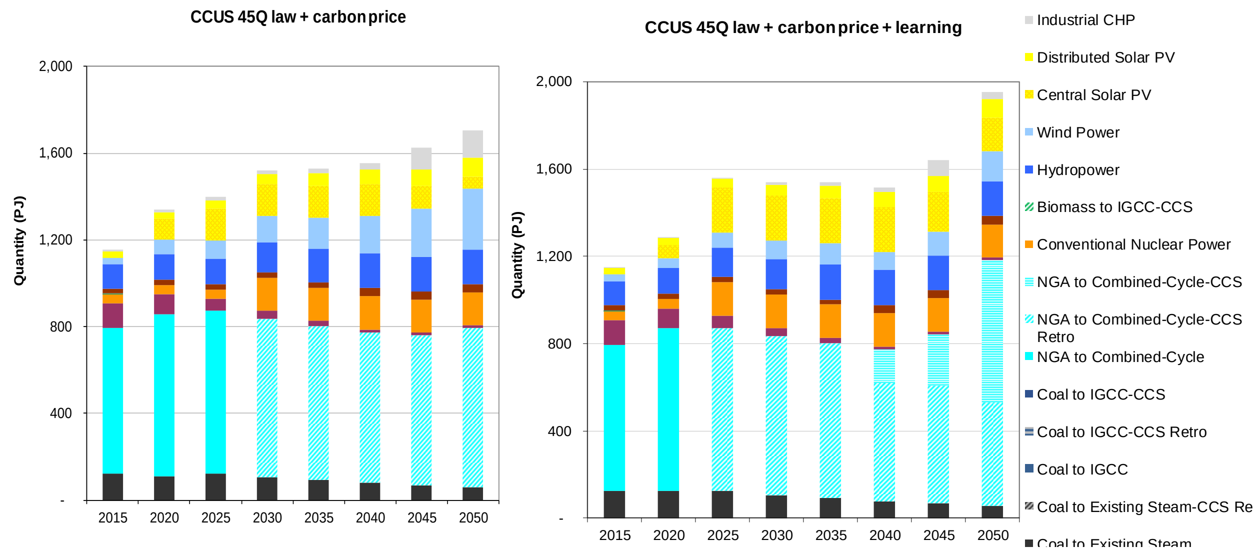

Figure 6b. Mexico electricity generation mix: CCUS 45Q law + Carbon Price and CCUS 45Q Law + Carbon Price + Learning scenarios

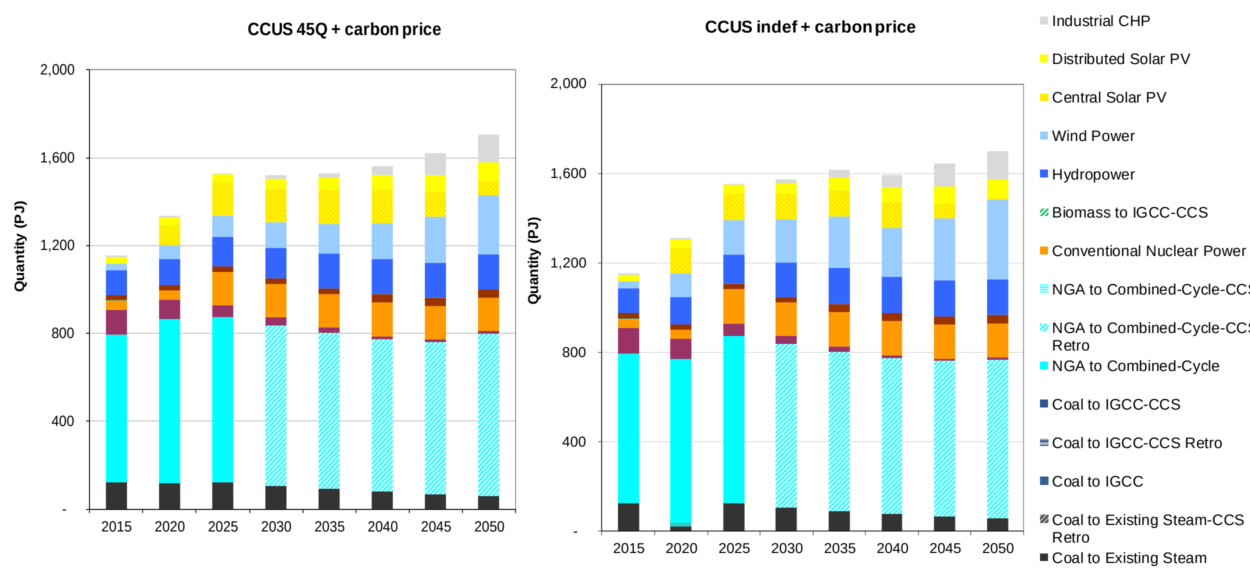

Figure 6c. Mexico electricity generation mix: CCUS 45Q + Carbon Price and CCUS Indef Life + Carbon Price scenarios

4. Discussion

In the United States, 45Q has a potential to support deployment of CCUS (retrofit and new power plants) at more than 200 GWe capacity by 2030 in the scenarios without technological learning. With technological learning, CCUS deployment decreases to about 330 GWe by 2030. In the scenario with CO_2-EOR and CO_2 taxes only (Carbon_All), CCUS deployment is much lower or about 38 GWe by 2030. Interestingly, in all scenarios, excluding Carbon_All, CCUS retrofits capacities are lower in 2050 than in 2040. Yet, in the long term (by 2050), CCUS deployment is about the same (around 300 GWe) in the scenario with CO_2 taxes and in the scenarios that include the 45Q tax credit without technological CCUS learning.

In the CCUS 45Q law + carbon price + learning scenario, CCUS deployment is twice as high as other 45Q scenarios. In the scenario with CO_2 taxation only, it is economically more attractive to deploy carbon capture retrofits in the short term and medium term, and new NGCC with CCS power plants in the long term instead of IGCC CCS. In the scenarios with 45Q, new IGCC with CCS plants deploy predominantly as 45Q implementation attracts higher CO_2 density than power plant retrofits or new natural gas CCS plants. After 45Q expiration, all new plants with carbon capture keep operating, but older carbon capture retrofitted plants are retired.

CCUS deployment leads to CO_2 emissions abatement in the U.S. power generation sector. CO_2-EOR projects alone can remove approximately 90 $MtCO_2$ cumulatively by 2030, then, after the end of the 45Q tax credit regime, CO_2 abatements with CO_2-EOR decrease and reach about 32–41 $MtCO_2$ by 2050. The highest level of cumulative CO_2 emissions abatement of 84 $GtCO_2$ is observed in the CCUS 45Q law + carbon price + learning scenario and the lowest level of 62 $GtCO_2$ in the Carbon_All scenario by 2050.

Importantly, with exclusion of the scenario with CCUS technological learning, the modeling results show that CO_2 abatement in the power sector due to 45Q deployment of CCUS is additive to those achieved through renewable sources of electricity generation. Explicitly, the modeling results show that carbon capture generation replaces uncontrolled fossil-fueled power, not new or existing renewables, so power generation and corresponding emission reductions from renewables remain unaffected by the availability of 45Q. However, in the CCUS 45Q law + carbon price + learning scenario, renewables can't compete with CCUS and by 2050, electricity production from renewables is about the same as in the Reference scenario. CO_2 emissions are higher and budget revenues are lower in the CCUS 45Q + carbon price case, due to the higher level of oil production (with higher CO_2 associated with oil) and higher subsidies that result in decrease of budget revenue.

The modeling results display that 45Q leads to an increase in CO_2-EOR production of 400,000 bbl a day in 2030 in all scenarios, but with 45Q expiration, CO_2-EOR production decreases. CO_2-EOR production in Canada and Mexico continuously increases and, by 2050, reaches about 50 Mbbl a day in Canada and 685–780 Mbbl a day in Mexico. The results show that CO_2-EOR production in Canada has much lower potential than in the United States and Mexico. The reason is that OOIP and TRR for CO_2-EOR in Canada are relatively lower. Another reason is that Canada doesn't have a significant non-anthropogenic source of CO_2, so only anthropogenic CO_2 sources can be used for CO_2-EOR. Electricity in Canada comes from hydropower primarily, while nuclear, coal, and natural gas provide the remaining supply. Thus, CO_2 supply from the power sector can contribute to a lesser extent than other sectors where the deployment of CCUS could happen. These include the oil sands, natural gas processing (e.g., from the new development of shale gas), and other sectors such as chemicals, fertilizer, steel making, and cement. The oil sands are Canada's unique challenge for advancing CCUS. Unlike power plants, other sector CCUS facilities are challenging as they have multiple point sources of emissions that vary in size and concentration of CO_2 [Mitrović and Malone, 2011].

The highest levels of CO_2-EOR productions can be observed in the CCUS 45Q law + carbon price + learning scenario. This suggests that government investment in R&D to bring down the cost of capture and infrastructure for sustainable supply of anthropogenic CO_2 to close the supply-demand gap could expand CO_2-EOR opportunities.

Scenario projections show that Mexico has a large potential for CO_2-EOR production. In March 2014, Mexico launched its CCUS technology roadmap containing recommendations for actions to be taken at a national level up to 2024 focusing on geological storage in deep saline aquifers and EOR projects [Mexican Ministry of Energy, 2014]. However, there are several factors that contribute to difficulties in CO_2-EOR in Mexico, including investment constraints and reservoir service capabilities.

While the current 45Q is projected to promote CCUS capacity related to EOR opportunities, duration length of the tax credit affects each capacity differently, for example, existing coal plants, and existing and new NGCC. In addition, the policymaker should explicitly consider the credit period because of the impact on fleet age bias as the efficiency of old units is lower than that of younger units, resulting in higher emissions than otherwise possible.

5. Conclusions

Though uncertainties remain regarding technological changes, economic growth, and political agendas that affect scenario projections, the following conclusions can be made from this study.

First, 45Q has the potential to increase CO_2-EOR production during periods of policy availability and support deployment of CCUS even after 45Q ends if CO_2 taxes are implemented.

Second, there are forms of synergies and trade-offs between 45Q and CO_2 taxation. In the short term, 45Q encourages new CCUS power plant deployments, which keep operating in the long term, after 45Q expiration, to support the CO_2 emission intensity reduction initiated by increasing CO_2 taxation. There are trade-offs between 45Q and CO_2 taxation associated with budget costs and budget revenues in the short term. However, in the long term (by 2050), cumulative 45Q tax credits are 1.2–1.8 trillion $US less than cumulative budget revenues from CO_2 taxation.

Third, in the scenarios with CO_2 taxation, decarbonization occurs principally in the power sector alone. Current emissions from the transportation sector account for about 40% of CO_2 emissions, so increasing the deployment of low-emission or emission-free vehicles, particularly heavy-duty vehicles, is a crucial part of climate change mitigation. Scenarios with CO_2 taxation results show that decarbonization only occurs in the power generation sector largely independent of the CO_2 price across all sources and sectors. Additionally, deep decarbonization in the transportation sector is a difficult task that will take decades, so there could be continuing need for EOR technology.

Fourth, results show that CCUS technological learning assumptions significantly affect total power generation and the U.S. power generation mix: electricity production in the CCUS 45Q law + carbon price + learning scenario is about 25% higher than in all other scenarios. Thus, less costly CCUS power plants lead to higher electricity demand and higher electrification rates in end-use sectors.

Fifth, although currently CCUS has not been particularly deployed, our scenario with CCUS technological learning indicates that CCUS could play a very important role under stringent environmental constraints. Thus, accelerated support and funding for the large-scale CCUS demonstrations is important for the execution of both short- and long-term climate mitigation goals.

Several caveats should be noted regarding the modeling assumptions and results. The scenario projections are not explicit predictions, but only possible future pathways based on specific modeling assumptions. Mexico and Canada are reproduced as single regions without further disaggregation; including multiple regions into the Mexico and Canada sub-modules could affect modeling results; exploring the impact of regional disaggregation on results could be an avenue for future work.

Water constraints were not included in the model, but power sector dependence on water exposes electricity generation to weather variability in some regions of North America, particularly in Mexico. Thermal-electric power has been identified as a major user of water; water scarcity or abundance will affect modeling results on the construction of new power plants. CCUS escalates the amount of water used [GCEP, 2005]; furthermore, the additional power used to capture and sequester CO_2 lowers the plant's output, thus raising the amount of water used per unit of energy generated.

Last, but not least, the U.S. goal to reach net-zero, economy-wide emissions by no later than 2050 is a part of re-entering the Paris Agreement, the new 2030 emissions target (the nationally determined contribution) of a 50–52% reduction from 2005 levels in economy-wide net greenhouse gas emissions in 2030, and a 100% carbon-free electricity sector by 2035 are significant challenges for the U.S. energy system transformation, so the role of 45Q must be investigated further under deep decarbonization scenarios.

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Appendix A.

Table A1: Cost and performance characteristics of new central station electricity generating technologies.

Technology	Online year	Investment costs 2005$US10e6/GW		Variable O&M 2005$US10e6/PJ		Fixed O&M 2005$US10e6/GW		Heat rate PJ/PJ[a]		Discount rate
		First year	2050	First year	2050	First year	2050	First year	2050	
Coal IGCC	2015	3088.21	2847.33	1.76	1.76	45.02	45.02	2.55	2.18	0.15
Coal IGCC CCS	2025	5368.05	4750.73	2.11	2.11	65.63	65.63	2.43	2.43	0.20
Coal IGCC CCS with R&D goals	2025	5368.05	2279.63	2.11	1.33	65.63	41.36	2.43	1.58	0.20
NGCC	2015	827.90	774.09	0.80	0.80	13.47	13.47	2.07	1.99	0.13
NGCC CCS	2025	1672.22	1471.56	1.70	1.70	28.64	28.64	2.20	2.20	0.20
NGCC CCS with R&D Goals	2025	1672.22	1067.90	1.70	1.22	28.64	20.66	2.20	1.42	0.20
NGCT	2020	809.51	809.51	2.52	2.52	6.17	6.17	3.20	2.60	0.13
Advanced nuclear	2015	4172.81	3717.68	0.52	0.52	81.72	81.72	0.65	0.65	0.25
Biomass IGCC	2015	3145.16	2899.83	1.28	1.28	92.55	92.55	3.96	3.96	0.15
Biomass IGCC CCS	2025	5426.62	5426.62	1.62	1.62	114.51	114.51	4.21	4.21	0.20
Geothermal	2010	2080.71	1872.64	0.00	0.00	98.93	98.93	2.85	2.85	0.13

Municipal solid waste	2010	2463.29	2463.29	5.27	5.27	42.14	42.14	5.00	5.00	0.15
Wind onshore	2010	1868.84	1868.84	0.00	0.00	28.67	21.45	2.85	2.85	0.15
Wind offshore	2015	4071.81	3257.45	0.00	0.00	64.83	64.83	2.85	2.85	0.15
Solar thermal	2015	4428.98	3186.08	0.00	0.00	58.93	58.93	2.85	2.85	0.15
Photovoltaic	2010	3243.39	2758.15	0.00	0.00	21.63	21.63	2.85	2.85	0.15

[a] Heat rate for nuclear is in tons of uranium per PJ.

Appendix B.

Table B1: Power sector CCUS deployment by scenarios (in GWe).

Scenarios	**2030**		**2040**		**2050**	
	CCS Retrofit	**New CCS**	**CCS Retrofit**	**New CCS**	**CCS Retrofit**	**New CCS**
	United States					
Carbon_All	38	0	40	0	85	1
CCUS 45Q law + carbon price	39	175	37	240	23	249
CCUS 45Q law + carbon price + learning	85	245	46	362	33	548
CCUS 45Q + carbon price	12	181	36	245	20	254
CCUS indef + carbon price	61	217	30	256	14	264
	Canada					
Carbon_All	0	0	0	0	0	4
CCUS 45Q law + carbon price	0	0	0	0	0	4
CCUS 45Q law + carbon price + learning	0	8	0	14	0	35
CCUS 45Q + carbon price	0	0	0	0	0	4
CCUS indef + carbon price	0	0	0	2	0	5
	Mexico					
Carbon_All	26	0	24	0	26	0
CCUS 45Q law + carbon price	26	0	24	0	26	0
CCUS 45Q law + carbon price + learning	26	0	19	5	17	23

CCUS 45Q + carbon price	26	0	24	0	26	0
CCUS indef + carbon price	26	0	24	0	25	0

Appendix C.

Table C1. 45Q tax credit costs to the U.S. tax payer by scenarios (in billion $US).

Scenarios	2020	2025	2030	2035	2040	2045	2050
Carbon_All	0	0	0	0	0	0	0
CCUS 45Q law + carbon price	2.0	3.1	11.4	15.7	0	0	0
CCUS 45Q law + carbon price + learning	1.8	53.2	74.8	80.1	0	0	0
CCUS 45Q + carbon price	1.8	55.6	95.4	122.2	0	0	0
CCUS indef + carbon price	1.8	44.3	64.7	77.6	0	0	0

Table C2. CO_2 emissions tax revenue in the U.S. by scenarios (in billion $US).

Scenarios	2020	2025	2030	2035	2040	2045	2050
Carbon_All	0	217	203	205	239	300	378
CCUS 45Q law + carbon price	0	194	182	200	216	275	353
CCUS 45Q law + carbon price + learning	0	195	169	198	185	200	205
CCUS 45Q + carbon price	0	194	182	200	216	275	353
CCUS indef + carbon price	0	192	204	218	265	334	425