# Low Carbon Futures with Carbon Capture and Storage:

interactions between technology-push policies and market mechanisms

## Appendices

# Appendix A

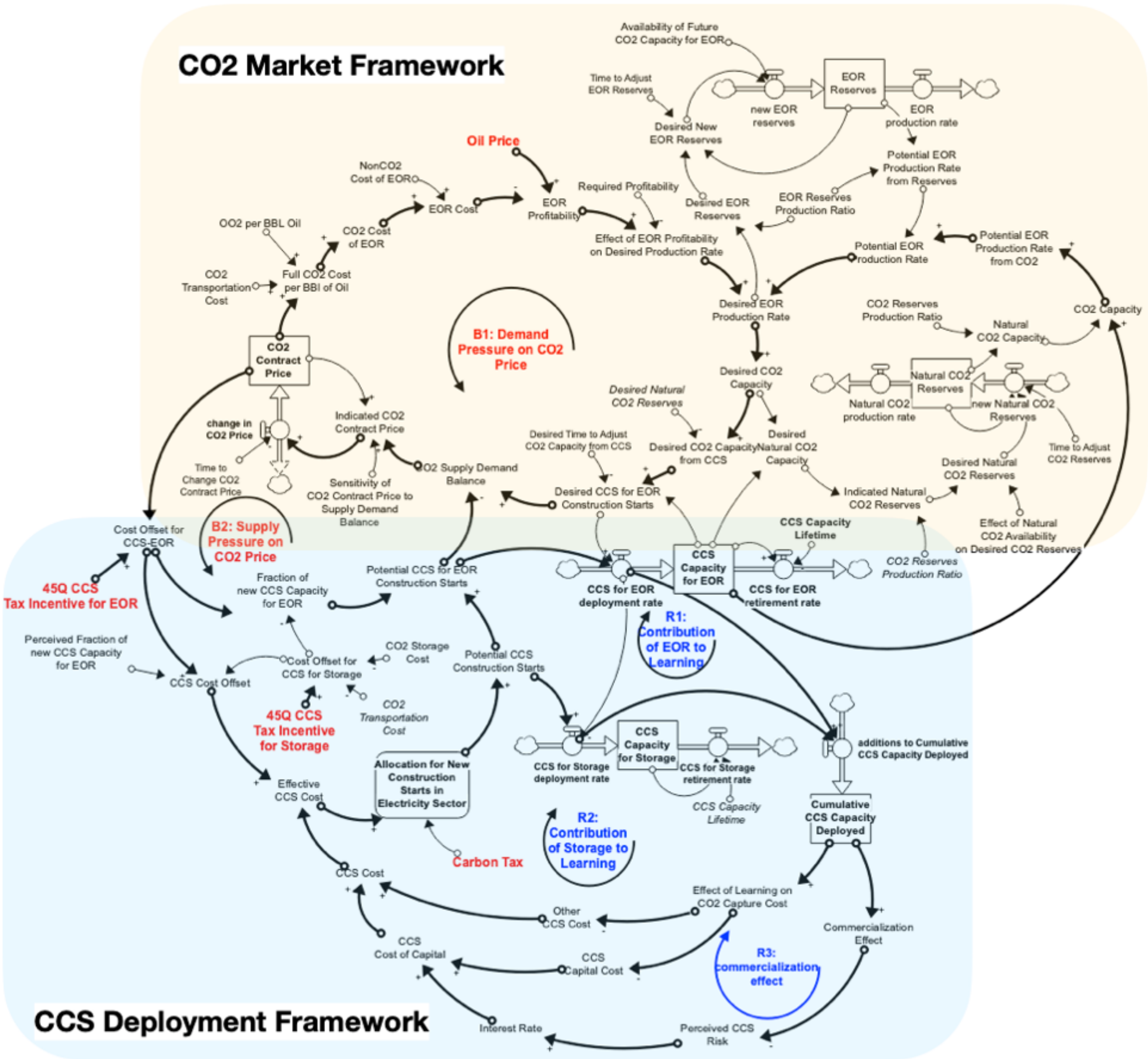



Figure A.1. The Core of CCUS-FREC: CCS Deployment and $CO_2$ Market Frameworks

# Appendix B

## Base Run: Context and CCS

Since CCUS-FREC is essentially calibrated to capture the key aspects of electricity, oil and energy-economy context of the U.S. as reflected by AEO2020, the *Base Run* reproduces reasonably well AEO2020 projections for the central variables (see *Figures B.1, B.9* and *B.10*). The present section discusses briefly the trajectory of CCS deployment and the most relevant features of the context through 2050 (the projection period by AEO2020) with more focus on the dynamics after mid-century.

Even though CCS starts off as a relatively expensive power technology, it still receives small share in new constructions that enable some CCS deployment and even modest cost reductions due to technological learning. Natural gas-fueled CCS, as a cheaper option relative to coal-fueled CCS, exhibits higher deployment and steeper cost reductions (*Figure B.5*). The deployment rates, however, are not enough to drive technological learning to the extent that makes CCS more cost-competitive relative to other power technologies. Furthermore, expiration of 45Q tax credits for CCS in 2024 leads to a slight increase in effective CCS costs before technology reduces the cost somewhat. As CCS remains at a small scale, it is still being perceived as a technology with high commercialization risk, which further limits market-driven deployment. On the other hand, unabated natural gas, solar and wind, continue being most cost-competitive choices for new capacity constructions. In 2030-2040, VRE shows modest growth in comparison to the first decade of the simulation as expensive and technologically immature battery storage limits the ability of power system to integrate higher shares of intermittent solar and wind (see *Figures B.6* and *B.7*).

CCS for EOR and CCS for storage exhibit roughly similar deployment scales through 2050 as EOR does not expand significantly in this period (*Figure B.4*): both CCS, on the supply side, is an expensive power capacity option relative to available technologies and EOR, on the demand side, is not a sufficiently attractive production option in the oil industry due to initially decreasing oil prices and availability of lower cost non-EOR resource (tight oil). EOR mainly maintains its production scale by keeping injection rate of natural $CO_2$ - the predominant source of $CO_2$ - roughly constant (*Figure B.8*). Limited flooding by $CO_2$ from CCS remains at the initial level. A slight decrease in prospective CCS construction starts due to phase out of 45Q tax credits for CCS in 2024 contributes further to CCS-EOR being stuck in the initial limited scale. Around 2030, however, oil price sets on an increasing trajectory. At the same time, as more productive tight and offshore oil resource is depleted, the production of oil moves to more challenging areas (*Figure B.1*). Both factors contribute to increasing ambitions for EOR, which is now able to set on some very modest expansion (*Figure B.8*).

The context for the future beyond 2050 in CCUS-FREC is driven by long-term assumptions about energy-economy, fuel prices and oil resource (tight and offshore oil). As a consequence of macroeconomic and energy efficiency assumptions, energy demand for all fuels, except for coal, continues increasing. CCUS-FREC maintains the assumption that coal is strategically displaced as an expanding option in the energy futures (*Figure B.3*). The growth in demand for oil is more dramatic than for electricity and natural gas, since oil consumption is driven mostly by transportation sector, where no meaningful energy efficiency improvements is assumed beyond 2050. The *Base Run* in fact portrays a very plausible realization of carbon-unconstrained future with continuous reliance on both oil and natural gas till the end of the century.

The production rates of tight and offshore oil resources are assumed to decline somewhat further after 2050, but then stabilize at still higher values than in 2018 for tight oil and at slightly lower values for offshore oil (*Figure B.1*). These scenarios are accomplished by allowing the technology to offset the rising development costs associated with new less productive tight and offshore resources. Note that no new discoveries are envisioned by these scenarios. The technologies assumptions are definitely optimistic for tight and offshore resources, however, they make up a more "resistant" oil context for $CO_2$ EOR, especially given the assumed continuing growth in oil demand throughout the century. A less rather than more favorable context for $CO_2$ EOR is desirable to reduce the risk of overestimating the role of $CO_2$-EOR for CCS. Even with these rather optimistic non-$CO_2$ EOR oil resource assumptions and consistent with the dynamics of end use demand in the economy, the growth in consumption of oil is being met by ever-increasing imports (*Figure B.2*).

Continuing deployment of VRE eventually leads to improvements in battery storage technology that allows VRE to grow more rapidly after 2050 (*Figure B.6*). This growth, however, saturates by the end of the century, as further improvements in battery storage technology are needed to lower the effective cost of solar and wind significantly below cost on natural gas generation. Overall, improvements in battery storage technology enable VRE to reach 51% of electricity generation by 2100. Since carbon is not priced or constrained, around 38% of electricity generation comes from unabated (non-CCS) fossil generation - mostly natural gas with some coal. In this mix, CCS comprises less than 2% of electricity generation by 2100. The *Base Run* essentially represents the future where CCS in power sector does not take off.

# Figures B.1 - B.6: Base Run

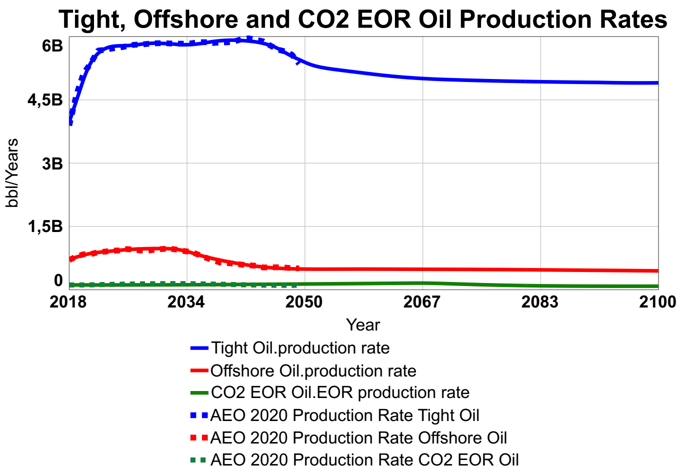



FIGURE B.1. TIGHT, OFFSHORE AND CO2 EOR OIL PRODUCTION RATES. CCUS-FREC BASE RUN 2100

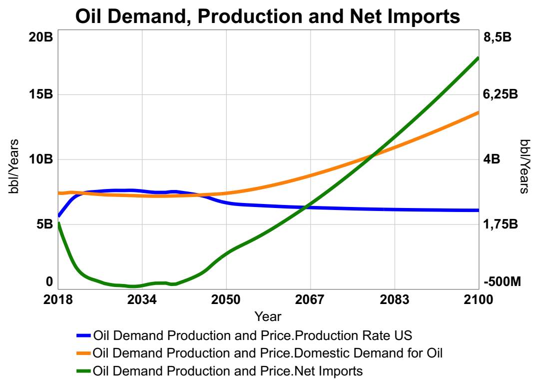



FIGURE B.2. TOTAL OIL PRODUCTION RATE, DOMESTIC DEMAND FOR OIL AND NET IMPORTS. CCUS-FREC BASE RUN 2100

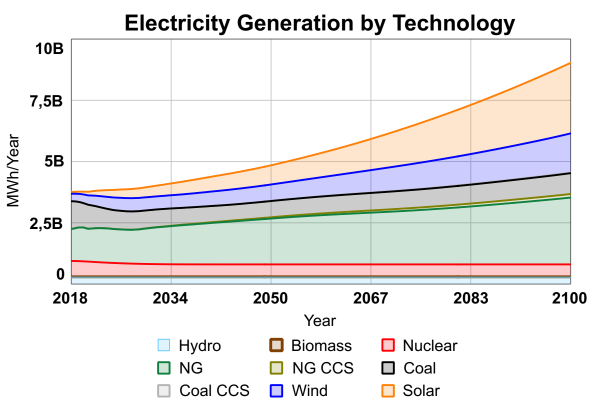



FIGURE B.3. ELECTRICITY GENERATION BY TECHNOLOGY. CCUS-FREC. BASE RUN 2100

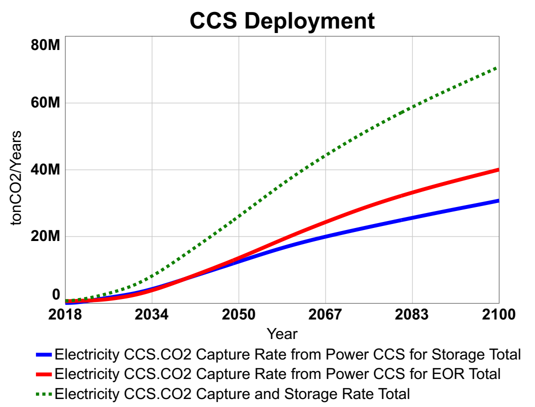



FIGURE B.4. CCS DEPLOYMENT: TOTAL AND SEPARATE FOR CCS FOR STORAGE AND CCS FOR EOR. CCUS-FREC. BASE RUN 2100

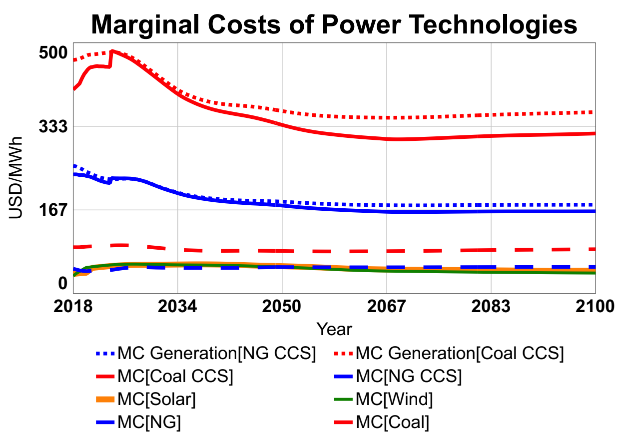



FIGURE B.5. THE DYNAMICS OF COST COMPETITIVENESS OF CCS AGAINST FOUR NON-CCS POLICY-UNCONSTRAINED TECHNOLOGIES. CCUS-FREC. BASE RUN 2100

CCS COSTS ARE PLOTTED AGAINST CORRESPONDING GENERATION COSTS TO REFLECT THE IMPACT OF BASELINE POLICY INCENTIVES FOR CCS

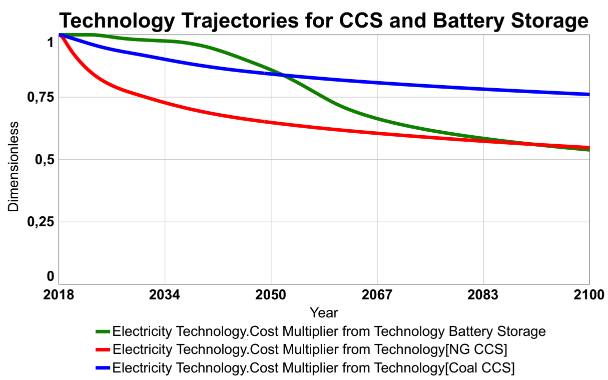



FIGURE B.6. THE DYNAMICS OF TECHNOLOGICAL IMPROVEMENTS FOR NG CCS, COAL CCS AND BATTERY STORAGE. CCUS-FREC. BASE RUN 2100

# Figures B.7 - B.10: Base Run

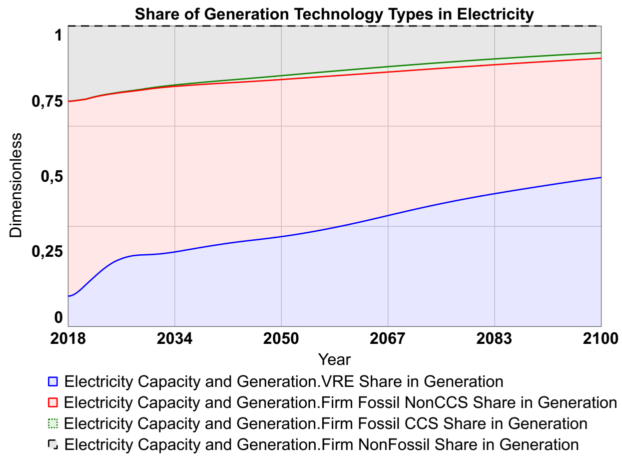



**FIGURE B.7. ELECTRICITY MIX BY TECHNOLOGY TYPES. CCUS-FREC. BASE RUN 2100**

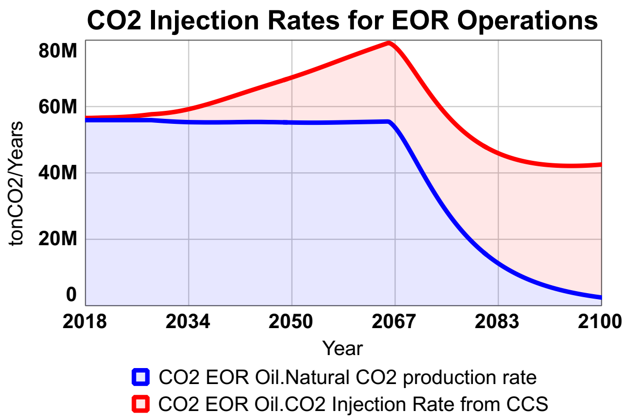



**FIGURE B.8. NATURAL AND ANTHROPOGENIC (CCS) CO2 INJECTION RATES FOR EOR OPERATIONS. CCUS-FREC. BASE RUN 2100**

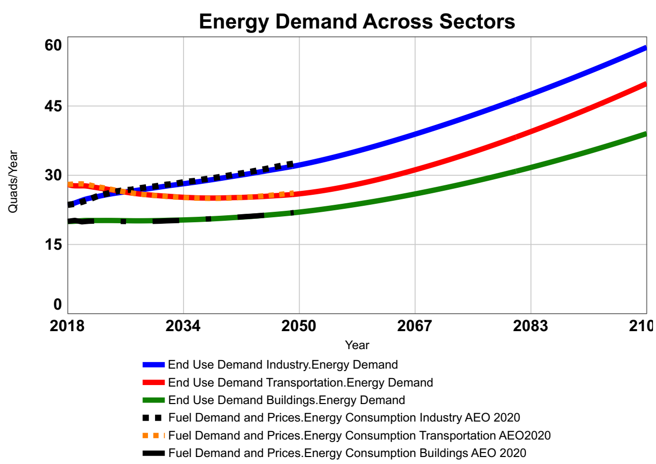



**FIGURE B.9. END-USE FUEL DEMAND. CCUS-FREC BASE RUN 2100**

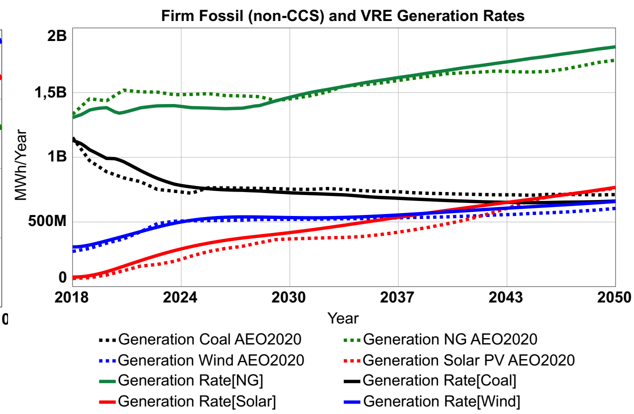



**FIGURE B.10. ELECTRICITY GENERATION FROM FIRM FOSSIL NON-CCS AND VRE TECHNOLOGY. CCUS-FREC BASE RUN 2050 AGAINST AEO2020**

# Appendix C

## C.1. CCS Deployment in the Carbon-Constrained Future: Carbon Tax

Carbon-constrained future in CCUS-FREC is simulated by introducing carbon tax. The carbon tax can be applied following either of two approaches. According to the first approach, carbon tax is imposed for electricity sector only. This design effectively mimics policies aimed at decarbonizing specifically power sector. By applying carbon pricing to electricity only, the effects of carbon tax on the rest of the economy and the related feedbacks that impact electricity sector, including many substitution effects, are "disabled". According to the second approach, carbon tax applied to the entire energy-economy system in CCUS-FREC. In this design, electricity-specific effects are combined together with the effects of carbon tax on the rest of the economy and the related feedbacks that impact electricity sector, including various substitution effects.

Carbon tax of USD 100 per ton$CO_2$ is introduced in 2025 and maintained for the remainder of the simulation horizon. Even though end-use demand for oil and electricity differ among the two carbon tax designs, the difference in the impacts on the scale and dynamics of CCS is minor (*Figure C.1.1*). In both simulation runs, CCS exhibits a more pronounced growth relative to the *Base Run* till around 2060, yet still remains at a small scale: the maximum achieved share in generation is less than 7% (*Figure C.1.2*). On the other hand, it is VRE that benefits more from carbon tax: induced by additional substantial cost advantage due to zero emissions, continuous investments into solar and wind lead to drastic improvements in the battery storage technology after 2035.

Note that CCS for EOR and storage are practically at the same scale throughout the entire simulation (*Figure C.1.3*). This implies that EOR does not provide much of the cost offset: $CO_2$ prices are lower in this carbon-constrained future, since the carbon tax makes CCS more available and easier to be contracted by EOR at lower prices. EOR benefits from lower $CO_2$ prices and expands its scale more significantly than in the *Base Run*. Since CCS scale for EOR is more expanded by the time natural $CO_2$ supplies run out, EOR is able to offer higher $CO_2$ prices later on when CCS is needed to replace depleted natural $CO_2$. These higher prices, however, are not sufficient to compensate for the increasing cost of CCS due to lower capacity utilization later in the century (the effect of high penetration of VRE in the power system). Simulation runs *Carbon Tax Electricity USD 100* and *Carbon Tax Economy USD 100* capture a currently expected carbon-constrained future, where CCS does not take off and VRE - solar and wind - become the major carbon-free technologies.

## Figures C.1.1 - C.1.3: Carbon Tax

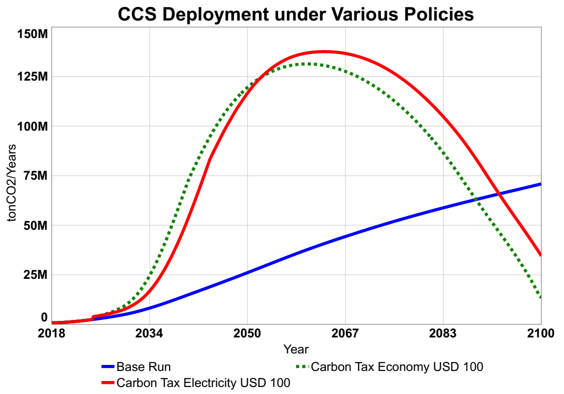



FIGURE C.1.1 CCS DEPLOYMENT UNDER CARBON TAX

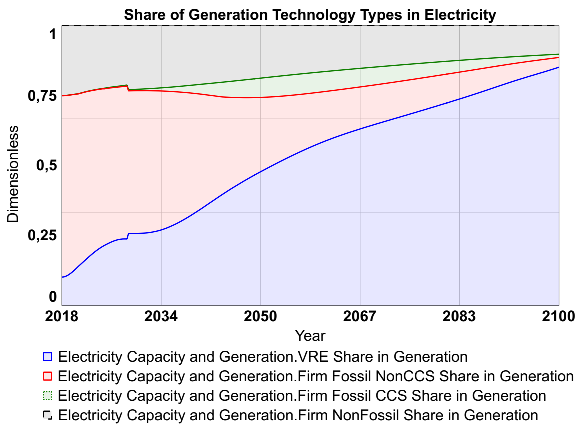



FIGURE C.1.2. ELECTRICITY MIX BY TECHNOLOGY TYPES UNDER 100 USD CARBON TAX APPLIED TO ELECTRICITY ONLY

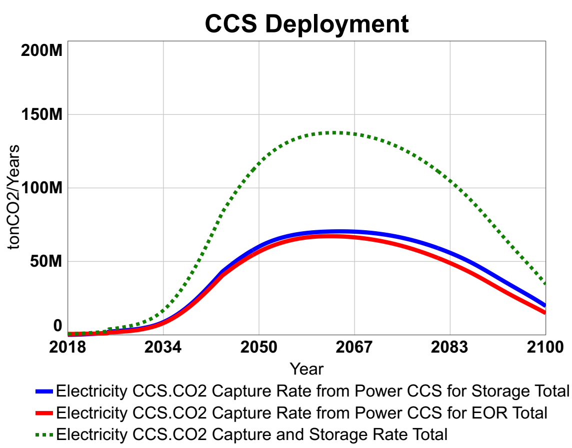



FIGURE C.1.3. CCS DEPLOYMENT: TOTAL AND SEPARATE FOR CCS FOR STORAGE AND CCS FOR EOR. CARBON TAX ELECTRICITY USD 100

## C.2. Side Simulation Experiments: Carbon Tax

The series of side cases demonstrates the trajectories of CCS deployment and $CO_2$ price under various carbon tax amounts (see *Figures C.2.1* and *C.2.2*). CCUS-FREC is simulated under seven alternative carbon tax amounts:

- weak carbon tax is represented by 30 USD/ton$CO_2$;
- moderate carbon tax below the reference value - 70 USD/ton$CO_2$;
- progressively higher carbon taxes at 150, 200, 250 and 300 USD/ton$CO_2$;
- very high carbon tax at 950 USD/ton$CO_2$ (close to the optimal carbon tax in Fiddaman (1997)).

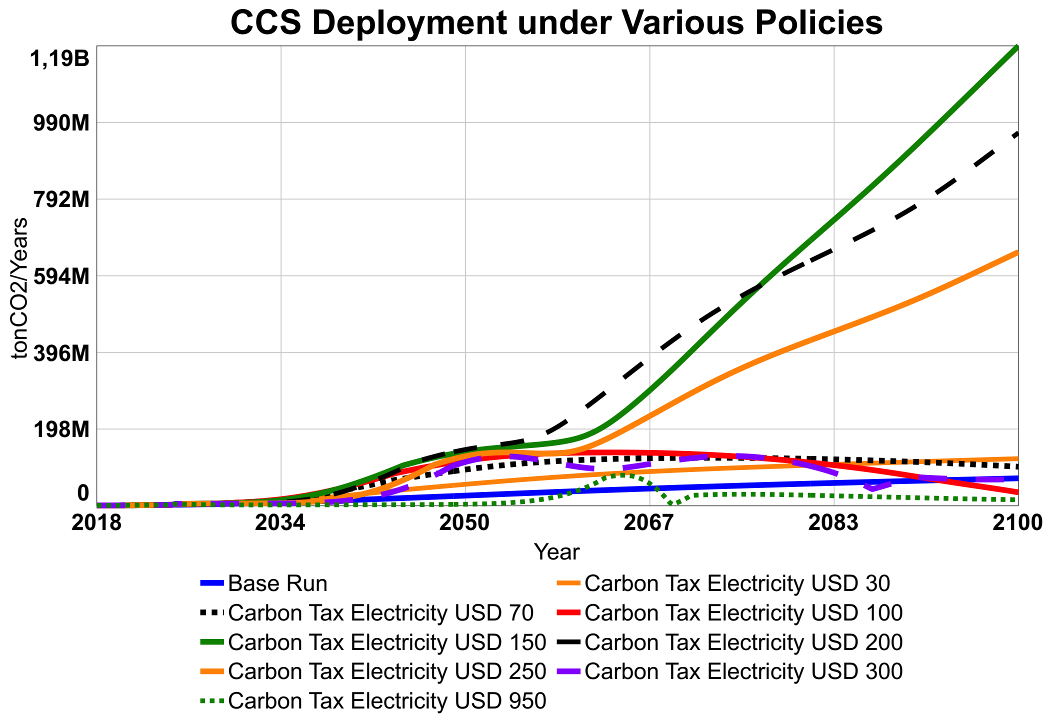
For all the amounts, carbon tax is applied to electricity sector only and introduced in 2025. *Figures C.2.1* and *C.2.2* demonstrate an interesting result: while CCS commercialization structure is parameterized to yield an assumed CCS deployment trajectory under *Carbon Tax Electricity USD 100*, CCUS-FREC is able to capture the potential for optimal amount of carbon tax that maximizes CCS deployment. For example, under 150 USD/ton$CO_2$, CCS exhibits a steady growth in its deployment after 2050 exceeding giga-tonne scale by the end of the century. Higher taxes (200 and 250 USD/ton$CO_2$) still support continuing CCS growth but achieve lower ultimate scales. Already starting 300 USD/ton$CO_2$, CCS deployment trajectory mimics the *Carbon Tax Electricity USD 100* pattern of growth, peak and decline, though the decline happens much earlier and is more drastic.

The reason for the observed differences in CCS deployment trajectories is in in interactions between the relativity of cost-advantage that VRE and CCS receive under various carbon tax amounts, the relativity of carbon tax-related cost advantage for CCS and the amount of cost offset provided by $CO_2$ price from EOR, the resulting effects on the deployment rates of the two low-carbon technologies, and the non-linear feedbacks through endogenous technological learning (and commercialization, in case of CCS). Since CCS is initially more expensive than other power technologies, lower carbon taxes support some increase in the deployment but not to the degree that is sufficient to realize the cost reductions potential. Therefore, over time VRE increases its cost competitiveness through technological improvements in the battery storage and takes over the position of CCS in the power sector. In the context captured by CCUS-FREC, carbon taxes in the range of around 150-200 USD/ton$CO_2$ provide, first, a sufficient cost advantage to stimulate CCS deployment in the medium-term that allows to realize a substantial part of the cost reduction potential and, second, a cost advantage that together with reduced CCS cost and the $CO_2$ price from EOR enables to sustain continuous deployment growth towards a larger scale later in the century. Very high carbon taxes (in CCUS-FREC context, starting 300 USD/ton$CO_2$) support CCS deployment initially but ultimately favor VRE due to incomplete capture rate by CCS: even at 90% capture, the emissions priced at very high carbon tax amounts tilt the relative attractiveness from CCS towards VRE. This general result pertaining to relative attractiveness of CCS and VRE under low, moderate and high carbon tax (or emissions limits) is consistent with the studies that explore deep decarbonization of power sector in the U.S. (Sepulveda *et al.,* 2018).

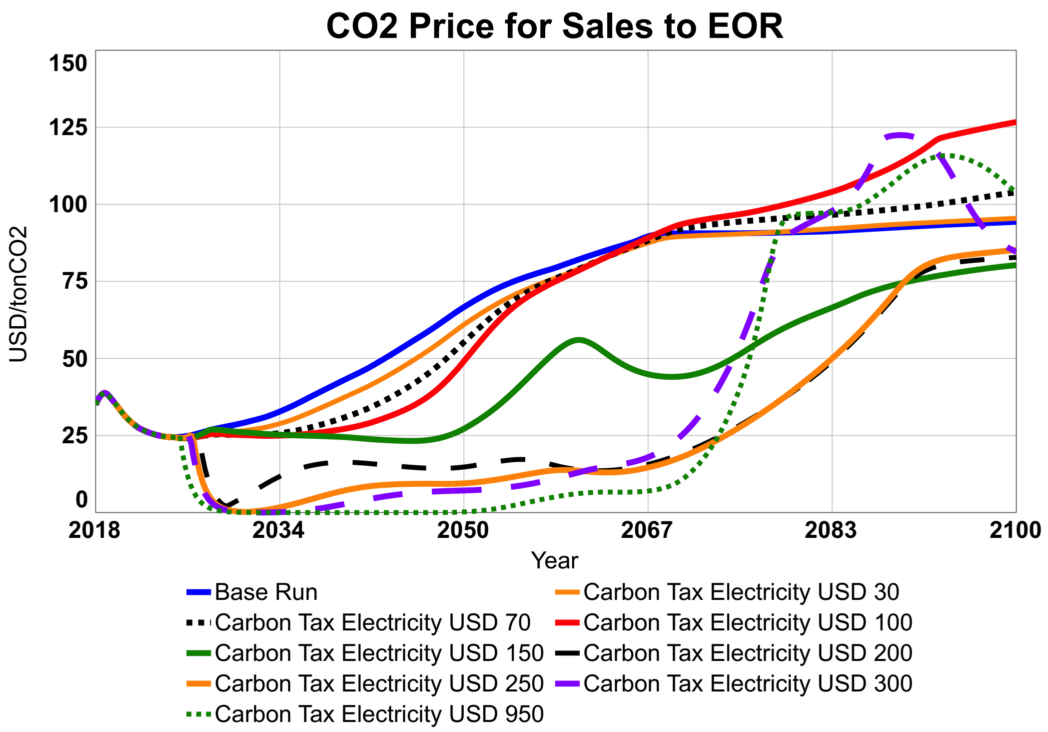
Two comments need to be made in order to supplement the present discussion. First, similar to the simulation experiments with CCS incentives in a carbon-constrained context, the role of EOR is crucial in enabling sustained growth of CCS under high carbon tax. Specifically, since CCS cost has been reduced by 2050 and the high carbon tax is still in place, the $CO_2$ price offered by EOR is just enough to make CCS a sufficiently attractive option for new constructions. *Figure C.2.3* demonstrates this role of EOR by plotting CCS deployment trajectory under *Carbon Tax Electricity USD 150* against a comparable run with the constant oil price at 2018 value (*Carbon Tax Electricity USD 150 Oil Price 2018*): while for most of the century the two deployment trajectories are nearly identical, CCS growth slows down by 2100 and, consequently, a lower scale is achieved by the technology. The difference is more dramatic when the same amount of carbon tax is applied for the entire economy. First, the deployment trajectory under *Carbon Tax Economy USD 150* is noticeably lower compared to the electricity only case (the result of lower demand for oil). Second, under economy-wide carbon tax (*Carbon Tax Economy USD 150 Oil Price 2018*) a constant moderate oil price is not sufficient to prevent CCS deployment from the decline observed in the *Base Run*.

Second, simulating CCS deployment under very high carbon tax (*Figure C.2.1*) shows that after the period of substantial decline the technology bounces slightly up and maintains this new scale for the remainder of the simulation. This behavior is a consequence of non-linear formulation in the *Electricity Sub-Model* (*Electricity Capacity and Generation Module*) that aims at maintaining a minimum utilization of the available fossil capacity under very high (above 90%) shares of VRE in generation.

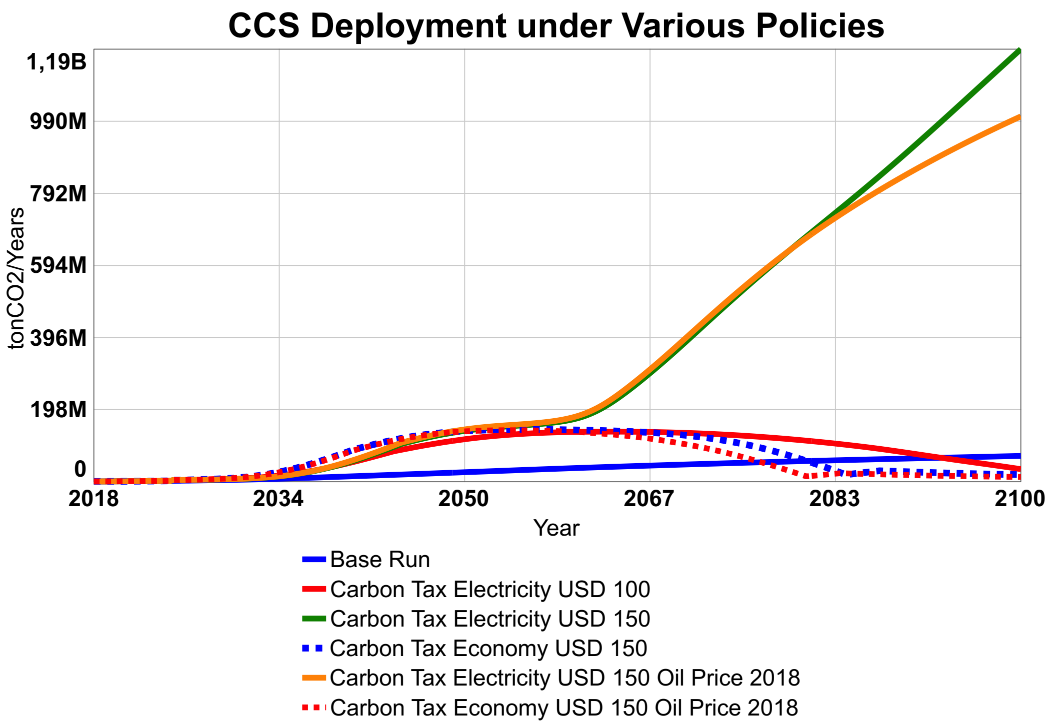
**Figures C.2.1 - C.2.3: Simulation Experiments under Various Amounts of Carbon Tax**




**C.2.1. CCS Deployment under Carbon Tax Side Cases**




**C.2.2. $CO_2$ Price under Carbon Tax Side Cases**




**C.2.3. CCS Deployment under Additional Carbon Tax Side Cases**