The role and value of BECCS in the USA

by

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1 Executive summary

This study assesses the role of bioenergy with carbon capture and storage (BECCS) in the deep decarbonisation of the US energy system. We evaluate the impacts of the existing policy support measures, such as the Bipartisan Infrastructure Law (BIL) and Inflation Reduction Act (IRA), for achieving a net-zero economy. Three major regional grids (CAISO, MISO, and ERCOT) are analysed, with six scenarios per regional grid for a total of 18 illustrative scenarios.

We compare low-carbon power generation, energy storage, and CDR technologies to assess least-cost electricity system evolutions, relying on data from regional electricity system operators (ESOs) and government projections. Three core scenarios (reference scenario without emission constraint, net-zero power system by 2035, net-negative power by 2050 for overall net-zero) are created to represent varying climate ambitions. These are further divided based on the inclusion of policy support measures, providing insights into their impact on the low-carbon transition. The results are evaluated using key performance metrics, such as the cost of electricity supply, size and composition of the generation mix, gross value added, and job creation over time.

In transitioning the US to net zero, the gas share reduces significantly (51-66%) with intermittent renewable energy sources – primarily wind – being extensively deployed. Consequently, the reliable renewable power provided by BECCS in supporting grid stability and resilience as well as a least-cost net zero transition. Across the different ESOs, BECCS is observed to play an important role in the energy system, with deployed capacity ranging from 4.6 GW (CAISO) to 21.5 GW (MISO). Thus, BECCS is observed to create substantial economic value through ensuring reliable and affordable electricity to consumers, whilst preserving and creating jobs and economic growth across multiple sectors, including agriculture. Absent BECCS, the net zero transition is up to 31% more costly where it is possible at all.

We examined the efficacy of incentive measures like ITCs and 45Q credits for CO_2 sequestration. ITCs make renewables competitive with gas-fired power generation, increasing their capacity share by 20-45% of the total capacity by 2050. In the reference scenario with subsidies, coal-CCS emerged as a viable generation technology due to the sustained low coal prices and 45Q credit. The share of BECCS and coal-CCS increased with subsidies in net-zero and net-negative scenarios. BECCS provided approximately 12 - 20% of the overall generation. However, the IRA and BIL measures alone are insufficient for deep decarbonisation, and additional policy and regulatory support will be necessary.

Importantly, we found that further increasing the 45Q tax credit to $100 - 150/t CO_2 did not lead to a material deployment of BECCS but rather boosted the uptake of coal-CCS, but a $40/t CO_2 targeted support for negative emissions combined with the existing 45Q tax credit facilitated a net zero economy by 2050.

2 Introduction

Bioenergy with carbon capture and storage (BECCS) is expected to be a critical technology in helping to tackle climate change. BECCS offers the potential for carbon removals to compensate for emissions from hard-to-abate sectors of the economy, whilst also offering zero-carbon energy vectors in the form of electricity, hydrogen, and fuels for decarbonisation. BECCS offers unique value to the global energy system through the displacement of carbon-intensive fuels (with electricity, hydrogen, etc.) whilst simultaneously removing CO_2 from the atmosphere. BECCS can utilise a variety of biomass resources, including wastes and residues to help maximise resource efficiency and reduce costs. Most of the scenarios by the IPCC which limit global average temperature rise to within 2 °C rely on the deployment of BECCS at the Gigatonnes scale for climate stabilisation[1].

As one of the largest global emitters, the United States's Nationally Determined Contribution aims to reduce greenhouse gas emissions by 50 – 52% from 2005 levels by 2030. The Long-term Climate Strategy of the United States includes goals such as a carbon pollution-free electricity grid by 2035 to help achieve the stated objective [2]. The Bipartisan Infrastructure Law (BIL) supports this mission with $21.5 billion for low-carbon technologies. The Inflation Reduction Act (ACT) of 2022 complements the BIL with billions of additional funding to support the deployment of carbon capture and storage (CCS), carbon dioxide removal (CDR), and hydrogen. Given the immediacy of the goal to achieve a net-zero power system by 2035, the role and value of BECCS to the regional electricity grid needs to be investigated in detail before developing near-term implementation roadmaps.

Studies have estimated the need for approximately 200 Mt/yr of BECCS in the US under varying assumptions on the availability of low-carbon technologies and associated infrastructure [3]. It is important that the differing profiles of demand, resource supply, and existing capacities across the different ESOs in the US is considered in systems assessments to develop least cost region-specific pathways for decarbonisation. Existing studies provide an indication of the potential of BECCS but lack regional and temporal resolution to support investment planning or business case development [4]. Often these assessments assume that a technology is available to scale up by the necessary time and do not provide adequate information on deployment timelines. Moreover, there is a paucity of evidence on the impact of policy support from the BIL and IRA on incentivising the uptake of low-carbon technologies that are necessary for net-zero. Studies have suggested that both BIL and IRA can generate an additional 900,000 net jobs by 2035 compared to a reference scenario without these laws [5]. However, a macroeconomic impact assessment of BECCS is largely missing in existing studies, thus obscuring its potential economic value to the regional economies.

In addressing these gaps, this study takes a quantitative whole-systems assessment of the role and value of BECCS for decarbonising the US energy system. The key analytical goals of the project are as follows:

- Evaluate the role and value of BECCS in the USA with three specific areas of interest, namely MISO, CAISO, and ERCOT, using key performance metrics such as the cost of electricity, GVA, job creation.
- Simulate a range of deployment pathways to establish the system value of low-carbon generation technologies in each ESO under different policy and market environments.
- Assess the suitability of the BIL and IRA policy support to accelerate the uptake of the necessary generation technologies.

The remainder of this report is structured as follows: chapter three presents the methodological approach used to quantify the role of BECCS within the wider low-carbon energy system. It introduces the modelling framework and summarises the formulation of the scenarios. Chapter four presents the analysis on cost-optimal evolutions of the CAISO, MISO, and ERCOT electricity grids under different levels of climate ambition. The section delves deeper into the impact of the current policy support on KPIs such as the size, composition, and level of BECCS deployment. Chapter five further supplements this analysis with an estimation of the gross value added and jobs associated with the electricity systems evolution. Chapter six concludes with the key findings and policy recommendations to accelerate the energy transition whilst simultaneously maximising the economic benefits.

3 Methodological approach

The analysis presented in this report is conducted using the ESO-JEDI model, a combination of the Energy System Optimisation (ESO) model developed within Foresight Transitions, and the Jobs and Economic Development Impact (JEDI) model [6], originally developed by the US National Renewable

Energy Laboratory (NREL) but adapted for our purposes. The following subsections present the key model features and assumptions. A more detailed set of input data is provided as a separate annex to this report.

3.1 Overview of ESO

ESO was originally developed as power generation capacity-expansion and dispatch optimisation model [7], [8], but it has been under continuous development and includes other energy sectors such as heating, hydrogen, and carbon dioxide removal (CDR) as well [9]. For this report, the power and CDR sectors are considered. The mathematical model is based on a mixed integer linear programming (MILP) formulation, which was tailored to capture the complex interactions among various components including generation units, energy storage systems, and seasonal variations in demand.

ESO performs a simultaneous optimisation of long-term strategic capacity expansion planning and short-term unit operation planning. Starting from the current installed capacity mix, investment and decommissioning decisions are optimised over 5-year planning time steps until 2050 to identify the cost-optimal evolution of the installed capacity. At the same time, for each one of these time steps, the technology dispatch schedule is optimised with hourly resolution to identify the optimal operation of assets. A simplified schematic of the model is shown in Figure 3-1.

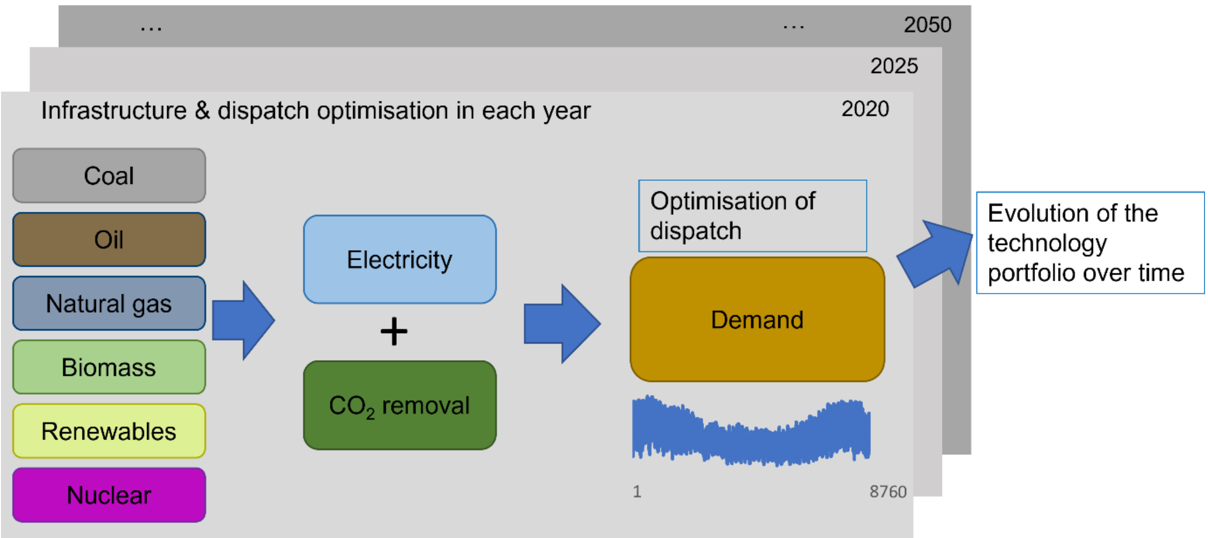


Figure 3-1: Simplified schematic of the simultaneous capacity-expansion and dispatch optimisation in ESO.

The objective of ESO is to minimise total system costs (TSC), which is the sum of all investment and operational costs across all considered sectors over the entire time horizon:

$$C_{\mathrm{TSC}} = \sum_{a=2020}^{2050} \left(\varphi(a) \sum_{\mathrm{Sectors}} \left(C_{\mathrm{Investment}}(a) + C_{\mathrm{Operation\&Maintenance}}(a) \right) \right). \tag{1}$$

Future costs are hereby discounted using a fixed discount rate of 3 %/a to account for inflation. The optimisation takes a central-planner perspective, assuming perfect foresight and perfect knowledge. Investment costs involve the costs of building new assets, while operation and maintenance costs include the most relevant costs to operate these assets, including:

- Fuel costs
- Fixed annual maintenance costs

- Variable maintenance costs
- Non-fuel running costs
- Startup/shutdown costs
- Costs of CO_2 transport and storage (for assets with CCS)
- Any carbon costs (if carbon tax or emissions trading scheme is present)

An extensive list of power generation technologies is considered in ESO:

- Open-cycle gas turbines (OCGT)
- Combined-cycle gas turbines (CCGT)
- Combined-cycle gas turbines with carbon-capture and storage (CCGT-CCS)
- Coal-fired power stations
- Coal-fired power stations with carbon-capture and storage (Coal-CCS)
- Nuclear power stations
- Bioenergy power stations
- Bioenergy power stations with carbon-capture and storage (BECCS)
- Onshore wind turbines
- Offshore wind turbines
- Solar photovoltaics (PV)
- Hydropower
- Synchronous compensators (to provide inertia to the system)

Additionally, pumped-hydroelectricity storage and Li-Ion battery storage are available in the model. The model considers CDR technologies such as BECCS and direct air carbon capture and storage (DACCS). Both low-temperature solid sorbent DACCS and high-temperature liquid solvent DACCS archetypes are considered in the analysis, which can be powered by electricity or natural gas[10], [11].

ESO is designed to assess the impact of various policies on the cost-optimal energy system evolution. As such, key policies such as 45Q tax credits for carbon sequestration, and investment tax credits (ITCs) for renewable energy technologies and energy storage are considered in the scenario analysis presented in the later sections of this report. Additionally, annual, and cumulative emission constraints can be enforced in ESO to investigate different decarbonisation pathways.

ESO incorporates a range of key constraints to promote feasibility of the identified solutions, which include:

- The electricity demand must be satisfied during each hour.
- A minimum inertia demand must be fulfilled to ensure grid stability.
- Minimum reserve capacities must be available.
- Build rate limits: The amount of new capacity built each year is limited to historically plausible values. Technology learning can increase maximum build rates from year to year.
- Flexibility: Minimum uptime and downtime constraints for assets, startup/shutdown costs are considered.
- Assets have a fixed lifetime and are forced to retire at the end of their lifetime.
- Hourly availability of wind and solar resources is explicitly considered. Inter-annual variations in availabilities are not captured in this analysis.

To reduce the computational complexity of ESO, we use a representative-day approach for the dispatch optimisation, which has been shown to be appropriate for energy system models[12], [13]. Using a clustering algorithm[14], we identify 12 typical days for each year, considering electricity demand and renewables availability. Additionally, we consider 2 extreme days: the day with the highest electricity demand, and the day with the lowest wind and solar availability. This ensures that the system is not undersized. For these 14 days for each of the 5-year timesteps, the technology dispatch is optimised with hourly resolution. Further details on the ESO model are provided in the appendix.

The ESO model requires inputs such as technology costs and operating parameters (efficiency, start-up and shut-down, ramp rates, etc.), fuel prices and information on the electricity systems, such as the demand for electricity across the planning horizon, together with the existing generation capacities. Key data sources are highlighted here, while more details are provided in the appendix.

Hourly electricity demand profiles for 2022 for the ERCOT, CAISO and MISO grids were extracted from the EIA open data platform[15]. From this, future demand profiles are extrapolated using peak demand increase forecasts as follows. For ERCOT, demand is projected to increase by 13% by 2030[16], which was extrapolated to a 39% demand increase by 2050. For CAISO, the projected demand increase is 27.6% by 2040 [17], corresponding to 41.4% by 2050, while for MISO demand is projected to increase by 24.9% by 2042[18], corresponding to 34% by 2050. It is assumed that the relative demand profile remains constant; therefore, the demand increase is evenly distributed across all hours of the year. The electricity demand projections used in this study, while comprehensive, do not account for the evolving landscape of electricity consumption resulting from the ongoing electrification of various sectors (e.g., transport, buildings, industry, etc.) within the economy. This will likely increase the need for both baseload and flexible generation of low-carbon power relative to the assumptions of this study.

Data on the current installed capacities are also taken from the EIA, using the EIA-860 database [15] containing a registry of power plants by block. The database is also used to determine the age of existing assets, which is used to calculate their remaining lifetime (see Table 2 in the appendix).

To match the demand data, we calculate wind and solar availability data for 2022. The raw data on solar irradiation and wind speeds is taken from NASA's MERRA-2 model [19], which is then processed to hourly capacity factors of wind farms and solar panels, using the methodology detailed in the appendix. To account for spatial variations in the generation profiles, we use five sample points per electricity grid and calculate average hourly capacity factors.

Cost projections on natural gas, coal, and uranium are taken from the latest EIA annual energy outlook[20] (AEO), which projects costs until 2050. Using Table 3 from the AEO, we use the electric power fuel prices for natural gas, steam coal, and uranium. These fuel prices are provided in the appendix. We assume a biomass price of 17.2 $/MWh (4.8 $/GJ).

Where possible, technology capital and operational costs were taken as average between the values reported in the NREL annual technology baseline report [21] and the EIA's annual energy outlook report, given the US-centric scenarios [20]. As neither source provides estimates on BECCS costs, European values from the UK Department of Business, Energy & Industrial Strategy (BEIS) [22]and the EU commission [23]are used. Operational costs not included in these data sets, such as startup and shutdown costs, are taken from Heuberger et al. [8]. Data on costs and performance of DACCS technologies is taken from Hanna et al. [24]. In line with analysis from the National Energy Technology Laboratory (NETL) [25], CO_2 transport and storage costs are assumed to be 10 $/t$CO_2$. This assumes pipeline transport and injection into known geological reservoirs.

3.2 Overview of JEDI

To address the social impact of decarbonising the power sector, we used a model originally developed by the National Renewable Energy Laboratory (NREL). The Jobs and Economic Development Impact (JEDI) model measures the Gross Value Added (GVA) and employment (Jobs) impacts of power sector transformations [6]. In this work, JEDI was adapted to work in tandem with ESO to evaluate socio-economic impact [26]. The methodological approach for JEDI evaluations is summarized in Figure 3-2.

Disaggregated technology costs (breakdown of CAPEX and OPEX) and macroeconomics parameters are combined with the outputs of the ESO formulation to evaluate the impacts on GVA and Jobs, and to distribute them across economic sectors, as identified in the International Standard Industrial Classification (ISIC) by the United Nations (UN)[27]. The key sectors of the economy, as characterised by JEDI, are as follows:

- Agriculture
- Mining and Extraction
- Utilities
- Construction
- Chemical Products
- Machinery/Electrical Equipment
- Maintenance
- Sales
- Transportation and Warehousing
- ICT
- Finance
- Professional, Science, and Technical Activities
- Administrative and Support Service Activities

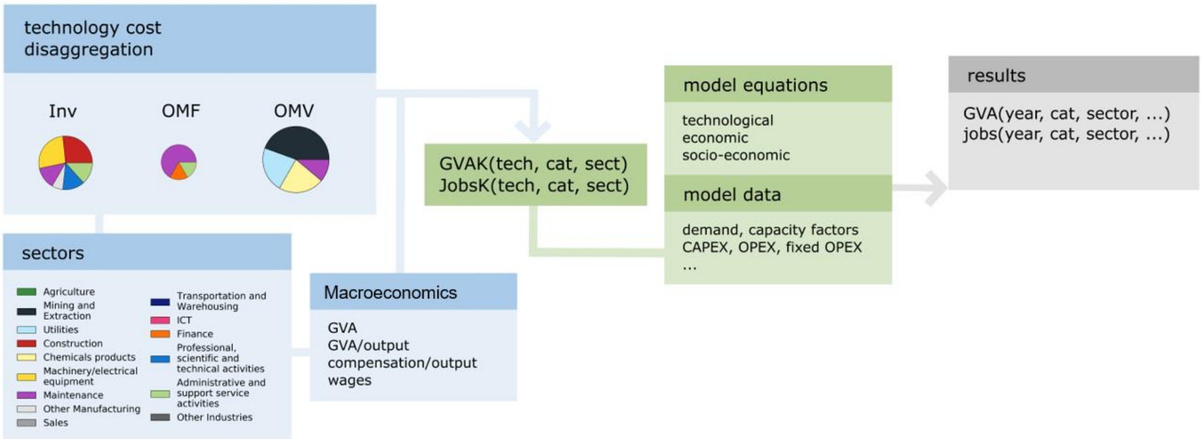


Figure 3-2: Overview of the JEDI model, where Inv: investment, OMF: operational and maintenance-fixed costs and OMV: operational and maintenance – variable costs [38].

Here, a definition of the main macroeconomic variables adopted in this study is detailed, both in the optimization process and in the quantification of the socioeconomic impacts descending from the technology deployment scenarios. Main macroeconomic variables such as: i) GVA, ii) Compensation of employees (or labour Costs) and iii) Wages and salaries by industry and at country level have been obtained from the national accounts reported in the STAN Database [28]. The GVA measures the contribution to the Gross Domestic Product (GDP) made by each individual producer, industry, or sector in the country. The GVA generated by any unit engaged in production activity can be calculated as the residual of the units' total output less intermediate consumption, goods and services used up in the process of producing the output (output approach), or as the sum of the factor incomes. In this study, the output and income measures of GVA by industry have been compared at sector level to validate the analysis. Combining these GVA measures with the investment analysis from ESO, we obtain a measure of the socio-economic benefits (GVA and its macro-economic components) resulting from the installation and operation activities of each technology.

As indicated earlier, JEDI requires two key inputs that are technology and macroeconomic parameters. The disaggregated technology costs are obtained from multiple sources and detailed in the data annex. The macro-economic parameters are derived from U.S. aggregate data from the OECD-STAN database [28] and consequently condensed into the economic sectors using a pre-processing step explained in the appendix.

3.3 Scenario formulation

The role and value of BECCS is evaluated in three representative scenarios, "reference", "net-zero power by 2035", and "carbon-negative power sector". Each of these scenarios is investigated with and without IRA incentives in place, for a total of 6 distinct scenarios. The scenarios are described in detail in the following subsections.

3.3.1 Reference

This scenario represents an economic optimisation of power generation absent any policy or legislative mandate to reduce emissions. As such, the objective is to minimise total system costs in meeting the electricity demand. No emission constraints or carbon prices are enforced, and no federal and state-level subsidies or tax credits are available for the generators. The electricity demand is expected to increase as detailed above.

3.3.2 Net-zero power by 2035

While still representing an economic optimisation, in this scenario carbon emissions from the power sector are constrained to reach net-zero by 2035, in line with the stated ambition of the current administration [2]. In the ESO model, a linear decarbonisation trajectory is enforced to reduce emissions from current levels to net-zero in 2035. In this scenario, no further emission reductions are enforced in the period from 2035 to 2050, and emissions from the power sector remain at net-zero. As in the reference scenario, no carbon prices and no subsidies or tax credits are available for the generators.

3.3.3 Carbon-negative power sector

This scenario represents a net-zero economy by 2050. In addition to reaching net-zero emissions from the power sector by 2035 as above, here the power sector is required to generate negative emissions from 2040 onwards to offset residual emissions from other sectors. Ultimately, CDR is required to provide negative emissions corresponding to around 10% of today's estimated total emissions in the region by 2050, to offset residual emissions from hard-to-abate sectors in the economy. For ERCOT, this corresponds to 66.4 Mt/a of CDR in 2050, CAISO requires 36.9 Mt/a of CDR in 2050, and MISO 100 Mt/a of CDR.

3.3.4 Scenarios with IRA tax credits

All three scenarios described above are also investigated with IRA tax credits in place. This includes both 45Q tax credits for carbon sequestration and investment tax credits (ITCs) for new renewable energy and energy storage assets.

45Q tax credits are 85 $/tCO_2$ sequestered from power generation assets, available for 12 years. For DACCS, the value of the tax credits is 180 $/tCO_2$. This is assuming that labour and wage standards are met, *i.e.*, at least the prevailing wage needs to be paid and a minimum number of apprenticeships need to be offered [29].

ITCs are available to fund wind and solar projects, as well as energy storage technologies. For the analysis here it is assumed that eligible projects can claim a maximum of 70% of investment costs. This requires projects to meet three additional criteria [30]:

1. Domestic materials: requires projects to source all their iron and steel, and 40% of other materials (by value) from US manufacturers.
2. Energy communities: bonus for siting the project in energy communities, which are communities that suffered from the decline of the fossil fuel industry.
3. Low-income communities: bonus for siting the project in low-income communities.

If any of these criteria is not met, the available ITCs reduce by 10 to 20 percentage points. Therefore, the scenarios analysed in this report represent the upper bound of available IRA tax credits. Finally, model evaluations are used to identify the most appropriate policy mechanisms to resolve any financial barriers and reach net-zero.

4 The evolution of the electricity system

4.1 Reference

The reference scenario shows a dominant role for gas-fired power generation in all three energy systems. The optimal generation capacity expansion in the power sector in ERCOT, CAISO and MISO are shown in Figure 4-1, while the corresponding annually generated power is shown in Figure 4-2. In all three energy systems, CCGTs and OCGTs are the predominantly installed power generation technology in 2050. Existing wind and solar generation capacity in the system is not replaced with new renewable generation, and instead relies on flexible gas-fired generation. The same is true for coal-fired power plants and nuclear power plants, which are being phased out after reaching the end of their lifetime.

Absent any emission targets, and due to the low gas prices, is appears that gas-fired CCGTs are the most economical way of providing power. They are supplemented by OCGTs for flexible peak power generation. A comparison of installed capacity (Figure 4-1) and annual power generation (Figure 4-2) shows that the capacity factor of the OCGTs is very low – they only run for a few hours per year. This is confirmed by the cost-optimal dispatch profile in 2050, shown for CAISO in Figure 4-3. The other energy systems show similar cost-optimal dispatch profiles. Specifically, CCGTs provide the majority of power, supplemented by solar capacity, which is harnessed whenever possible, and OCGTs are strategically deployed to meet peak demands.

Due to the replacement of low-carbon generation capacity with CCGTs at their end of life and the expected demand increase, power sector emissions increase by 2050 relative to current levels in the reference scenario for all three energy systems. The retirement of coal-fired power generation attenuates this effect, so that MISO experiences the smallest increase in emissions, of around 12% from 2020 to 2050. y

Estimated average levelised cost of energy (LCOE) in the reference scenario are shown in Figure 4-4. In all three energy systems, the system LCOE remains close to current values and show only limited variation over the years. Long-term average LCOE are around 50 $/MWh in all considered energy systems.

As the reference scenario does not include incentives or constraints to decarbonise, BECCS remains absent in all the considered energy systems, owing to its non-economic competitiveness with gas-fired power generation.

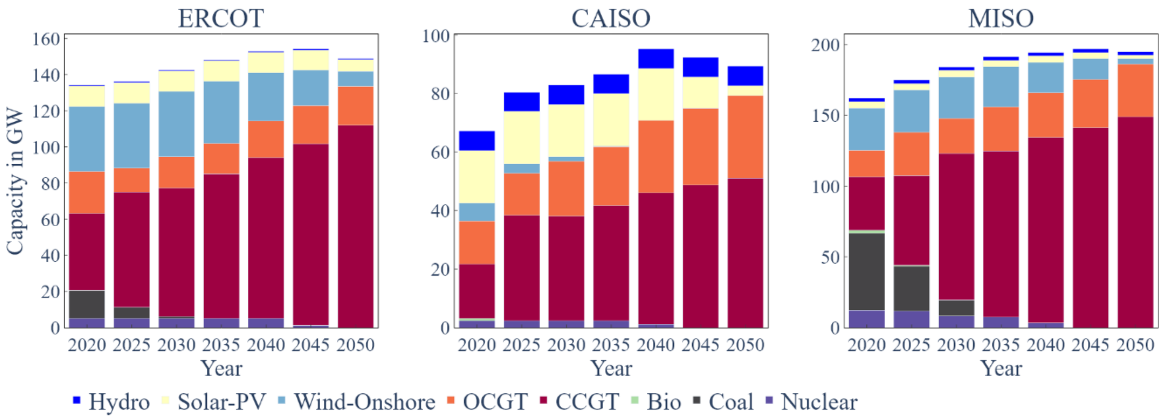


Figure 4-1: Optimal power generation capacity expansion in the reference scenario.

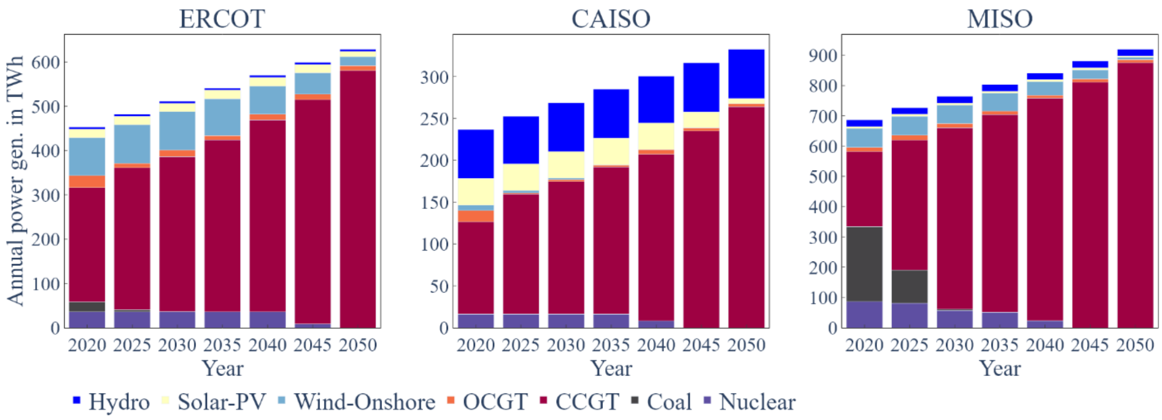


Figure 4-2: Optimal annual power generation in the reference scenario.

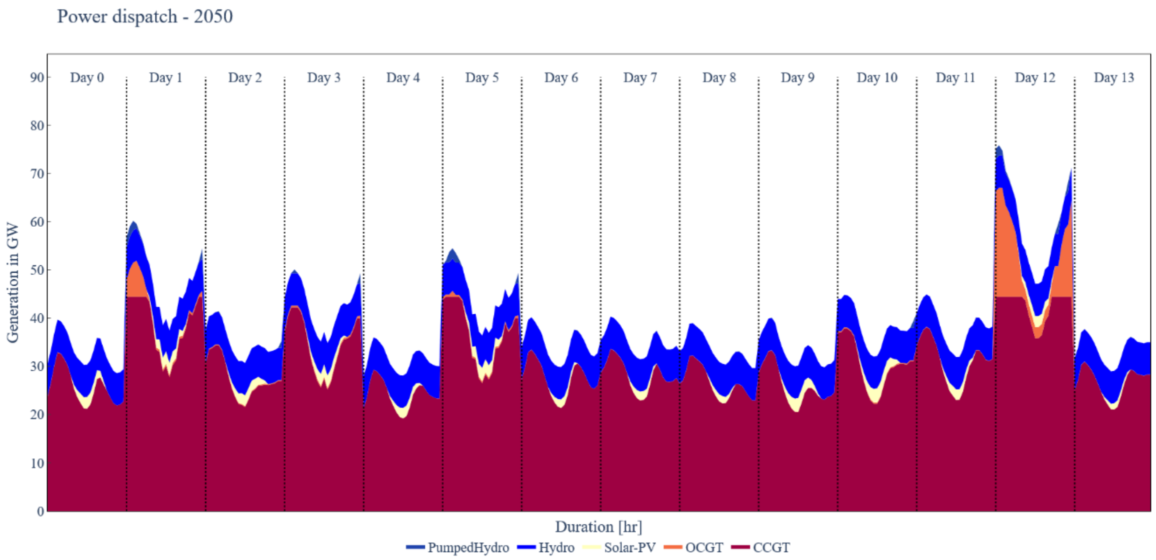


Figure 4-3: Optimal power dispatch profile for the CAISO grid in 2050 in the reference scenario.

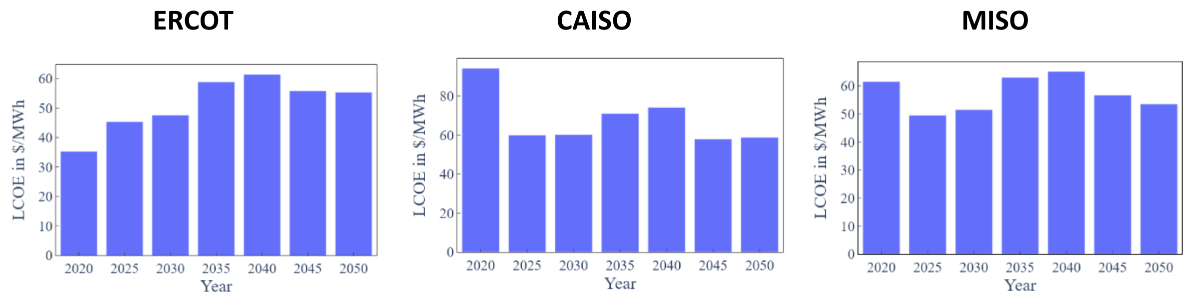


Figure 4-4: LCOE estimates in the reference scenario for ERCOT, CAISO, and MISO.

4.2 Net-zero power by 2035

The "reference" scenario is not compatible with the stated net-zero vision by the current US administration, as emissions increase in all considered energy systems compared to current values. Therefore, we investigate a scenario with a linear decarbonisation constraint to reach net-zero emissions from the power sector by 2035, as detailed in Section 3.3.2.

The optimal power generation capacity expansion and annually generated power values in the net-zero are shown in Figure 4-5 and Figure 4-6, respectively. All systems still rely heavily on power generation from unabated natural gas in CCGTs, but the share of gas-fired generation is significantly smaller compared to the reference scenario. The installed CCGT capacity in 2050 is 28 % to 37 % lower compared to the reference scenario, while the total power generated from CCGTs in 2050 is reduced by 51 % to 66 %.

Renewable power generation, especially from wind, plays a large role in providing low-carbon electricity in ERCOT and MISO. CAISO on the other hand relies more on solar power, as the wind resource availability is not as good (see Table 1). Nuclear power makes up 14 – 27 GW in all three energy systems, but especially in CAISO its role increases towards 2050. Renewable resource availability is lower in California, resulting in a diminished role for renewables and a less volatile dispatchable power demand, which favours nuclear power generation.

Table 1: Average wind and solar capacity factors in ERCOT, CAISO and MISO.

	Average wind capacity factor	Average solar capacity factor
ERCOT	29.4 %	19.9 %
CAISO	15.0 %	20.7 %
MISO	25.1 %	17.2 %

BECCS is deployed in all three energy systems to offset residual emissions from the unabated natural gas power plants. The installed BECCS capacity in 2050 ranges from 4.6 GW (CAISO) to 21.5 GW (MISO), with the capacity deployed in ERCOT falling in the middle of this range. BECCS allows the energy systems to capitalise on cheap and dispatchable natural gas-fired power generation. It is important to note that public support may pose a challenge for systems that extensively burn unabated natural gas and rely heavily on BECCS to offset these emissions. Additionally, currently proposed legislation [31] may rule out the use of unabated fossil fuels for non-peaking power generation. Moreover, the negative emissions from BECCS are likely more valuable to offset hard-to-abate emissions from other sectors, as explored in the carbon-negative power scenario, and as discussed in Section 4.3.

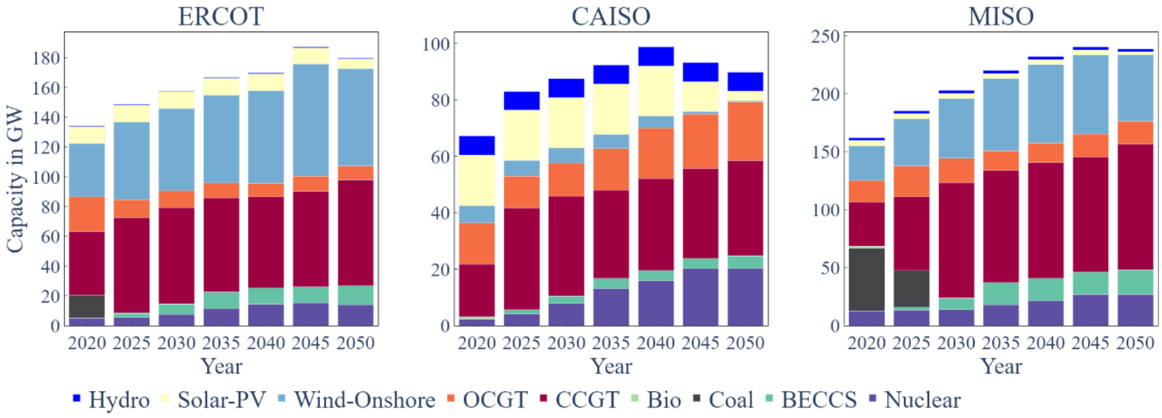


Figure 4-5: Optimal power generation capacity expansion in the net-zero power grid by 2035 and beyond.

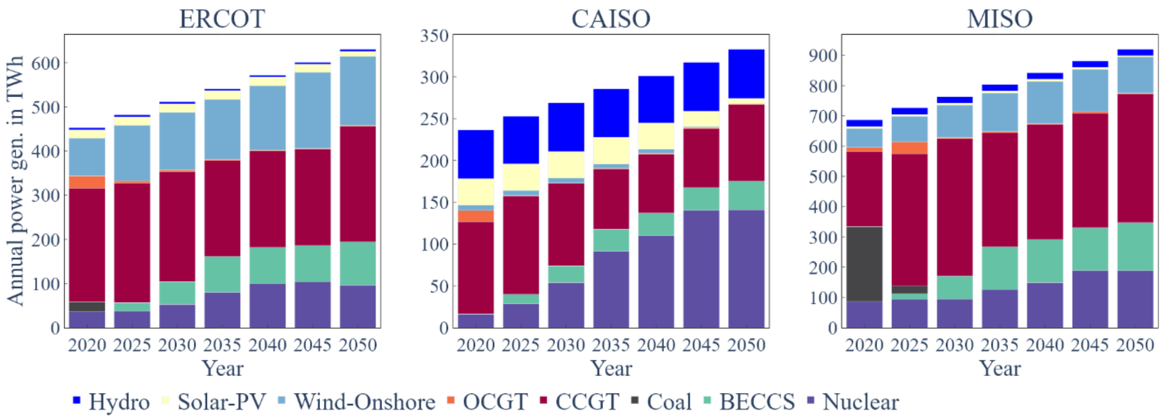
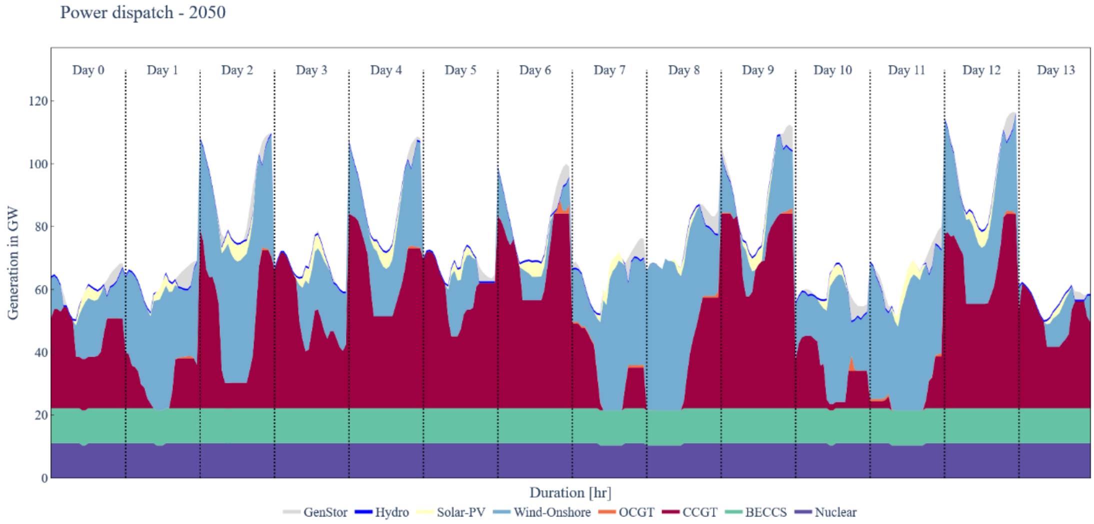
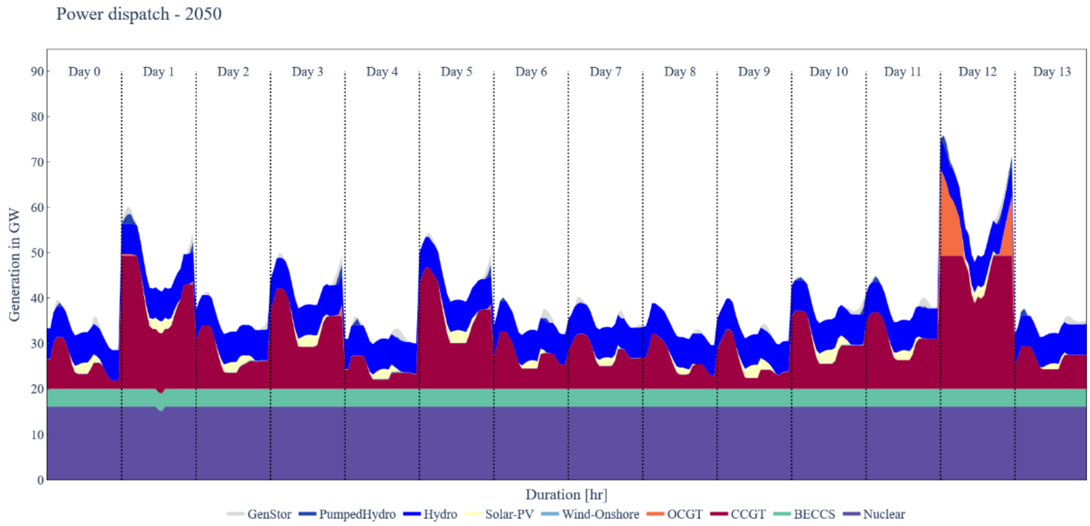


Figure 4-6: Optimal annual power generation in the net-zero power grid by 2035 and beyond.

ERCOT



CAISO



MISO

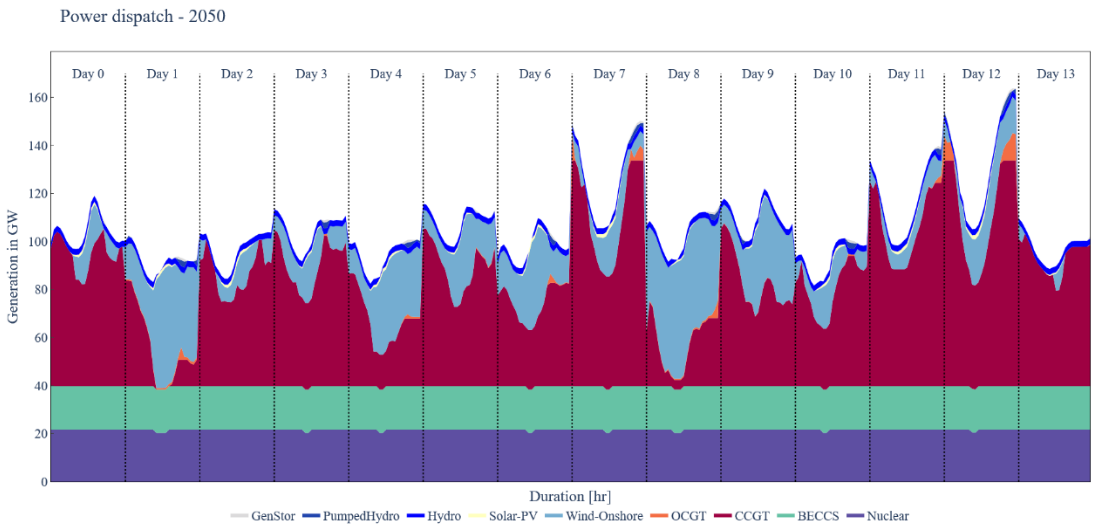


Figure 4-7: Optimal power dispatch profiles in 2050 in the net-zero power by 2035 scenario.

The optimal dispatch profiles for ERCOT, CAISO and MISO in 2050 are shown in Figure 4-7. In all cases, BECCS and nuclear power plants provide the baseload power, renewables operate whenever available, and the gas-fired generation capacity provides the required flexibility. This shows that BECCS complements other intermittent renewable power generation, as both fulfil different roles in the energy system. It also appears that the key value of BECCS lies in the negative emissions that are being provided rather than the generated power. The baseload operation maximises the negative emissions per unit of installed capacity, since BECCS runs baseload despite being more expensive than other technologies (as shown in the reference scenario).

The LCOE estimated in the net-zero scenario, as shown in Figure 4-8, highlights that without additional support LCOE in the net-zero scenario is expected to be significantly higher compared to the reference scenario, reaching more than 100 $/MWh. The peak is expected to be in 2035 to 2045, as this period requires the greatest investments in new power generation capacity.

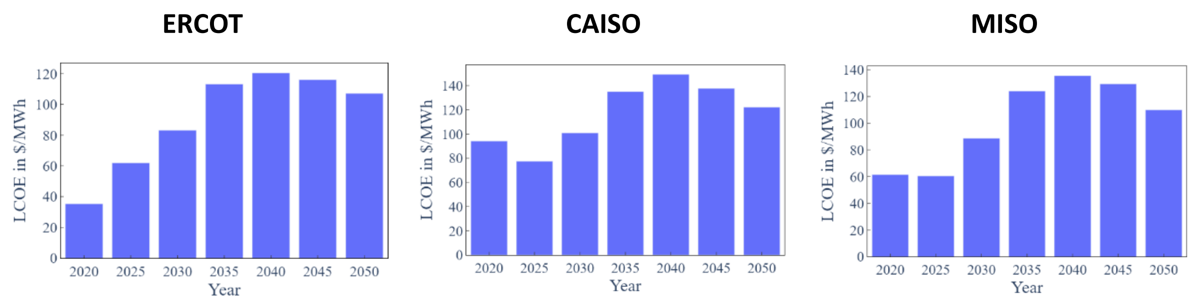


Figure 4-8: LCOE estimates in the net-zero power by 2035 scenario for ERCOT, CAISO and MISO.

4.3 Carbon-negative power by 2050

In the carbon-negative power scenario, the power sector is required to offset emissions from hard-to-abate sectors, as detailed in Section 3.3.3. Here, BECCS plays a larger role compared to the net-zero power by 2035 scenario, as significantly more negative emissions are required. The optimal power generation capacity expansion and annual power generation is shown in Figure 4-9 and Figure 4-10, respectively.

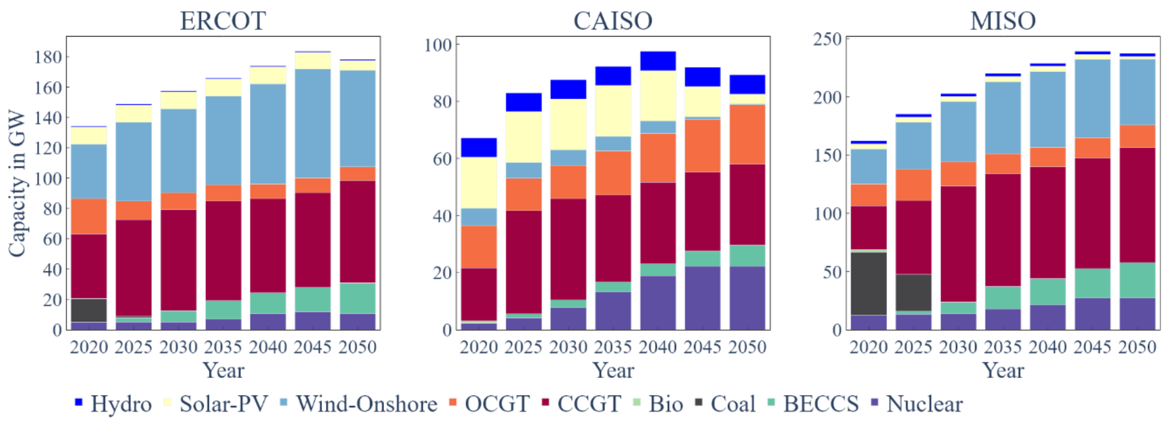


Figure 4-9: Optimal power generation capacity expansion in the carbon-negative power scenario.

The first thing to note is that the power generation mixes in all three energy systems look very similar to the ones in the net-zero power by 2035 scenarios (see Figure 4-5 and Figure 4-6). The key quantitative change is an increase in BECCS capacity and generation to meet the increased demand for negative emissions. In ERCOT, the BECCS capacity is 7 GW higher in the carbon-negative power scenario compared to the net-zero scenario, and in CAISO it is 3 GW higher and in MISO 10 GW higher.

Given that a typical passenger vehicle emits about 4.6 metric tons of CO2 per year, this is equivalent to removing 28 million cars from ERCOT, 11 million cars from CAISO, and 46 million cars from MISO, based on system performance in 2050. In MISO, BECCS principally displaces CCGTs. In CAISO, it mainly displaces CCGTs and approximately 1 GW of nuclear generation capacity. In ERCOT, BECCS not displaces a combination of unabated CCGTs, nuclear power and onshore wind.

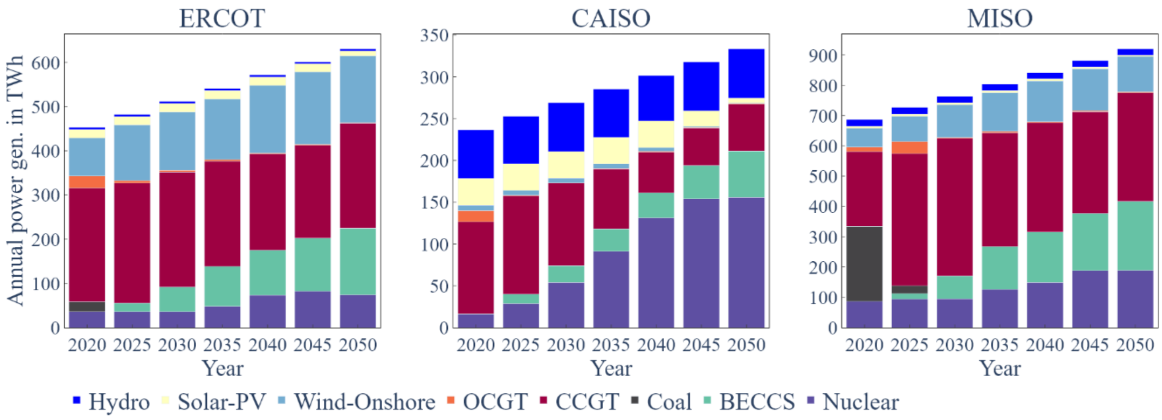


Figure 4-10: Optimal annual power generation in the carbon-negative power scenario.

The optimal dispatch profiles in the carbon-negative power scenario are also very similar to the ones of the net-zero scenario (see Figure 4-7). Nuclear and BECCS are operating baseload, renewables whenever available and CCGTs provide the required flexibility, while OCGTs are used during peak hours.

Estimated LCOEs in the carbon-negative power scenario are approximately 10 to 20 $/MWh higher compared to the net-zero scenario from 2040 onwards, as in addition to reaching net zero the electricity system now needs to provide negative emissions, incurring additional costs. It is important to note, however, that the power sector provides carbon removal services to other sectors, but the costs have been completely attributed to the power sector. Payments for these carbon removal services can reasonably be expected to reduce the estimated LCOE significantly. Importantly, depending on the market value attributed to the carbon removal service, this could result in a reduced electricity price to rate payers.

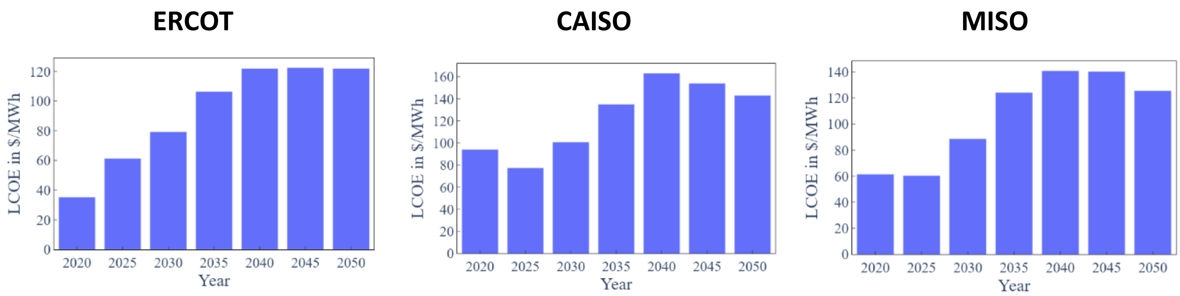


Figure 4-11: LCOE estimates in the carbon-negative power scenario for ERCOT, CAISO and MISO.

4.3.1 The value of BECCS in carbon-negative power scenarios

This subsection presents evidence on the system value of BECCS in achieving a net-zero economy by 2050. Here, system value is defined as the reduction in total system costs through the investment in BECCS compared to a counterfactual without. This is investigated by increasing the availability of BECCS, from a scenario where BECCS is not deployed at all to that where any further investment in BECCS does not reduce the system costs. Any negative emissions that cannot be provided from BECCS have to be provided by an optimised DACCS system in the counterfactual to meet the legislative targets. It is important to note that costs and performance of DACCS is still highly uncertain and has the capacity to impact the results shown here.

Figure 4-12 shows the impact of limiting the maximum BECCS capacity on the TSC of the three energy systems. The results show that CAISO and ERCOT are likely to be 25 - 31% more expensive in the absence of BECCS, while MISO is unlikely to meet a net-zero power grid by 2035 and reach a net-zero economy by 2050 under historically available maximum build rate constraints for process facilities. The graphs show an exponential shape, indicating that the marginal value of the first BECCS plant is very high, but returns diminish with increased deployment. This assessment suggests that investments in BECCS should be facilitated insofar as it offers material reductions in system costs and any further investments should be evaluated using a decision-making criterion which values energy security, affordability, and sustainability.

MISO requires historically unprecedented build rates of nuclear power plants and CCGTs with CCS to achieve carbon offsets of the order of 10% of today's emissions by 2050 with less than 10 GW of BECCS capacity. In that case, more than 100 $MtCO_2$/a of CDR is required from DACCS, which consumes vast amounts of low-carbon power.

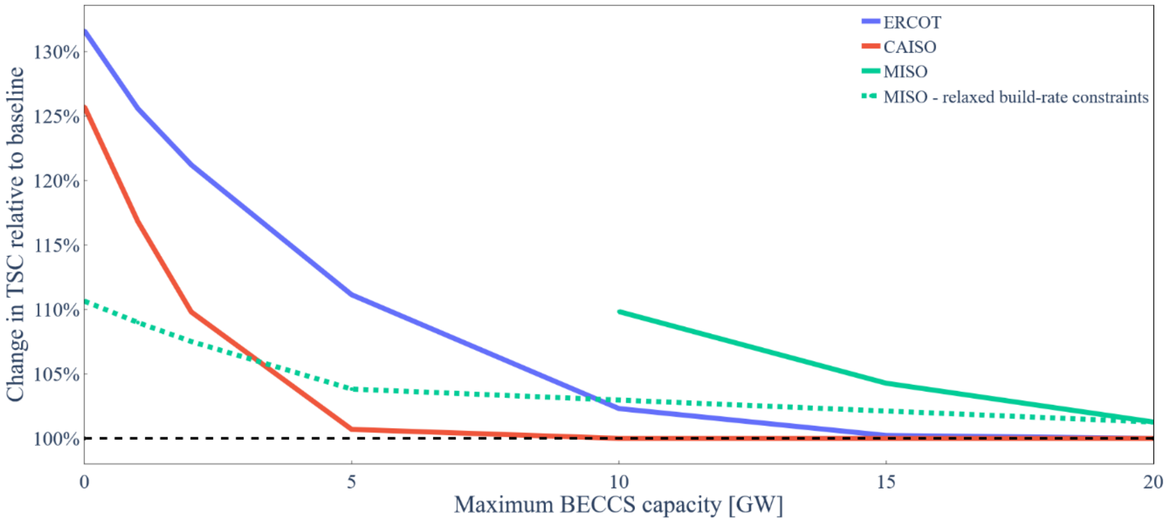


Figure 4-12: Change in TSC relative to baseline (BECCS capacity not constrained) depending on the maximum allowable BECCS capacity. Note that under default build rate limits reaching 10% CDR in MISO is infeasible with less than 10 GW of BECCS. To generate the results for lower maximum BECCS capacities, maximum build rate constraints of nuclear power plants and CCGTs with CCS were relaxed, which explains the discontinuity in the graph.

Figure 4-13 shows the impact of constraining the maximum allowable BECCS capacity on the overall power generation capacity. When BECCS is moderately constrained (*e.g.*, 10 GW in ERCOT and MISO, 2 GW in CAISO – middle panel in Figure 4-13), emissions from the power sector are reduced by deploying more nuclear power generation and renewables, and by using CCGTs with CCS instead of unabated gas-fired generation. Note that the total installed power generation capacity in 2050 increases by about 11% in ERCOT and 25% in MISO, as renewables require more capacity per generated power compared to firm generation assets, and DACCS adds a substantial power demand. The generation overcapacity is limited only in scenarios which rely heavily on nuclear power generation. This trend persists when we consider a system without any BECCS. The total power generation capacity is even greater. Large DACCS facilities are powered by a mix of renewables, nuclear, abated CCGT power, and a small share of unabated gas-fired generation.

The results show that BECCS has the potential to reduce overcapacity in the system, which can also reduce the risk of connection delays by avoiding the need for excess renewable generation [32], [33]. This point has increased salience, given increasing delays increasing project costs. This has the potential to improve the reliability of the system. As shown for MISO, the likelihood of reaching net-zero by 2035 is greatly reduced if investments in BECCS are not scaled up in the near-term. Therefore, it can increase the chances of achieving climate targets, but should not delay the decarbonisation of the wider economy, as even offsetting only 10% of today's emissions is challenging.

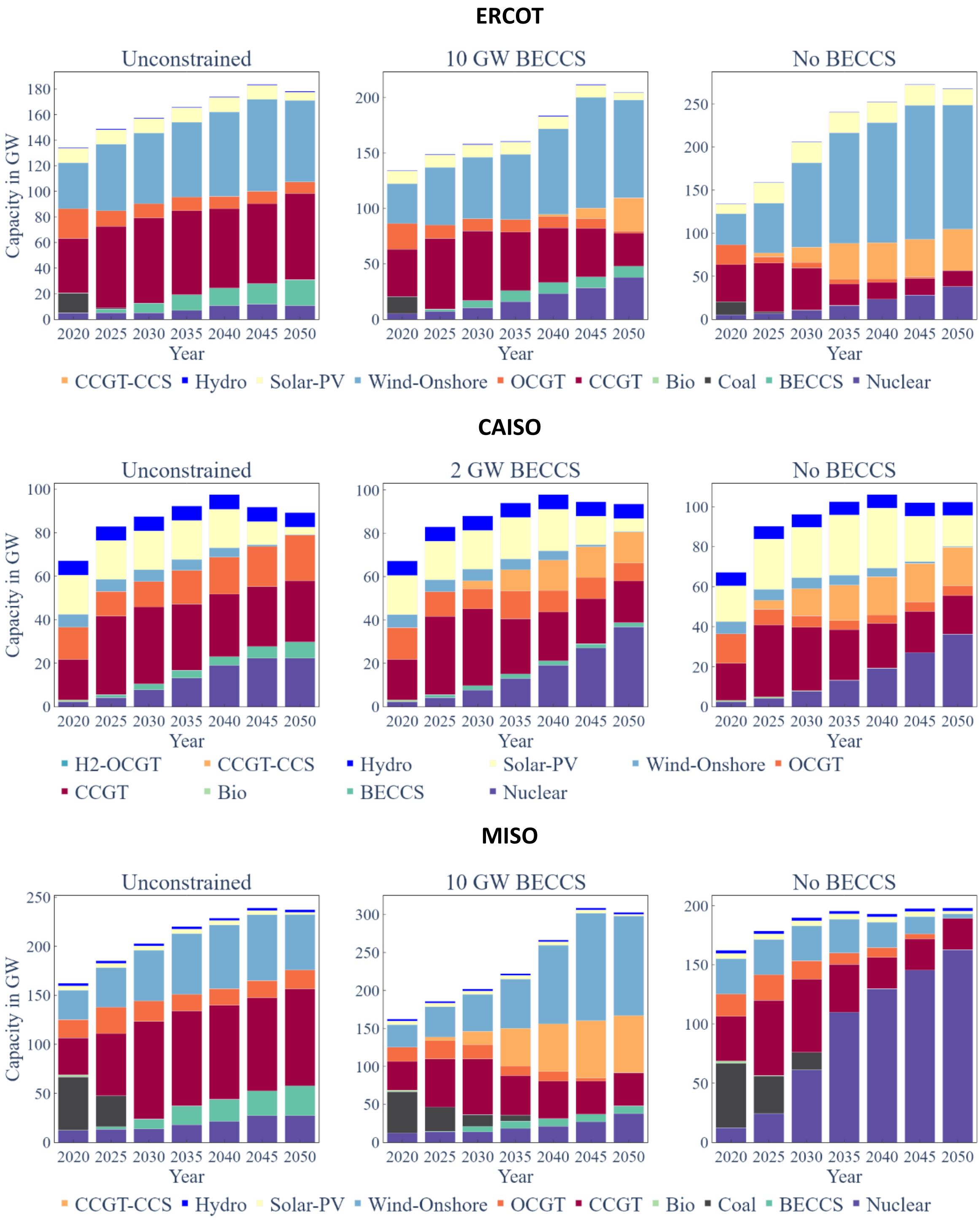


Figure 4-13: Optimal power generation capacity expansion in the carbon-negative power scenario if the maximum allowable BECCS capacity is limited.

4.4 Impact of current IRA subsidies on optimal energy system transition pathways

After evaluating the three scenarios for all three energy systems without any subsidies in place, in the following the same three scenarios are investigated with ITCs and 45Q tax credits available, as described in Section 3.3.4.

Optimal power generation capacity and annual power generation in the reference scenario with IRA subsidies, shown in Figure 4-14 and Figure 4-15, illustrate how the subsidies shift the economics of power generation. Thanks to the ITCs, renewable power generation is now competitive with gas-fired power generation and expanded in all three energy systems, accounting for 20% to 45% of generation capacity in 2050. Due to the resource availability, as before wind power is favoured in ERCOT and MISO, while solar PVs are preferred in CAISO.

The support for carbon dioxide sequestration in form of 45Q tax credits, combined with the expected continued low coal prices, turns coal-fired power plants with CCS into a major generator in all three energy systems. Nuclear power on the other hand is being retired at the end of the lifetime of assets, as it receives no dedicated support.

Despite the increased deployment of renewable power generation and fossil generation with CCS, none of the energy systems achieve deep decarbonisation in the reference scenario with IRA subsidies. Emissions from ERCOT drop by about 23% compared to current levels, while emissions from CAISO and MISO reduce by 17% and 44%, respectively. MISO, as the most emission-intensive energy system of the three, benefits the most from the support for clean energy technologies. However, the results indicate that current policy and support measures, on their own, are insufficient to achieve the net-zero target. Proposed legislation, such as carbon emission limits for power plants [31] may change this. However, the results show that the available 45Q tax credits are not sufficient to promote BECCS deployment.

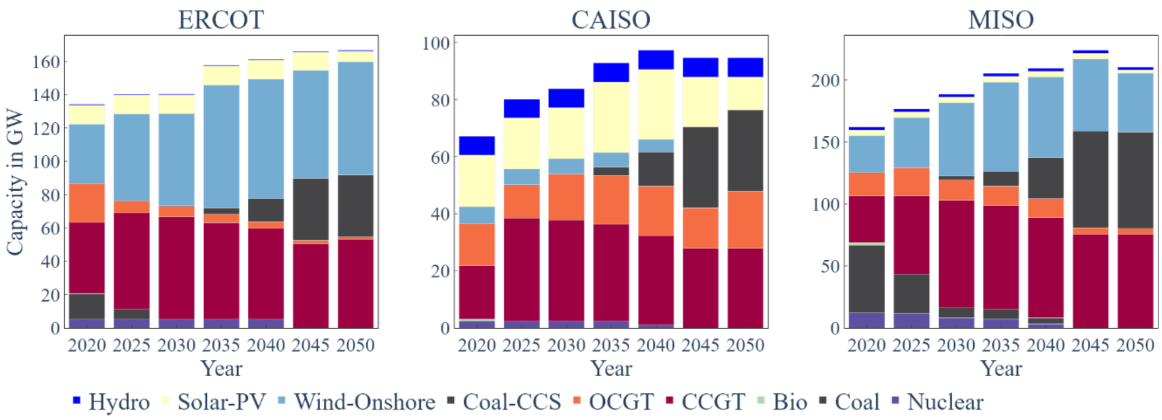


Figure 4-14: Optimal power generation capacity expansion in the reference scenario with IRA subsidies.

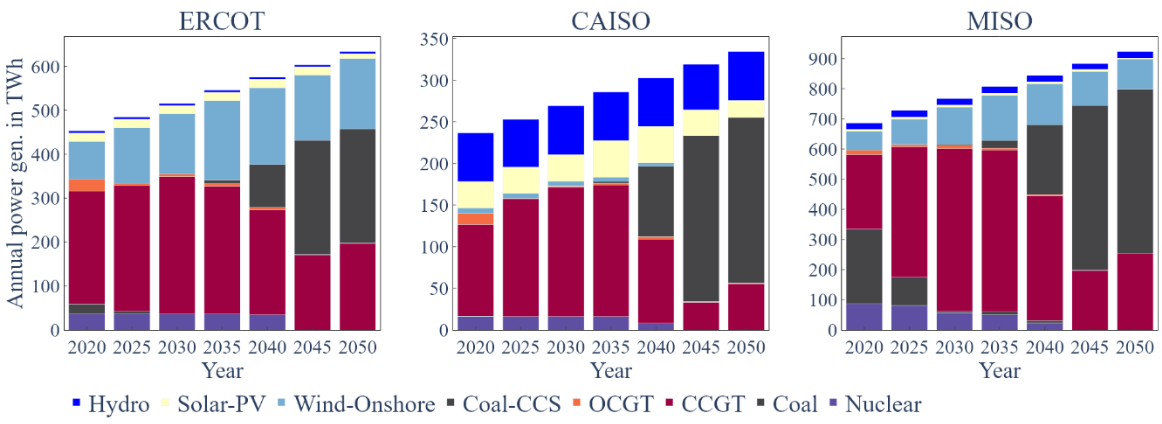


Figure 4-15: Optimal annual power generation in the reference scenario with IRA subsidies.

The net-zero power by 2035 scenario with IRA subsidies show a less prominent role for BECCS, though it is still instrumental in achieving net-zero emissions. Figure 4-16 shows the cost-optimal power generation capacities, while Figure 4-17 shows the corresponding annual power generation. All energy systems rely on renewable energy generation from wind and solar, with support from post-combustion capture in the power sector compared to the scenario without subsidies, as 45Q tax credits make carbon sequestration more economical. However, in all systems, unabated gas-fired generation is combined with negative emissions to attain net-zero emissions.

BECCS capacities decrease in ERCOT and MISO by 5 GW and 7 GW, respectively, in 2050 lower compared to the net-zero scenario without IRA subsidies. In CAISO, however, the installed BECCS capacities do not change substantially. Here, nuclear generation capacity is displaced by renewables and coal-fired power plants with CCS, such that the amount of required negative emissions does not change significantly.

The observation that nuclear does not play a role in any of the energy systems in the net-zero scenarios with IRA subsidies, but BECCS generates power together with renewables and gas-fired generation shows again that the value of BECCS lies in the combination of carbon removal combined with the ability to generate baseload power The optimal dispatch profiles are like all the ones shown before, with BECCS and coal-fired power plants with CCS running baseload, renewables whenever available and unabated gas-fired generation providing flexibility.

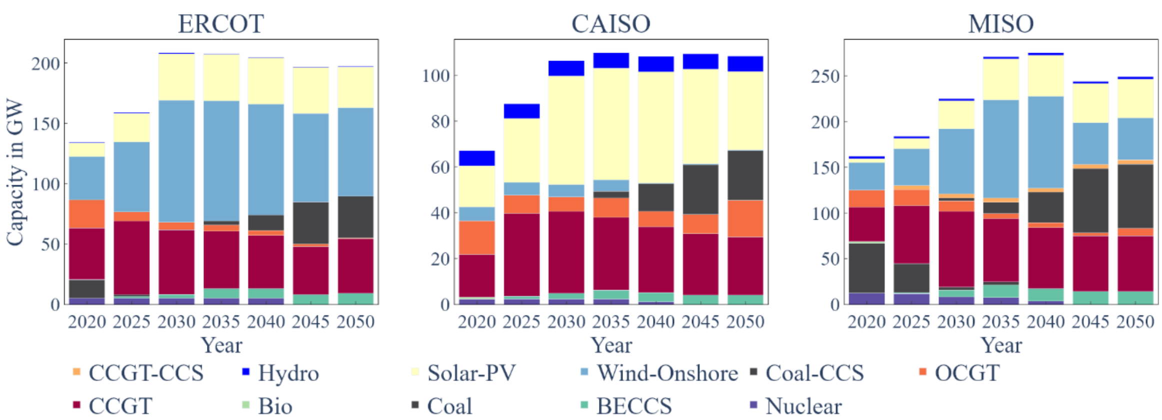


Figure 4-16: Optimal power generation capacity expansion in the net-zero power by 2035 scenario with IRA subsidies.

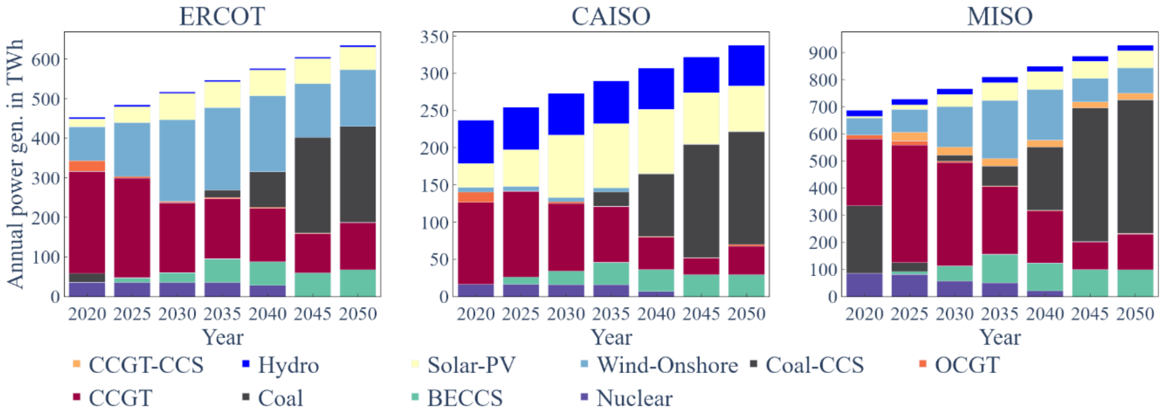


Figure 4-17: Optimal annual power generation in the net-zero power by 2035 scenario with IRA subsidies.

Finally, Figure 4-18 and Figure 4-19 show optimal power generation capacities and annual power generation in the carbon-negative power scenario with IRA subsidies. As in the scenarios without subsidies, the carbon-negative power scenario is very similar to the net-zero power scenario. The main difference being that BECCS deployment is increased to meet the higher negative emission demand, replacing predominantly gas-fired generation capacity. Compared to the case without IRA subsidies, however, BECCS capacities are smaller as renewables and thermal power generation with CCS are more competitive.

Figure 4-20 shows the sensitivity of these results toward natural gas and coal prices. The shares of total power generated by coal-fired power plants with CCS, CCGTs with CCS, and BECCS in ERCOT in 2050 are shown in the figure. The results suggest that the cost-competitiveness of coal-fired power plants or CCGTs with CCS is sensitive to fuel prices. At high gas and coal prices, the 45Q tax credits are insufficient to support investments in either technology. Nonetheless, BECCS provides 12 to 20% of total annual power generation to generate negative emissions. Thus, BECCS plays a larger role as residual emissions from the power sector are higher and more carbon dioxide removal is required.

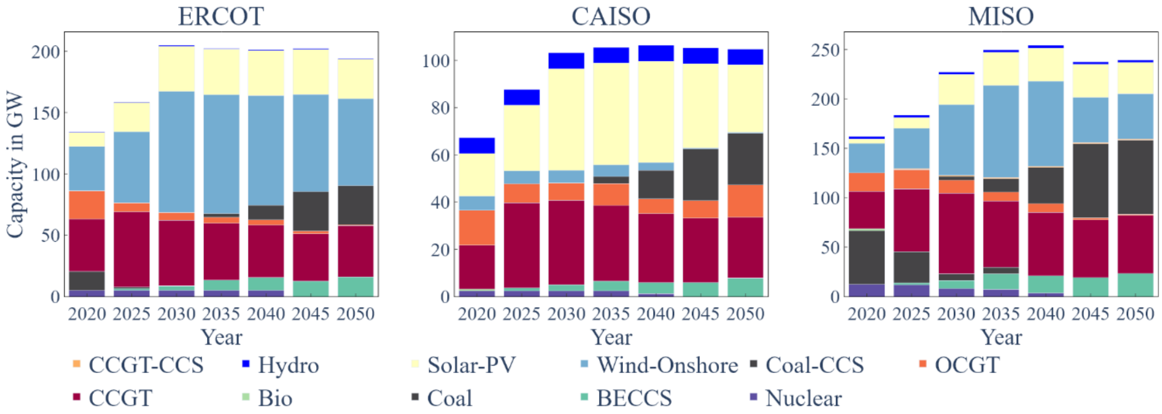


Figure 4-18: Optimal power generation capacity expansion in the carbon-negative power scenario with IRA subsidies.

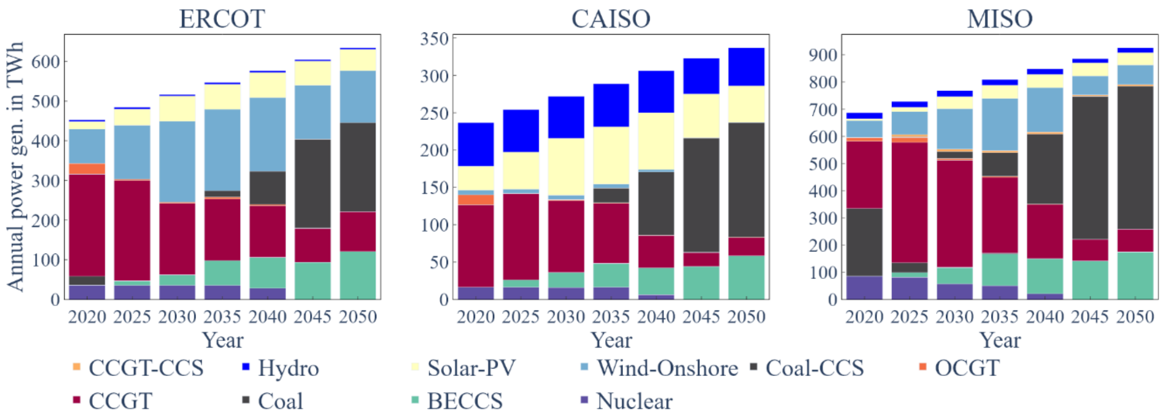


Figure 4-19: Optimal annual power generation in the carbon-negative power scenario with IRA subsidies.

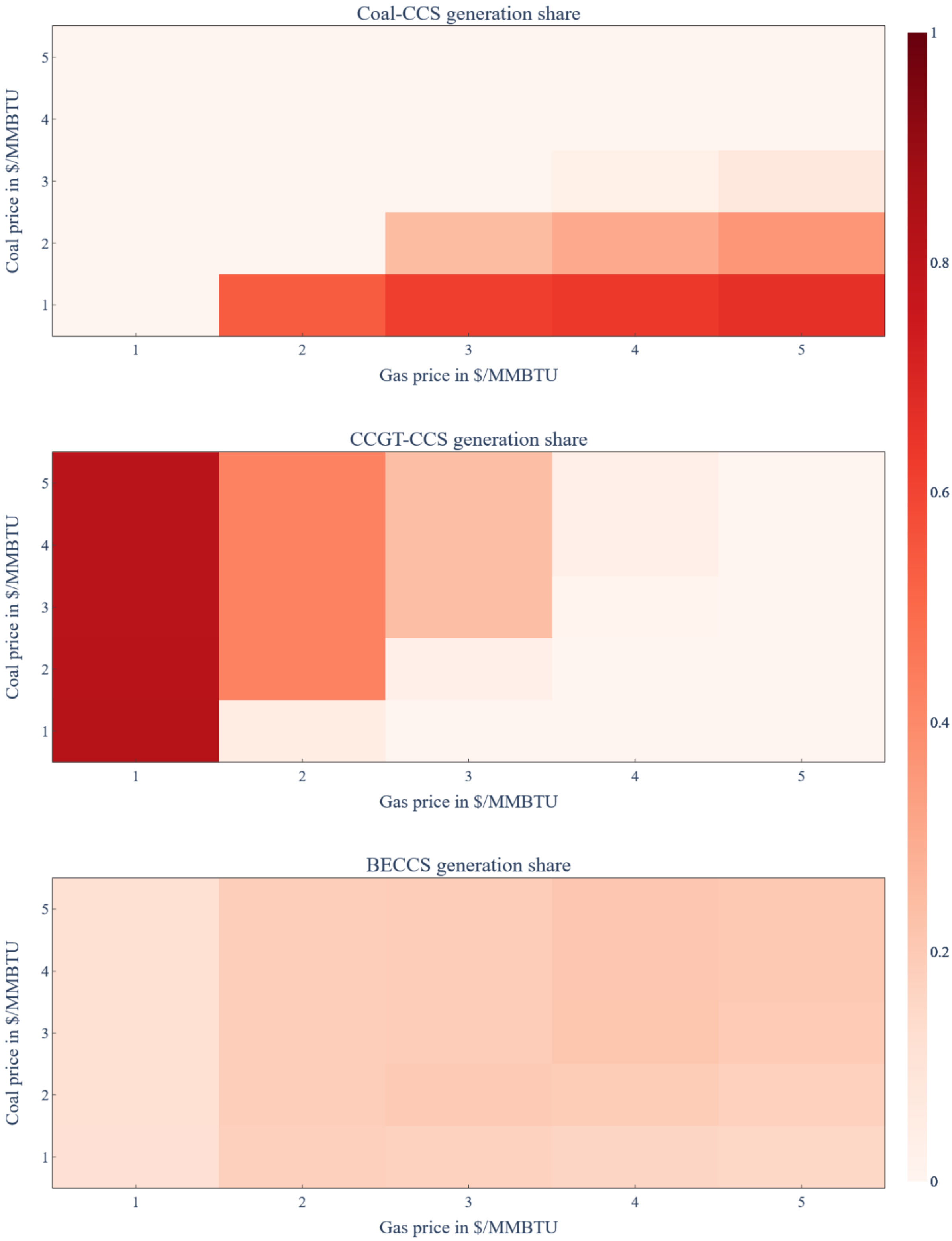


Figure 4-20: Share of Coal-CCS, CCGT-CCS and BECCS in total annual power generation in 2050. The results are for the carbon-negative power sector scenario with IRA subsidies, for ERCOT.

4.4.1 Measures to close the cost gap and reach net-zero

As shown in the reference scenario with IRA subsidies, the current level of financial support available to generators and project developers appears insufficient to drive deep decarbonisation of the power sector in the absence of emissions constraints. A wide variety of policy and regulatory measures can be used to address these investment barriers [34]. However, in the following, we quantify the minimum levels of financial support needed to achieve these targets. Two different cases are considered: (i) increasing subsidy payment for carbon sequestration via the existing 45Q mechanism for the full period of 12 years; and (ii) introducing a dedicated incentive support mechanism for negative emission technologies. The latter can be in the form of either government support, such as tax credits, or via voluntary carbon markets (VCMs), or compliance markets.

4.4.1.1 Increasing 45Q tax credits to reach net-zero

Currently, 45Q tax credits for carbon sequestration are valued at 85 \$/tCO_2 for point source carbon sequestration and are available for 12 years from the start of the project. To further support carbon sequestration, either the value of 45Q tax credits or the duration they are available can be extended. In this analysis the focus is on increasing the value of the 45Q tax credits, as the duration has been unchanged in past and current policy.

Figure 4-21 shows the optimal power generation capacity expansion in ERCOT under increased 45Q tax credits. The other energy systems show similar results and are shown in Appendix (Figure 9-1 and Figure 9-2). The results highlight that 45Q, on its own, is an inadequate measure to drive the power system towards net-zero emissions, and, to realise the benefits of BECCS. As it rewards carbon sequestration without discriminating between the value provided in the energy system, it is only suitable to drive the deployment of the most economical CCS technology, in this case coal-fired power stations with CCS [35]. The combination of low coal prices and high emissions translate into high volumes of carbon sequestered, with an associated boost in support from 45Q tax credits. Consequently, these assets are always more cost competitive than BECCS plants regardless of the 45Q value.

A relatively small amount of BECCS is deployed when the 45Q tax credit reaches a value of 150 \$/tCO_2, primarily because build rate constraints limit the rate at which coal-fired power plants with CCS can be deployed, and the credit is high enough to support BECCS deployment. Note that coal-CCS is more economical than BECCS when supported by increased 45Q credits.

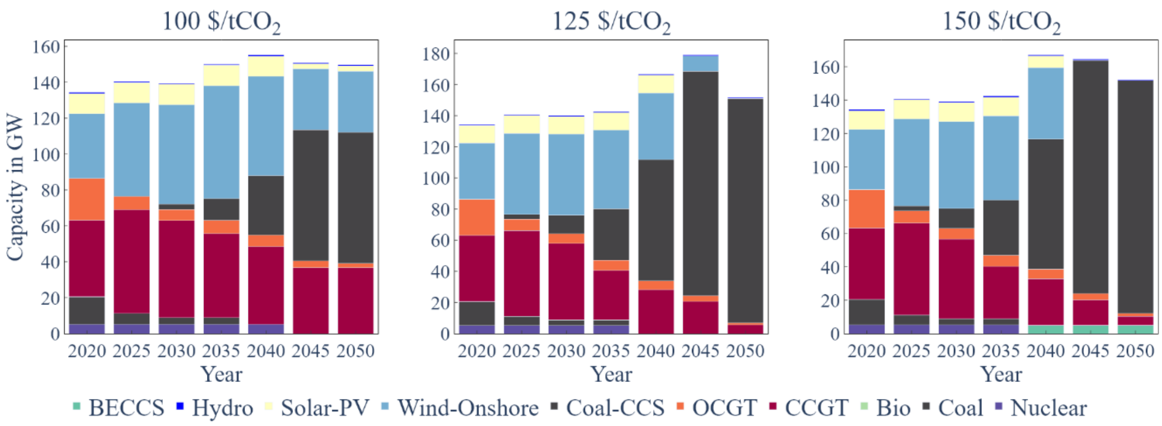


Figure 4-21: Optimal power generation capacity expansion in ERCOT without an emission constraint and increased 45Q tax credit values of 100 \$/t CO_2, 125 \$/t CO_2, and 150 \$/t CO_2.

4.4.1.2 Introducing negative emission credits to reach net-zero

Negative emission credits differ from 45Q tax credits in that they provide dedicated support for carbon-offsetting technologies rather than just the CCS technology. In the following, the level of negative emission credits required to reach net-zero is investigated, while 45Q tax credits remain available at their current levels.

A parametric analysis reveals that negative emission credits of 30 to 40 $/t$CO_2$ sequestered is required for carbon dioxide removal technologies in addition to the 85 $/t$CO_2$ provided by 45Q. Figure 4-22 and Figure 4-23 show the optimal power generation capacity and annual power generation in ERCOT in scenarios without emission constraints but with current IRA subsidies and increasing negative emission credit values. Small capacities of BECCS are first deployed at negative emission credits of 30 $/t$CO_2$. However, they are insufficient to offset the remaining power sector emissions, such that overall net-zero is not achieved. At 40 $/t$CO_2$ however, about 36 GW of BECCS are installed in ERCOT in 2050. The negative emissions from these assets can not only offset the residual power sector emissions, but also emissions form the wider economy, as overall the power sector is strongly carbon negative.

While Figure 4-22 and Figure 4-23 only show results from ERCOT, they are similar in CAISO and MISO. Negative emission credits below 30 $/t$CO_2$ are insufficient to support large-scale carbon dioxide removal. At 30 $/t$CO_2$, some BECCS capacity is deployed, which in CAISO is sufficient to reach net-zero emissions from the power sector, but not to offset other sectors. In MISO, negative emission credits of 30 $/t$CO_2$ lead to a power sector emission reduction of about 80% compared to today's values. At 40 $/t$CO_2$ however, a carbon-negative power sector is achieved in all three energy systems, capable of offsetting large volumes of residual emissions from other sectors.

Overall, the results show that negative emission credits, when supplemented by the current IRA subsidies, may be an appropriate tool to drive deep decarbonisation and deployment of BECCS, whereas 45Q credits alone is not an adequate policy tool. Negative emission credits of 30 to 40 $/t$CO_2$ are needed in addition to the 85 $/t$CO_2$ available in 45Q tax credits as well as the ITCs for renewables and storage to achieve deep decarbonisation in line with previous studies [36].

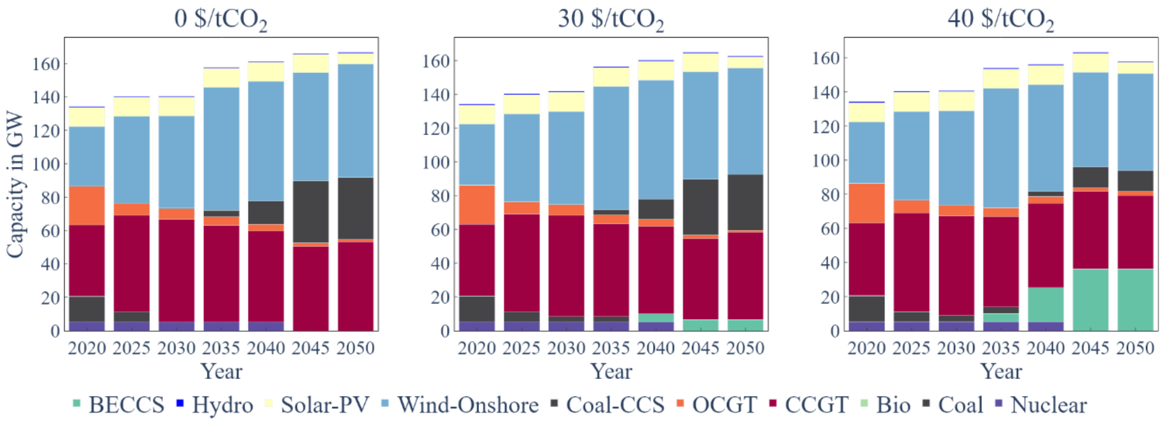


Figure 4-22: Optimal power generation capacity expansion in the reference scenario in ERCOT with IRA subsidies and negative emission credits of 0 $/t$CO_2$, 30 $/t$CO_2$, and 40 $/t$CO_2$.

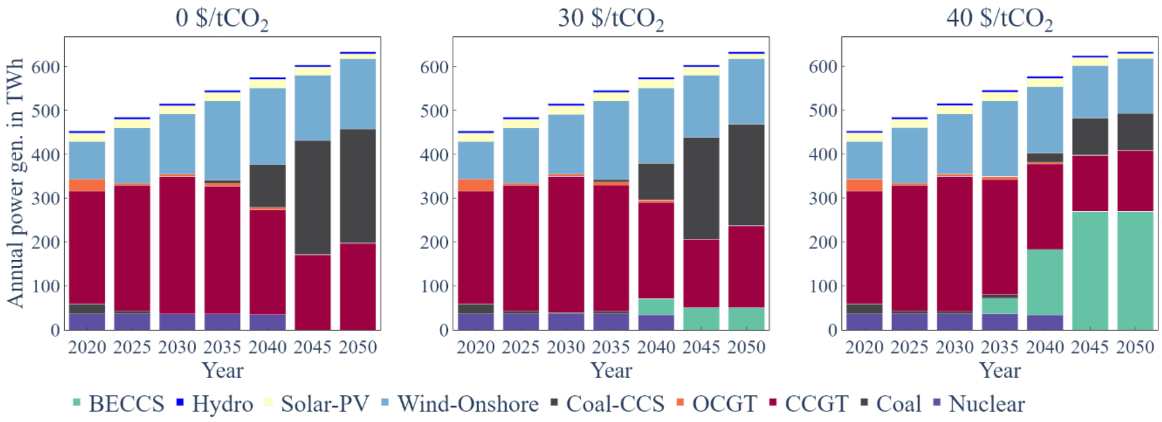


Figure 4-23: Optimal annual power generation in the reference scenario in ERCOT with IRA subsidies and negative emission credits of 0 $/tCO_2$, 30 $/tCO_2$, and 40 $/tCO_2$.

5 Economic impacts of BECCS investment

This section evaluates the macroeconomic impacts across ERCOT, CAISO and MISO regions, building upon the insights from the electricity systems optimisation analysis.

5.1 Reference

In the reference scenario, the ESO results showed that where the focus is on cost optimisation without emissions targets or carbon pricing, the energy system is strongly reliant on gas-fired power generation to meet electricity demand. Due to the need to retire aged generation capacity with new assets, the GVA increases from 2020 to 2025 by 36 %, 94 %, and 33 % in ERCOT, CAISO, and MISO, respectively (Figure 5-1). However, after this initial period of strong investment, there is a subsequent decrease in GVA from 2025 to 2050 of 53 %, 64 %, and 57 % in ERCOT, CAISO, and MISO, respectively, as only little new investment is required to replace retiring assets and the CCGTs and OCGTs are comparatively cheap to operate.

Although each of the regions studied exhibit unique characteristics and achieve different levels of GVA, which correlate directly to the size of the respective system, there are common trends seen in the results such as the sectors where jobs produced (Figure 5-2) are more prominent and sectors that contributed to GVA. Notably, mining and utilities, construction, maintenance, machinery and electrical equipment, and professional activities are key contributors to the GVA across all regions. In the reference scenario, due to the high share of gas-fired power generation, mining and utilities has an especially important role in GVA and job creation, accounting for over 80 % of total GVA in ERCOT in 2050. Employment levels remain relatively steady, despite a decrease in GVA after 2030. More than two-thirds of jobs in 2050 are in mining and utilities, while maintenance and machinery and electrical equipment are the other key contributors.

Section 4.1 showed that in the absence of incentives and constraints for decarbonisation, BECCS does not play a significant role in the energy mix. Consequently, BECCS is not a major driver of economic activity in these regions in the reference scenario without emission targets or specific policy support.

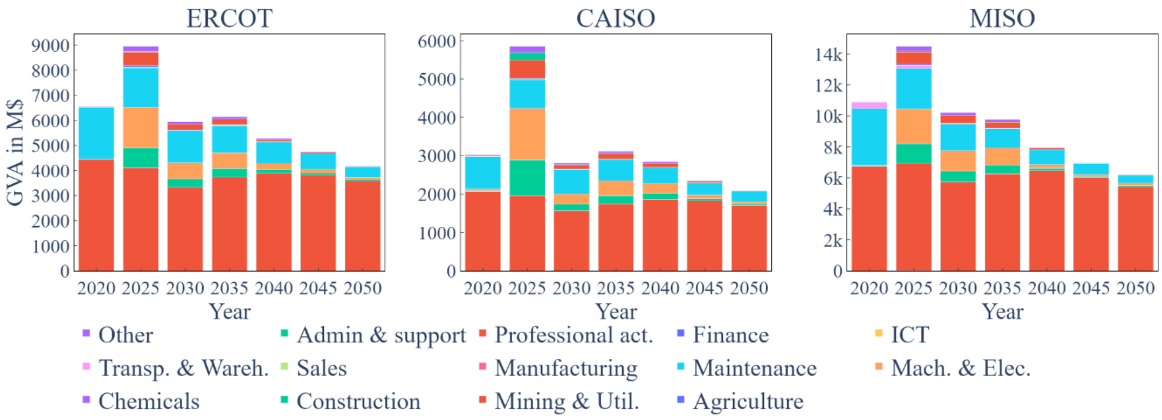


Figure 5-1: GVA as a function of the electricity system expansion over time in the reference scenario.

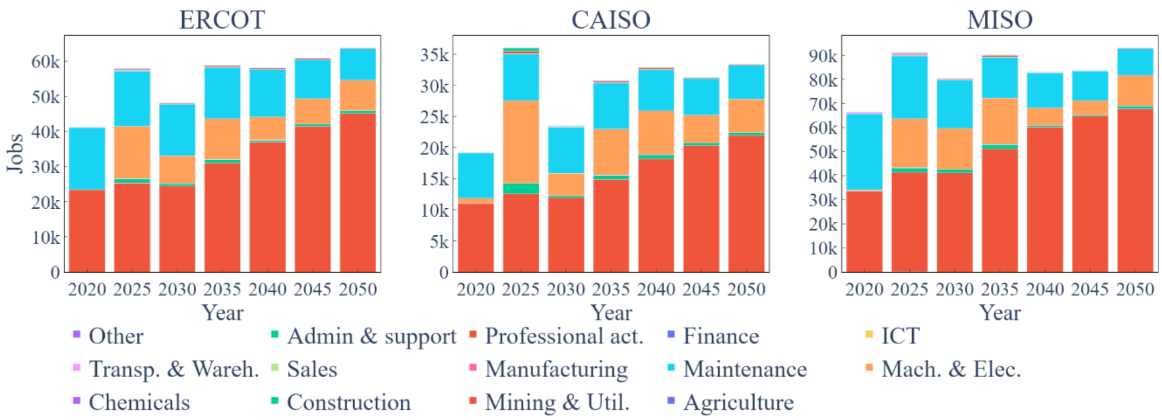


Figure 5-2: Jobs as a function of the electricity system expansion over time in the reference scenario.

5.2 Net-zero power by 2035

The macroeconomic impact assessments in the net-zero power by 2035 scenario show several notable trends and regional distinctions. In 2020, the GVA from power generation activities is estimated to be $6.6 bn, 3.0 bn, and 10.9 bn for ERCOT, CAISO and MISO, respectively (Figure 5-3). These estimates increase to $12.5 bn, 7.3 bn, and 14.5 bn in 2025 respectively, and large investments are required to replace retiring generation capacity. Then, GVA declines over time until by 2050, GVA is lower than the 2020 figures in all regions.

The GVA contributions by sector are more diversified compared to the reference scenario, as the generation mix is also more diverse. The main sector is still mining and utilities, but its relative value is lower and contributions from sectors such as agriculture, maintenance, machinery and electrical equipment, transportation and warehousing, and professional activities are higher. This reflects the broader economic impact of the energy transition and its connections to other industry. Notably, mining and utilities see a continuous decrease in GVA contribution from 2025 to 2050 which indicates the reduced reliance on fossil energy sources and a shift toward cleaner alternatives including wind, solar, nuclear power and bioenergy as seen from section 4. Mining and utilities, agriculture, maintenance, and machinery and electrical equipment sectors consistently create a substantial number of jobs (Figure 5-4), in line with the need to deliver low-carbon power at scale, as identified in Section 4.

The specific contribution of BECCS to GVA and jobs occurs across multiple sectors, including agriculture, transportation and warehousing, and machinery and electrical equipment. This shows that BECCS can diversify economic growth across industries. BECCS contributes 16 %, 16 %, and 13 % of the region's GVA, and 14 %, 15 %, and 10 % of the jobs in 2025 in ERCOT, CAISO, and MISO, respectively (Figure 5-5). The contribution of BECCS to the GVA generally increases from 2020 to 2050 in all three regions as more capacity is installed, with regional fluctuations, owing to construction and operation-related jobs. The agriculture sector takes an imperative role in facilitating the deployment of BECCS.

The increase in the share of renewables and low-carbon generation alongside BECCS plays a significant role in job creation and GVA, as highlighted here and in Section 4. ERCOT and MISO with their larger grid sizes and higher carbon intensity [37] create more jobs (Figure 5-6) and produce more GVA, owing to the larger investment requirements for the energy transition when compared to CAISO. To effectively address this challenge, a comprehensive skills assessment is crucial. Such assessment would include the analysis of current skills of the workforce, identification of skill gaps, and anticipation of future skill needs for the transition and hence training or reskilling requirements.

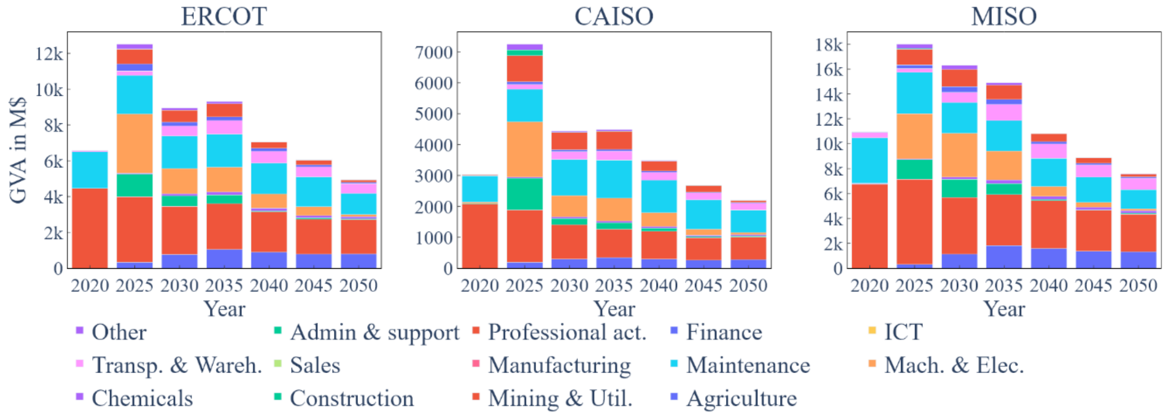


Figure 5-3: GVA as a function of the electricity system expansion over time in the Net-zero scenario

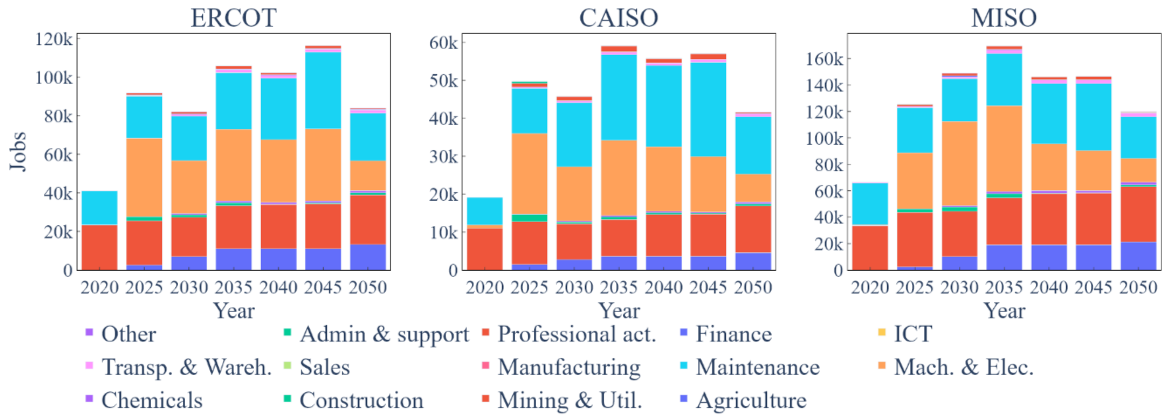


Figure 5-4: Jobs as a function of the electricity system expansion over time in the net-zero scenario

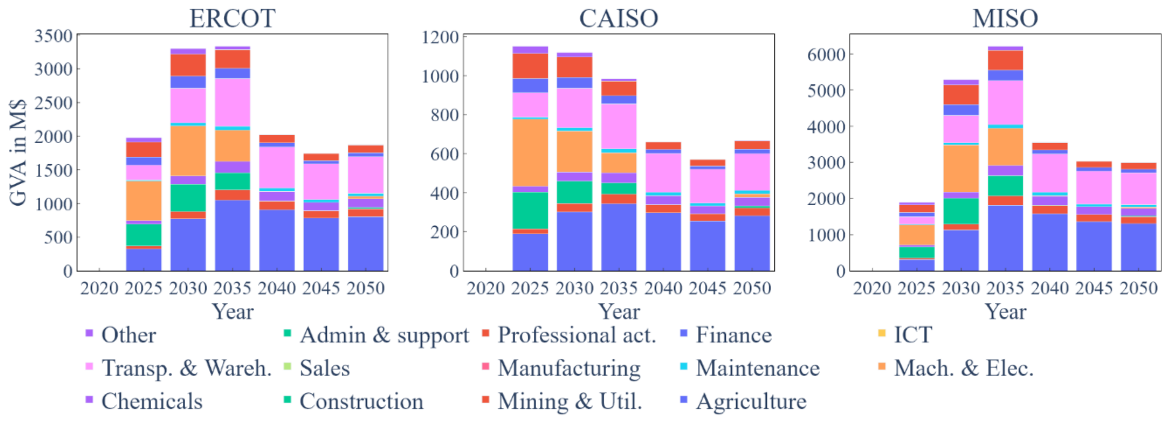


Figure 5-5: BECCS GVA as a function of the electricity system expansion over time in the net-zero scenario

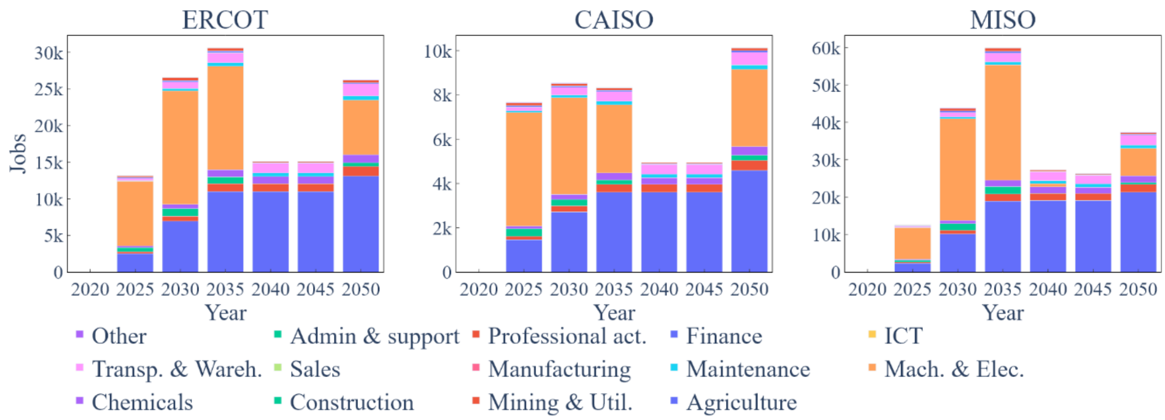


Figure 5-6: BECCS Jobs as a function of the electricity system expansion over time in the net-zero scenario

5.3 Carbon-negative power by 2050

In this scenario, the power sector is not only required to achieve net-zero emissions by 2035 but also to generate negative emissions to offset residual emissions from other sectors. The GVA shows similar trends to the previous scenarios where it increases in all regions by 2025 and then continues to decrease until 2050.

As in the net-zero power scenario, key sectors contributing to GVA (Figure 5-7) across all three regions include mining and utilities, machinery and electrical equipment, and maintenance, but also agriculture and transportation and warehousing attributed to BECCS. The GVA produced from mining and utilities and maintenance sectors is relatively stable from 2025 to 2050, which shows their importance in supporting and maintaining the evolving energy landscape. The machinery and electrical equipment sector, which also notably contributes to the GVA produced, experiences a decrease from 2025 to 2050, indicating a potential shift in the demand for specific skill sets within this sector. Over the same period, the agriculture sector is expected to grow to support carbon-negative power generation.

Jobs generally increase from 2020 to 2050, with a jump from 2020 to 2025 and stabilise thereafter, showing that the new jobs are not just temporary (Figure 5-8). Agriculture emerges as a notable sector for job creation and continually increases in significance from 2025 to 2050, indicating the potential for employment opportunities in a sector closely aligned with carbon-negative power. The mining and utilities sector, which exhibits a significant and relatively stable GVA contribution across the years, also has a substantial contribution to jobs produced. For instance, in ERCOT, the agricultural, and mining and utilities sectors accounted for 21 %, and 24 %, respectively, of total jobs in 2050. This is an increase from 2025, where the agricultural and mining and utilities sectors accounted for 3 % and 25 %, respectively.

The higher deployment of BECCS to generate negative emissions compared to the other scenarios results in boosts in the macroeconomic outputs. The role of BECCS, alongside nuclear and renewable power, is consistent with the net-zero power by 2035 scenario, but with increased emphasis on carbon removal technologies, boosting GVA (Figure 5-9) and jobs (Figure 5-10) in the agricultural and transportation and warehousing sectors.

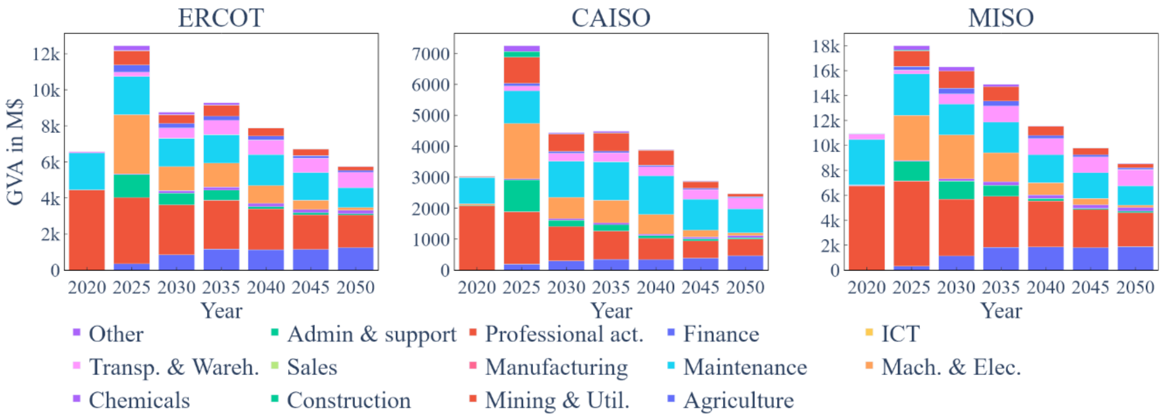


Figure 5-7: GVA as a function of the electricity system expansion over time in the CDR scenario.

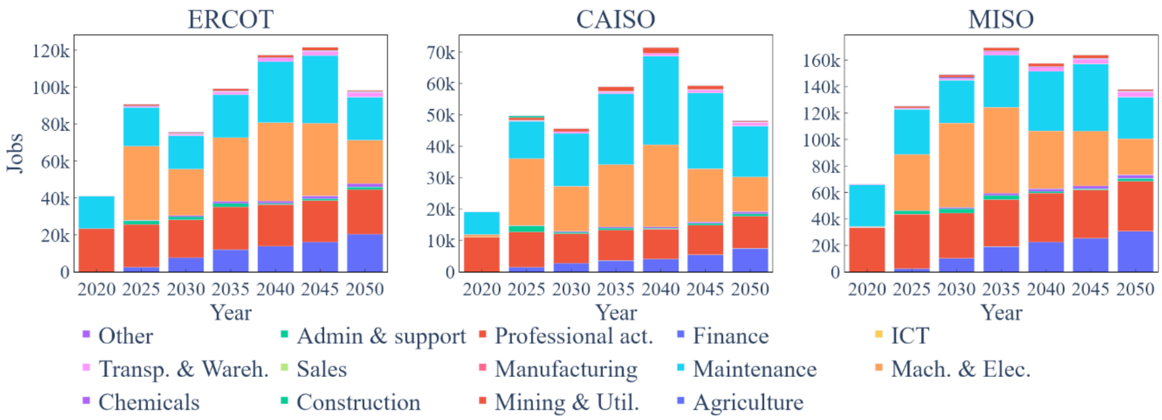


Figure 5-8: Jobs as a function of the electricity system expansion over time in the CDR scenario.

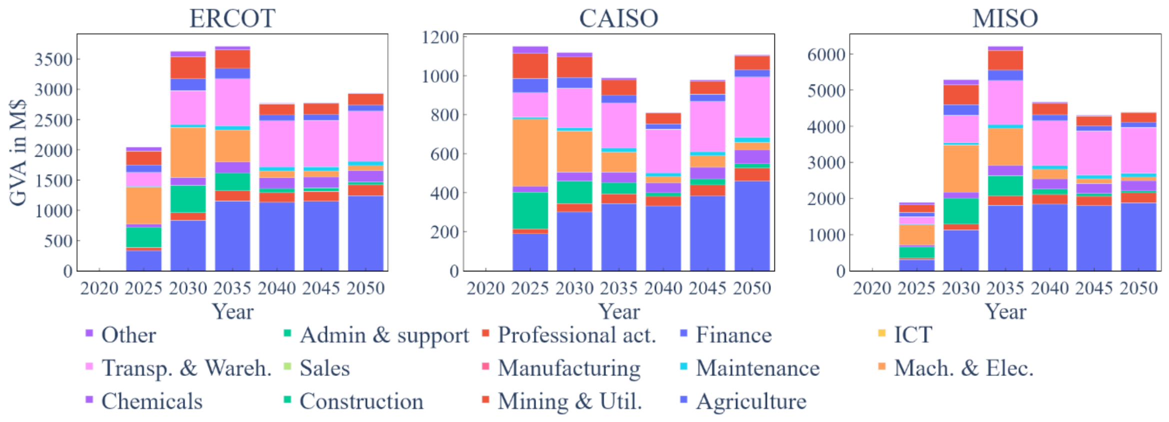


Figure 5-9: BECCS GVA as a function of the electricity system expansion over time in the CDR scenario.

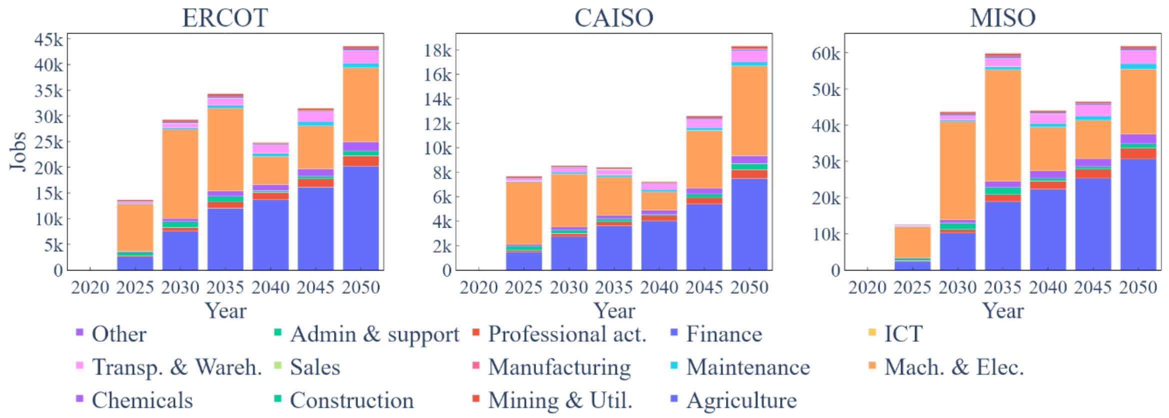


Figure 5-10: BECCS jobs as a function of the electricity system expansion over time in the CDR scenario.

5.4 Impact of BIL and IRA support

The introduction of policy support, including 45Q tax credits for carbon sequestration and ITCs for renewable energy and energy storage assets increase the uptake of low-carbon generation. In the reference scenario with IRA subsidies, GVA remains comparable to that of the scenario without subsidies (Figure 5-11). Despite the subsidies, BECCS still plays a negligible role in this scenario, indicating its limited economic viability without direct policy support. The number of jobs increase substantially with IRA (Figure 5-12), driven mainly by the deployment of wind power generation, but they stabilise by 2050 at comparable levels to those seen in the reference scenario without the IRA subsidies.

The net-zero power by 2035 scenario with IRA subsidies shows a reduction of around 5 and 15% in GVA compared to the scenario without the IRA in 2025 in CAISO and ERCOT, respectively (Figure 5-13). Whereas it shows an increase of 14% in GVA with IRA subsidies in MISO. On the other hand, all regions show an increase in GVA with IRA subsidies in 2050 when compared to the net-zero scenario without IRA subsidies. The contribution of different sectors to GVA and job production (Figure 5-14) remain like the scenario without the IRA. Agriculture experiences an increase from 2025 to 2050 as with the scenario without the IRA. BECCS contributions to GVA are marginally higher without the IRA subsidies, as less renewables are deployed and thus more BECCS is required. The carbon-negative power scenario with IRA subsidies shows the same trends (Figure 5-15 and Figure 5-16).

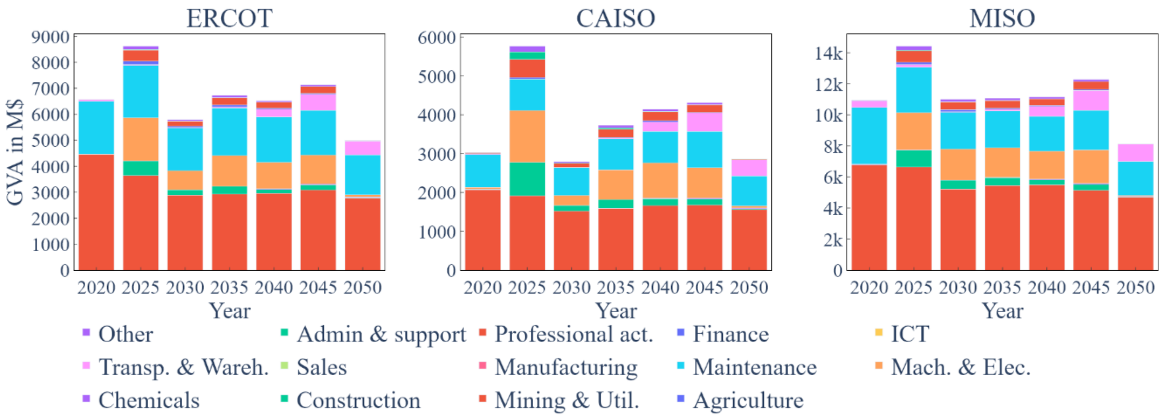


Figure 5-11: GVA as a function of the electricity system expansion over time in the reference scenario with IRA.

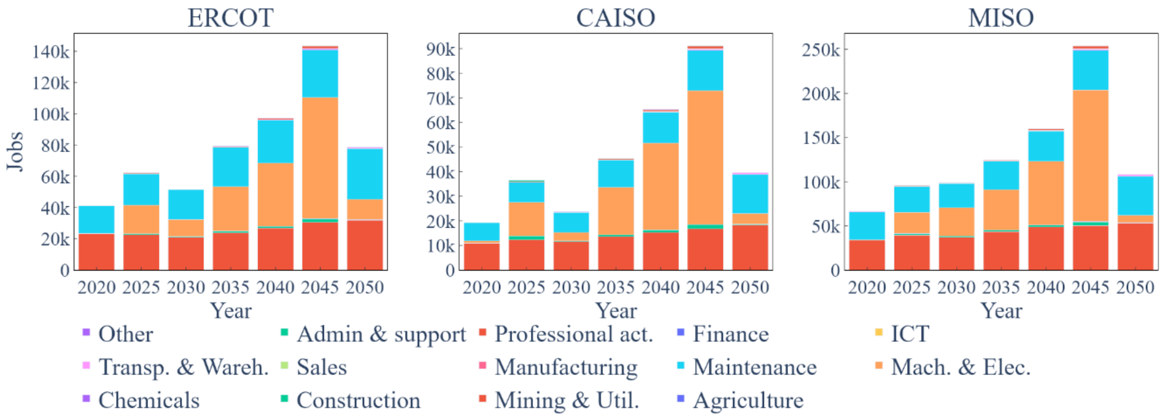


Figure 5-12: Jobs as a function of the electricity system expansion over time in the reference scenario with IRA.

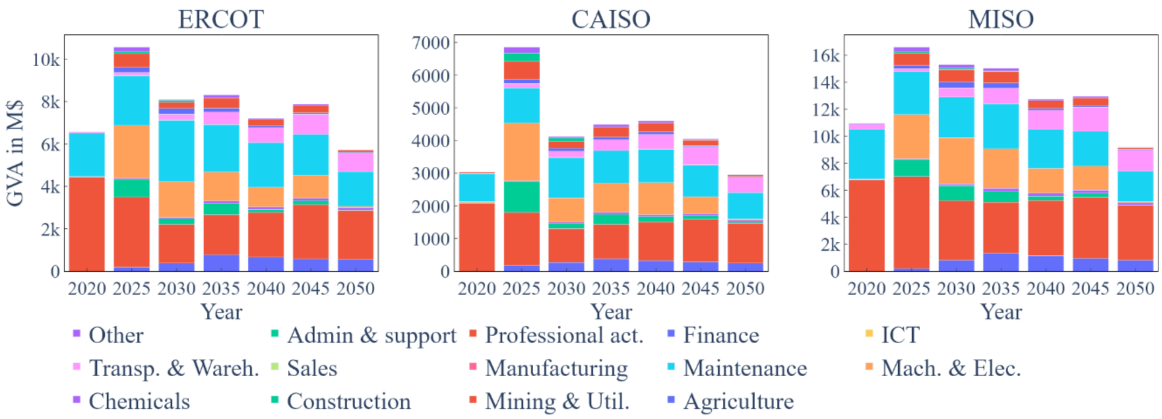


Figure 5-13: GVA as a function of the electricity system expansion over time in the net-zero scenario with IRA.

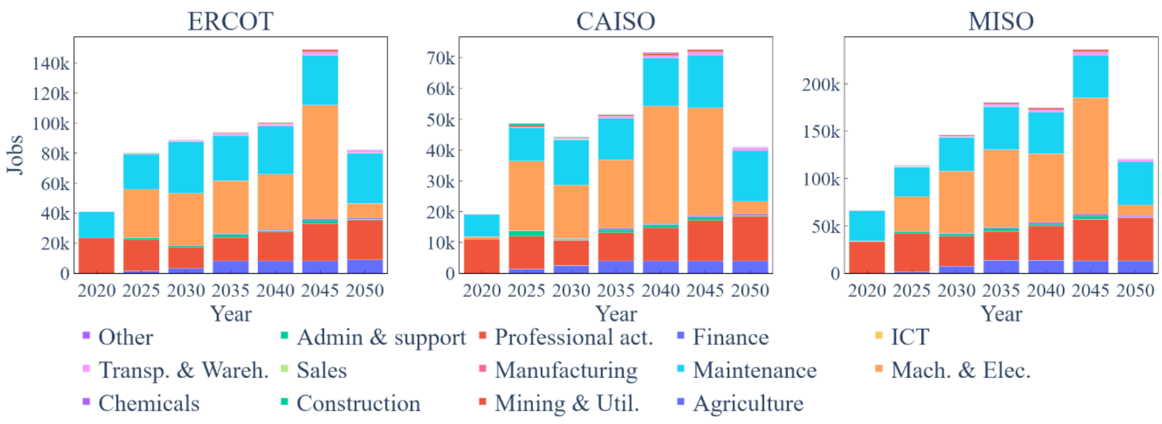


Figure 5-14: Jobs as a function of the electricity system expansion over time in the net-zero scenario with IRA.

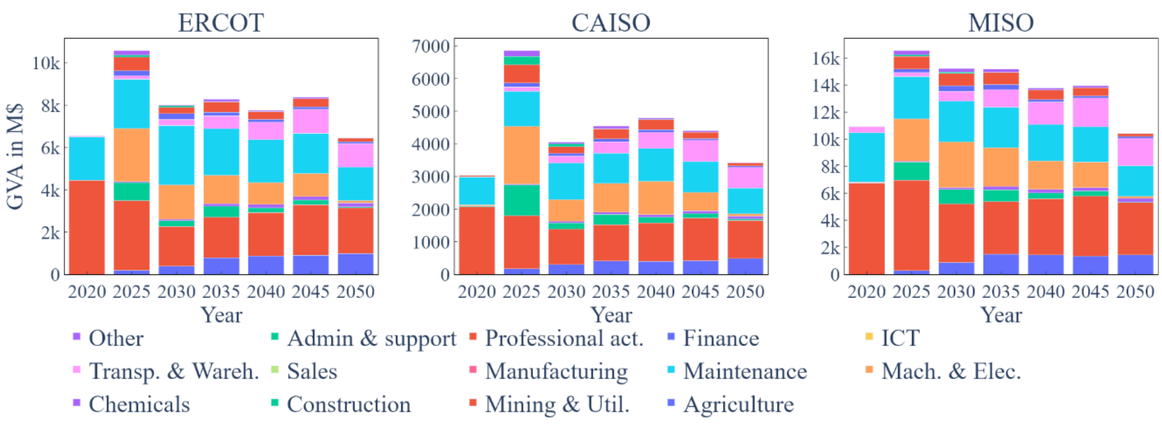


Figure 5-15: GVA as a function of the electricity system expansion over time in the CDR scenario with IRA.

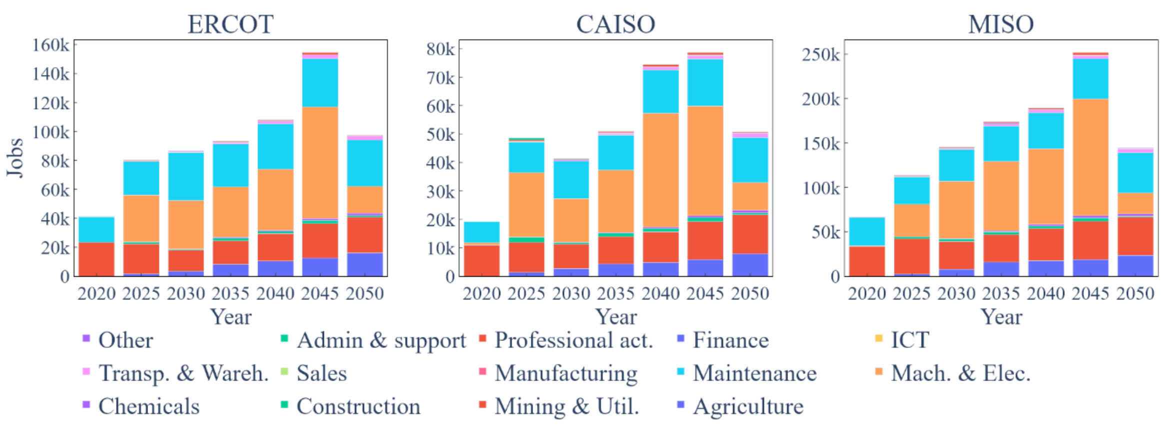


Figure 5-16: Jobs as a function of the electricity system expansion over time in the CDR scenario with IRA.

In summary, the scenarios show the impacts of different climate ambition, represented by emission targets, on jobs and GVA in ERCOT, CAISO and MISO. The reference scenario shows an increasing role for mining and utilities driven by high utilisation of natural gas for power generation. The net-zero power and carbon-negative power scenarios on the other hand showed a stronger diversification across sectors, driven by the deployment of low carbon technologies such as renewables, nuclear and BECCS.

ERCOT showed relatively consistent GVA and jobs production in both the net-zero power by 2035 and carbon negative scenarios. CAISO exhibits lower GVA, and jobs produced compared to ERCOT and MISO, reflecting the smaller scale of the system. ERCOT has an abundance of wind and sees an increase in value in renewable energy sectors. MISO is the most emission-intensive region today and experiences the most significant job creation, due to the need for an aggressive transition to clean energy technologies.

BECCS has a negligible contribution to the reference scenarios, whereas it stimulated economic growth and jobs across multiple sectors, especially agriculture and transportation and warehousing, in the net-zero power by 2035 scenario. The GVA and job creation from BECCS is slightly lower in scenarios with IRA subsidies (e.g., GVA associated with BECCS is about 17 % lower in the carbon-negative power scenario in ERCOT in 2050), as more renewables are deployed and therefore less BECCS is required. Overall, we found that early investments in BECCS (circa 2025) resulted in an increase in regional jobs and GVA by 38k job-years/ GW, and $6.7bn/ GW, respectively, by 2050. These figures increased to 52k job-years/ GW and $ 8.0bn/ GW over the lifetime of the BECCS facility.

6 Conclusions and recommendations

This study evaluated the role of BECCS in facilitating a deep decarbonisation of the US economy. The main objectives were to identify whether the deployment of BECCS is imperative for achieving a cost-effective decarbonisation of the local power grids, as well as a quantification of its value to the system across different degrees of climate ambition. Furthermore, this study examined the effectiveness of prevailing policy support measures in the BIL and IRA and assessed their adequacy in enabling a net-zero economy.

The key conclusions are that without BECCS, a net zero transition is up to 31% more costly, where it is possible at all. Further, whilst helpful, the BIL and IRA are the insufficient to provide a commercial justification for the deployment of BECCS, and that further support directly targeted at carbon dioxide removal is required. Importantly, this additional support is compensated for by additional job creation and generation of value at all levels of the economy.

Three important regional ESOs – namely, CAISO, MISO, and ERCOT – were selected for this study. Investment and decommissioning decisions were optimised over for the period to 2050 to identify the cost-optimal evolution of the installed power generation capacity. Simultaneously, dispatch decisions are optimised with hourly resolution to optimise the operation of the system, and to account for variability in demand, and intermittent availability of wind and solar power.

Three core model scenarios were constructed per regional grid to denote the varying levels of climate ambition:

1. A reference scenario where the power system is optimised purely based on minimum cost without any restrictions on its emissions footprint.
2. A scenario to cost-optimally design a net-zero power system by 2035 in line with the pledges by the current US administration.
3. A scenario to cost-optimally design a net-negative power system by 2050 to offset hard-to-abate emissions from elsewhere in the economy and reach overall net-zero by 2050.

These scenarios were further categorised into two groups: one augmented with a description of the currently available IRA and BIL subsidies, and the other where these policy support measures were not captured. This distinction delineates the impacts of the existing policy measures and their ability to support investments in low-carbon generation. Thus, eighteen distinct scenarios were evaluated.

The results were compared using key performance metrics such as the levelised cost of electricity supply, the aggregate installed capacity of renewable and other low-carbon generation sources, GVA impacts, as well as the generation of jobs over time.

The findings of the study suggest a strong role for gas-fired power generation (around 90% of installed capacity) in all three of the regional ESOs in the reference scenario, owing to their cost-effectiveness over other generation technologies. Gas-fired CCGTs are supplemented by OCGTs for flexible peak power generation, and they replace other forms of generation at the end of asset lifetime. This results in systems with a greater emission footprint by 2050 compared to the 2020s, which is inconsistent with the aspiration for achieving a net-zero emissions target. The long-term average LCOE is around 50 $/MWh in all considered energy systems, thus remaining competitive on cost compared to current levels.

In stark contrast, power systems that achieve net-zero by 2035 show a notable reduction of approximately 51% to 66% in the share of unabated gas in annual power generation compared to the reference scenario. This decline is offset by a significant increase in renewable power generation, particularly from wind, which displaces the aforementioned share and provides a source of low-carbon electricity in the ERCOT and MISO regions. Conversely, CAISO relies more heavily on solar power due to lower wind availability. Furthermore, nuclear power contributes around 14 – 27 GW of capacity in all three energy systems, with a specific uptick in CAISO, stemming from the reduced availability of renewable resources in California. BECCS is deployed in all three energy systems to offset residual emissions from the unabated gas-fired power plants. The installed capacity of BECCS in 2050 ranges from 4.6 GW (CAISO) to 21.5 GW (MISO). Consequently, the LCOE in the net-zero scenario is expected to be significantly higher compared to the reference scenario, reaching $100 - 140/MWh in the period from 2030 – 2050.

Power systems that achieve net-zero cost-effectively by 2035 are expected to be able to reach net-negative by 2050 to compensate for the hard-to-abate emissions in the economy. The results suggest that the composition of the power system is similar for both the systems that reach net-zero power by 2035 and net-negative power by 2050. The main difference is the level of ambition on CDR and the role of BECCS. In fact, the BECCS capacity is 7 GW higher in the carbon-negative power scenario compared to the net-zero scenario in ERCOT, and in CAISO it is 3 GW higher and in MISO 10 GW higher. Owing to the similar composition and scales, the LCOE in the carbon-negative power scenario is approximately 10 to 20 $/MWh higher compared to the net-zero power by 2035 scenario for the different ESOs.

BECCS investments in the US have the potential to make substantial contributions to job creation and regional economic development. Generally, BECCS investments, when supported by the appropriate incentives, are poised to play an imperative role in promoting economic growth whilst curbing emissions. The macro-economic impact assessment showed that job creation in the system is more resilient than GVA over time. While GVA may decrease, jobs either remain consistent or decrease at a slower rate, indicating their potential to offer long-term employment opportunities. Moreover, investments in BECCS appear to distribute the economic value over a greater range of sectors than in the present system, especially agriculture.

The findings suggest that BECCS offers unique value to the system by enabling deeper reductions in emissions more rapidly and cost-effectively than via other counterfactual technologies such as DACCS. In fact, the CAISO and ERCOT regions are likely to be 25 - 31% more expensive to decarbonise in the absence of BECCS. The MISO power grid is unlikely to reach net-zero by 2035, and the wider region may struggle to reach a net-zero economy by 2050 under historically available maximum build rate constraints for process facilities. There is strong agreement on the role of BECCS across the different regions, and it is important to support its deployment through appropriate policy measures.

We assessed the role of incentive support measures such as the ITCs and 45Q tax credits for CO_2 sequestration in the USA. The results indicate that ITCs influence the cost-competitiveness of renewables to the levels of gas-fired power generation in the reference scenario, increasing their relative share to 20 – 45% of generation capacity by 2050. Notably, the reference scenario sees the emergence of coal-CCS in comparison to the case without the incentives. This is largely owed to low coal prices and financial support offered by 45Q subsidies. Despite these trends, none of the ESOs achieve deep decarbonisation in the reference scenario with IRA subsidies. Emissions from ERCOT, CAISO, and MISO reduce by around 23%, 17%, and 44%, respectively, compared to current levels. This suggests that existing policy measures are insufficient to reach net-zero. The share of both BECCS and coal-CCS increases in both the net-zero power system by 2035 and net-negative power system by 2050 when supported by subsidies. Coal-fired plants with CCS largely displaces the gas-fired generation that would otherwise have been present in the absence of the 45Q support. However, environmental regulations on NOx and other pollutants may also limit the ability for coal-CCS plants to capitalise on these support measures. Nonetheless, BECCS provides 12 to 20% of the annual power generation to generate negative emissions.

The observation that the reference scenario when supported by the policy incentives did not lead to a net-zero or net-negative power system suggests that there is a cost gap between the least-cost power generation technologies and BECCS. This suggests that IRA and BIL alone remain insufficient to incentivise BECCS. Additional policy and regulatory support are likely to be necessary to scale up the deployment of BECCS. We assessed two specific policy interventions: a) raising the value of the 45Q tax credit, and b) introducing a dedicated negative emissions credit. We found that increasing the 45Q tax credit to \$100 – 150/t CO_2 provides little value to the system as it does not result in any material deployment in BECCS. In contrast, a negative emissions credit of \$40/t CO_2 was sufficient to incentivise the uptake of BECCS and to facilitate a net-negative power system by 2050.

This study did not explicitly consider electrification of other sectors of the economy, and instead used projections by the respective ESOs to define the evolution of the electricity demand over time. Moreover, the quantity of negative emissions needed to achieve a net-zero economy was estimated by assuming that approximately 10% of the economy-wide emissions will need to be offset through CDR, in line with other regional assessments. However, this is likely to be region- and scenario-specific in practice. Both limitations could be addressed by expanding on the methodological approach to explicitly consider these factors in future work. Finally, the study attributed all the costs of CDR to the electricity supply and did not consider the impact of CDR credits from either Federal reverse auction or VCMs on the LCOE. This will require more detailed analysis of the available financial support measures and it has the potential to reduce the LCOE relative to that presented in this report.

In summary, this study evaluates the role of BECCS in supporting deep decarbonisation of the US economy. Through comprehensive analysis using the ESO-JEDI framework, we have examined a range of scenarios, each representing varying degrees of climate ambition, and assessed the effectiveness of policy support measures in delivering a net-zero economy. These results suggest that BECCS is necessary to achieve ambitious decarbonisation trajectories, particularly in scenarios aiming for net-zero by 2035 and net-negative by 2050. The integration of BECCS not only enables deeper emissions reductions but also proves to be a cost-effective solution, outweighing alternatives such as DACCS on cost. Furthermore, BECCS investments offer the potential for distributed job creation and regional economic development.

7 Acknowledgements

Foresight Transitions Ltd wishes to acknowledge the funding received from Drax Group Plc to undertake this study.

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9 Appendix

9.1 Supplementary results

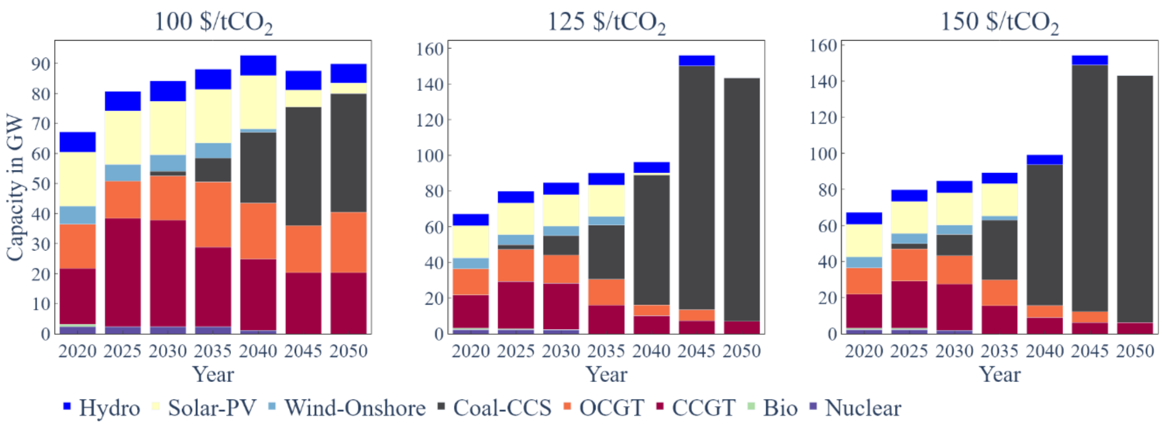

Figure 9-1: Optimal power generation capacity expansion in CAISO without an emission constraint and increased 45Q tax credit values of 100 \$/t CO_2, 125 \$/t CO_2, and 150 \$/t CO_2.

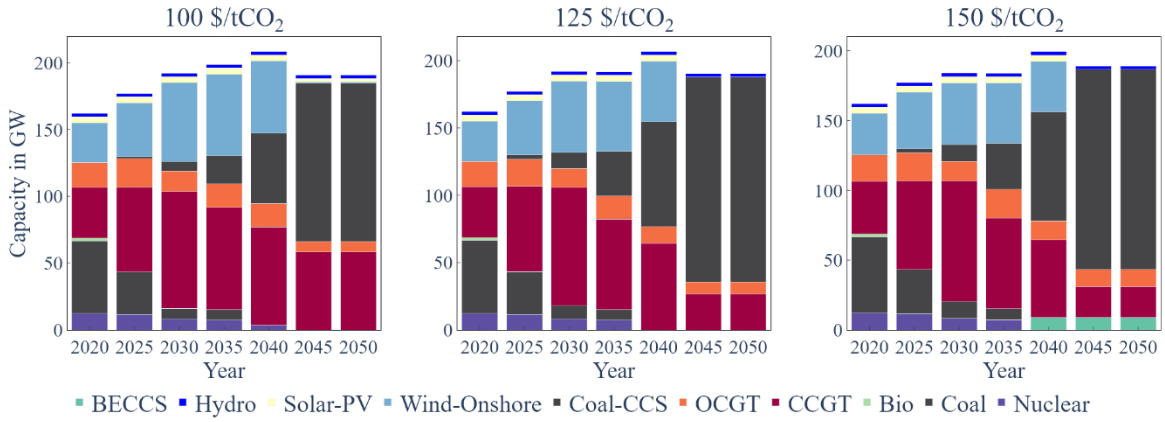

Figure 9-2: Optimal power generation capacity expansion in MISO without an emission constraint and increased 45Q tax credit values of 100 \$/t CO_2, 125 \$/t CO_2, and 150 \$/t CO_2.3.12

9.2 Renewables generation

Spatial representation. The spatial resolution for NASA MERRA-2 data of 0.5°×0.625° (latitude, longitude) is used to capture regional variation in the different technologies' performances based on solar irradiation, wind, and ambient condition profiles[1]. Using NASA MERRA-2 spatial resolution, the world is divided into a grid with 361×576 nodes in the latitudinal and longitudinal directions, respectively.

Solar PV. Hourly generated electricity using solar PV is calculated using the equation below, which is a function of the solar PV installed capacity, global horizontal irradiance (GHI), and solar PV efficiency. The solar PV efficiency is calculated using the simplified model accounting for the local optimum angle developed by Huld et al. [2], which itself is a function of ambient temperature at the surface and GHI. The GHI data and solar PV electricity generation potential from Huld et al.[2] were validated based on Global Solar Atlas 2.0[3], which was calculated for a period of more than 10 years for most locations worldwide. The results demonstrate good agreements between our model and Global Solar Atlas 2.0 data.

$$gen_{\mathrm{solarPV,El},h} = instCap_{\mathrm{solarPV}} \times GHI_h \times \eta_{\mathrm{solarPV},h}(GHI_h, Temp_h^{\mathrm{S}}) \quad \forall h$$

Wind. Hourly electricity generated by wind turbines is a function of wind turbine installed capacity and its capacity factor, which is a function of wind speed shown in the equations below. The capacity

[1] *Gelaro, R., et al., The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2). Journal of Climate, 2017. 30(14): p. 5419-5454.*
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[3] *Global Solar Atlas, 2.0, a free, web-based application is developed and operated by the company Solargis sro on behalf of the World Bank Group, utilizing Solargis data, with funding provided by the Energy Sector Management Assistance Program (ESMAP).*

factor curve used in this work is adopted from Staffell and Green[4], which is based on a 50 MW farm of Vestas V80 2 MW turbines. The obtained wind speed data from NASA MERRA-2 at the height of 10m (z_r) along with surface roughness (z_0) was used to obtain the wind speed at the height of 150m (z), which is used in our model, using logarithmic profile model[5]. Using the same approach, wind speed at the height of 100m was validated against Global Wind Atlas 3.0 [6] which is based on sample data in the period between 1998-2017 where both data sets show good agreement.

$$gen_{\text{wind,El},h} = instCap_{\text{wind}} \times CF_{\text{wind},h}(WS_h) \quad \forall h$$

$$WS(z) = WS(z_r) \times \ln(\frac{z}{z_0}) / \ln(\frac{z_r}{z_0})$$

CSP. CSP is modelled as a solar power tower system, utilising Melton salt as heating fluid, using an adopted model from previous works[7,8] and captured in the equations below. Hourly HT heat generated by CSP is a function of the installed capacity based on the heliostat field area, heliostat field efficiency ($\eta^{\text{field}}_{\text{CSP},h}$), radiative and convective losses. $\eta^{\text{field}}_{\text{CSP},h}$ is a function of solar zenith angle (θ_h) which is calculated using the performance curve presented by Ghirardi et al.[8]. Direct normal irradiance (DNI) is calculated using the Direct Insolation Simulation Code (DISC) model[9] using GHI, θ_h , and the day of the year as inputs. Radiative and convective losses are calculated, respectively, where CSP receiver heat flux ($\varphi^{\text{rec}}_{\text{CSP}}$) of 600 kW m^{-2} is used to estimate the receiver area, and CSP receiver emissivity ($\varepsilon^{\text{rec}}_{\text{CSP}}$) is assumed to be 0.88. Melton salt outlet temperature ($\text{temp}^{\text{out}}_{\text{CSP}}$) and inlet temperature ($\text{temp}^{\text{in}}_{\text{CSP}}$) of 574°C and 290°C, respectively, were used to calculate an area-weighted average molten salt temperature at the receiver ($\text{temp}^{\text{eff}}_{\text{CSP}}$). CSP deployment was only allowed in regions with annual DNI above 1800 kWh m^{-2} to ensure stable operation. Data validation for the obtained DNI from the DISC model with DNI data from Global Solar Atlas 2.0[3], as well as comparison of the conversion of DNI to electricity efficiency to the data available in the literature to ensure goodness of fit.

$$\begin{aligned} gen_{\text{CSP,HeatHT},h} &= instCap_{\text{CSP}} \times \eta^{\text{field}}_{\text{CSP},h}(\theta_h) \times DNI_h(GHI_h, \theta_h, DOY_h) \\ &\times \left(1 - Loss^{\text{rad}}_{\text{CSP},h}(Temp_h) - Loss^{\text{conv}}_{\text{CSP},h}(Temp_h, WS_h)\right) \quad \forall h \end{aligned}$$

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[4] *Staffell, I. and R. Green, How does wind farm performance decline with age? Renewable Energy, 2014. 66: p. 775-786.*

[5] *Manwell, J.F., J.G. McGowan, and A.L. Rogers, Wind energy explained: theory, design and application. 2010: John Wiley & Sons.*

[6] Global Wind Atlas, *3.0, a free, web-based application developed, owned and operated by the Technical University of Denmark (DTU).*

[7] Wagner, M.J., et al., Optimized dispatch in a first-principles concentrating solar power production model. Applied Energy, 2017. 203: p. 959-971.

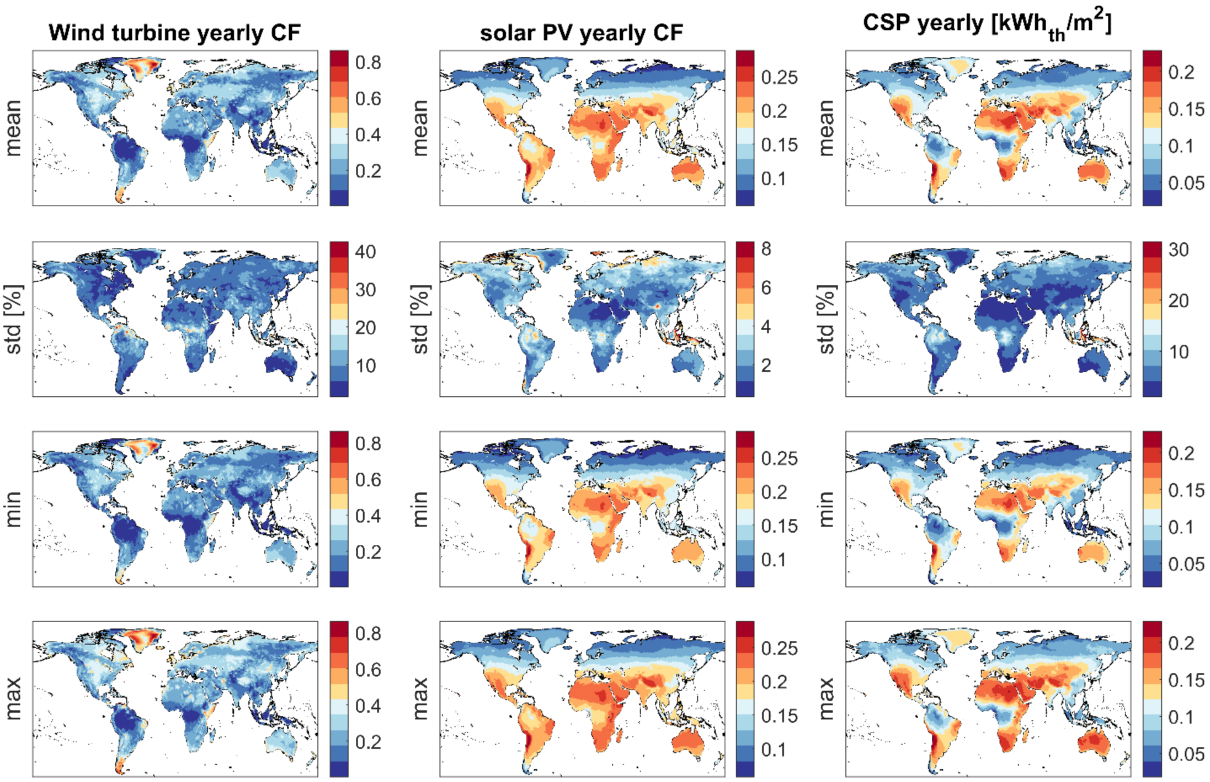
[8] Ghirardi, E., et al., The optimal share of PV and CSP for highly renewable power systems in the GCC region. Renewable Energy, 2021. 179: p. 1990-2003.

[9] Stein, J.S., et al. *PVLIB: Open-source photovoltaic performance modeling functions for Matlab and Python*. in *2016 IEEE 43rd photovoltaic specialists conference (pvsc)*. 2016. IEEE.

$$Loss^{red}_{CSP,h}(Temp_h) = \frac{1}{\varphi^{rec}_{CSP}} \times \sigma \times \varepsilon^{rec}_{CSP} \times \left((temp^{eff}_{CSP})^4 - (Temp_h)^4 \right) \quad \forall h$$

$$Loss^{conv}_{CSP,h}(Temp_h, WS_h) = Loss^{red}_{CSP,h}(Temp_h)$$
$$\times(-5.645 \times 10^{-4}\, WS_h^{\,3} + 0.01561 WS_h^{\,2} - 0.00911 WS_h + 0.48124) \quad \forall h$$

$$temp^{eff}_{CSP} = 0.55(temp^{out}_{CSP} + temp^{in}_{CSP})$$



9.3 JEDI formulation and input data

As ESO generates expenditure for each scenario, this cost consists of investment (Inv) needed for building a new technology, variable OPEX (OMV) and fixed OPEX (OMF) to operate the technology. In JEDI, these costs are disaggregated further into components that resemble the specific cost of an industrial activity that is related to ISIC code. For examples, fuel and transportation costs are part of variable OPEX and these are components go under ISIC Mining/Utility and Transport & Warehousing respectively. The ISIC codes are further condensed into 15 JEDI industrial classifications after the pre-processing step with each. Each technology is allocated these classifications with GVA and Jobs multipliers and they are as shown in Table 6 and Table 7. To obtain the multipliers, the below steps were used:

$$GVAK^{cat}_{i,sect} = \frac{cost^{cat}_{i,sect}}{\sum_{sect} cost^{cat}_{i,sect}} \left(\frac{GVA}{output}\right)_{sect}$$

$$cat \in \{Inv, OMF, OMG\}$$

The GVAK$^{cat}_{i,sec}$ (m\$/m\$) is the GVA multiplier and is based on technology disaggregated costs and macroeconomic parameters that are GVA and output. GVA and output are U.S. aggregate values obtained from OECD database [28] and are allocated to specific ISIC sector. Similarly, the JobsK$^{cat}_{i,sect}$ multiplier is obtained, where compensations (comp in m\$) and average annual wage (wage in \$) are obtained from the OECD.

$$JobsK^{cat}_{i,sect} = \frac{cost^{cat}_{i,sect}}{\sum_{sect} cost^{cat}_{i,sect}} \cdot \left(\frac{GVA}{output}\right)_{sect} \cdot \frac{comp_{sect}}{GVA_{sect}} \cdot \frac{1}{wage_{sect}}$$

$$cat \in \{Inv, OMF, OMG\}$$

The above multipliers are specific to each technology i, category cat and economic sector sect. These multipliers are ESO inputs, and they are used to calculate the GVA along the Jobs added by each technology.

The investment GVA (GVASecInv) is calculated as follows and is a function of technology CAPEX:

$$GVASectInv^{power}_{sect,a} = \sum_{ip} CAPEX_{ip}\, b_{ip,a}\, Des_{ip}\, WFA_{ip,a} GVAK^{Inv}_{ip,sect} / Disc_a$$

In terms of the GVA obtained from operating and maintenance (GVASectOM), it is a function of OMV and OMF as shown below:

$$\begin{aligned} GVASectOM^{power}_{sect,a} &= \sum_{ipg,c,t} (OPEXSU_{ipg} u_{ipg,a,c,t} + OPEX_{ipg,a} p_{ipg,a,c,t} \\ &+ OPEXNL_{ipg,a} n_{ipg,a,c,t})\, WF_{ac} GVAK^{OMV}_{ipg,sect} / Disc_a \\ &+ \sum_{ips,c,t} (OPEX_{ips,a} s2d_{ips,a,c,t} + OPEXNL_{ips,a} o_{ips,a,c,t}) WF_{ac}\, GVAK^{OMV}_{ips,sect} / Disc_a \\ &+ \sum_{ip,c,t} d_{ip} Des_{ip} CAPEX_{ip} OPEXFix_{ip}\, GVAK^{OMF}_{ip,sect} / Disc_a \end{aligned}$$

To find the total GVA per sector (GVASect) over the time horizon, the weight of each planning period is used following the trapezoid rule. 2020 and 2050 are the first planning periods and each represent 2.5 year, where the rest of the years represent 5 years.

$$\begin{aligned} GVASect_{sect} &= \sum_{a} GVASectInv_{sect,a} + 2.5 \sum_{a \in \{1,7\}} GVASectOM_{sect,a} \\ &+ 5 \sum_{2 \le a \le 6} GVASectOM_{sect,a} \end{aligned}$$

The total direct GVA (GVAdir) generated by the power sector is calculated by adding all the sectors together:

$$GVAdir = \sum_{sect} GVASect_{sect}$$

Similarly, Jobs from investments (JobsSectInv) are calculated as follows, however the WFA factor for the end of time horizon is not considered as jobs are added during the construction period of the plant regardless of the planning period:

$$JobsSectInv_{sect,a}^{power} = \sum_{ip} CAPEX_{ip}\, b_{ip,a}\, Des_{ip}\, JobsK_{ip,sect}^{Inv}$$

In a similar manner, Jobs from the operation and maintenance activities (JobsSectOM) is calculated, however in comparison to the GVA formulation, this part does not contain the discount factor Disc as Jobs is not a monetary value:

$$\begin{aligned} &JobsSectOM_{sect,a}^{power} \\ &\quad = \sum_{ipg,c,t} (OPEXSU_{ipg} u_{ipg,a,c,t} + OPEX_{ipg,a} p_{ipg,a,c,t} \\ &\quad + OPEXNL_{ipg,a} n_{ipg,a,c,t})\, WF_{ac} JobsK_{ipg,sect}^{OMV} \\ &\quad + \sum_{ips,c,t} (OPEX_{ips,a} s2d_{ips,a,c,t} + OPEXNL_{ips,a}\, o_{ips,a,c,t}) WF_{ac}\, JobsK_{ips,sect}^{OMV} \\ &\quad + \sum_{ip,c,t} d_{ip} Des_{ip} CAPEX_{ip} OPEXFix_{ip}\, JobsK_{ip,sect}^{OMF} \end{aligned}$$

The total jobs from each sector (JobsSect) is found as follows

$$\begin{aligned} &JobsSect_{sect} \\ &\qquad = \sum_{a} JobsSectInv_{sect,a} + 2.5 \sum_{a\in\{1,7\}} JobsSectOM_{sect,a} \\ &\qquad + 5 \sum_{2 \le a \le 6} JobsSectOM_{sect,a} \end{aligned}$$

The total number of jobs (Jobsdir) is found as shown below:

$$Jobsdir = \sum_{sect} JobsSect_{sect}$$