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Assessing the Interactive Impacts of Energy Efficiency and Demand Response on Power System Costs and Emissions

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BERKELEY LAB

NREL

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Report Outline

I. Overview and key findings

II. Introduction

III. Analytical Approach

IV. Results

V. Conclusions and Discussion

VI. Supplemental information detailing EE measure and package assumptions, DR technology assumptions, a description of key power system features, and additional results

Preface: This report is part of a larger and interrelated effort to understand the interactions between energy efficiency (EE) and demand response (DR) from the building and power system perspectives.

Conceptual framework

Identify attributes, system conditions, and technological factors driving EE and DR interactions.

Publication

Satchwell et al., 2020. *A Conceptual Framework to Describe Energy Efficiency and Demand Response Interactions*.

Load interactions

Quantitative analysis of how EE and DR interact with each other on a load-shaping basis, based on key attributes identified in the conceptual framework.

Publications

Gerke et al., 2022. *Load-driven Interactions Between Energy Efficiency and Demand Response on Regional Grid Scales*.

Murthy et al., 2022. *Metrics to Describe Changes in the Power System Need for Demand Response Resources*.

Power system interactions

Quantify changes in power system capacity, transmission, and variable costs, and CO_2 emissions across 3 U.S. regions and 3 future grid scenarios (including high renewable energy resource mix), based on the EE and DR scenarios established by the load interactions study.

This study

Assessing the Interactive Impacts of Energy Efficiency and Demand Response on Power System Costs and Emissions

I. Overview and key findings

Key Findings

- We quantify the impacts of EE and DR in isolation and in combination on bulk power system costs and emissions based on changes in generation expansion, transmission expansion, and dispatch patterns. The study is intended to assess how EE and DR affect each other’s power system value and to identify the most valuable technologies and strategies that can be jointly deployed.
- Concerns about competition between EE and DR may be overstated when considering bulk power system cost and emissions impacts. The study results also emphasize the importance of electricity system characteristics in determining precise impacts of EE and DR interactions.
- EE and DR provide value to the power system by reducing bulk power system costs in isolation *and* in combination. In our analysis of ERCOT, net system costs decline when both EE and DR are added to the system regardless of the type of EE package or DR (i.e., load shedding or load shifting DR). Net system costs similarly decline when EE and DR are jointly deployed when assessing impacts across the entire contiguous US (CONUS) regardless of EE package, DR type, or grid scenario.
- Importantly, adding EE to DR, and vice-versa, in ERCOT reduces generation emissions in most cases. The same is true for results across the CONUS. The emissions impacts in our study identify strong complementarity between EE and DR and a significant source of value for grid-interactive efficient buildings.
- The results are also sensitive to different baseline electricity system characteristics, particularly constraints on new transmission expansion. When transmission can be built in ERCOT, EE and DR reduces generation capacity and often favors increased transmission builds to regions with less aggressive demand-side policies; whereas when transmission expansion is limited, EE and DR are used to either reduce generation capacity (Shed DR) or switch from higher- to lower-cost generation capacity (Shift DR).
- The study has implications for EE and DR program design and shows that existing EE controls (e.g., smart thermostat) and envelope technologies and measures can enhance the capabilities and value of DR (e.g., by enabling load shifting by changing the magnitude and timing of heating/cooling consumption). Such combinations may be near-term opportunities for integrated EE and DR programs.
- The study also demonstrates the importance of considering EE and DR interactions, especially co-benefits, in regulatory processes (e.g., integrated resource planning, EE and DR program cost-effectiveness studies). The approach used in this study mimics utility resource planning and uses more novel techniques to select least-cost generation and transmission capacity from supply- *and* demand-side resources, as compared to more commonly used utility approaches that only consider supply-side resources.

II. Introduction

How do EE and DR interact with one another on a system cost and emissions basis in different power system configurations?

For system operators…	For utility planners…	For regulators and utilities…
How do EE and DR meet system needs to maintain reliability and service levels, and how does one resource affect the other?	What integrated EE and DR technologies and strategies are most valuable to the power system, and how robust are those valuations across different grid futures?	How should EE and DR program design and valuation frameworks evolve to account for interactive effects?

Study context and motivation

- Building owners, utility planners, and regulators have an interest in understanding what EE and DR should be prioritized in the context of ongoing energy system transitions, as well as how to avoid unintended competition.
- From the power system perspective, the amount of DR that is utilized is the net effect of how EE impacts the system need for DR and how much DR resource is available to meet system needs (see figure at right).
- This study describes those impacts and interactive effects and identifies combinations of EE and DR packages that maximize cost and emissions savings in the context of multiple power system configurations.

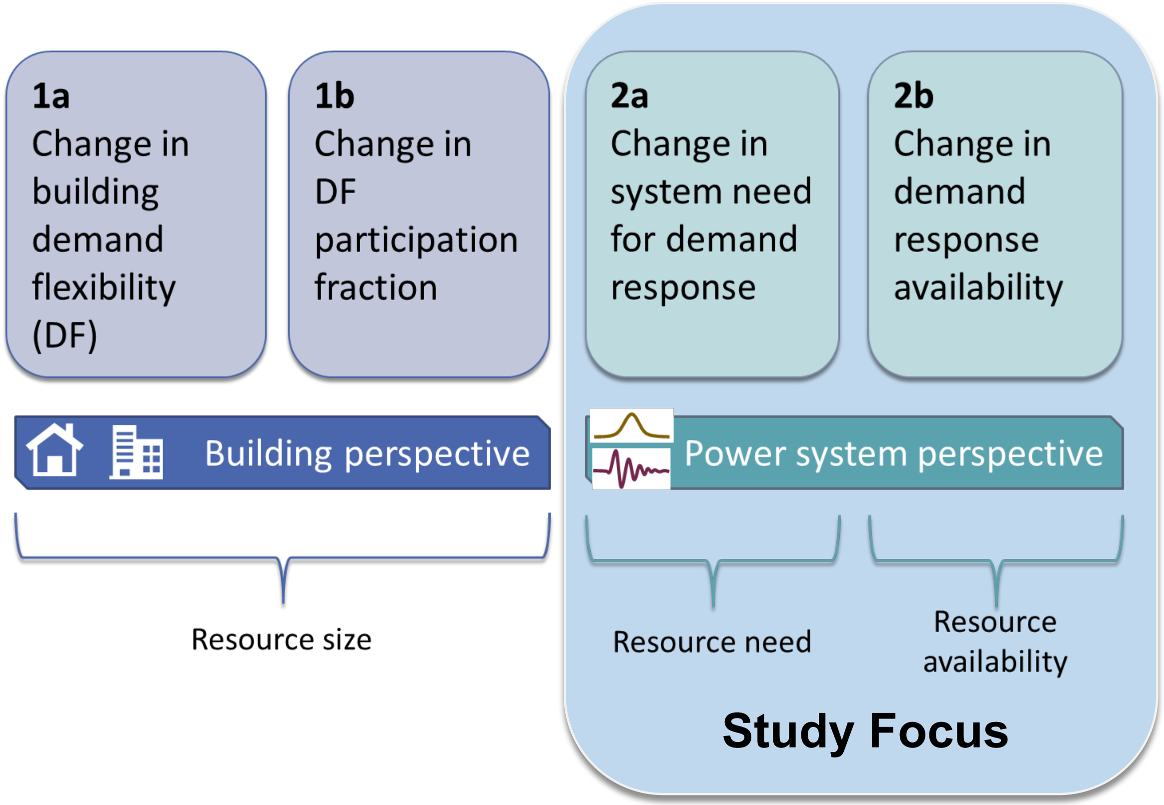
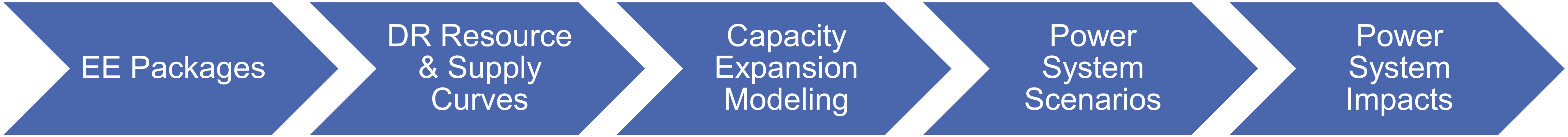


Figure source: Satchwell et al., 2020. Available at: https://emp.lbl.gov/publications/conceptual-framework-describe-energy

Study boundaries

This study is *not*…	Instead, our intent is to…
An EE or DR potential study	Assess change in DR value under different EE packages and the most valuable combinations of EE and DR
Representative of "typical" or average EE savings and DR capacity amounts	Use aggressive energy savings packages reflecting high-efficiency technologies and aggressive estimates of DR availability to create identifiable impacts
A cost-benefit analysis	EE hourly load impacts are determined outside the least-cost expansion model; DR is selected by the model and is economic based on grid needs; Typical historical weather is assumed
Capturing all operational factors (e.g., transmission constraints) and/or 8760 dispatch costs	Identify key factors driving EE and DR interactions from power system perspective using a reduced-order national-scale model

III. Analytical Approach



Overview

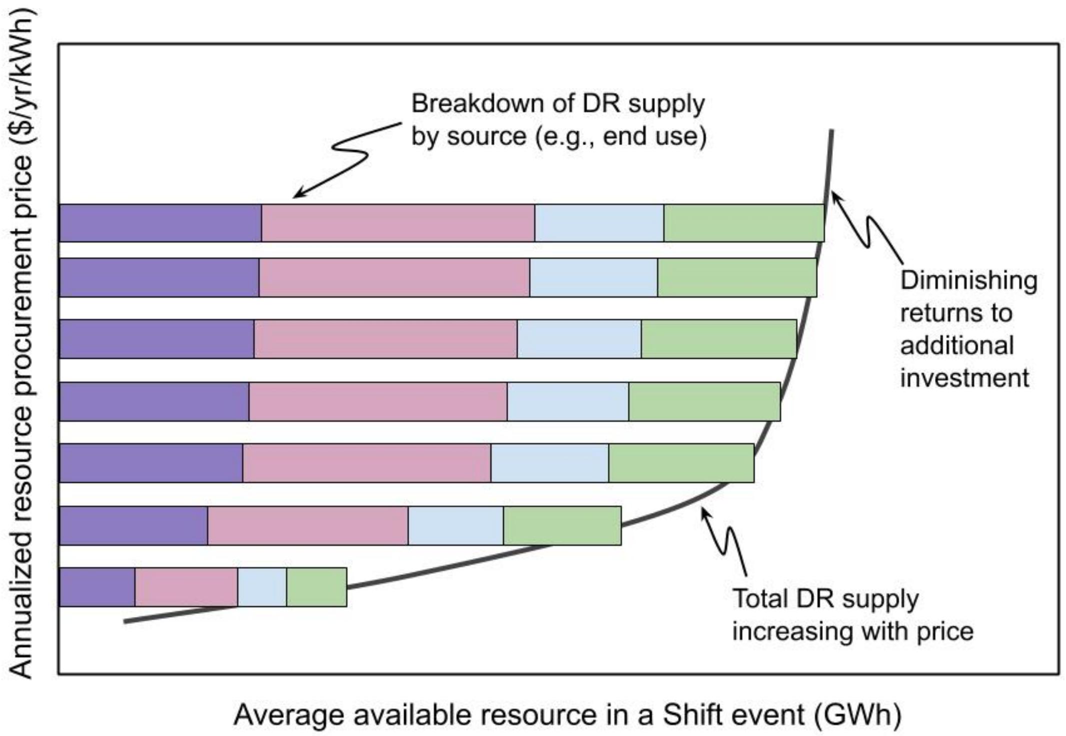
- **EE Packages** – Characterized by NREL ResStock and ComStock baseline and more efficient load shapes representing typical EE measures under fairly aggressive performance assumptions and at high customer adoption levels in weather locations in California Independent System Operator (CAISO), Electricity Reliability Council of Texas (ERCOT), and Independent System Operator New England (ISO-NE) service territories.
- **DR Resource & Supply Curves** – Available DR resource for residential and commercial buildings represented by hourly profiles of load shedding and shifting availability procurable by the utility at discrete (i.e., binned) cost levels.
- **Capacity Expansion Modeling** – The ReEDS capacity expansion model was modified to represent load shedding (“Shed DR") and load shifting (“Shift DR") supply curves and operations as investment options. Adjusted load profiles incorporating hourly EE load time series changes represent the EE package scenarios. EE and DR are added to CAISO, ERCOT, and ISO-NE, which are selected as regions with relatively large loads (and, thus, relatively large EE and DR potential) and represent a diverse mix of building types and baseline building end-use consumption. ReEDS models balancing areas (BAs) across the entire contiguous United States (CONUS) to capture changes in imported and exported electricity (and associated transmission costs).
- **Power System Scenarios** – EE and DR are analyzed in the context of three power system scenarios using the NREL 2020 Standard Scenarios Mid Case, Low Transmission Expansion ("Limited Transmission"), and Low RE Cost ("High RE") assumptions.
- **Power System Impacts** – Changes in system costs and emissions are computed for all combinations of EE packages, DR options, and power system scenarios. Impacts are interpreted by examining changes in: 1) load, 2) generation, storage, DR and transmission capacity builds, and 3) dispatch.

- Residential and commercial EE packages modeled in NREL's ResStock and ComStock analysis tools and reflecting widespread adoption of high-efficiency technologies grouped into four portfolios (see figure at right). EE packages draw on key EE and DR interactive attributes from Satchwell et al. (2020).
- EE package adoption is assumed for all eligible buildings (i.e., all new construction and all buildings undergoing renovations) in each year from 2020-2040. Impacts scale over time consistent with EIA AEO population, building stock, and commercial floor space growth assumptions. We also assume a 1% per year renovation rate for residential buildings and 3% per year renovation rate for commercial buildings. We note these are all aggressive assumptions and intended to produce interpretable impacts on power system load, costs, and emissions.
- Building-level load shapes are aggregated to system-level loads using parcel-level building data that matches total building floor space associated with each weather station for each modeled building type.*

Baseline	Standard ResStock and ComStock inputs for present-day building stock and assuming 2012 actual meteorological year (AMY)
Controls	Include programmed HVAC controls, lighting occupancy sensors, demand-controlled ventilation, and advanced power strips.
Envelope	Upgrade windows, roof materials, and attic/wall/floor insulation; improve air sealing.
Equipment	Upgrade HVAC equipment, water heating equipment, appliances, lighting, electronics.

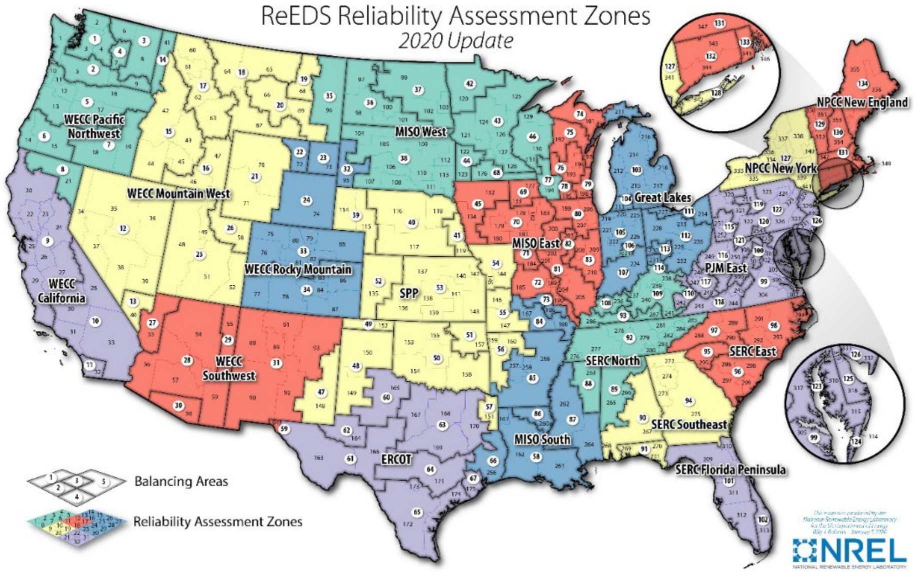
*See Gerke et al. (2022) for more details on the load shape aggregation model.

- LBNL's DR-Path model estimates the available DR resource by building type and end-use. DR-Path was developed to support DR research for the California Public Utilities Commission (CPUC).*
- Hourly end-use load shapes are combined with a DR dispatch probability model based on hourly system net load to produce a weighted average DR resource. This represents the technical potential for each building type and end use.
- Shed and Shift DR resource potential are modeled separately and assumed to be preferentially dispatched during extreme net load peaks and ramping events, respectively. The net loads in this portion of the study are computed using the modeled system-level loads for each EE package, coupled with renewable generation profiles from ReEDS.
- DR-Path then couples the DR technical potential for each end use with a database of DR-enabling measures having different performance levels and costs. Each pairing is a technological pathway that delivers a particular fraction of the technical potential for a particular cost. We exclude non-building technology DR resources (e.g., electric vehicles).
- Finally, DR-Path builds a supply curve for DR by selecting the technological pathways that maximize the amount of DR resource that is available in each procurement cost bin, starting with the lowest cost bin (see figure at right).



*For more on DR-Path, see the Phase 3 CPUC DR Potential Study, available at: https://eta.lbl.gov/publications/california-demand-response-potential

- The study uses NREL's Regional Energy Deployment System (ReEDS) capacity expansion model.* ReEDS projects the type of future generation, storage, and inter-regional transmission capacity across 134 BAs in the US based on least-cost system-wide optimization (see figure at right). Temporally, 17 time-slices are included in the main dispatch model; pre-processing steps use hourly data to better estimate unit commitment impacts, firm capacity contributions, and curtailment impacts. In this study, EE and DR are deployed in the NPCC New England (ISO-NE), ERCOT, and WECC California (CAISO) reliability assessment zones. The modeled weather year for all load and variable generation (VG) is 2012. Load growth is calculated from Energy Information Administration (EIA) Annual Energy Outlook (AEO) electricity consumption data.



- EE is modeled in ReEDS as a change in load based on the system profiles described previously, for each EE package. These changes are then added onto the standard load profiles used in ReEDS for each modeled year. EE is therefore not an investment decision but rather an exogenous assumption affecting the ReEDS power system investment decisions.
- DR is incorporated in ReEDS as an investment decision and represented by DR-Path supply-curves disaggregated into individual DR end uses. Each supply curve represents the amount of capacity that can be deployed at a series of cost points, each of which represents a binning of enabling technologies for the given end-use. The supply curve capacities represent the amount of energy that could be reduced (Shed DR) or shifted (Shift DR) at each hour (for ReEDS pre-processing steps) and time-slice (for the ReEDS dispatch model). The Shift DR resource potential is also characterized by the length of the allowable shifting window. DR can also provide firm capacity to the system and that contribution is computed in the ReEDS preprocessing step. In this study we analyze Shed DR and Shift DR separately within ReEDS.

*For more on ReEDS, see the model documentation, available at: https://www.nrel.gov/docs/fy21osti/78195.pdf

- This analysis focuses on the evolution of the power system over 20 years (i.e., 2020-2040), with results reported predominantly in 2020, 2030, and 2040. We report results for ERCOT in this report (see pages 19 and 20) with additional results for the CONUS reported in the supplemental information (see Section VI).
- Three future grid scenarios were modeled for the analysis and scenario definitions are based on NREL's 2020 Standard Scenarios.* The figure at right describes the scenarios in this study and provides the alternative scenario names used in this study when applicable.
- Importantly, the scenarios only differ in their economic assumptions and there are no differences in policy assumptions. Generation technology cost and performance assumptions are based on the NREL Annual Technology Baseline (ATB).**
- This analysis uses a single weather year (2012) that the ReEDS team identified as having most typical wind and solar generation at the national scale. A more realistic analysis using multiple weather years and incorporating climate change forecasts is out of scope for this study.

Scenario	Description
Mid Case	• Uses mid-line generation, storage, and transmission cost assumptions and technology parameters for the US bulk power system.
Barriers to Transmission System Expansion ("Limited Transmission")	• Assumes higher transmission costs and only allows transmission builds between BAs *within* the same RTO with limited expansion options compared to the Mid Case assumptions.
Low Renewable Energy Cost ("High RE")	• Assumes lower costs for renewable technologies along with more aggressive technology advancements than the Mid Case assumptions.

*For more detail and definitions of the NREL Standard Scenarios see: https://www.nrel.gov/analysis/standard-scenarios.html.
**For more detail and definitions of the NREL ATB see: https://atb.nrel.gov/.

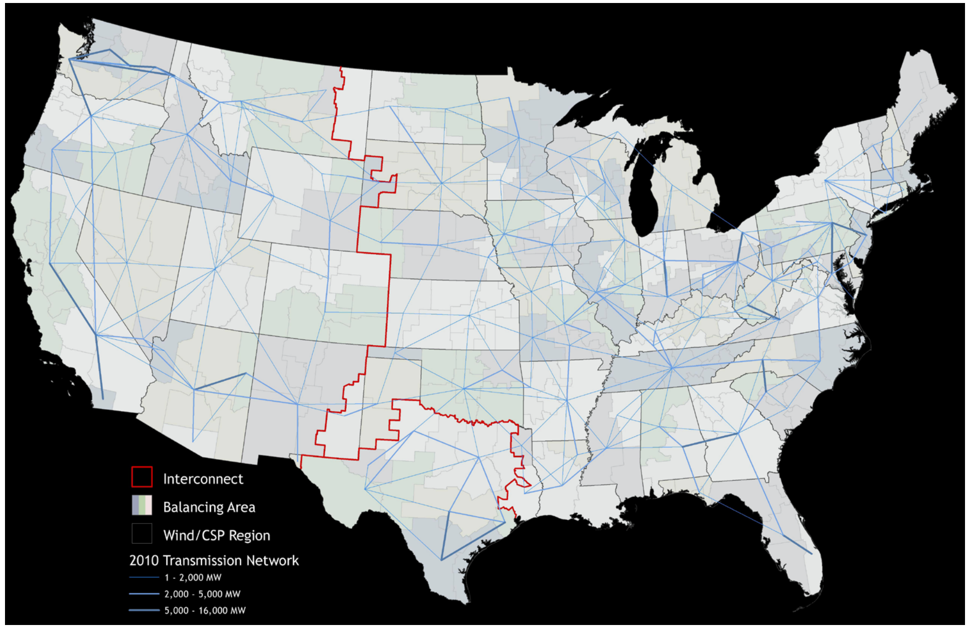
- The impacts on the power system begin with the decisions in ReEDS about what types of capacity to install based on the needs and capabilities of the system as a whole. ReEDS represents constraints for generator classes, ensures sufficient operating reserves, and ensures resource adequacy (RA) based on estimated firm capacity contributions of installed technologies. Investments are selected to minimize total system costs subject to all operational constraints and reliability criteria.
- RA is a key driver of ReEDS build decisions by ensuring the system has enough "firm" capacity installed. Firm capacity is capacity that can be depended on during times of system stress to meet expected peak demand plus a generous reserve margin (i.e., 10-21% depending on ReEDS BA). In ReEDS the firm capacity contribution of thermal and hydro generators is set equal to nameplate capacity; forced outage derates are covered by the reserve margin. ReEDS estimates firm capacity contributions for variable and storage/DR resources (i.e., wind, solar, storage, and DR) as fractions of nameplate capacity that could be relied upon at different times of the year. Those fractions of nameplate capacity then contribute to seasonal RA requirements in the dispatch model.
- Total system costs capture the new generation, storage and DR investments (capacity costs); new transmission investments or upgrades to ensure all generation can reach load (transmission costs); and fuel and operations and maintenance (O&M) costs for new and existing resources (variable costs) that are incurred during operation of the generation fleet. In each scenario, costs in each of these individual categories may increase or decrease depending on the ReEDS investment decisions. The system costs are reported for 2020-2040; Capacity and transmission costs are accounted for as model year present value for the year installed and variable costs are accounted for as model year present value for the year incurred.
- Another key metric in this study is power system emissions. We analyze the cumulative CO_2 emissions over the study period based on the annual operation of the generation fleet as estimated by ReEDS. Natural gas has an assumed emissions content of 0.053 metric tons per MMBtu. Coal has an assumed emissions content of 0.095 metric tons per MMBtu. Emissions rates per MWh generation are an outcome of combining the fuel emissions contents with individual coal and gas plant heat rates (in MWh/MMBtu). In this study, emissions are not considered in the economic objective function of the ReEDS model except where existing state policies exist; therefore, emissions impacts are incidental to the least-cost optimization that occurs but are a key output that we track to analyze tradeoffs among different investment choices (see page 38).

IV. Results

Orientation

Why focus on ERCOT results?

- The study adds EE and DR to CAISO, ERCOT, and ISO-NE and regional connections in ReEDS allow the benefits of demand-side changes to be shared between these regions and other RTOs throughout the continental U.S.
- ERCOT is less connected to other RTOs than CAISO and ISO-NE. Specifically, ERCOT is its own interconnection (i.e., grid system synchronized to the same AC frequency), whereas CAISO is part of the Western Interconnection and ISO-NE is part of the Eastern Interconnection (see figure below).
- While ERCOT is connected to other RTOs, these connections are small relative to ERCOT's size. Therefore, we focus our results on ERCOT because it allows us to observe the interactions between EE, DR, and supply-side investment decisions with fewer transmission-related complications. Results for the entire CONUS are similarly unaffected by the nuances of sharing of costs and benefits with neighboring regions and are reported in the supplemental information.



Interconnections are shown here outlined in red. ERCOT, representing most of Texas, is the most isolated region of our study. ERCOT only has three connections outside of its interconnection, while both CAISO and ISO-NE are more connected to neighboring regions and rely on imports for a portion of their generation needs.

Orientation

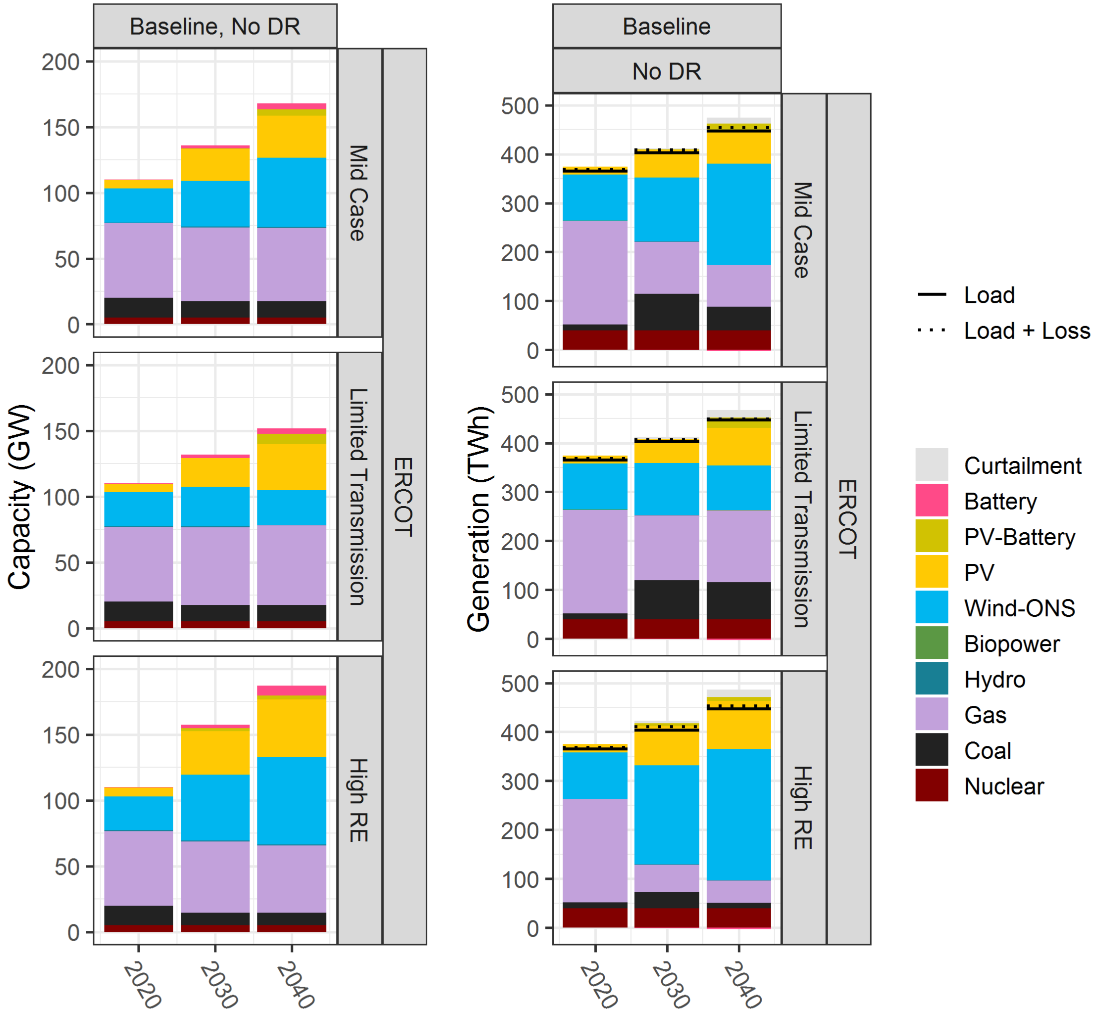
Scenario Framework

- In the following pages, we show results for all three grid scenarios: Mid Case, Limited Transmission, and High RE.
- We start by examining the reference cases for each grid condition, which correspond to “Baseline, No DR”. “Baseline” includes no incremental EE and uses ReEDS default load. “No DR” means that ReEDS was run without access to DR supply curves for its investment portfolio.
- We then analyze the impact of each EE package in isolation (Baseline, Controls, Envelope, Equipment), each DR type in isolation (No DR, Shed DR, Shift DR), and then EE and DR in combination.
- When analyzing interactive effects, the reference cases often shift to consider DR layered on top of EE or vice-versa, in which case the reference cases often correspond to the first intervention without the second intervention layered on (e.g., Baseline, No DR; Controls, No DR; Envelope, No DR; Equipment, No DR) and the alternative cases include a non-reference selection for both interventions (e.g., Baseline, Shed DR; Controls, Shed DR; Envelope, Shed DR; Equipment, Shed DR). In plots showing differences among scenarios, reference scenarios being considered are explicitly shown with zero difference to clarify what reference case is being used for comparison.

Description of key Electricity Reliability Council of Texas (ERCOT) system features

ERCOT Capacity and Generation

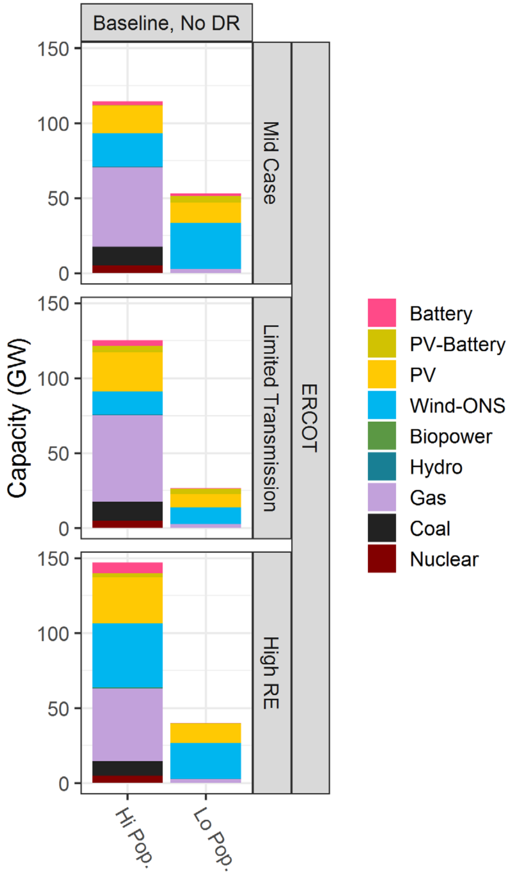
- ERCOT is its own interconnection and largely isolated from the Eastern and Western interconnections. This implies that operating reserves and planning reserve margin (i.e., firm capacity) must be met by ERCOT generating resources with limited reliance on imports. Exported generation to other interconnections is similarly limited. ERCOT Baseline annual load as modeled in ReEDS is 365 TWh in 2020, rising to 447 TWh in 2040 (see top-right panel in figure at right).
- **Mid Case** maintains gas-combined cycle capacity at around 56 GW and builds significant wind, solar, and storage (94 GW total, becoming 56% of the fleet by 2040). ERCOT is a net exporter (2% of generation). VG is 63% of total generation with limited VG curtailment (4% of available VG) by 2040.
- **Limited Transmission** supports PV and storage builds at the expense of wind capacity (i.e., wind capacity share of 17%, compared to 31% in the Mid Case). Compared to the Mid Case there are fewer exports (1% of generation) and more curtailment (7% of available VG) despite a lower VG share of 42% by 2040.
- **High RE** assumes lower VG technology costs, which favors wind, solar, and storage deployments (121 GW total, 64% of the fleet capacity by 2040), as well as coal and gas retirements. VG shares rise to 80% by 2040 (compared to 63% in the Mid Case). ERCOT exports 4% of generation and curtails 4% of available VG.

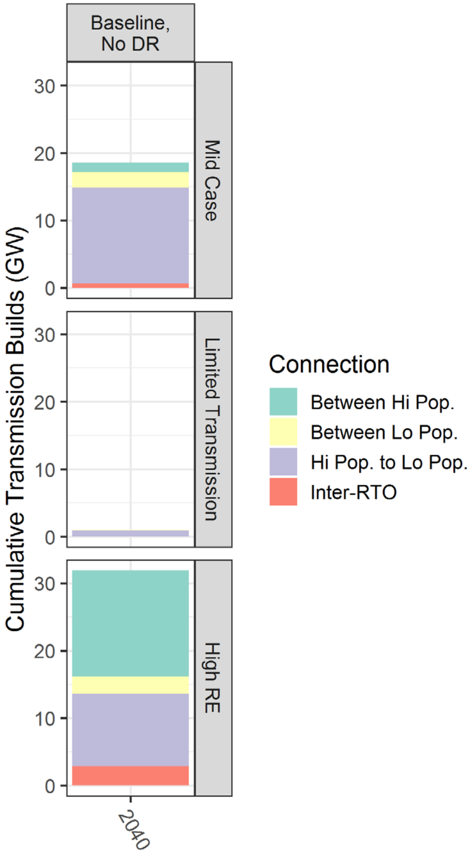


PV=solar photovoltaic; Wind-ONS=onshore wind

ERCOT Capacity and Transmission

- In all grid scenarios, the majority of generation and storage capacity is in areas with high population (i.e., ReEDS BAs p63 (Dallas/Ft. Worth), p64 (Austin), p65 (San Antonio), and p67 (Houston)); and some capacity, especially wind and solar capacity, is located in regions with low population (i.e., in ReEDS BAs p60, p61, p62 that constitute West Texas; see map of ReEDS BAs on page 15).
- **Mid Case** builds the most wind and solar capacity in low population regions, because the higher capacity factors there offset the transmission costs associated with getting that generation to load centers. Most of the new transmission connects load centers to these generation resources, but some transmission is built between ERCOT regions of the same type (high or low population regions) and between ERCOT and other RTOs (inter-RTO).
- **Limited Transmission** builds the least amount of wind and solar capacity in low population regions and only builds small quantities of transmission to connect those resources to load centers due to the higher transmission cost assumptions than in the Mid Case. Relatedly, the higher transmission cost assumptions result in no new inter-RTO transmission builds connecting ERCOT with other RTOs.
- **High RE** builds 50% more transmission than the Mid Case because lower RE costs result in more economic VG even with the additional transmission costs. This scenario builds nearly 16 GW of transmission capacity to connect the high population regions to each other and 11 GW to connect high and low population regions. There is also more transmission capacity to connect ERCOT to other RTOs built in this scenario compared to the Mid Case, and more wind, solar, and battery capacity is built directly within high population regions.



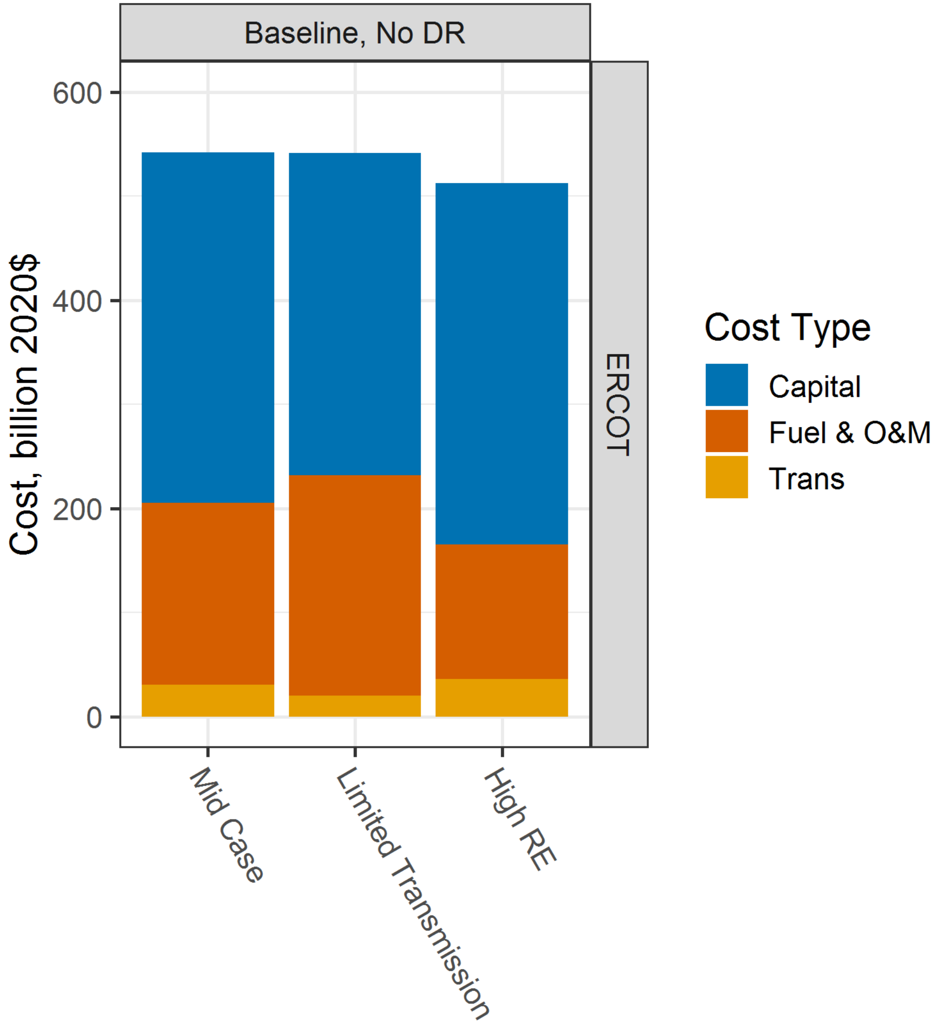


Hi Pop.=high population (areas), p63, p64, p65, p67
Lo Pop.=low population (areas), p60, p61, p62

System cost, generation capacity, and transmission expansion impacts

ERCOT System Costs

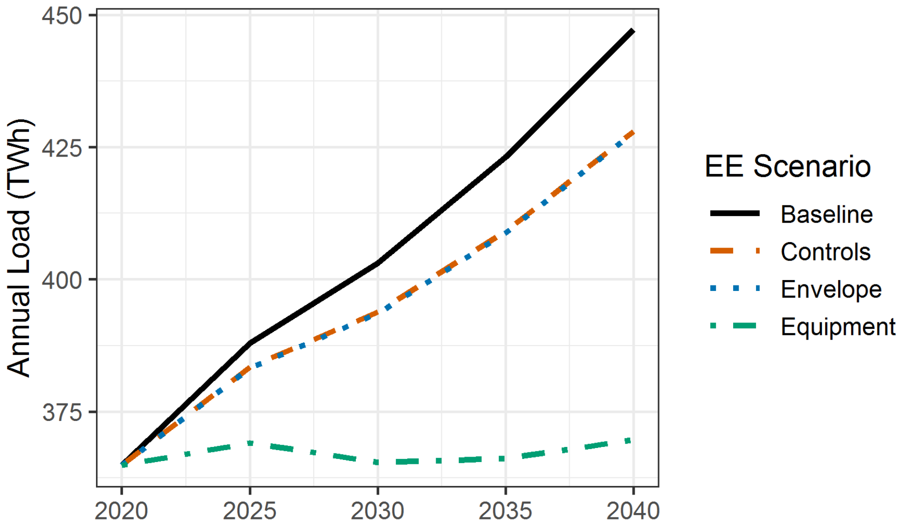
- In all grid scenarios, power system costs are an outcome of build, retirement and dispatch decisions. New generation and storage resource capital costs are the largest component, followed by variable fuel and O&M costs.* Transmission costs, both capital and O&M, are the smallest component of ERCOT system costs in this analysis, comprising 7% or less of costs in all cases.
- **Mid Case** total power system cost is 542 billion 2020$, with 62% for capital, 32% for Fuel and O&M, and 6% for Transmission.
- **Limited Transmission** total power system cost is 541 billion 2020$, or $1 billion less than Mid Case. For all of CONUS, Mid Case is a lower cost solution—the fact that ERCOT system costs are lower under Limited Transmission conditions implies that a portion of ERCOT Mid Case resources are developed for use elsewhere. Unsurprisingly, Limited Transmission spends less on transmission (4%) and capital (57%) and more on the fuel and O&M (39%) required to meet load with resources located in the same region compared to the Mid Case.
- **High RE** assumes that wind and solar technologies follow a lower cost trajectory than in the Mid Case. This reduces total system costs to 513 billion 2020$ and results in a greater reliance on capital costs and transmission (68% and 7%, respectively) as compared to fuel and O&M costs (25%).

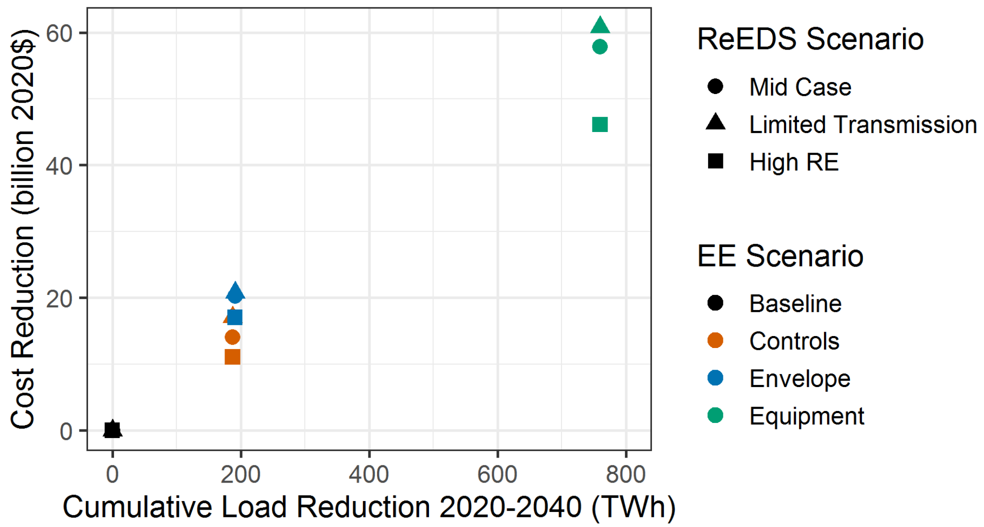


*Power system cost accounting and the 2020$ metric are described on page 17.

EE reduces system costs through annual energy savings

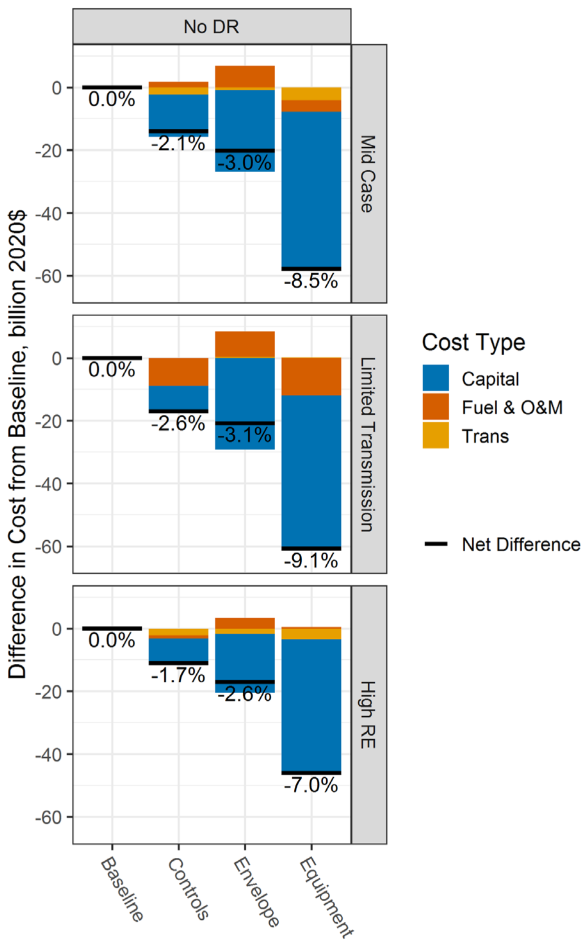
- Aggressive EE measures installed in all eligible buildings over the 2020-2040 analysis period result in significant system annual load and cost savings (e.g., the Equipment EE package results in essentially flat load growth and an ~11% reduction in system costs). The EE packages are installed without incremental costs and the level of savings is determined exogenous to ReEDS (i.e., the EE is not necessarily economic).
- Cost savings are largely proportional to the amount of load reduction, but they are also influenced by grid scenario costs (e.g., EE-driven cost reductions are the least in absolute dollars in the High RE scenario, which is the least expensive under baseline conditions) and EE package (e.g., the Envelope package reduces ERCOT power system costs more than the Controls package even though they save similar amounts of energy).
- EE is most valuable in ERCOT in the Limited Transmission scenario because EE displaces generally higher-cost transmission capacity than in the other scenarios. This effect is highly dependent on the particulars of the ERCOT region, which is a net exporting region (e.g., regions with significant existing import capacity might be impacted differently in a Limited Transmission scenario).

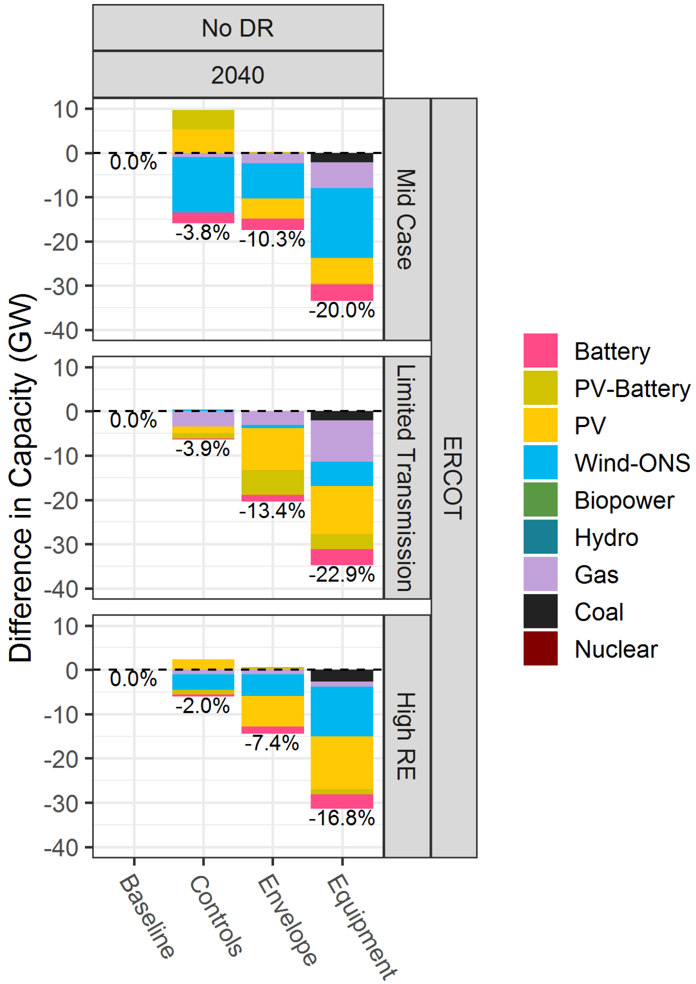




EE reduces system costs by reducing net-capacity

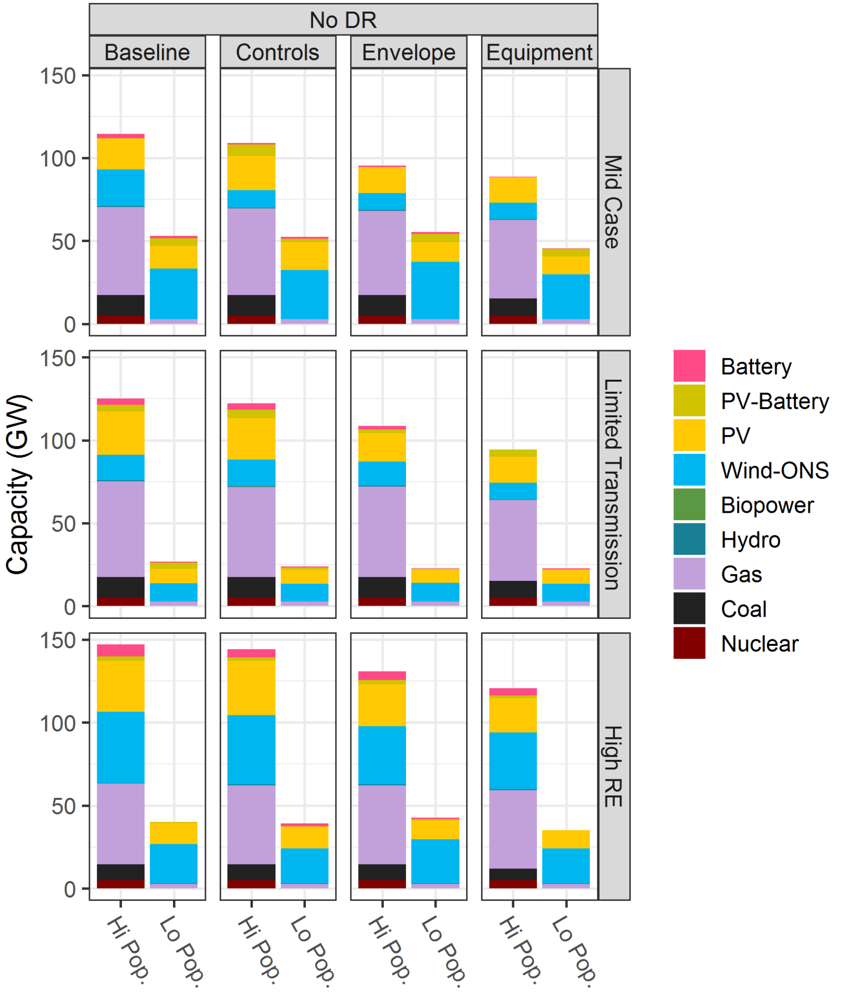
- As a result of lower load, all EE packages reduce capital costs by avoiding new fossil, wind, solar, and storage builds and sometimes inducing fossil retirements.
- A minor exception is that the Controls package is sometimes supportive of PV capacity because it reduces nighttime loads significantly more than daytime loads
- The Envelope package tends to increase fuel costs as a result of flattening the overall load shape and building less gas capacity. A flatter load shape supports more coal generation dispatch throughout the entire year in all scenarios, and especially in the winter and spring in the Limited Transmission scenario, by reducing net load valleys. While the model avoids the capital cost of building new units, the operational costs of coal plants are higher than those for the displaced VG and gas, leading to an increase in fuel and O&M costs in this scenario (as well as an increase in emissions, which is discussed on page 41).
- Transmission cost changes are relatively small and mostly limited to the Mid Case and High RE scenarios where EE adoption reduces transmission builds. The Limited Transmission scenario has an already small transmission build-out prior to adding EE, thereby reducing opportunities for EE to avoid transmission costs.

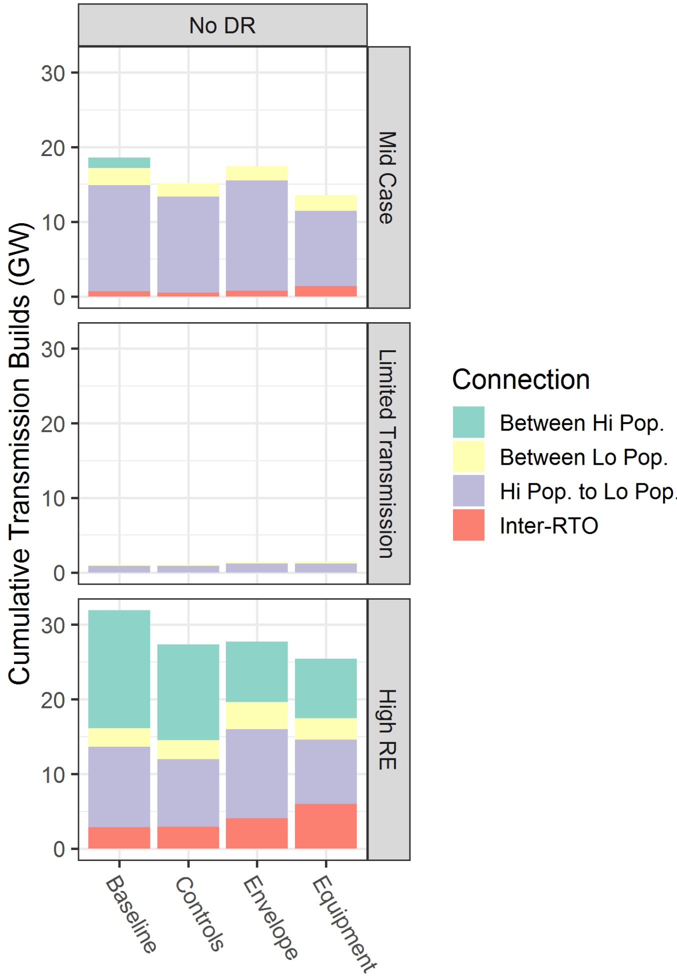




EE reduces transmission in total and can support more exports

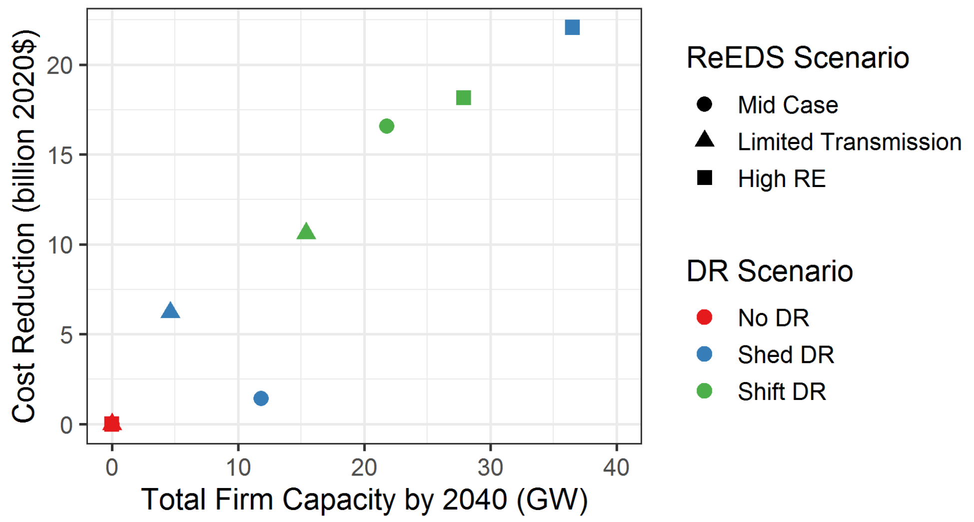
- All EE packages reduce generation capacity in high population regions in all grid scenarios. Accordingly, transmission builds between high population regions are also reduced.
- The impact of EE on low population region generation and transmission capacity is mixed.
- In the Mid Case and High RE scenarios, the Envelope package enables installing and building slightly more wind, solar, and storage generation capacity and associated transmission in the low population regions compared to the baseline and other EE packages.
- The Envelope and, especially, Equipment packages increase opportunities for and value of exports, which results in more Inter-RTO transmission builds.
- There is relatively little change in transmission builds from EE and among the EE packages in the Limited Transmission scenario because the underlying transmission build-out is already substantially reduced.

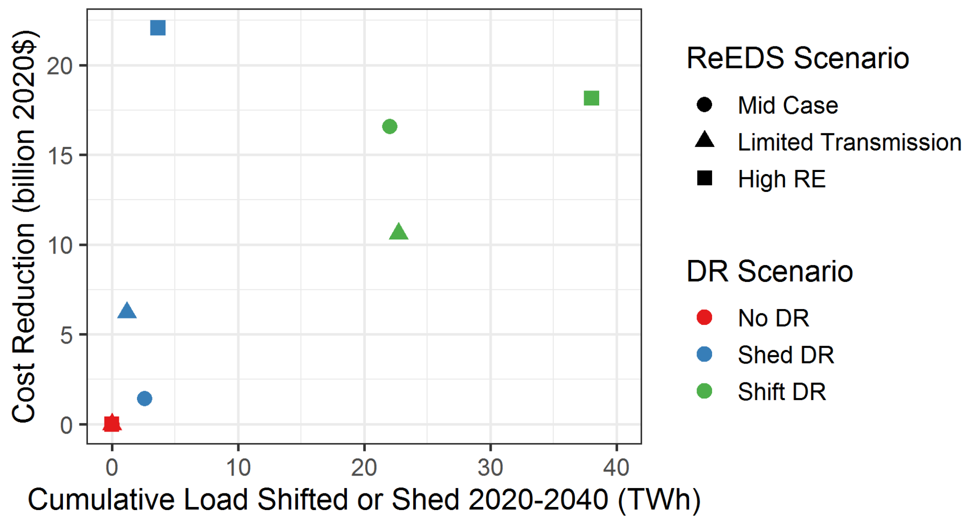




DR reduces system costs by providing firm capacity and energy shifting

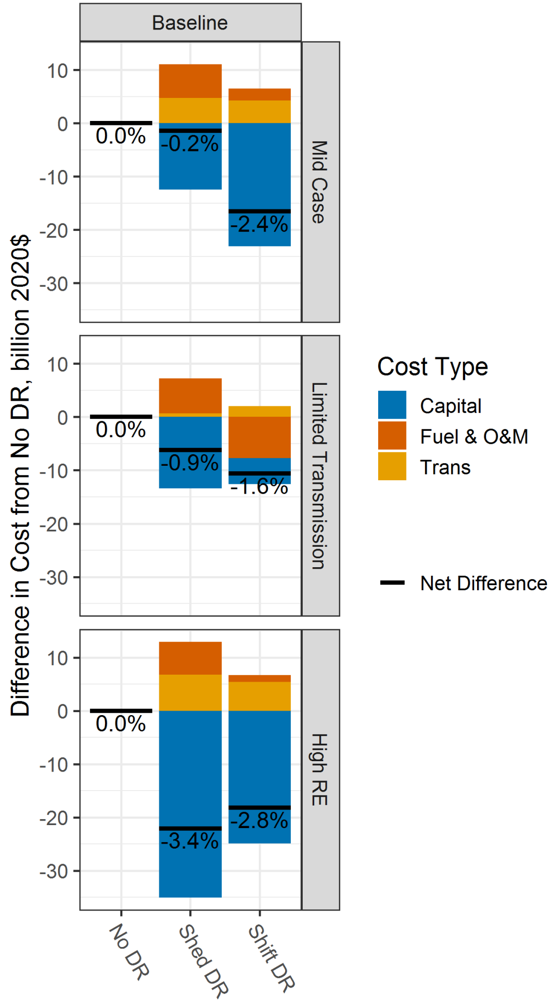
- DR is selected by ReEDS on a least-cost basis, using a supply curve of dispatchable shed or shift capability provided by DR-Path. Because ReEDS selects what DR it wants to build, DR always reduces net system costs and impacts are highly dependent on the grid scenario. For example, the impact of Shed DR in the High RE scenario is 17x higher on net than in the Mid Case scenario.
- Cost reductions from DR are largely proportional to the total firm capacity it provides. A minor exception is that the cost savings for Shed DR are lower in the Mid Case relative to Shed DR's firm capacity contribution.
- Corroborating other studies, DR is most valuable in the High RE scenario. Both Shed DR and Shift DR provide the greatest amount of firm capacity under these grid conditions (37 GW and 28 GW, which provide 30% and 24% of RA requirements, respectively, in 2040). These large RA contributions reduce costs by offsetting the need to build additional capacity to meet firm capacity requirements.
- Shift DR is also able to move 73% more load under High RE, as compared to the Mid Case and Limited Transmission scenarios (see green points in bottom plot). On an annual basis by 2040, the High RE scenario shifts 3% of total load, or 15 TWh per year, from higher-cost to lower-cost time slices.

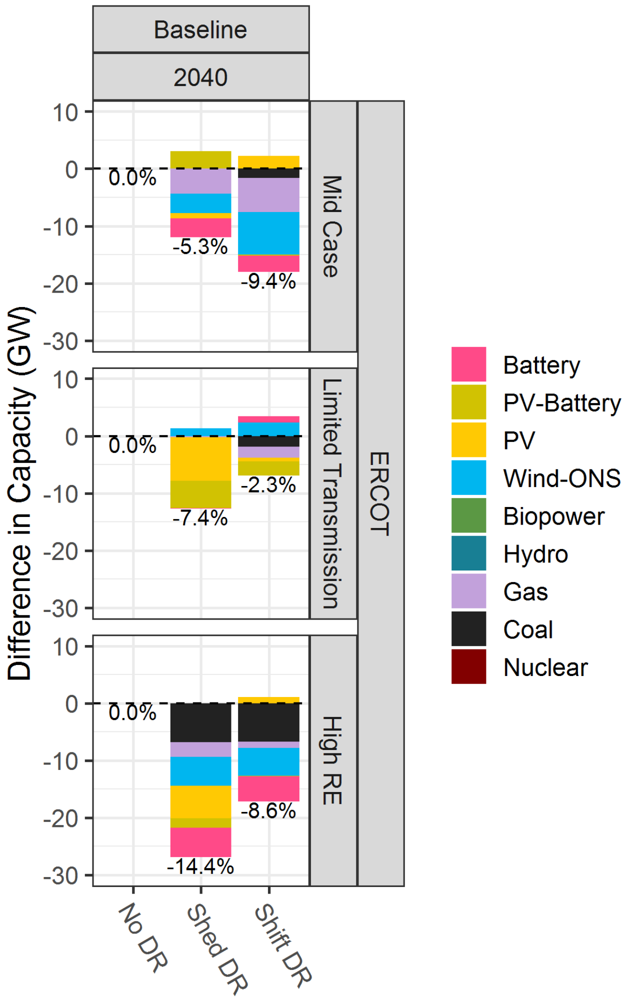




DR reduces system costs by reducing non-DR net-capacity and impacting the generation mix

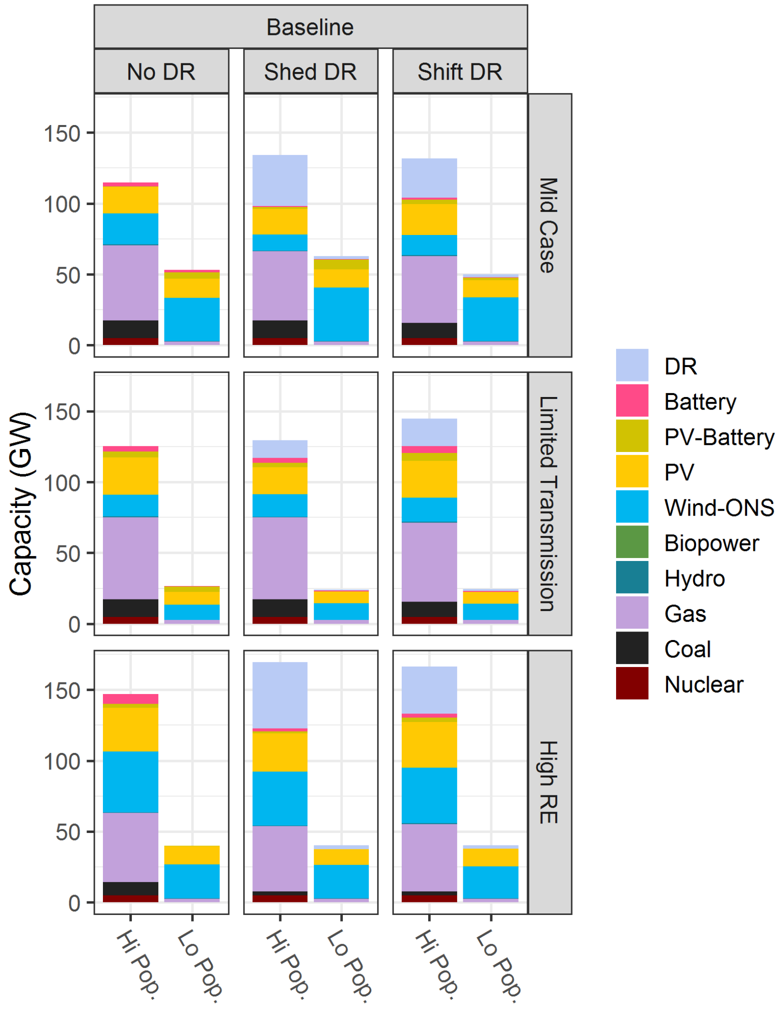
- DR always reduces capital costs, but the mix of resources that is displaced varies by grid scenario and DR type (see right panel of figure at right). In almost all cases, battery capacity, either alone or paired with PV, is displaced by DR reflecting the fact that DR can substitute for storage in many contexts.
- DR usually increases transmission costs in this model by shifting where transmission capacity gets built (see page 31). This effect is largest in the High RE scenario and smallest under Limited Transmission conditions.
- Limited Transmission with Shift DR is the only case that reduces variable costs on net. Throughout the analysis period, this case consistently reduces coal and gas capacity in favor of more wind and solar capacity compared to the Baseline, No DR scenario. In contrast, all the other DR scenarios increase gas and coal generation on net, thereby increasing variable fuel and O&M costs.
- In the High RE scenario, avoided capacity investment drives the cost savings from DR, which is the largest source of value for Shed DR. Shed and Shift DR particularly reduce battery capacity in the High RE scenario.

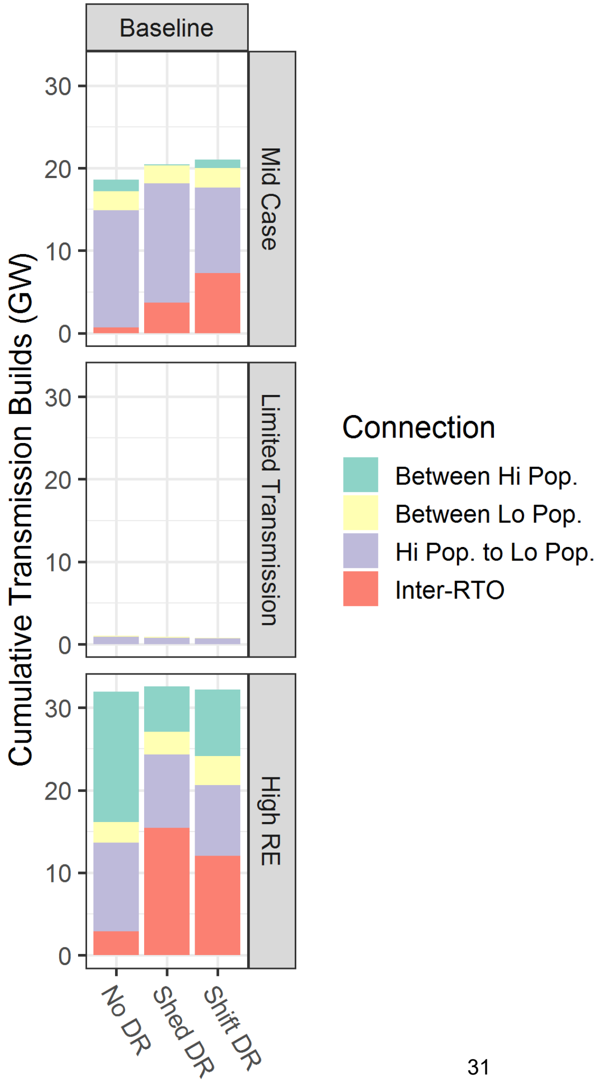




DR increases transmission export capacity in the Mid Case and High RE scenarios

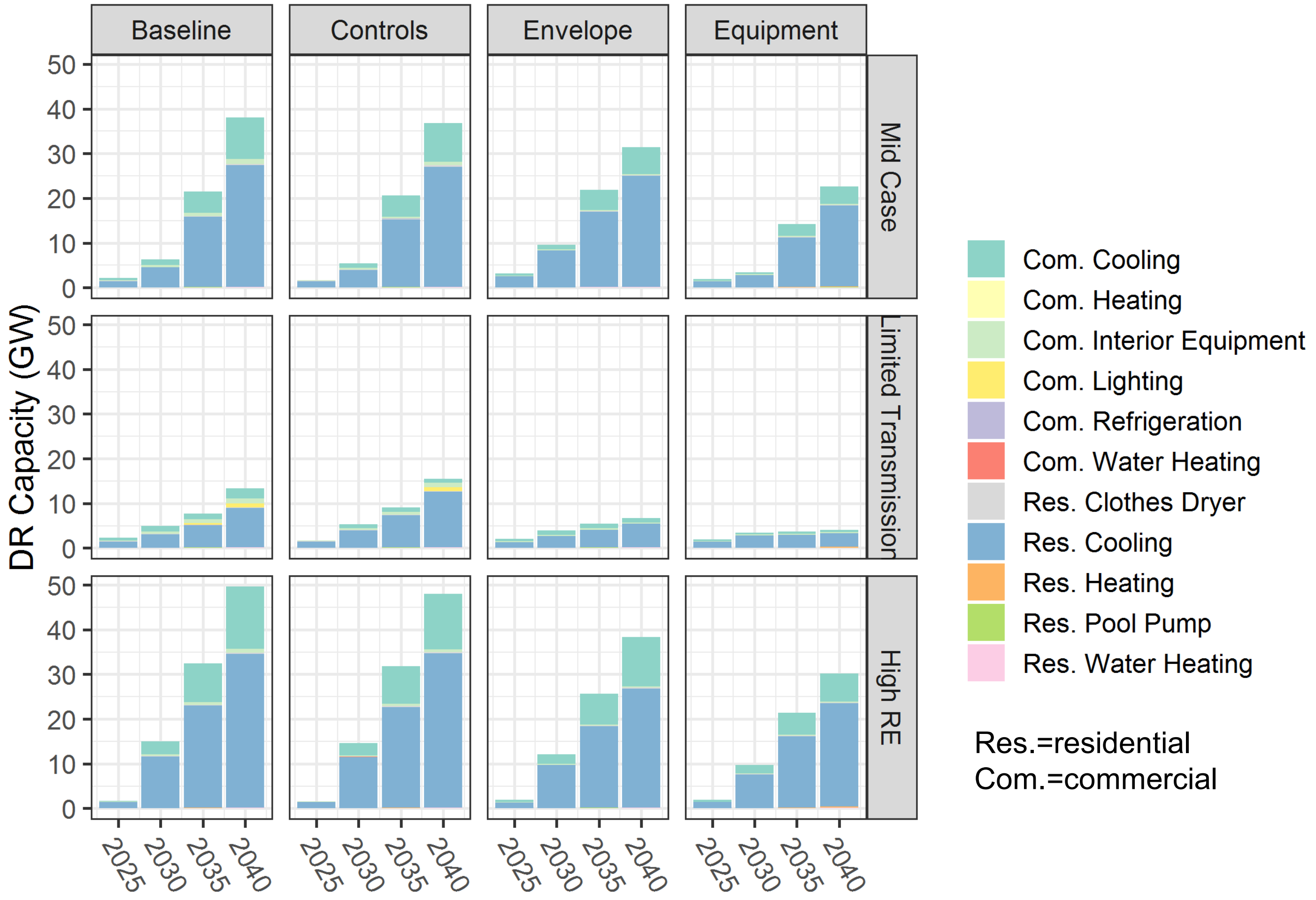
- Generally, DR reduces transmission builds in high population BAs through reductions in non-DR generation capacity, reducing the need to move capacity between regions. Renewables in low-population regions are largely unchanged or slightly increased (especially co-located PV and storage) with DR (see left panel of figure at right).
- While the cumulative amount of transmission builds do not significantly change with the addition of DR, there is a much higher proportion of Inter-RTO transmission with DR (see right panel of figure at right).
- DR impacts on transmission builds are more pronounced in the High RE scenario, in which DR builds 4-5 times more Inter-RTO transmission and 2-3 times less transmission between high population BAs compared to the No DR case. This result is driven by the large firm capacity contributions from Shed and Shift DR in the High RE case (see page 29).





Shed DR is predominantly sourced from residential and commercial cooling

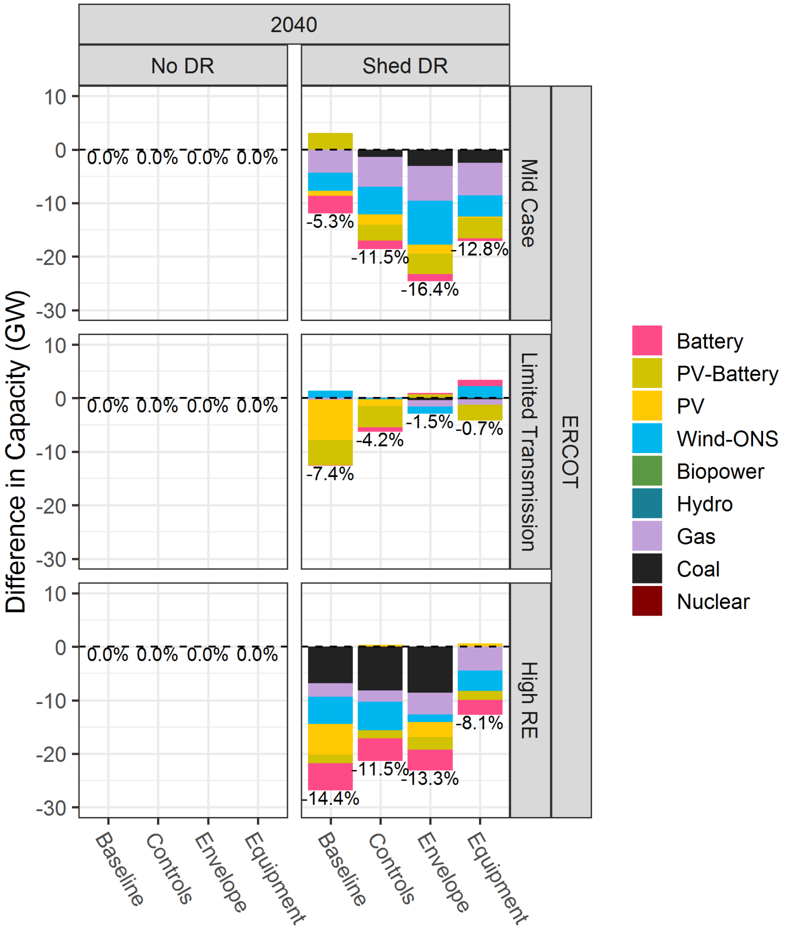
- EE packages reduce peak demands, thereby decreasing both the supply of and the need for Shed DR technologies that are coincident with peak demand (i.e., residential and commercial cooling).
- Shed DR almost entirely comes from residential and commercial cooling, which are loads that are well correlated with ERCOT's summer peak. The figure at right identifies all end-uses that are selected in at least one scenario-year, but the built capacities of most end-uses are on the order of MW, not GW.
- The High RE scenario builds significantly more Shed DR than the other grid conditions, which is consistent with Shed DR's higher economic value in the High RE scenario.
- EE reduces the amount of Shed DR capacity that is available to ReEDS for investment and is built by the model, except for the Controls package in the Limited Transmission scenario where EE and Shed DR are slightly complementary on a capacity basis.
- The Controls package tends to produce the smallest change in Shed DR capacity and the Equipment package tends to produce largest change in Shed DR capacity.

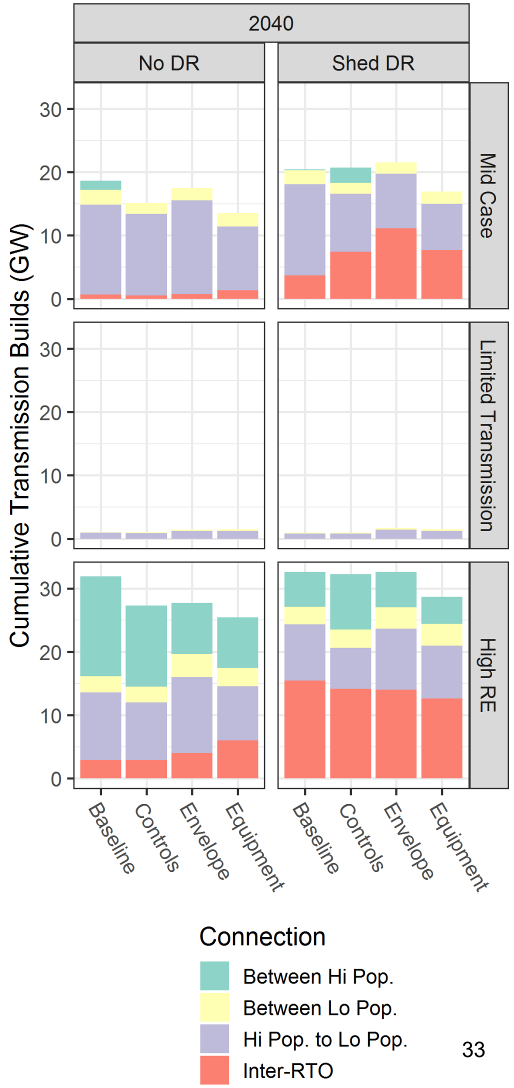


Res.=residential
Com.=commercial

EE and Shed DR have different generation and transmission capacity impacts depending on grid conditions

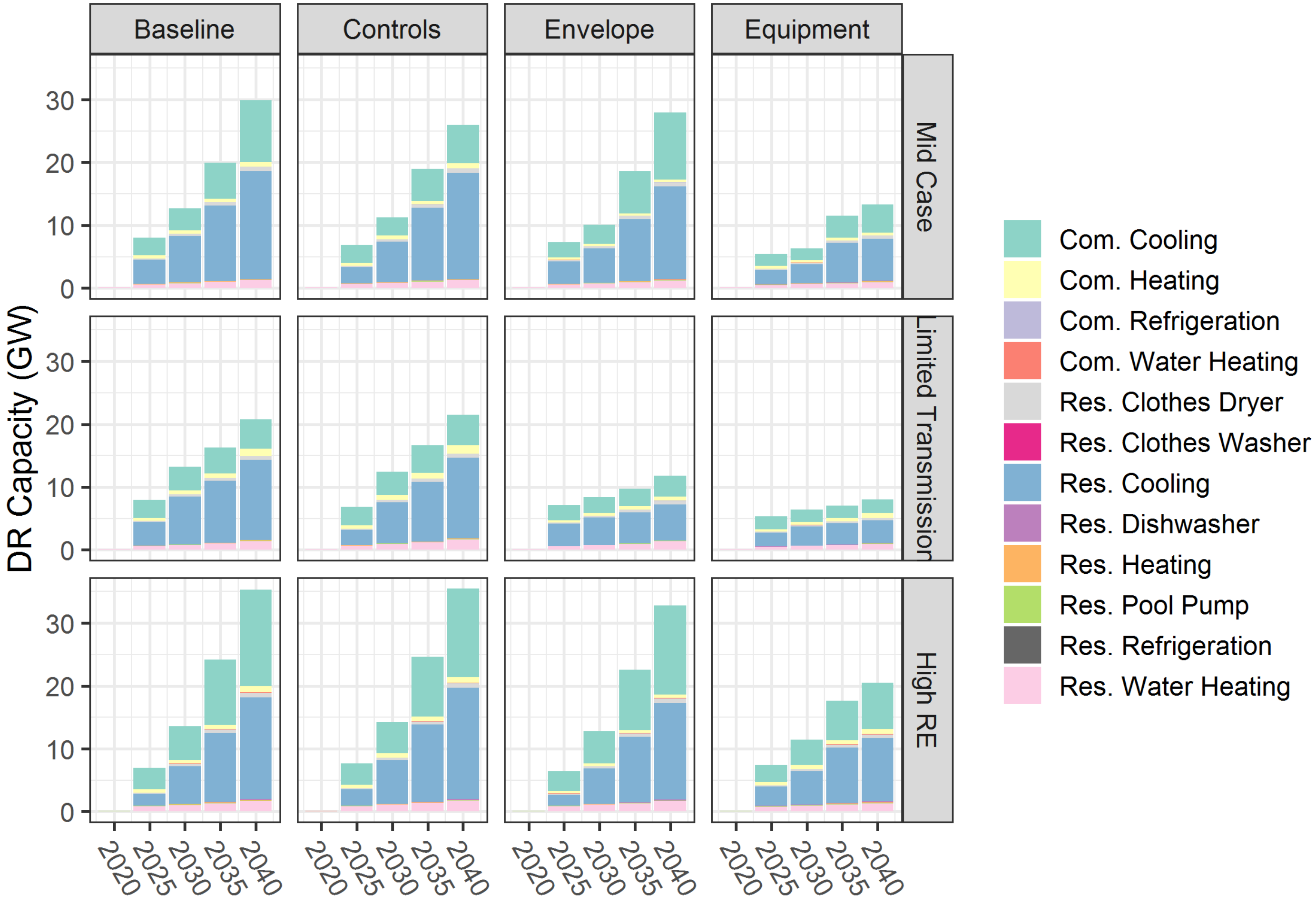
- In the Mid Case scenario, EE significantly enhances Shed DR value by reducing gas, wind, battery (alone and with PV), and coal capacity relative to Shed DR's impact under Baseline conditions. EE paired with Shed DR also increases Inter-RTO and decreases high population to low population transmission, implying that a reduced need for firm capacity from low population resources enables more energy exports.
- In contrast, in the Limited Transmission scenario EE strongly competes with Shed DR. The capacity reductions and shifts from new-VG to existing-thermal generation induced by Shed DR are smaller when EE has already been deployed, and almost non-existent with the Equipment package (see left panel of figure at right).
- The High RE scenario results in EE and Shed DR competition. The competition is most significant for the Equipment package that eliminates the additional coal retirements otherwise induced by Shed DR. Inter-RTO transmission builds are also lower when the EE packages are paired with Shed DR, relative to Baseline, Shed DR conditions.





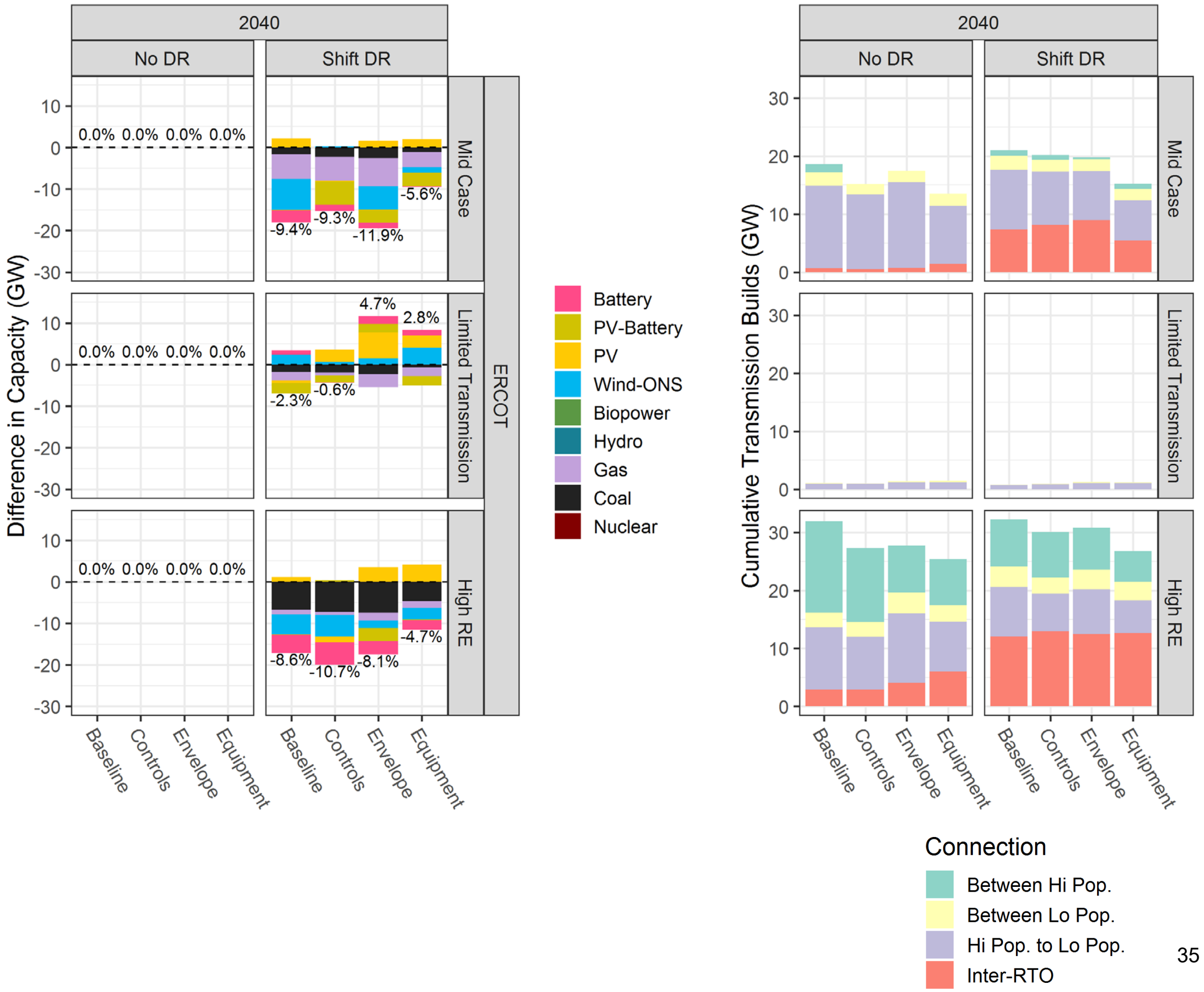
Shift DR is also largely provided by residential and commercial cooling, with some contributions from water and space heating

- Like Shed DR, Shift DR is mostly provided by residential and commercial cooling given their significance in total baseline end-use consumption. However, residential water heating and commercial space heating also contribute at the ~GW scale (see figure at right). Although Shift DR provides more and more frequent services compared to Shed DR, much of its value is still derived from providing firm capacity. Thus, loads like space cooling that are well correlated with peak have an advantage in terms of providing more value than their cost.
- Grid scenarios and EE packages impact how much Shift DR is built but do not qualitatively change the mix of Shift DR types that are deployed.
- Much less Shift DR is built when Shift DR is paired with the Equipment EE package. The Controls package has a small impact on how much Shift DR is built across all of the grid scenarios. Envelope EE limits the Shift DR build-out in the Limited Transmission scenario, but not in the Mid Case and High RE scenarios.



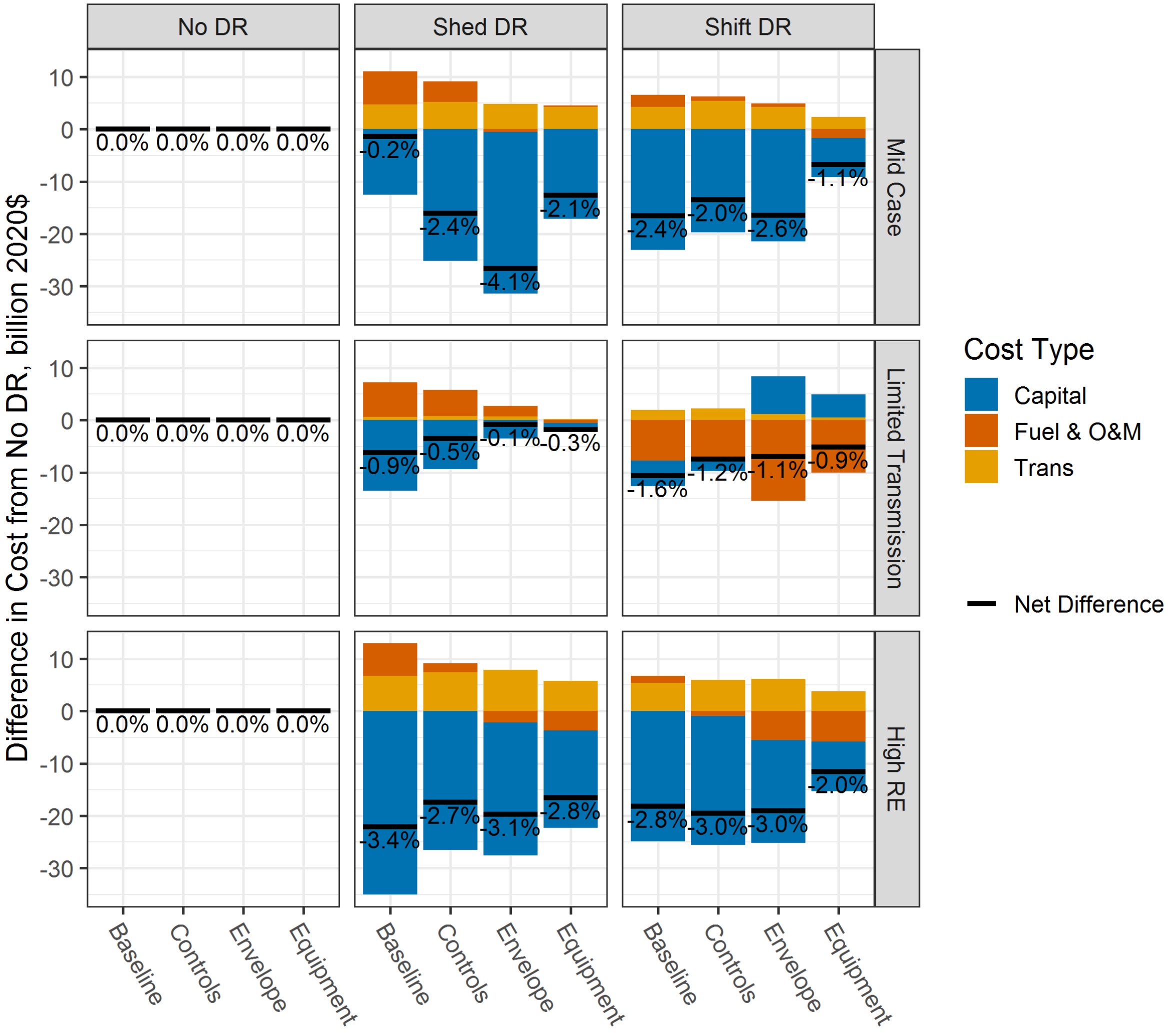
Combinations of certain EE packages and Shift DR reduce generation capacity, but there is strong competition with the Equipment EE package

- Shift DR is valuable for all grid conditions and in combination with all EE packages (see system cost impacts on page 36).
- Shift DR is most valuable in the Mid Case and High RE scenarios in which Shift DR both reduces generation and storage capacity and greatly increases Inter-RTO transmission. This suggests that Shift DR provides firm capacity value and enables exports.
- Shift DR paired with the Equipment EE package always reduces the amount of generation capacity savings induced by Shift DR in isolation, which reduces the cost savings provided by Shift DR.
- Nonetheless, we observe that Shift DR paired with Equipment EE enables reductions in coal and gas capacity in favor of more wind and solar capacity throughout the modeling horizon for all grid scenarios (compare Baseline and Equipment in the left panel of figure at right and the reductions in variable costs on page 36).
- The Controls and Envelope packages have either a generally neutral or very modest complementary impact on the value of Shift DR via increased non-DR capacity reductions (Mid Case and High RE) or variable cost savings (Limited Transmission, see page 36).



Depending on grid conditions, EE and DR can have complementary or competitive impacts on power system costs; though, costs are always lower compared to no DR

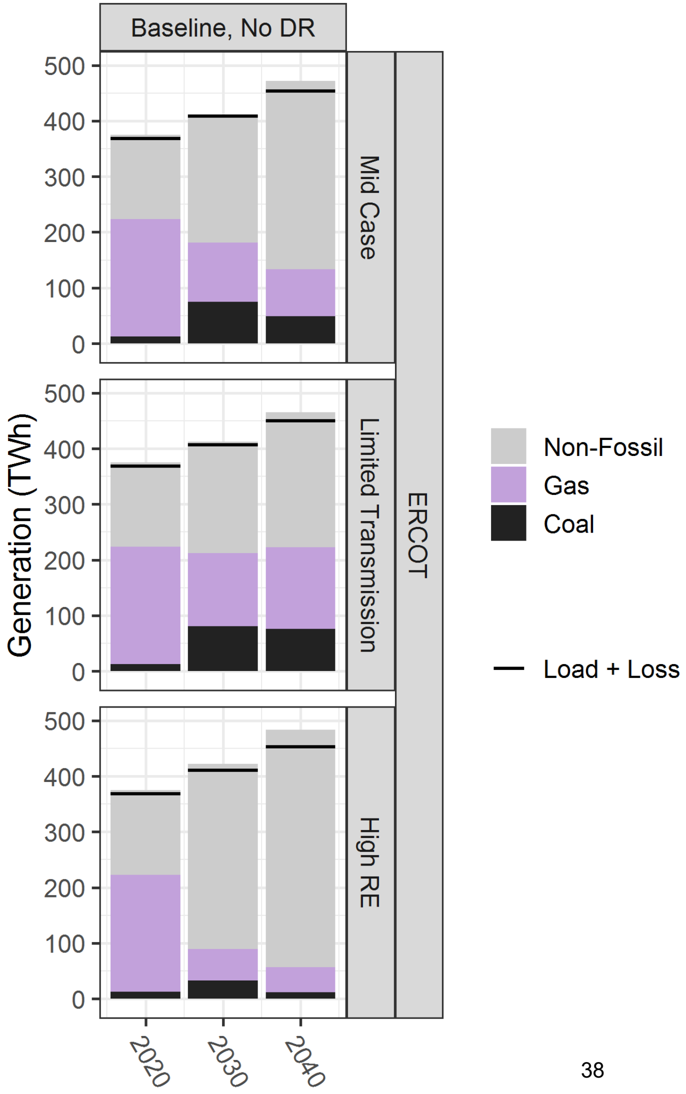
- Under Mid Case conditions, EE always enhances Shed DR value (e.g., shed DR paired with the Envelope package increases net cost savings ~20 times), while all EE packages in the Limited Transmission scenario greatly reduce Shed DR cost savings. Under High RE conditions, the impact of EE on Shed DR value is mildly competitive.
- EE and Shift DR tend to compete compared to Shift DR in isolation. The Equipment EE package always reduces the cost savings achievable with Shift DR regardless of the grid scenario. The interactions between Shift DR and the Controls and Envelope packages are more subtle. Specifically, Controls and Envelope EE packages and Shift DR are strictly competitive under Limited Transmission conditions, but slightly complementary under High RE conditions and with mixed effects in the Mid Case scenario.
- Except under Limited Transmission conditions, both types of DR and the Envelope EE package pair particularly well in the sense of providing the most cost savings of all the combined EE and DR options.



Emissions impacts

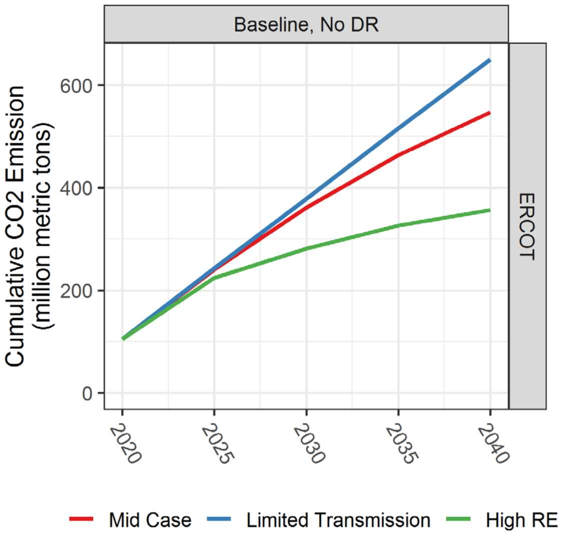
<u>Context for emissions results</u>: The ReEDS model used in this study assumes current RPS policy and no national emissions costs

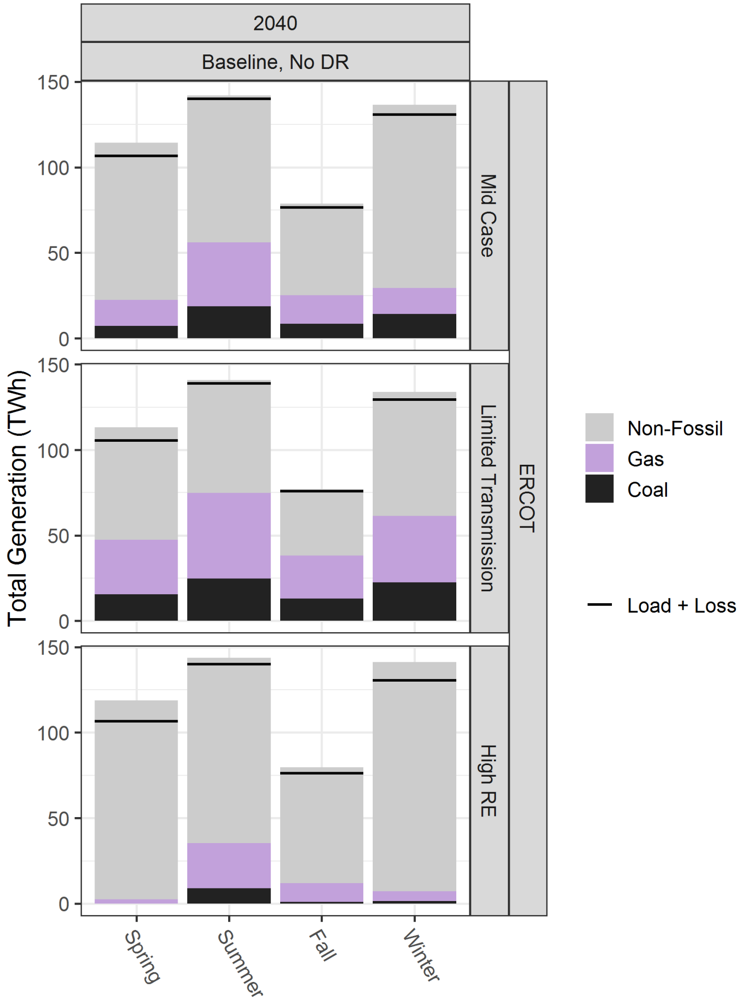
- This modeling in this study is based on least-cost optimization of the capacity investments required to meet demand through 2040. In the formulation used for this project, we did not include a national cost on emissions because there is no current national carbon price in the United States. We did however include state-level policies such as RGGI and the California carbon cap. As such, *emissions are consequences of other model choices and do not themselves drive investments*.
- Cumulative emissions from 2020 through 2040 in ERCOT are driven by generation from two fossil-fueled technologies: natural gas and coal. To the extent that EE packages or DR investments impact generation from these technologies, the EE or DR will have an impact on emissions.
- In an economic model without emissions costs or binding renewable energy policies, it is nearly always the least-cost solution to keep existing capacity online instead of building new capacity. Thus, lower load growth (via EE) or lower firm capacity requirements (via DR) are likely to lead to fewer investments and higher utilization of existing assets. In our ERCOT model, this sometimes manifests as EE and/or DR enabling *increases* in coal generation as existing coal plants are kept online rather than building and utilizing new gas, wind, or solar capacity.
- Furthermore, this study quantifies emissions from changes in bulk power system generating resources and does not include emissions savings from EE and DR from reductions in customer consumption of other fuels (e.g., the Envelope package may reduce direct natural gas emissions from gas furnaces), as well as indirect power sector emissions (e.g., from fracking).



ERCOT Emissions

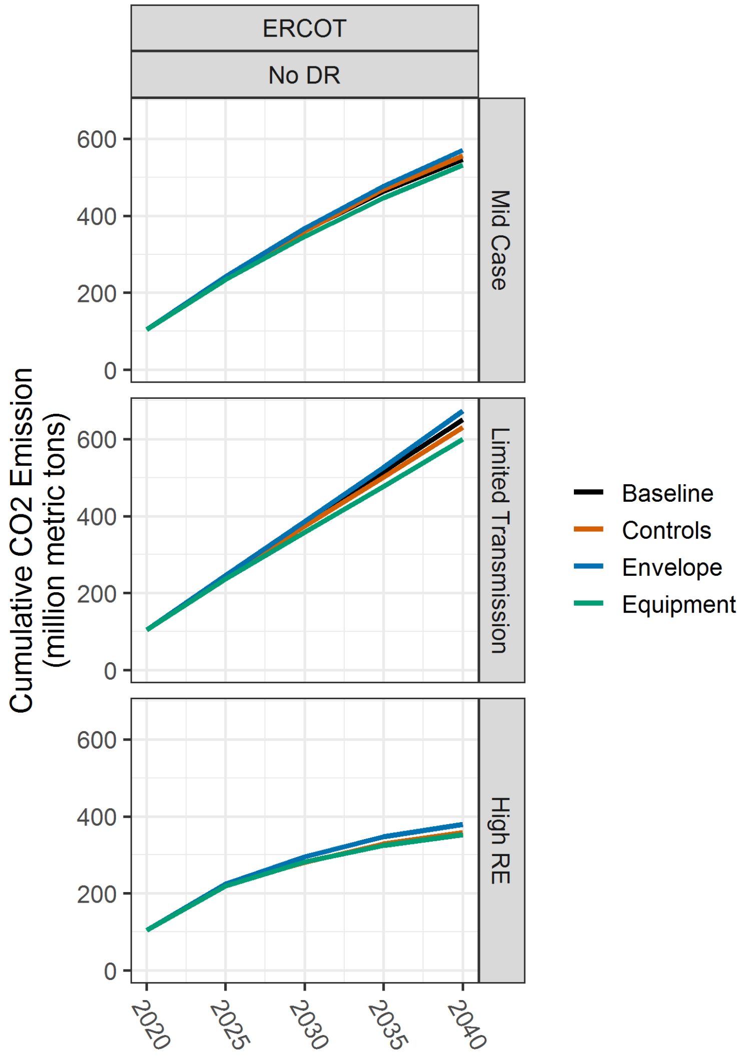
- In all grid scenarios, power sector emissions are driven by the amount of coal and gas generation and the emissions rate for coal is almost twice the emissions rate for gas (i.e., 0.095 vs 0.053 metric tons per MMBtu, respectively). We report cumulative emissions that represent emissions from total coal and gas generation throughout the modeling horizon (i.e., 2020-2040).
- **Mid Case** uses coal and gas generators the most during summer months, but all seasons contribute to cumulative emissions that total 547 billion metric tons of CO_2 from 2020-2040.
- **Limited Transmission** relies the most on existing generators to meet load, greatly increasing coal and gas emissions relative to the Mid Case, especially in non-summer months. This scenario emits 650 billion metric tons of CO_2 from 2020-2040, which is 19% more than in the Mid Case.
- **High RE** mostly uses coal and gas generators in the summer to meet peak load, although there is some fossil generation throughout the year. Overall amounts of fossil generation are significantly reduced compared to the other two scenarios, resulting in 357 billion metric tons of CO_2 from 2020-2040, which is 35% less than in the Mid Case.

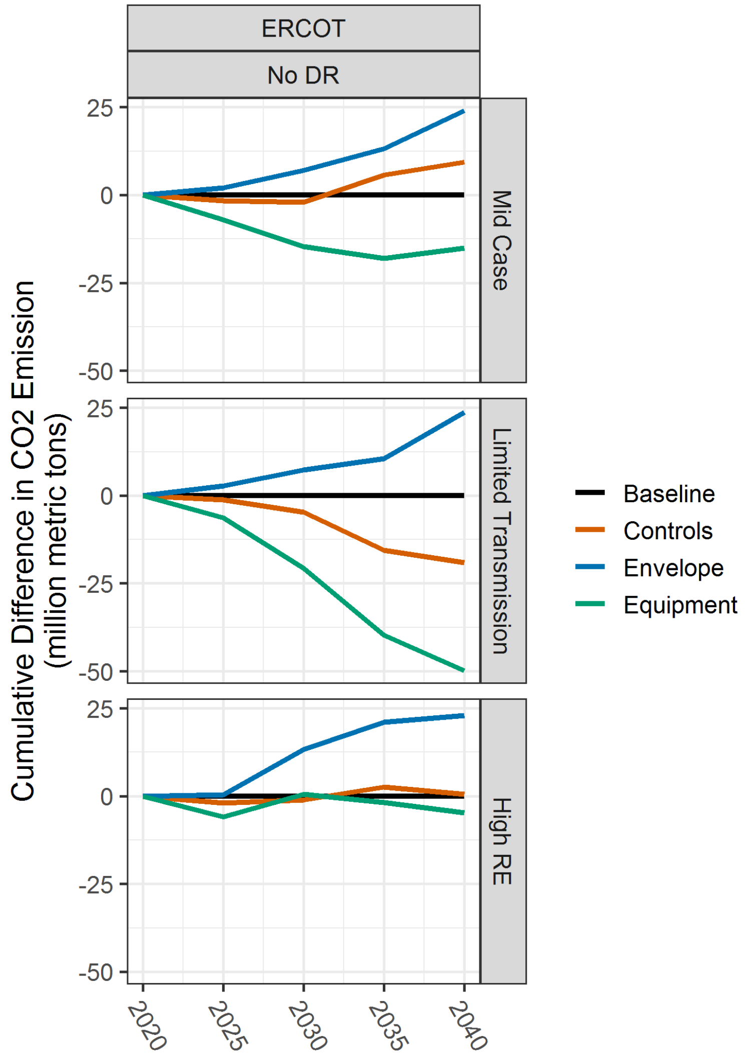




On their own, EE packages have a small and mixed impact on emissions

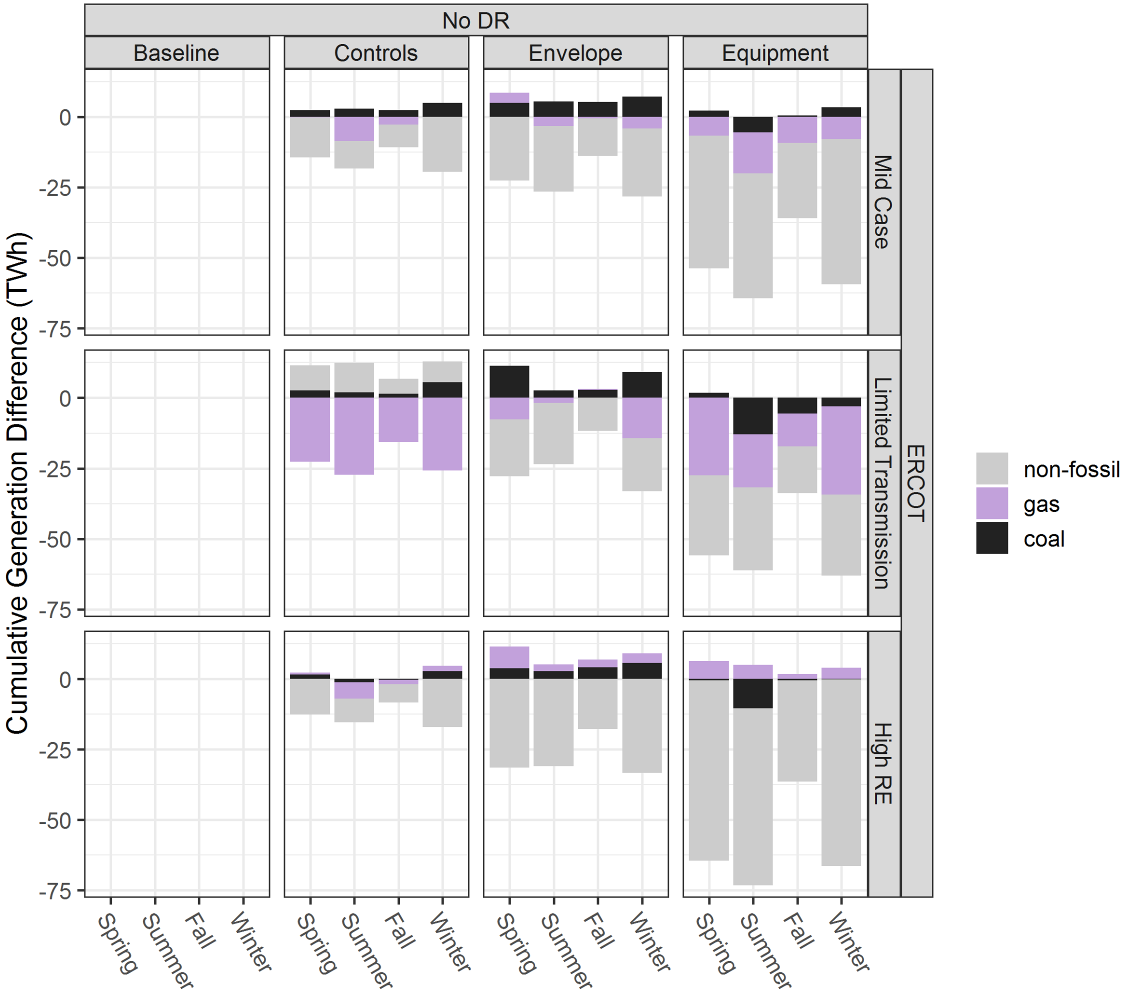
- Overall, EE impacts on cumulative emissions are modest: less than 9% by 2040 in all cases, despite this study's aggressive exogenous assumptions.
- On a package basis, EE impacts tend to be small and mixed. As described on page 27, the temporal profile of the Envelope EE package tends to support more coal and gas generation from existing resources. This is in contrast to the Equipment package that reduces emissions in the Mid Case and Limited Transmission scenarios simply through load reductions.
- Overall, these results show that ERCOT has transitioned from the 20th century paradigm in which EE almost always reduced emissions to a new paradigm in which the emissions impacts of EE are a complex outcome of existing infrastructure, new investment needs, and technology costs and characteristics.





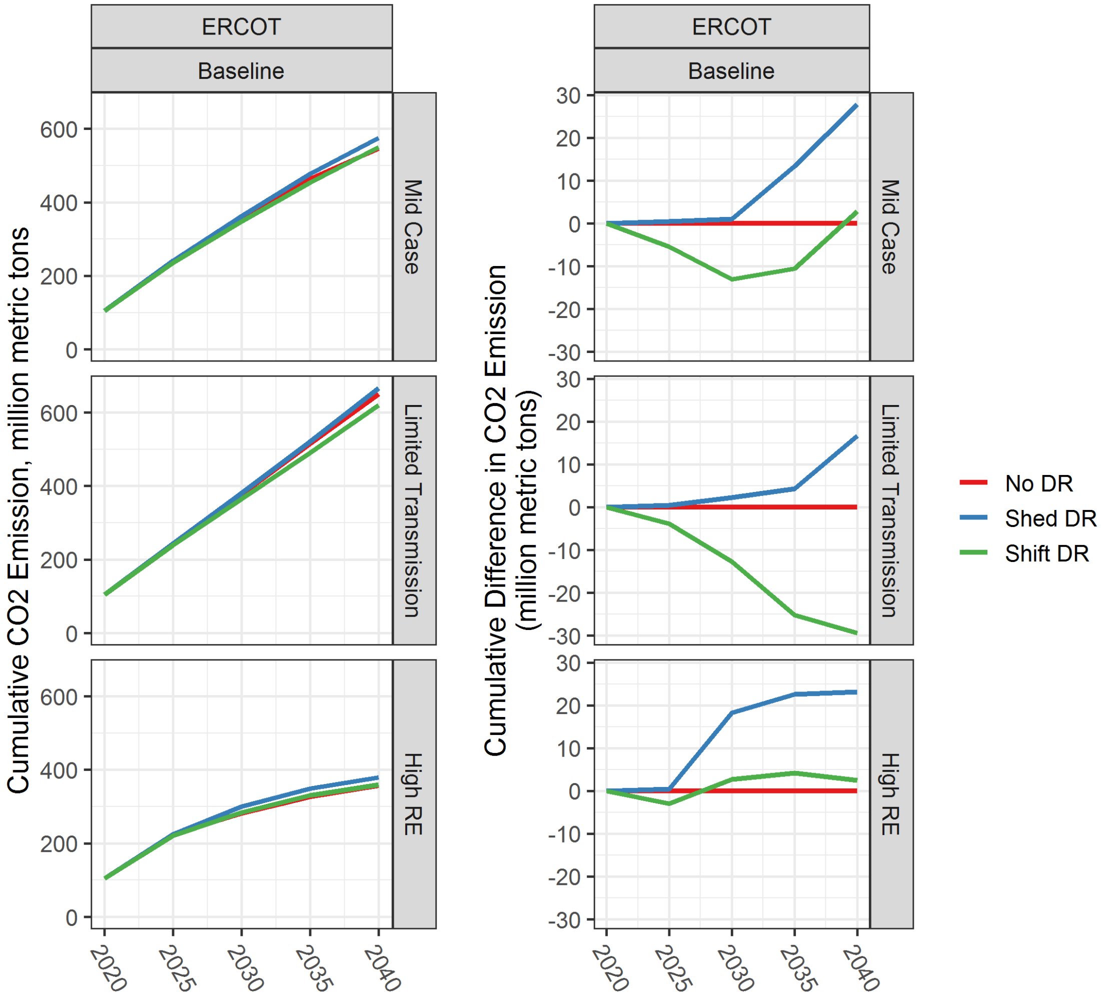
Some EE packages can slightly increase emissions in ERCOT by inducing more generation from existing coal plants

- The power system emissions impact of EE packages is a direct effect of their impact on gas and coal generation. The figure at right shows the cumulative difference in generation of these two fossil fuels, as well as non-fossil fuel generation types, from 2020 through 2040, represented as the *total* generation that occurs in each season.
- Fuel switching (e.g., gas for coal) can occur when less capacity is built, leading to higher capacity factors for existing generators. It can also occur when demand shape changes allow some generators to remain online for longer than was otherwise optimal.
- The Equipment package, which has very little load growth and induces coal retirements under all grid conditions (see page 27), nearly always reduces generation of both gas and coal and results in similar or lower emissions in all grid scenarios.
- The Controls package, which induces the least amount of capacity change relative to the Baseline (see page 27), tends to trade generation between gas and coal with a higher reduction in gas making up for the increase in coal in the Limited Transmission case. Emissions increases and decreases are essentially cancelled out in the other grid scenarios with the Controls package.
- The Envelope package tends to build less gas than in the Baseline while not inducing any coal retirements (see page 27). The Envelope package also flattens the overall load shape. Both of these effects increase coal generation more than they reduce gas generation (if at all), thus increasing emissions.



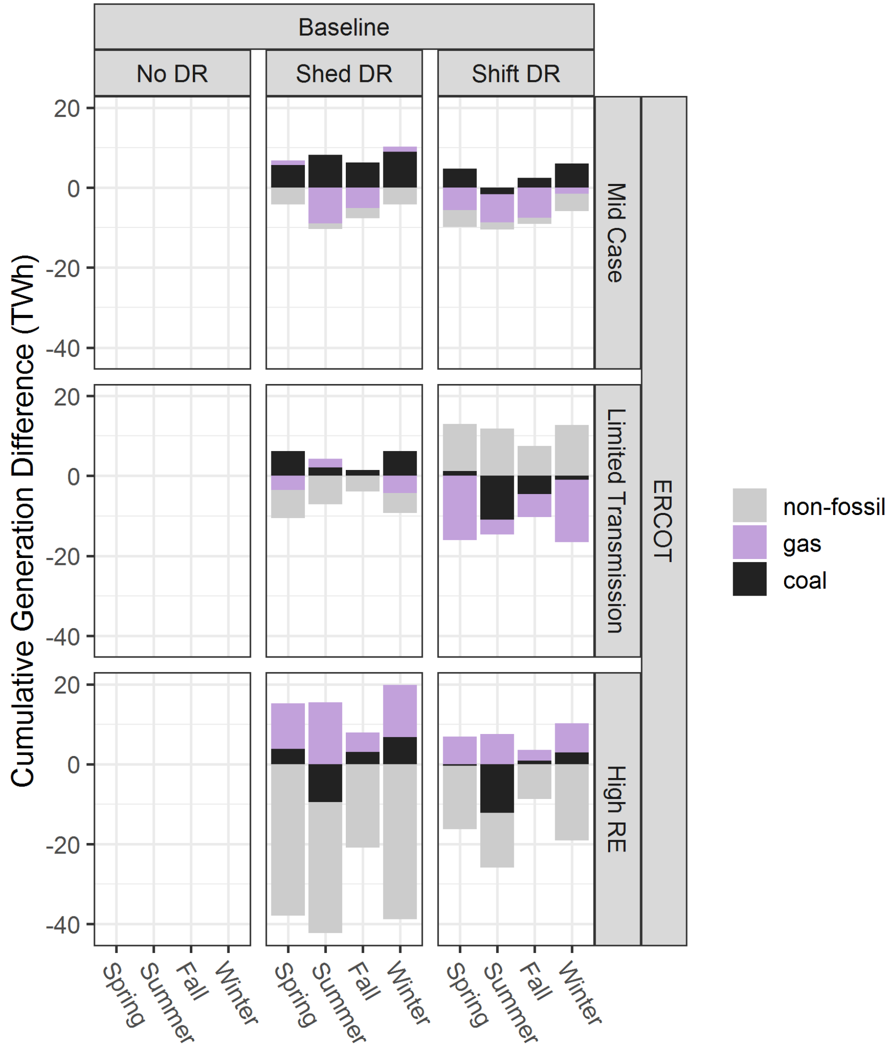
DR alone similarly has a small and mixed impact on cumulative emissions

- DR impacts on cumulative emissions are even smaller than the EE impacts (less than 6% in 2040 compared to less than 9% in 2040 for EE), though there is less DR than EE added to the system (see pages 13 and 14).
- Shed DR reduces non-DR capacity (see page 30). Only in the High RE case do those capacity reductions include some coal retirements. Overall, Shed DR reduces VG and gas builds while keeping overall demand largely the same, which results in more generation from existing coal and gas resources, thereby increasing cumulative emissions.
- The impact of Shift DR is more mixed. Shift DR drives coal retirements in all ERCOT grid scenarios (see page 30), but in the Mid Case and High RE scenarios less VG capacity means that more demand must be served by existing generators, which nets out the coal retirement-driven emission reductions by 2040.



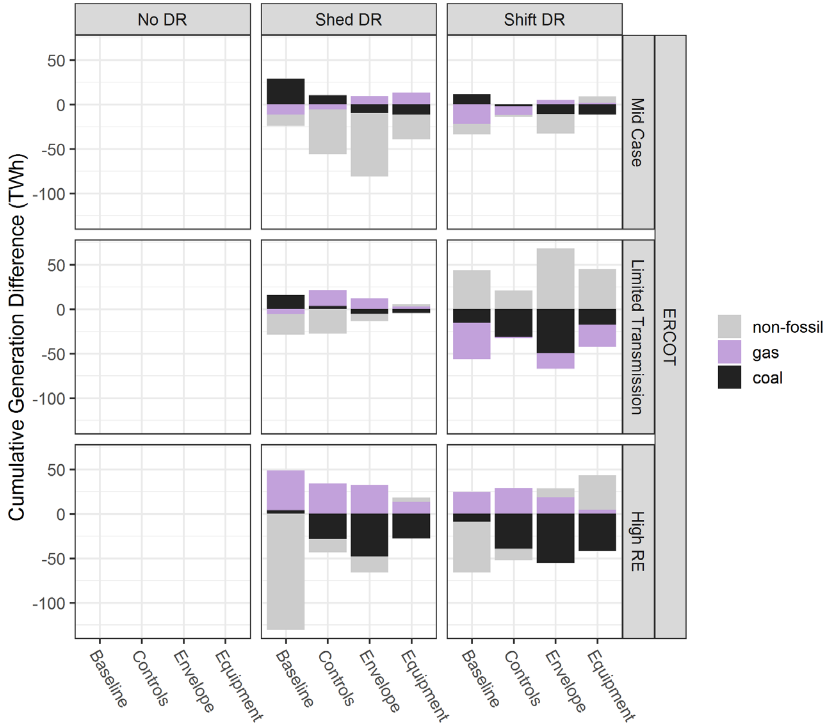
Shed DR increases generation from existing coal and gas units and Shift DR has a mixed impact on emissions depending on grid scenario

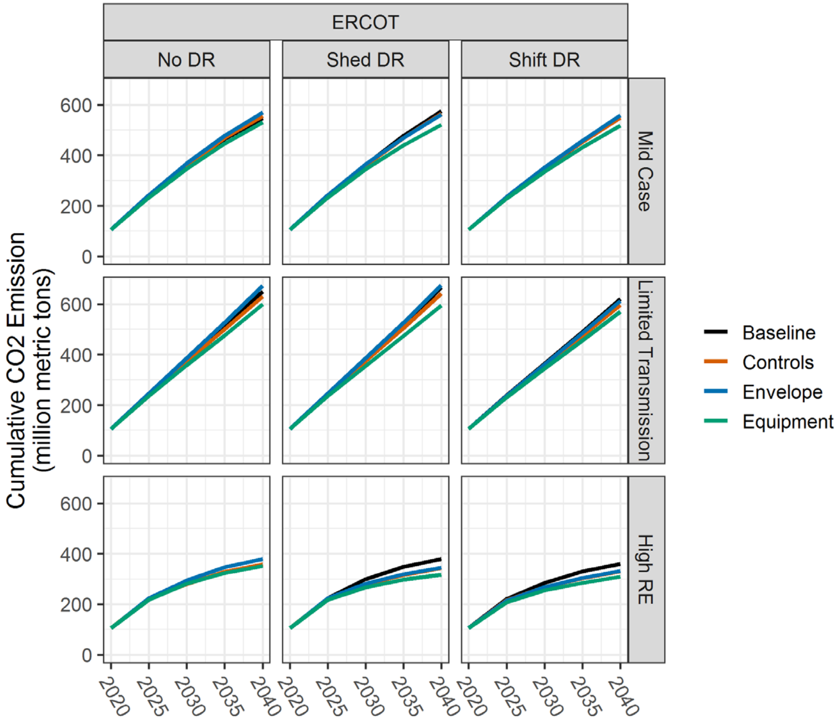
- In the Mid Case and Limited Transmission scenarios, Shed DR increases generation from existing coal generators with limited accompanying reductions in gas generation.
- Shed DR also increases emissions in the High RE scenario, but mostly through increased gas emissions, whereas changes in total coal generation largely net out between reductions in the summer months and increases at all other times of year.
- Shift DR has different impacts depending on grid scenario. Shift DR increases coal and decreases gas generation in the Mid Case, but increases gas and decreases coal generation in the High RE case. Only in the Limited Transmission case does Shift DR consistently enable the integration of more VG and reduce both coal and gas generation.



EE and DR tend to reduce emissions when combined

- Although EE and DR on their own have a mixed impact on emissions, together they can be highly complementary and drive emissions reductions. EE and DR in combination result in modest-to-significant decreases in coal generation, which more than offsets some instances of increases in gas generation (with a lower emissions rate than coal) (see top left figure).

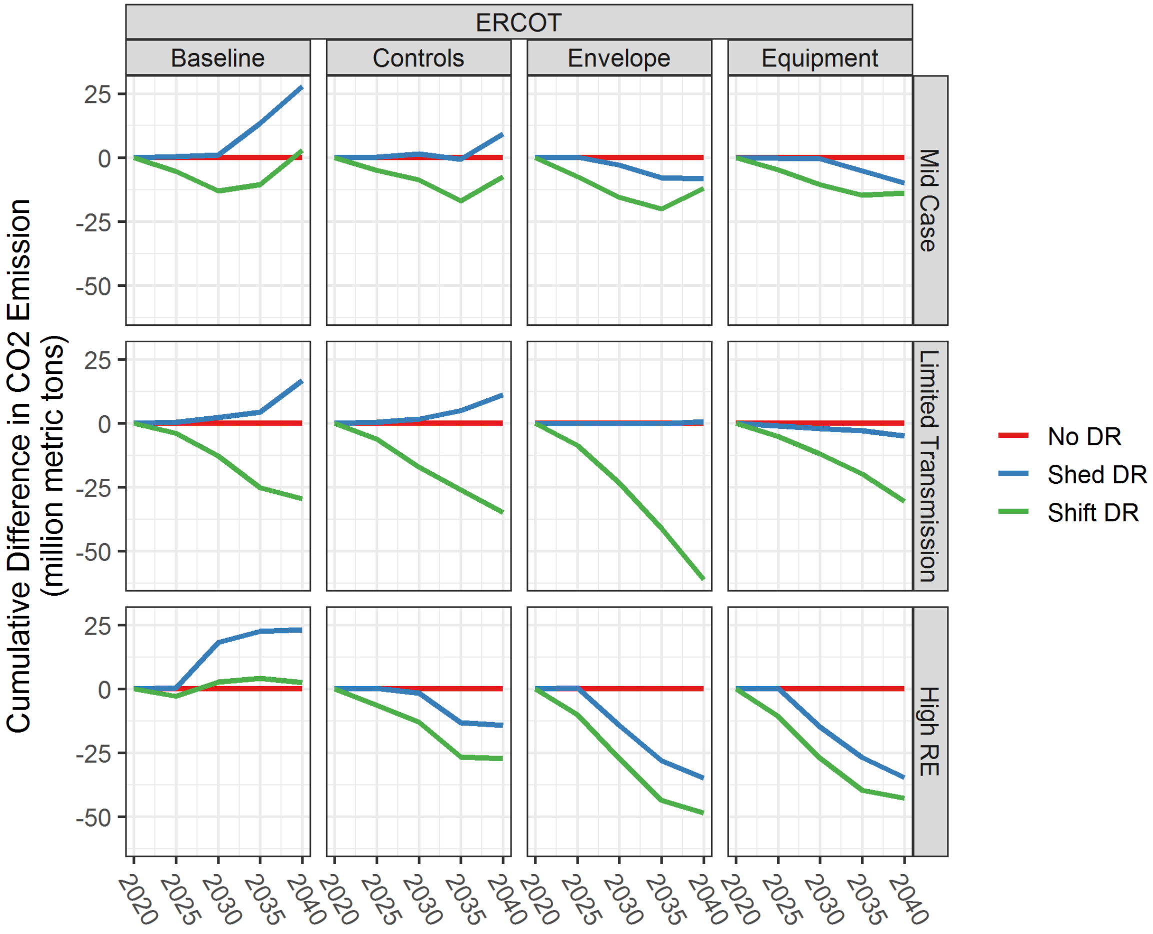




- DR combined with the Equipment package is especially complementary, resulting in consistent and significant cumulative emission reductions by 2040 relative to the Baseline (No DR) (see top right figure).
- Results are highly dependent on the grid scenario. For example, in the High RE scenario, the type of DR and EE doesn't matter—in combination EE and DR always reduce cumulative emissions. In the Mid Case scenario, combining EE with Shed DR reduces the significant increase in coal generation that results from Shed DR alone. In the Limited Transmission scenario, Shift DR and EE are more complementary on an emissions basis. This is because Shift DR enables better use of energy resources in the absence of new transmission.

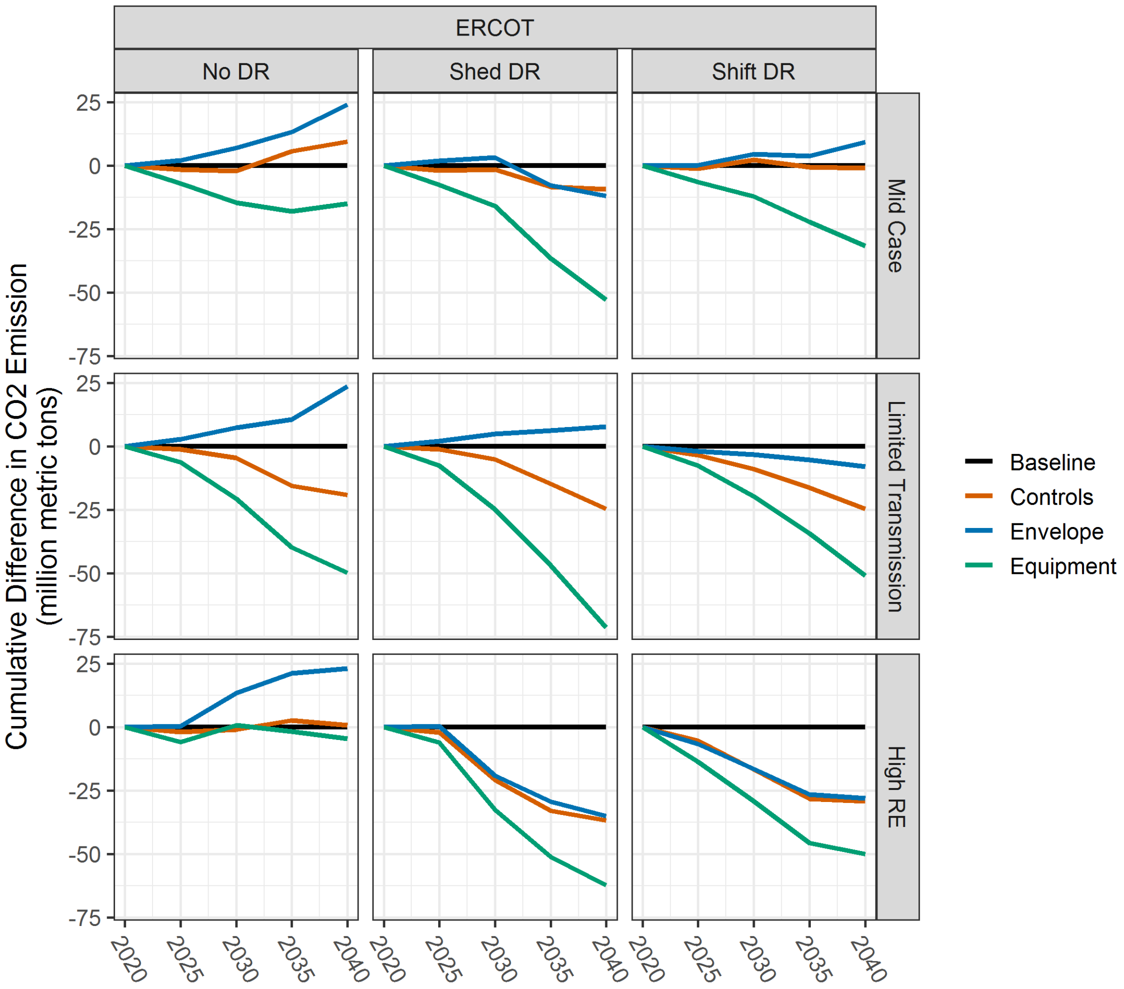
Demand response reduces emissions if Envelope or Equipment EE packages have been deployed

- When assuming the EE packages as a background condition, adding DR almost always reduces emissions (particularly for most non-Baseline EE packages). Both Shed DR and Shift DR reduce emissions for all grid scenarios in combination with Envelope or Equipment packages. Shift DR also always reduces emissions when paired with the Controls package (see figure at right).
- Shift DR especially helps reduce emissions for the Envelope package scenarios. As described on page 27, the Envelope package in isolation increases coal generation. Shift DR is able to mitigate or reverse these effects by shifting generation away from coal generators in favor of less expensive gas and VG.
- Shed DR, while increasing emissions in the High RE scenario with the Baseline EE package, consistently reduces emissions in the High RE scenarios with non-Baseline EE packages. This happens because the combination induces reductions in coal generation.
- Shift DR also has a strong complementary impact on emissions when paired with EE in both the Limited Transmission and High RE scenarios. Again, this is because the combination, much more so than Shift DR on its own, reduces coal generation. In fact, Shift DR combined with the Equipment package in the High RE scenario makes nearly a one-for-one trade between coal and VG.



Equipment EE paired with DR reduces cumulative emissions; Other EE packages and DR are also usually complementary on an emissions basis

- Adding EE to Shed DR or Shift DR results in (sometimes significant) emissions reductions across almost all EE packages (the exception being the Envelope package).
- When EE is added to DR, emissions increases with the Envelope package are fairly modest (i.e., less than 2%) and under specific conditions (i.e., combined with Shed DR in the Limited Transmission scenario, combined with Shift DR in the Mid Case scenario).
- Emissions impacts of EE alone range from –8% to +6% in the No DR cases to –16% to +2% when EE is added to DR.
- No matter whether DR is deployed nor which type of DR, the Equipment EE package always results in the largest cumulative emissions savings from 1% (High RE, No DR) to 16% (High RE, Shed DR).
- Although the proportion of emissions avoided by EE when added to DR is highest under High RE conditions, the absolute emissions avoided can be of similar magnitude under Limited Transmission and Mid Case conditions. For example, the Equipment EE package when paired with Shed DR avoids 71 million metric tons in the Limited Transmission scenario and 62 million metric tons in the High RE scenario



V. Conclusions and Discussion

How do EE and DR meet system needs to maintain reliability and service levels, and how does one resource affect the other?

- In isolation, EE and DR reduce power system costs and capacity (on net) in ERCOT. Specifically:
  - EE capacity savings are a result of lower overall load, which reduces costs to build new generation capacity and associated transmission costs.
  - DR capacity and cost savings are a result of DR providing a new source of firm capacity that avoids reliability-based generation capacity builds, as well as shifting energy from high-price to low-price times. In ERCOT, there is an economic opportunity to increase electricity exports to neighboring power systems (with increases in associated transmission costs) (e.g., value from exporting cheaper resources in Texas to the Eastern Interconnection).
- In combination, EE and DR reduce power system costs and capacity (on net). But some combinations of EE and DR result in larger or smaller combined cost and capacity savings than in isolation. For example, in ERCOT:
  - EE controls measures do not substantially compete with DR and enhance the avoided generation cost savings in some instances with Shed DR (in the Mid Case scenario). The EE controls package also increases inter-RTO transmission capacity with Shift DR particularly in the Mid Case scenario, which enables more energy exports.
  - EE envelope measures exhibit slightly greater complementarity with Shift DR as compared to EE controls measures because the DR shifts generation away from coal in favor of less expensive gas and VG.
  - EE equipment measures are mostly competitive with Shed and Shift DR because the substantial EE impacts reduce resource size as well as incremental cost and capacity savings for DR.

What integrated EE and DR technologies and strategies are most valuable to the power system, and how robust are those valuations across different grid futures?

- When deployed in combination in ERCOT, EE and DR reduce net system costs regardless of the type of EE package or DR (i.e., load shedding or load shifting DR) and across the three grid scenarios we considered.
- Adding Controls or Equipment EE packages to either Shed DR or Shift DR reduce emissions for all modeled ERCOT grid scenarios. Adding Shift DR to any EE package also always reduces emissions for all ERCOT grid scenarios.
- Grid scenario assumptions also drive important EE and DR pairings. For example, in ERCOT:
  - Under Mid Case scenario assumptions, EE always enhances Shed DR value (e.g., Shed DR paired with the Envelope package increases net cost savings ~20 times).
  - Given higher transmission cost assumptions in the Limited Transmission scenario, there is a need to increase the utilization of existing generation which results in greater complementarity between EE and Shift DR than between EE and Shed DR, especially in terms of variable cost savings and emissions reductions.
  - Envelope package savings flatten the load profile in the High RE scenario. This enhances the value of Shift DR and results in increased solar capacity, lower coal generation, and increased variable cost savings. In terms of emissions reductions in the High RE scenario, EE and DR in isolation are not particularly impactful but EE and DR in combination always reduce cumulative emissions (regardless of the EE package and DR type combination).

How should EE and DR program design and valuation frameworks evolve to account for interactive effects?

- The findings suggest that concerns about competition between EE and DR may be overstated when considering bulk power system cost and emissions impacts.
- The policy, planning, and regulatory context matters for assessing whether or not EE and DR interactions are important. In the context of policy goals that require crediting individual resources (e.g., separate EE and DR targets/goals), accounting for interactive effects likely matters. However, broader policy goals measured by a single objective (e.g., least-cost resource mix) might obviate the need to deal with explicit EE and DR competition and complementarity.
- The power system impact metric, particularly system costs vs. emissions, also matters and the study results suggest valuation frameworks should be comprehensive in order to capture all sources of EE and DR complementarity. For example, the Equipment EE package in ERCOT always reduced the amount of capacity reductions induced by Shift DR, which reduces the cost savings provided by Shift DR. Nonetheless, when Shift DR is paired with Equipment EE, Shift DR enabled reductions in coal and gas capacity in favor of more wind and solar capacity throughout the modeling horizon for all grid scenarios. This resulted in lower emissions and higher renewable energy deployment. Considering the emissions results broadly, deploying EE and DR in combination may help states or utilities achieve clean energy goals.

Important caveats - 1

1. **The exogenous specification of aggressive EE scenarios likely overstates the amount of EE that could be deployed in the coming decades.** In addition, this study neither modeled electrification of end uses such as space heating, water heating, cooking, and clothes drying nor captured expected electrification in other sectors (e.g., transportation). As such, baseline load growth could be much higher than what is shown in these results. Higher load growth would support more investment in new generation and transmission resources and might erode some use cases for the current fossil fleet seen in this study.
2. **Modeling long-term planning decisions using only a single weather year does not capture the diversity of correlated wind, solar, and load patterns to which future power systems will need to be robust.** Because we use a single weather year, the capacity expansion plans we compute might not be reliable on a peak net-load basis (e.g., impacted by different weather patterns, evaluating solar and wind capacity credits based on one, rather than several, years of data). Particularly for this study, modeling higher peak net-loads for all CONUS regions would impact our results given that the capacity value of EE and DR depends on their ability to reduce loads during all hours in which the system is at risk of unserved reserves and load.
3. **Climate change impacts on temperature, humidity, and weather patterns more generally, including extreme events, are going to be significant, but were not captured in this study.** Climate change impacts are likely to increase the importance of the space cooling end-use as well as create more challenging extreme weather events. The former is likely to magnify our finding that space cooling is they key DR resource from buildings. The latter needs further study, namely to what extent can EE and DR mitigate the impact of such extreme weather events.

Important caveats - 2

4. **The planning model used in this study uses hourly resolution data for some calculations, but coarse temporal resolution for dispatch decisions. Spatially, the model only captures transmission between, but not within, balancing authorities.** Because the hourly operations of the power systems prescribed by the planning model have been checked many times using detailed production cost models in other studies with much more aggressive supply-side assumptions, we would generally expect the system build-outs for this study to perform well on an hourly scale. The exact physical capabilities of the DR resources at both the hourly and coarser timescales are a larger uncertainty than whether the grid systems as planned would balance hour-to-hour. Regarding transmission, EE and DR would likely avoid or shift intra-regional transmission builds, and we are not capturing the resulting cost savings. Additionally, the spatial resolution may particularly impact the emissions results as intra-regional transmission constraints could impact the dispatch decisions of generators.
5. **The planning scenarios used in this study did not include any clean energy goals or grid decarbonization targets beyond already-enacted state-level policies.** As such, EE and DR were not directly credited for nor incentivized to reduce emissions. Supply-side build-outs were also largely driven by cost minimization rather than decarbonization goals. Overall, the main impact of this study design decision is that the emission impacts of EE and DR, especially on their own, are quite mixed and depend markedly on the assumed economics of supply-side resources.
6. **The regions modeled with EE and DR represent a subset of the modeled area, which may impact the precision of the overall results.** The total amount of EE and DR added to the model is small relative to the size of the overall CONUS system, and even in the ERCOT results, which focus on a specific sub-region, the model optimization occurs over the entire area. As such, small variations between solutions may be impacted by modeling precision.

Future research opportunities

1. **Generation dispatch modeling of EE and DR to account for operational constraints and assess time-dependent (i.e., hourly) value of co-deployment of EE and DR.** While this study developed portfolios of EE and DR resources, production cost modeling would determine how much of the EE and DR resource portfolios are economic on an hourly basis given certain operational constraints. This research could identify additional sources of EE and DR value (e.g., to mitigate system ramps, especially under a high renewables grid future) and better represent temporal alignment (or misalignment) between EE and DR.
2. **Endogenous model selection of EE and DR to find optimal portfolios.** This study used exogenous characterizations of the EE packages that were not necessarily economic. Using the specific modeled system conditions to determine least system cost EE packages and selected with and without DR would provide additional insights into the interactions of EE and DR in cost-effectiveness frameworks.
3. **Expand the DR and EE data sets to cover the entire continental U.S.** This study focused on three specific regions with unique characteristics, however expansion of the data more broadly would allow for a more complete understanding of the impacts of EE and DR, potentially identifying unique areas or load shapes in which EE and DR might have high value.
4. **Explore interactions between EE, DR, and other DERs.** The study results showed several instances where DR reduced battery storage and/or solar PV capacity. We also excluded non-building technologies that can be used for load shedding and shifting (e.g., behind-the-meter storage, electric vehicles) from the study scope. Given the importance of storage and solar PV in a decarbonized power system, it is important to more fully understand interactions and consider how to integrate DERs with grid-interactive efficient buildings.

Acknowledgements

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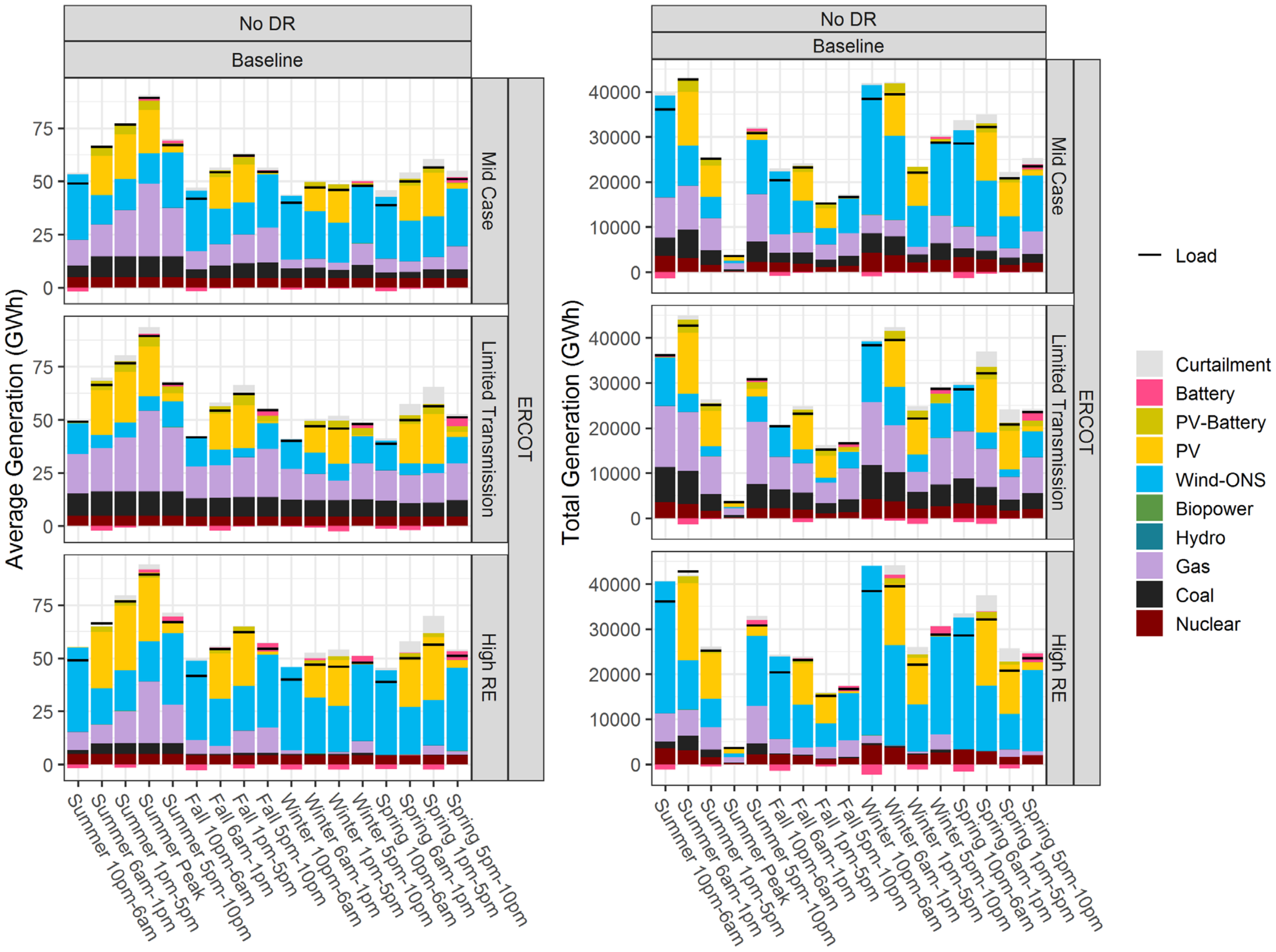
The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof, or The Regents of the University of California.

VI. Supplemental Information

ReEDS modeling approach

Dispatch in ReEDS

- In ReEDS, the emissions are driven by the dispatch of units. Each time-slice has its own total load and generation, representing the *average* dispatch during that time-slice. However, each time-slice represents a different number of hours of the year, and so must be mapped back to those hours to calculate the *total* dispatch each time-slice represents
- The second plot shows the time-slice generation for the *total* year, with each bar representing the full amount of dispatch that period contains for the full year. The sum of these bars is the total annual dispatch.
- It is important to note here that while the peak dispatch period contains the most load, it only represents a small fraction of the year. Time-slices such as the winter night and morning include more total hours, leading to that time-slice having an overall greater impact on the total emissions than time-slices with higher *average* load.



Timeslice	# Hrs
Sum. 10pm-6am	736
Sum. 6am-1pm	644
Sum. 1pm-5pm	328
Summer Peak	40
Sum. 5pm-10pm	460
Fall 10pm-6am	488
Fall 6am-1pm	427
Fall 1pm-5pm	244
Fall 5pm-10pm	305
Winter 10pm-6am	960
Winter 6am-1pm	840
Winter 1pm-5pm	480
Winter 5pm-10pm	600
Spring 10pm-6am	736
Spring 6am-1pm	644
Spring 1pm-5pm	368
Spring 5pm-10pm	460

EE and DR measure, technology, and package detail

Residential EE Measure Performance Levels: Equipment

Central AC	• Upgrade central AC to SEER 18
Air Source HP	• Upgrade ducted ASHP to SEER 22, HSPF 10 • Upgrade baseboard heaters to mini-split HP with SEER 29.3, HSPF 14
Water Heater	• ENERGY STAR Heat Pump Water Heater (EF 2.4, 80 gallon)
Pool Pump	• 25% reduction in pool pump energy consumption
Dishwasher	• Upgrade existing dishwasher to a unit with rated consumption of 199 kWh/yr
Clothes Washer	• Upgrade existing clothes washer to IMEF=2.92
Clothes Dryer	• Upgrade existing electric clothes dryer to ventless heat pump
Lighting	• Upgrade to 100% LED lighting
Refrigerator	• Upgrade existing refrigerator to EF=22.2
Electronics	• 50% reduction in energy consumption from electronics

Residential EE Measure Performance Levels: Controls and Envelope

Measure	Performance Level
Thermostat	• Apply setbacks and schedule from the ENERGY STAR programmable thermostat specification
Air Sealing	• 25% air leakage reduction applied from current ACH50 levels for homes with current ACH50 > 10
Attic Insulation	• Insulate vented attics to R-49
Wall Insulation	• Wood stud walls to R-13; R-20 external EPS insulation
Floor Insulation	• Crawlspace/basement insulation R13 to R30 (building configuration dependent) in colder climates
Windows	• Windows with U-factor 0.27 and SHGC 0.2

Residential DR measure details

End use	Measure
Cooling and Heating	Direct load control
	Programmable Communicating Thermostat
Pool Pump	Direct load control
Dishwasher	Connected dishwasher
Clothes Washer	Connected clothes washer
Electric Clothes Dryer	Connected clothes dryer
Plug Loads	Connected power strips
Refrigerator	Connected refrigerator
Lighting	Connected LED light bulb
Water Heating	Direct load control
	Retrofit communicating temperature controls + t'static mixing valve
	Smart water heater + t'static mixing valve

Commercial EE Measure Performance Levels: Equipment

Rooftop AC/HP	• Upgrade AC to IEER 17; HP to IEER 16.5
Split AC	• Upgrade to SEER 18
PTAC	• Upgrade to efficient unit (EER 10.45-13.1 depending on capacity)
Chiller	• Replace with efficient unit compliant with anticipated 2035 building code (min. full load efficiency 0.53-1.16 kW/ton, depending on compressor type and capacity)
HVAC system	• Add economizers for ACs and chillers; add heat-recovery equipment for ACs and HPs; upgrade cooling tower to variable speed.
Motors	• Replace existing motors with ECMs (except those used for service water heating or refrigeration)
Pumps	• Add VFD to existing pumps
Lighting	• Upgrade compact, linear, high-bay, specialty, and outdoor lighting to LED lighting
Computers	• Replace 50% of desktop computers in office spaces with laptops
Water Heating	• Upgrade all small (<50 gal.) electric water heaters to heat pump water heaters (EF 3.5)

Commercial EE Measure Performance Levels: Controls

HVAC system	• Demand controlled ventilation; close dampers during low occupancy; exhaust-fan interlock; supply temperature reset; reduce VAV minimum airflow
PTAC	• Adjust operating schedules based on occupancy
Thermostat	• Add predictive thermostat control
Chilled/hot water loops	• Supply temperature reset: lower supply temperature setpoint as outdoor air temperature rises, and vice-versa
Kitchen exhaust fan	• Reduce exhaust fan speed during low occupancy
Lighting	• Add occupancy controls to all spaces • Add daylighting controls to selected perimeter zones
Computers	• Power down during unoccupied periods
Plug loads	• Add advanced power strips, which reduce electric equipment energy use during unoccupied periods

Commercial EE Measure Performance Levels: Envelope

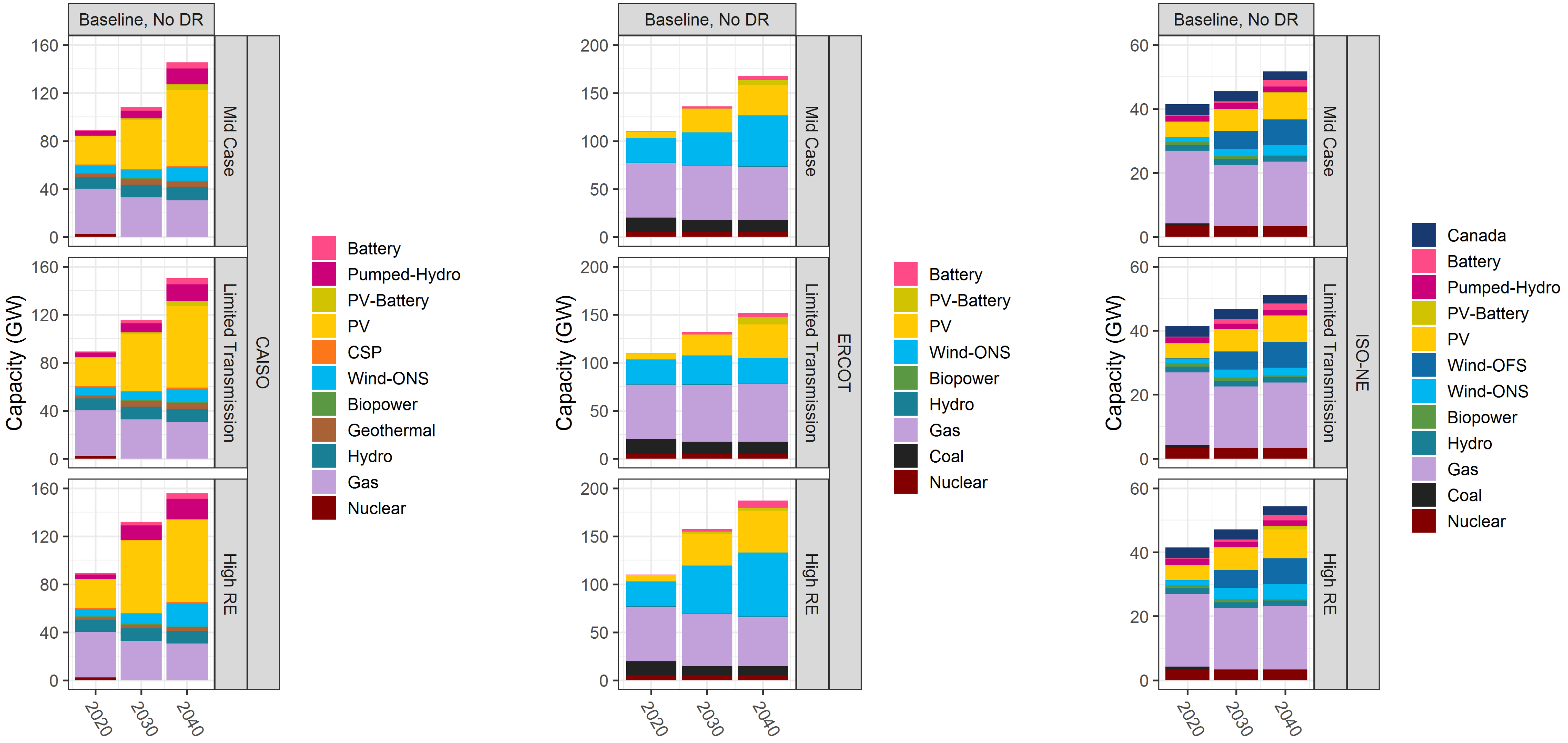
Roof insulation	• Upgrade all roofs with lower insulation levels to R-30
Wall insulation	• Upgrade all walls with lower insulation levels to R-13
Roof	• Upgrade all roof surfaces with current thermal emittance <0.75 to cool roof material with thermal emittance 0.75 and reflectance 0.45
Windows	• Upgrade all exterior windows with current U-factor >1.77 to windows with U-factor 0.31, SHGC 0.58, and VLT 0.70

Commercial DR measure details

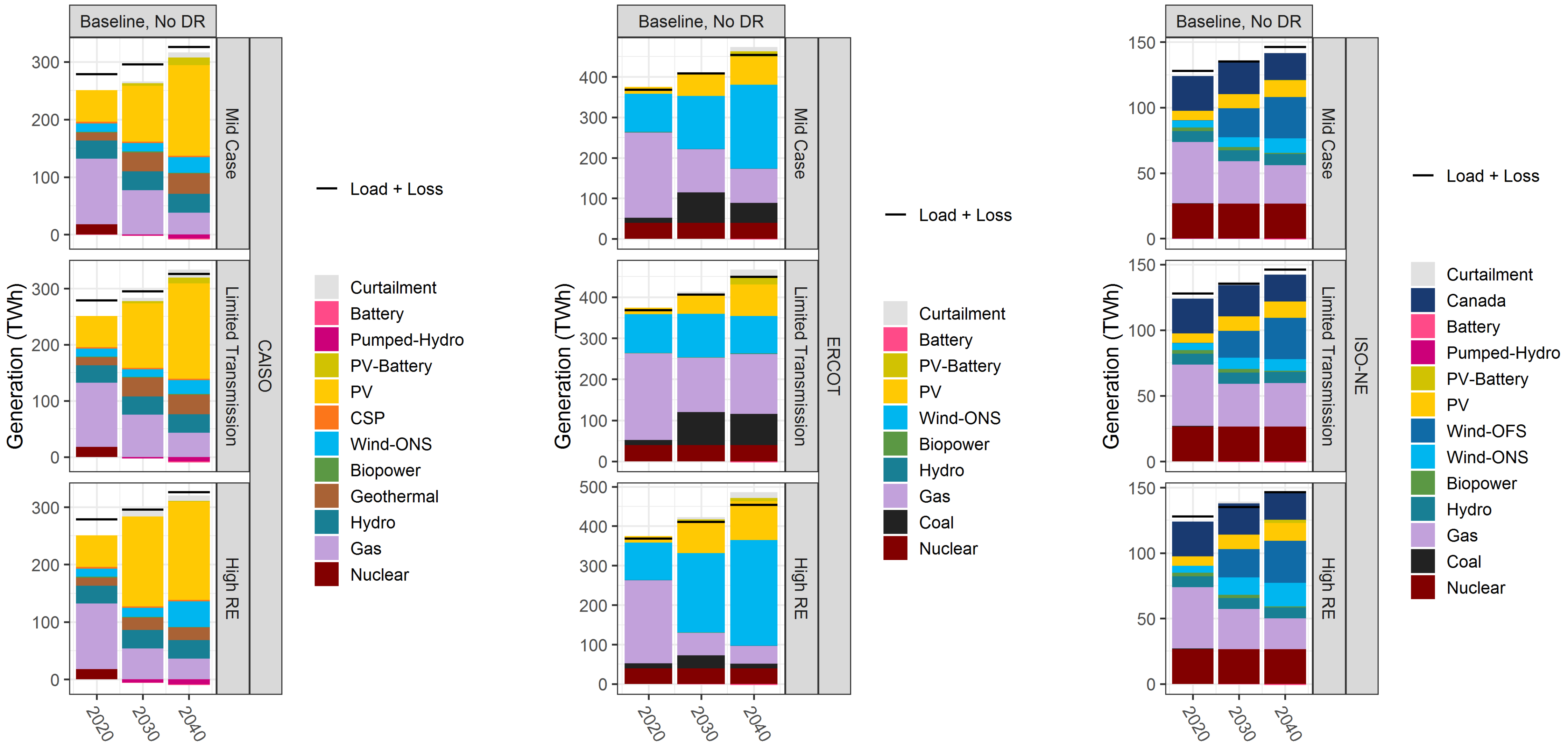
End use	Measure
Cooling and Heating	Direct load control
	Programmable Communicating Thermostat
	Energy Management system, manual control
	Energy management system, automated control
	Space cooling thermal energy storage
Refrigeration	Refrigeration thermal energy storage
Interior equipment	Smart power strips
Lighting	Networked lighting controls
Water Heating	Direct load control
	Retrofit communicating temperature controls + t’static mixing valve
	Smart water heater + t’static mixing valve

Modeled regional electricity system features

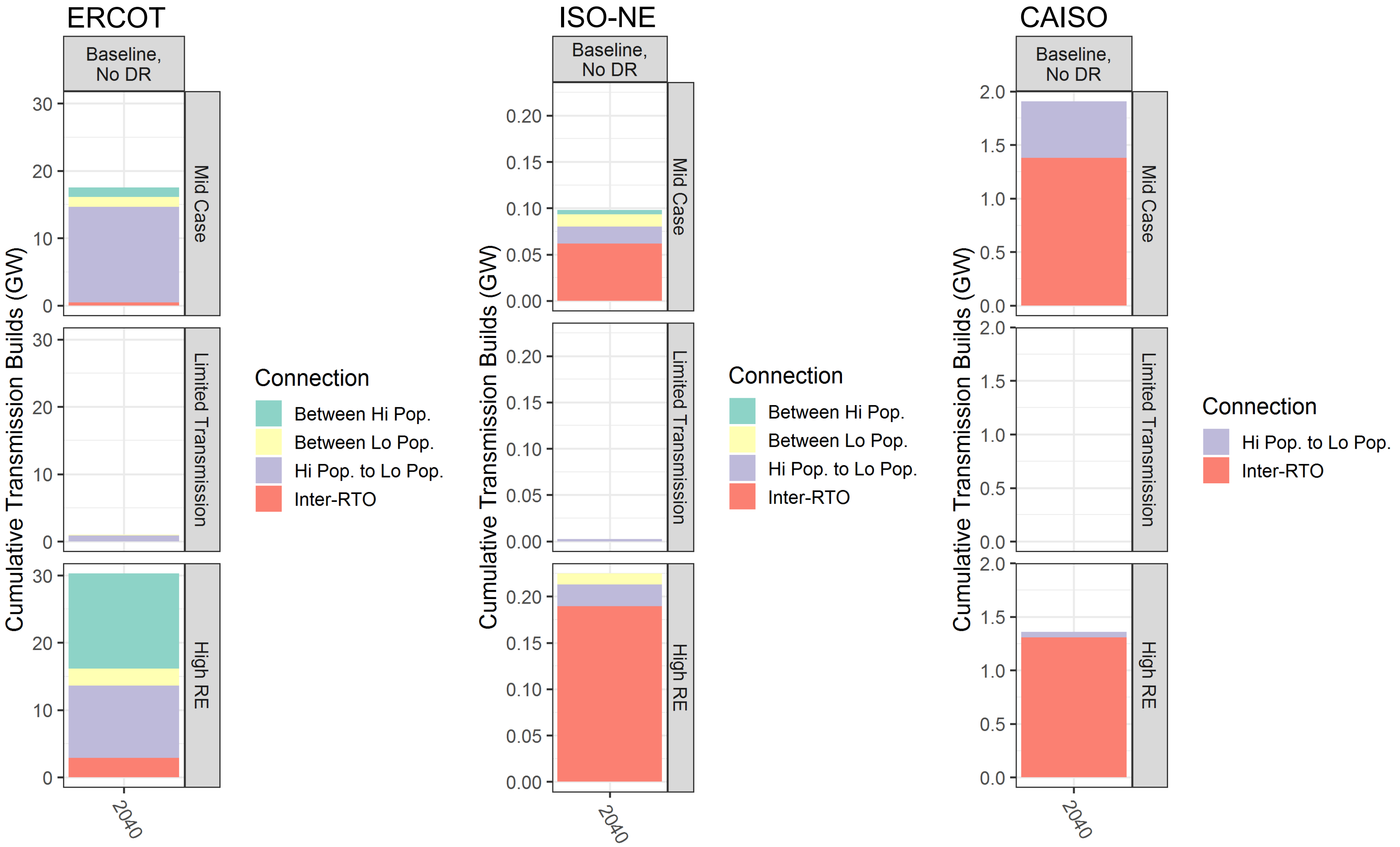
Regional electricity system capacity



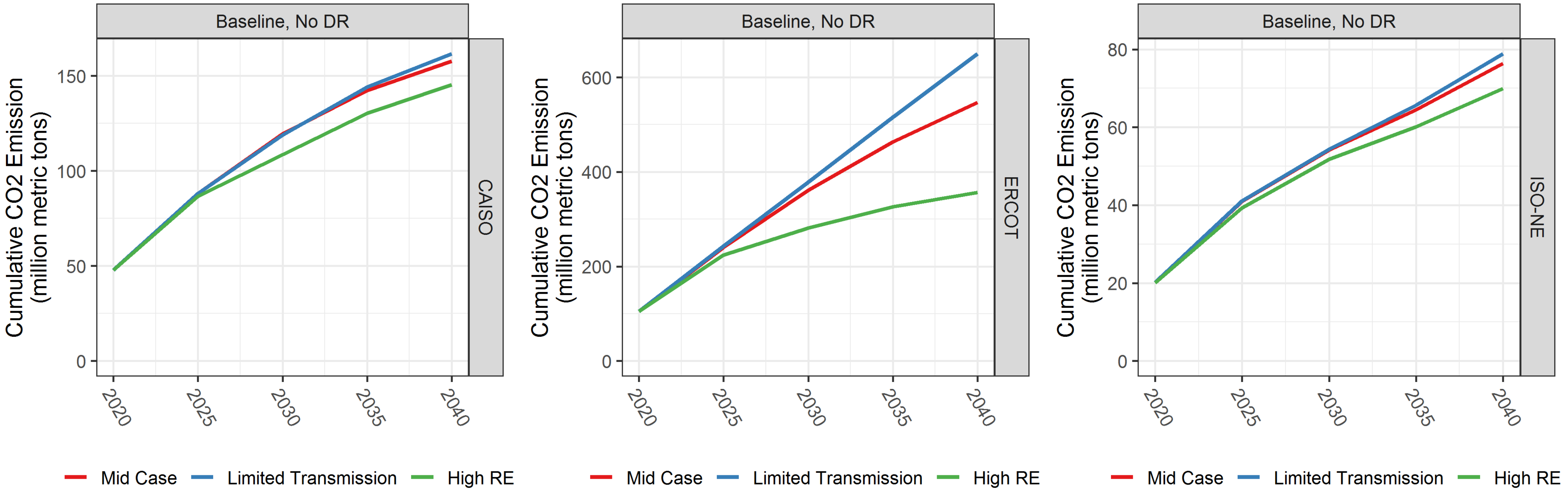
Regional electricity system generation



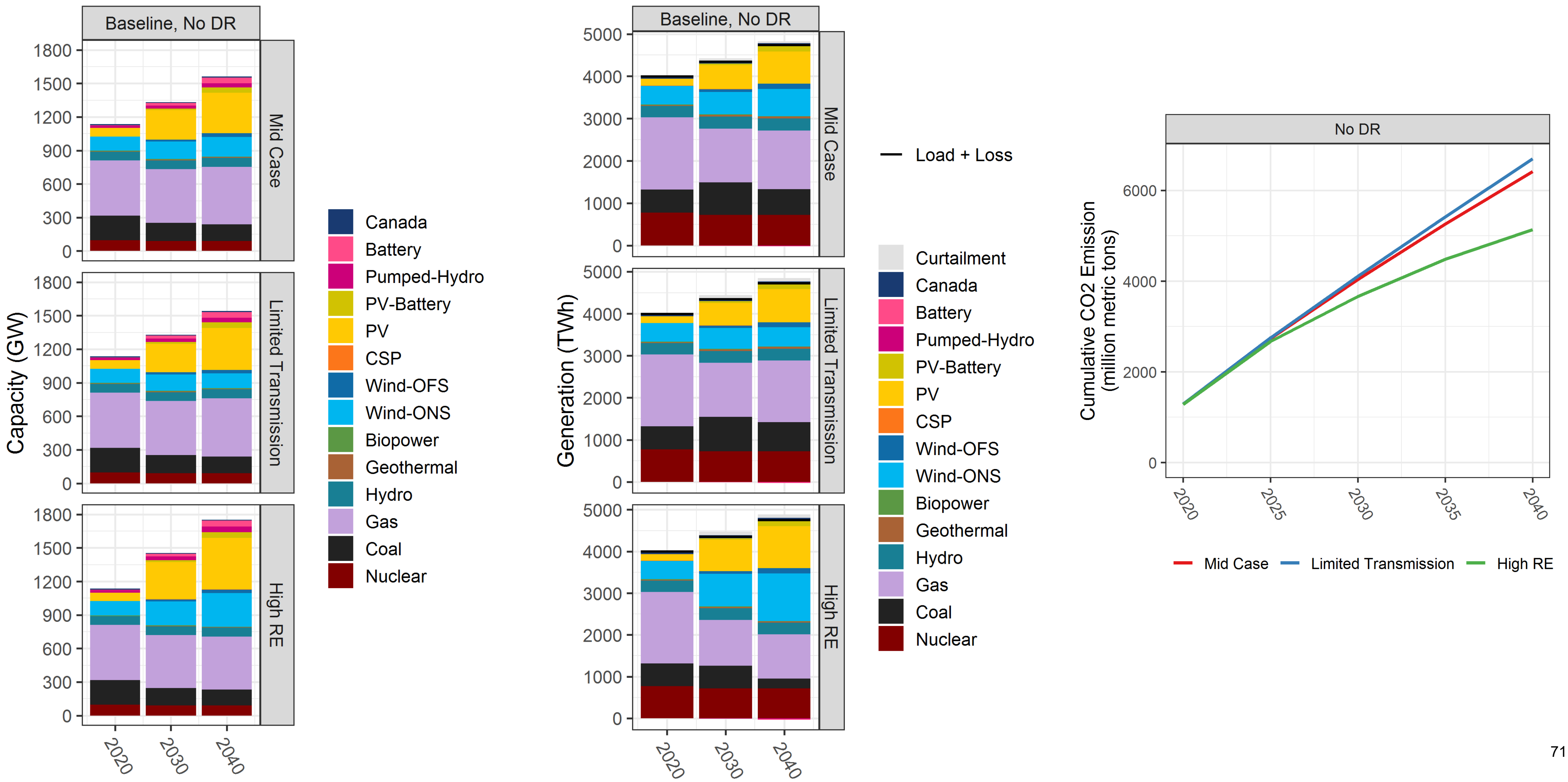
Regional electricity system transmission



Regional electricity system emissions

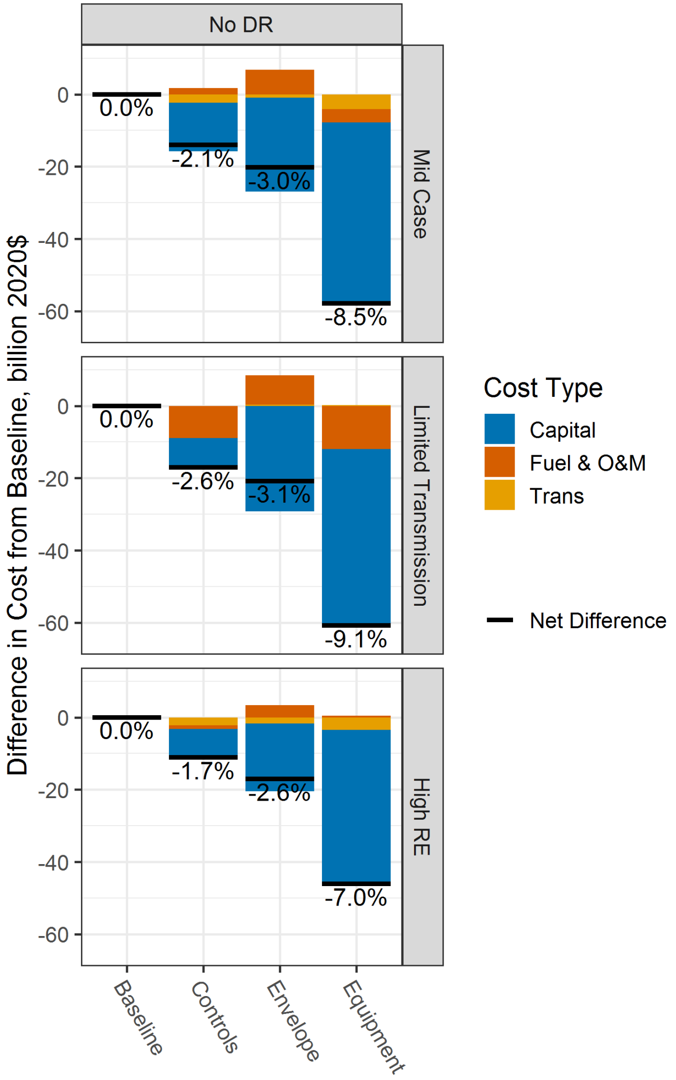


CONUS Summary

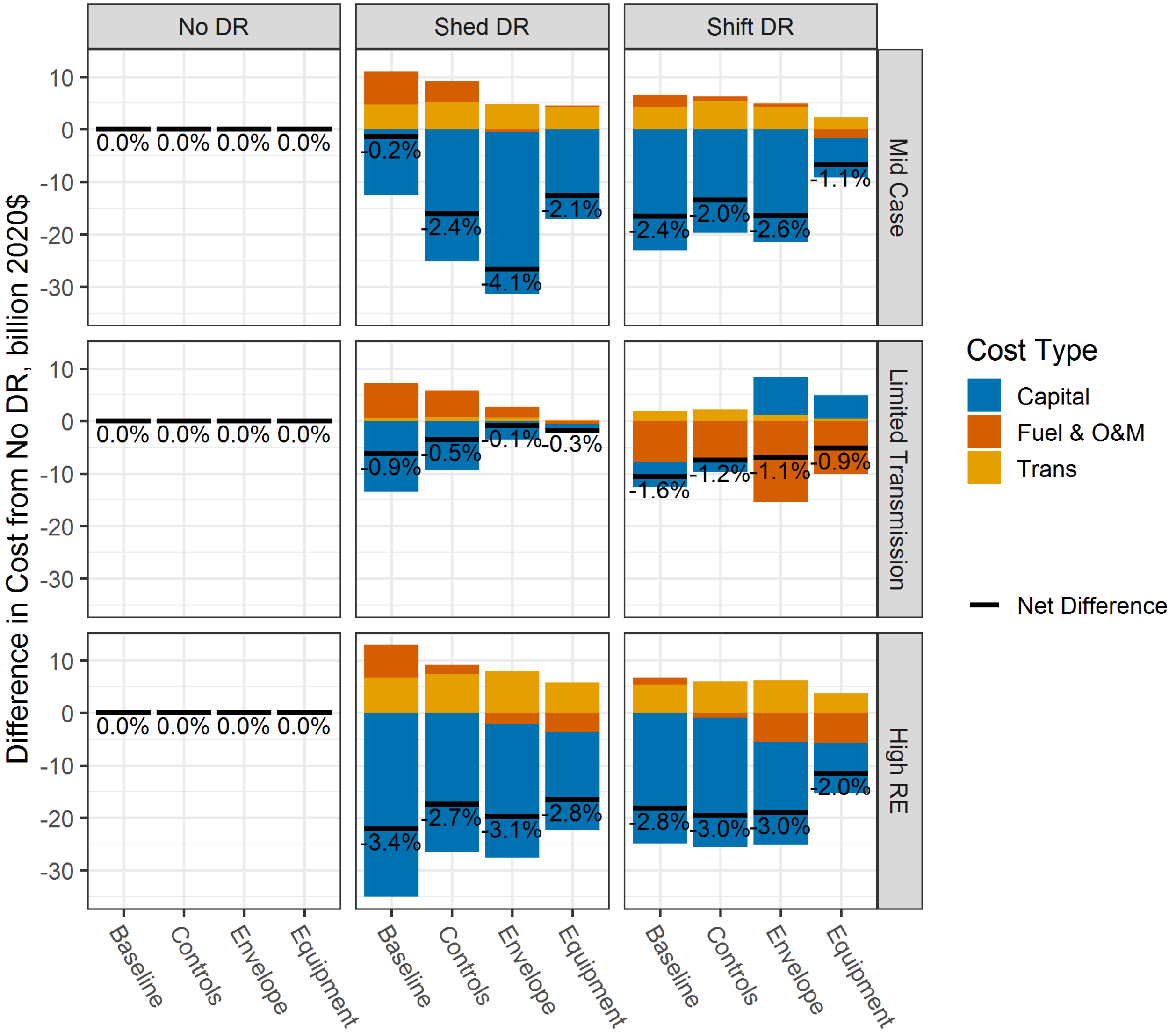


EE and DR system cost impacts

ERCOT

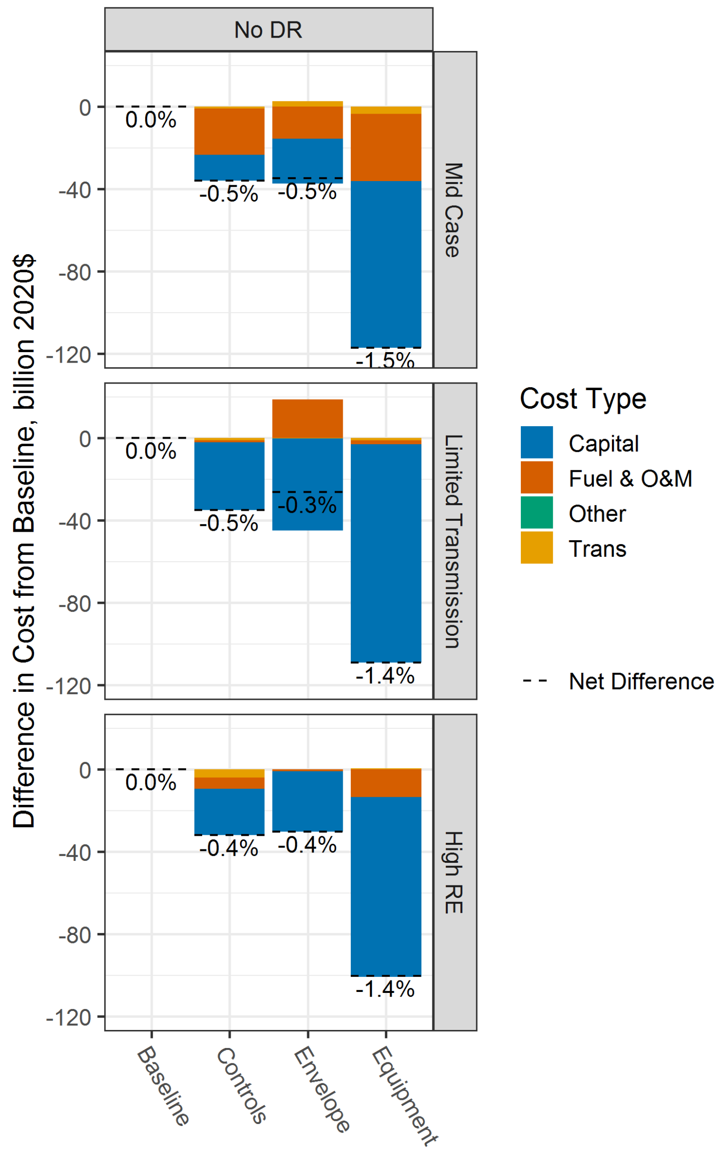


No DR
Mid Case
Limited Transmission
High RE
Difference in Cost from Baseline, billion 2020$
0.0%
-2.1%
-3.0%
-8.5%
-2.6%
-3.1%
-9.1%
-1.7%
-2.6%
-7.0%
Baseline
Controls
Envelope
Equipment
Cost Type
Capital
Fuel & O&M
Trans
Net Difference

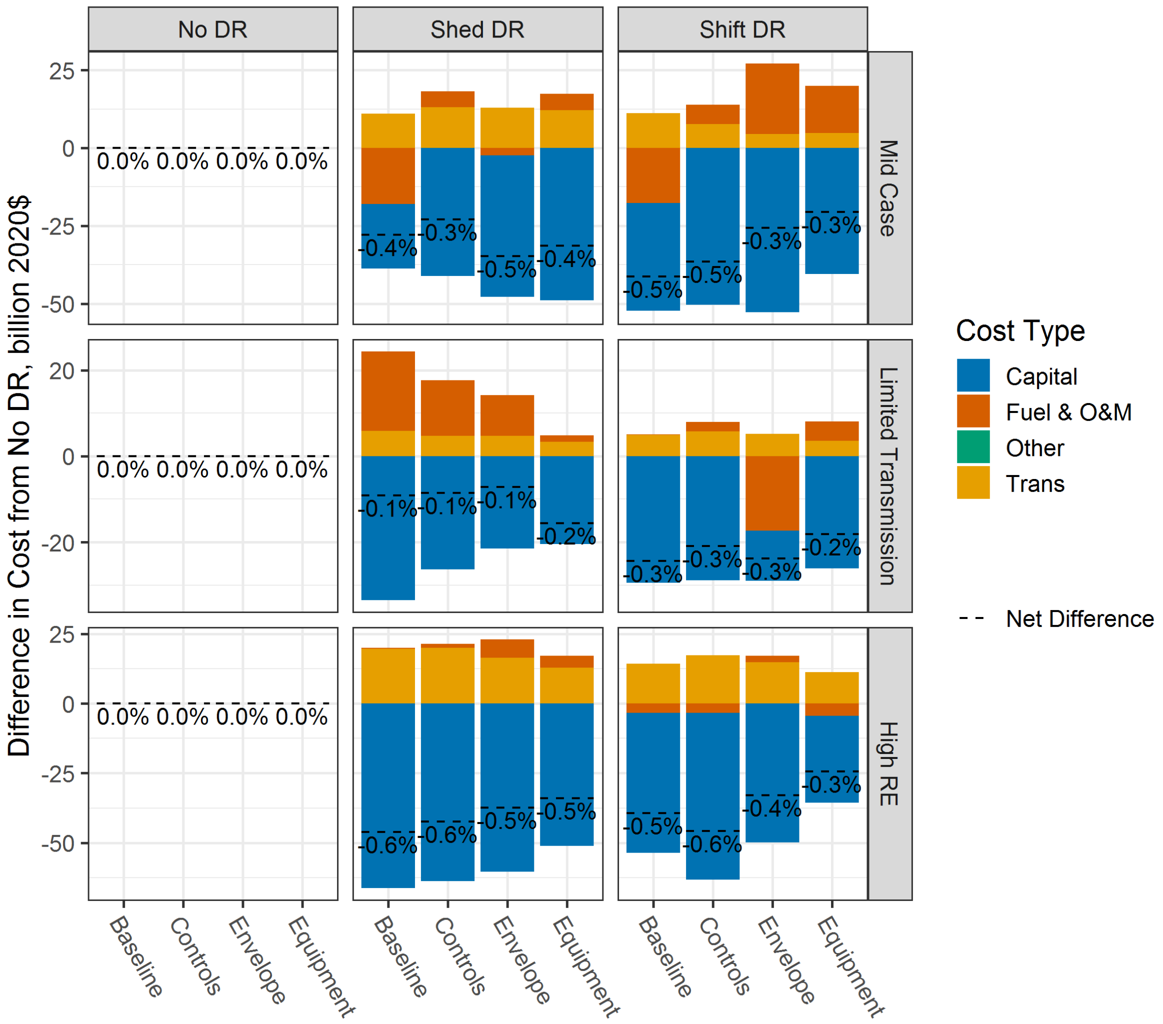


No DR
Shed DR
Shift DR
Mid Case
Limited Transmission
High RE
Difference in Cost from No DR, billion 2020$
0.0% 0.0% 0.0% 0.0%
-0.2%
-2.4%
-4.1%
-2.1%
-2.4%
-2.0%
-2.6%
-1.1%
-0.9%
-0.5%
-0.1%
-0.3%
-1.6%
-1.2%
-1.1%
-0.9%
-3.4%
-2.7%
-3.1%
-2.8%
-2.8%
-3.0%
-3.0%
-2.0%
Baseline
Controls
Envelope
Equipment
Cost Type
Capital
Fuel & O&M
Trans
Net Difference

CONUS



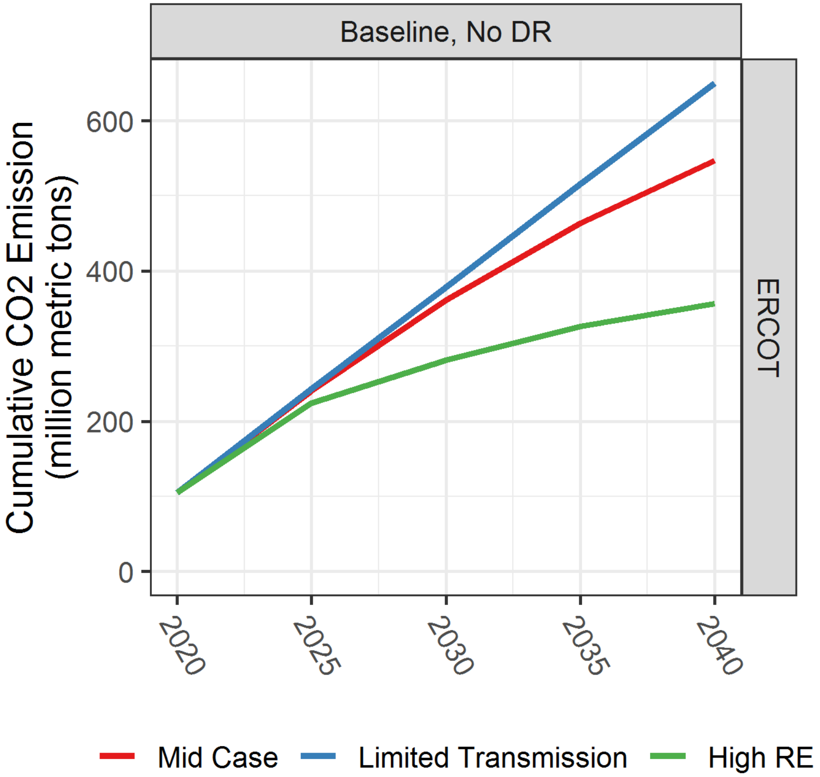
No DR
Mid Case
Limited Transmission
High RE
Difference in Cost from Baseline, billion 2020$
0.0%
-0.5%
-0.5%
-1.5%
-0.5%
-0.3%
-1.4%
-0.4%
-0.4%
-1.4%
Baseline
Controls
Envelope
Equipment
Cost Type
Capital
Fuel & O&M
Other
Trans
Net Difference



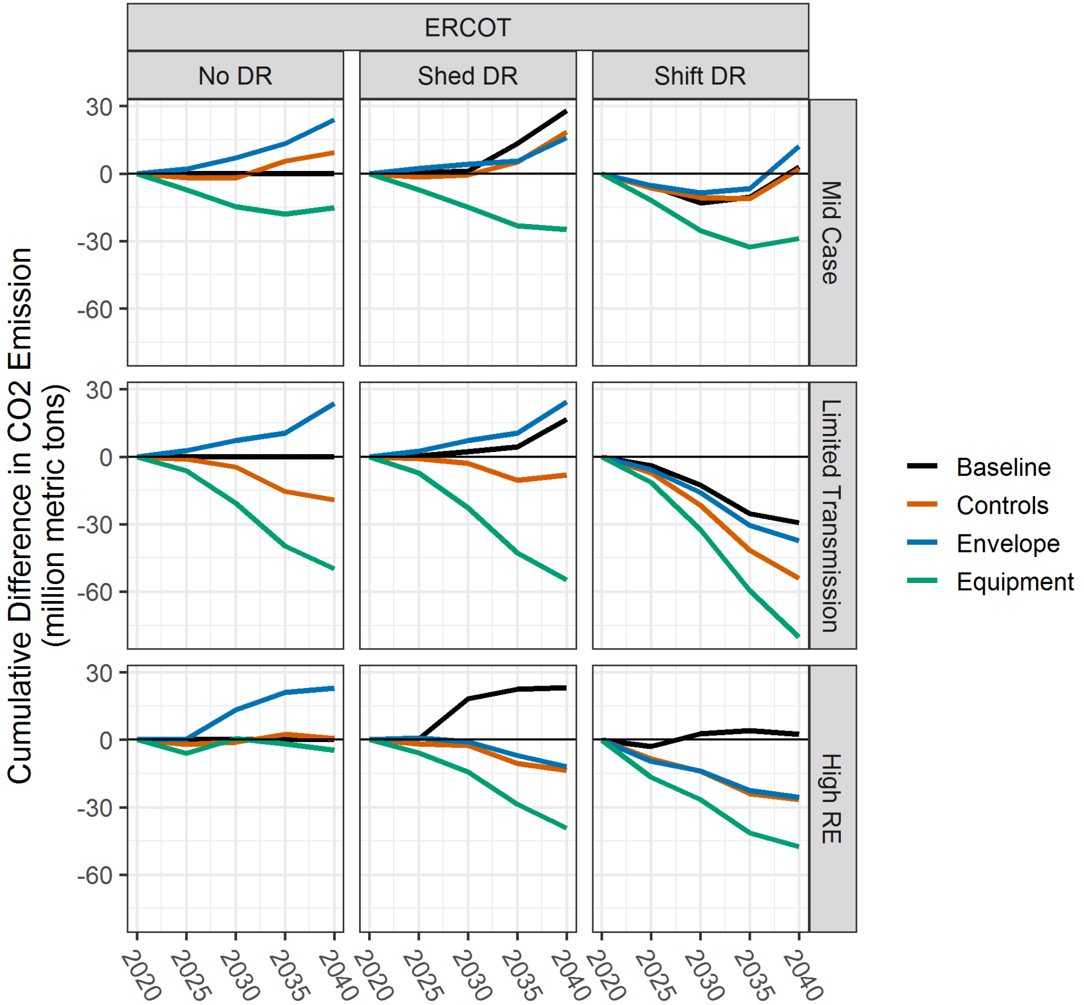
No DR
Shed DR
Shift DR
Mid Case
Limited Transmission
High RE
Difference in Cost from No DR, billion 2020$
0.0% 0.0% 0.0% 0.0%
Baseline
Controls
Envelope
Equipment
Cost Type
Capital
Fuel & O&M
Other
Trans
Net Difference

EE and DR system emissions impacts

ERCOT

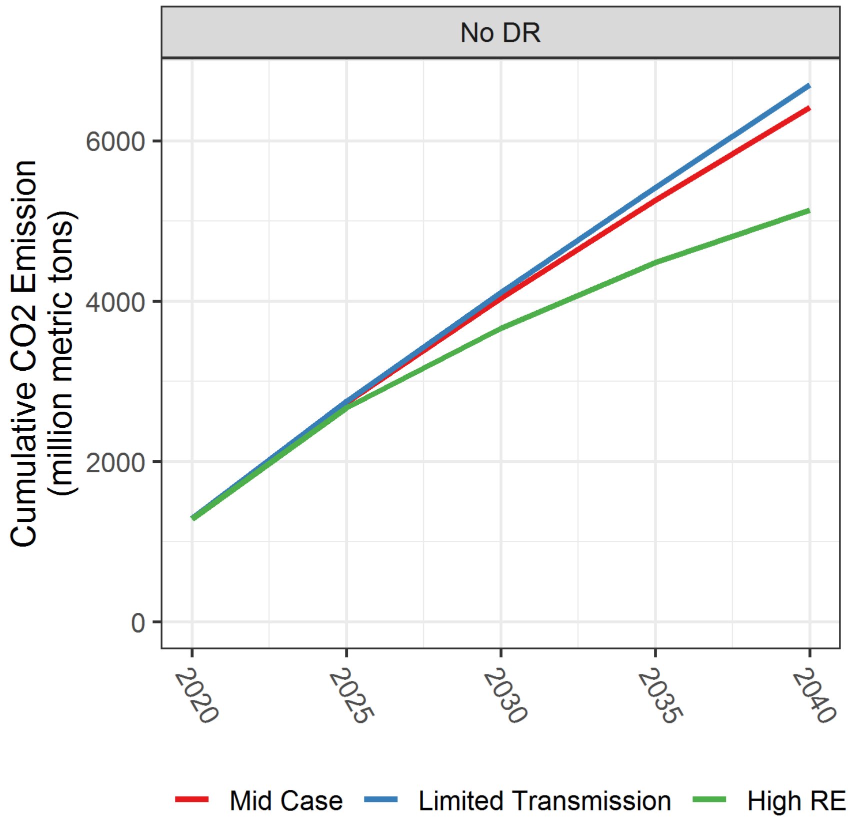


Baseline, No DR
ERCOT
Cumulative CO2 Emission (million metric tons)
600
400
200
0
2020
2025
2030
2035
2040
Mid Case
Limited Transmission
High RE

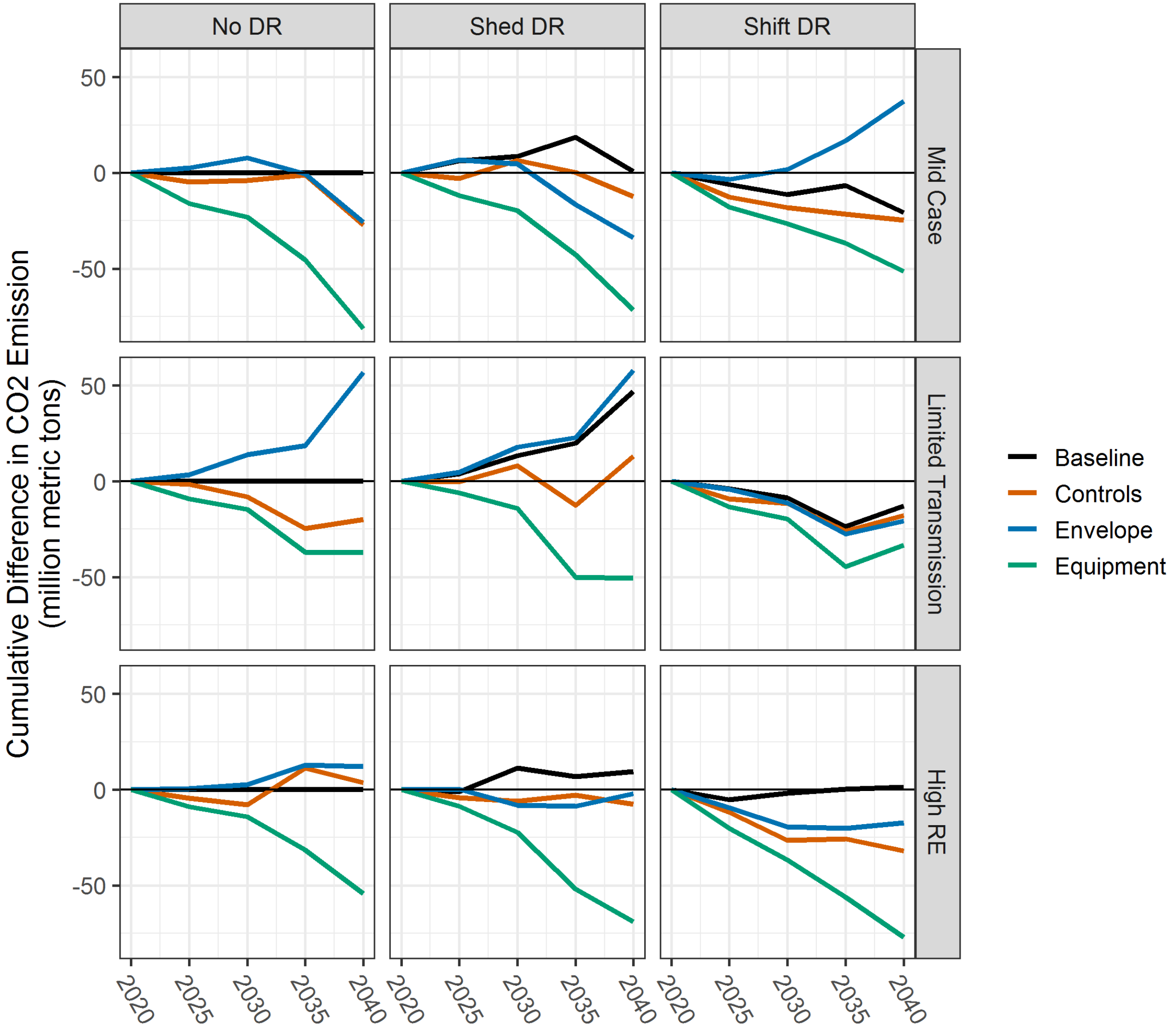


ERCOT
No DR
Shed DR
Shift DR
Mid Case
Limited Transmission
High RE
Cumulative Difference in CO2 Emission (million metric tons)
30
0
-30
-60
2020
2025
2030
2035
2040
Baseline
Controls
Envelope
Equipment

CONUS

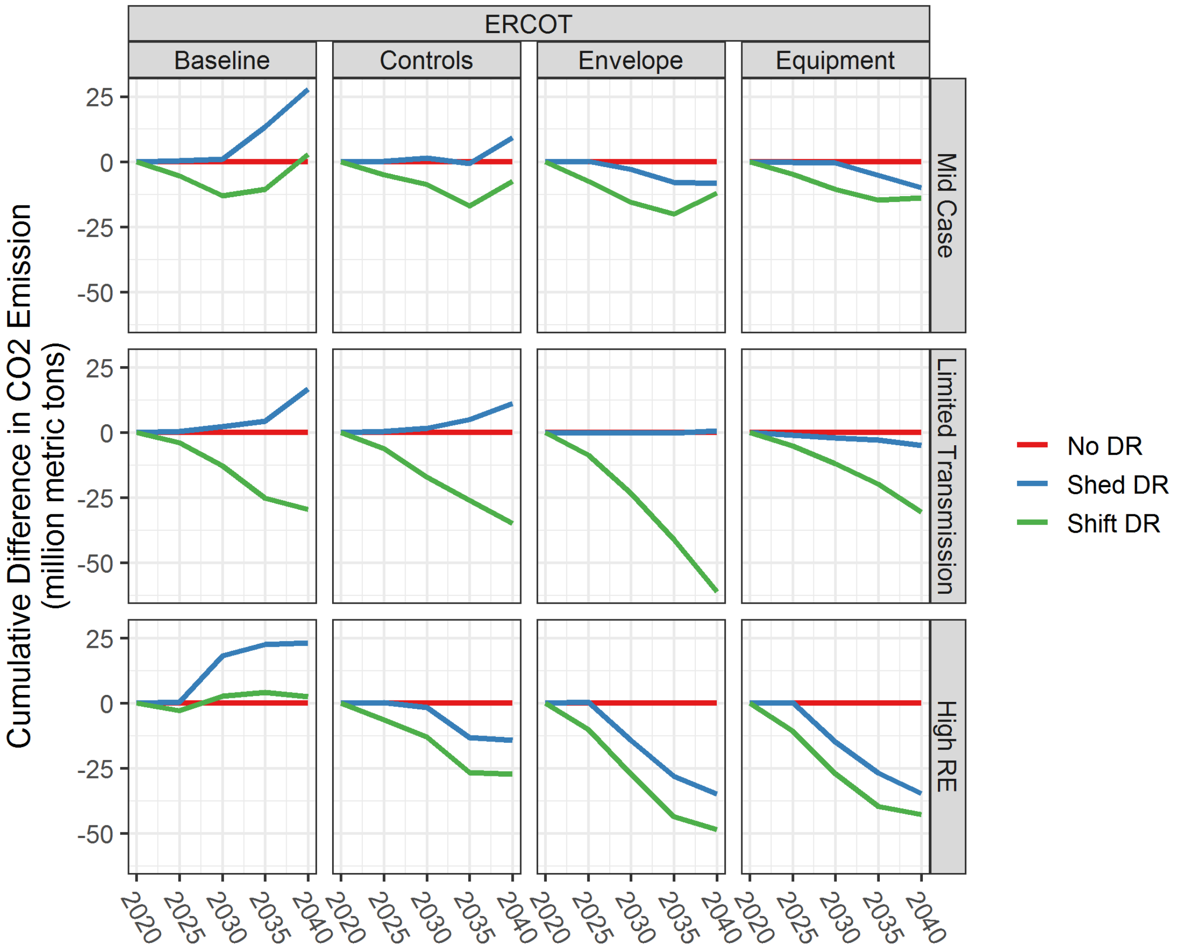


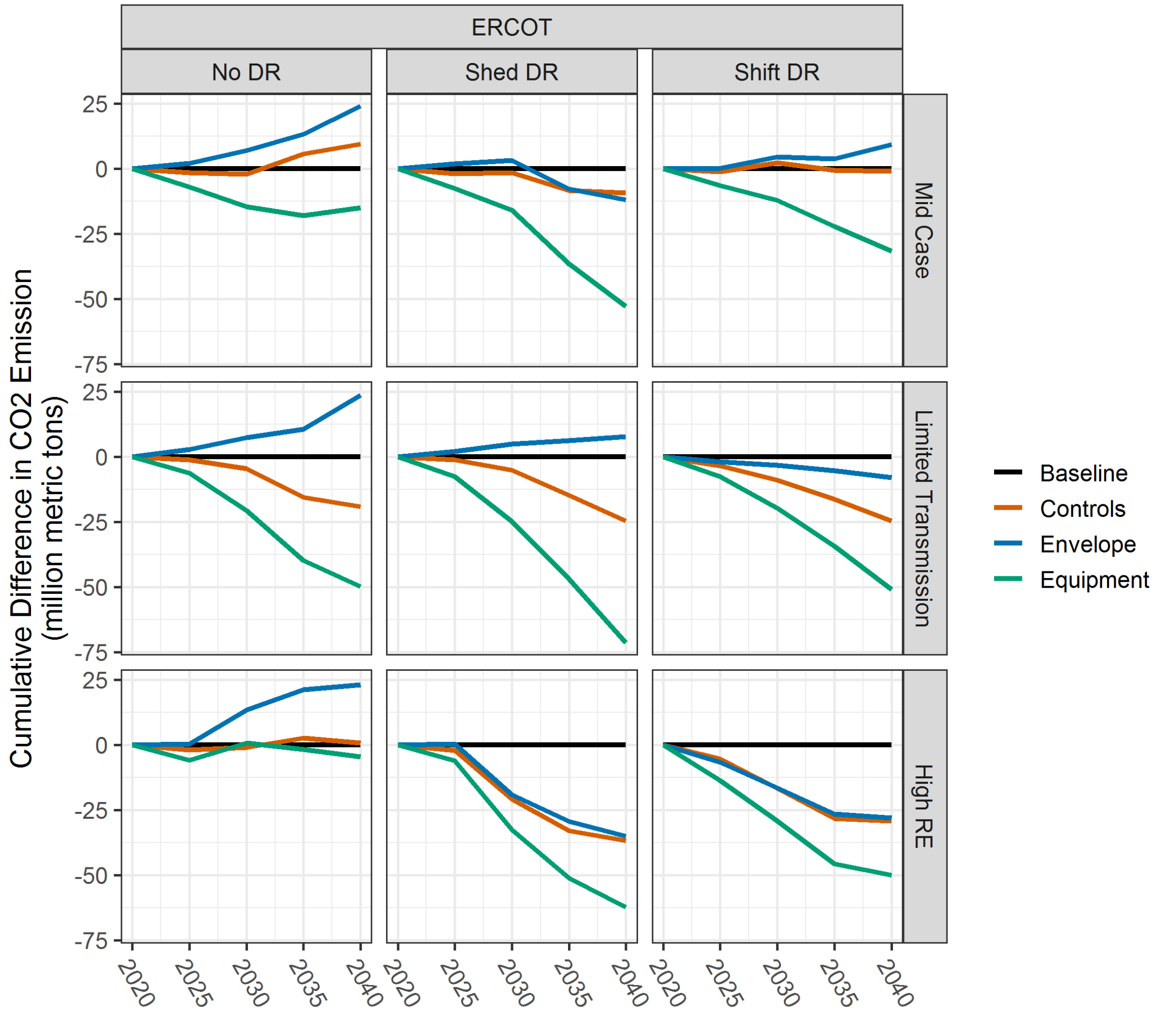
No DR
Cumulative CO2 Emission (million metric tons)
0
2000
4000
6000
2020
2025
2030
2035
2040
Mid Case
Limited Transmission
High RE



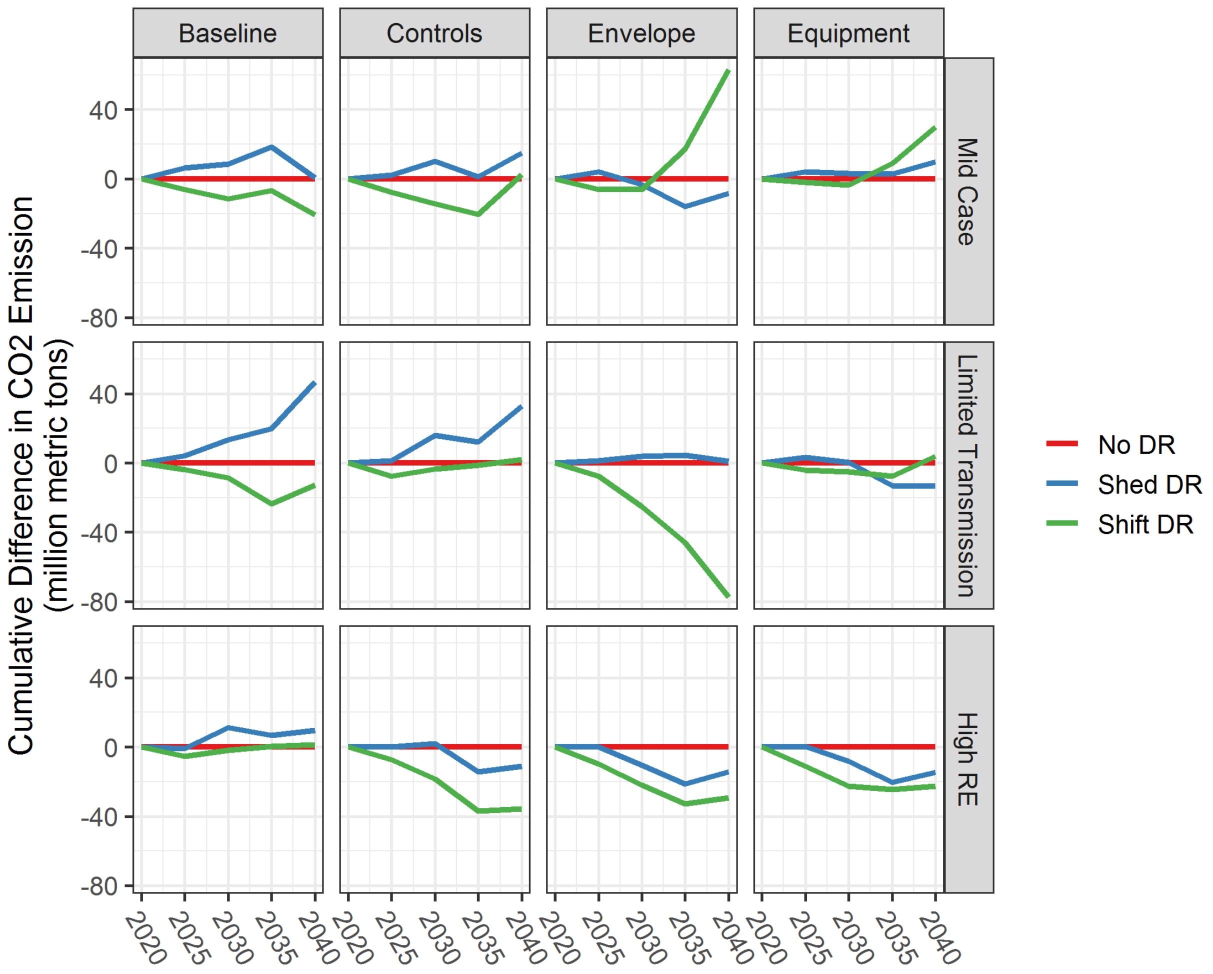
No DR
Shed DR
Shift DR
Mid Case
Limited Transmission
High RE
Cumulative Difference in CO2 Emission (million metric tons)
50
0
-50
2020
2025
2030
2035
2040
Baseline
Controls
Envelope
Equipment

ERCOT

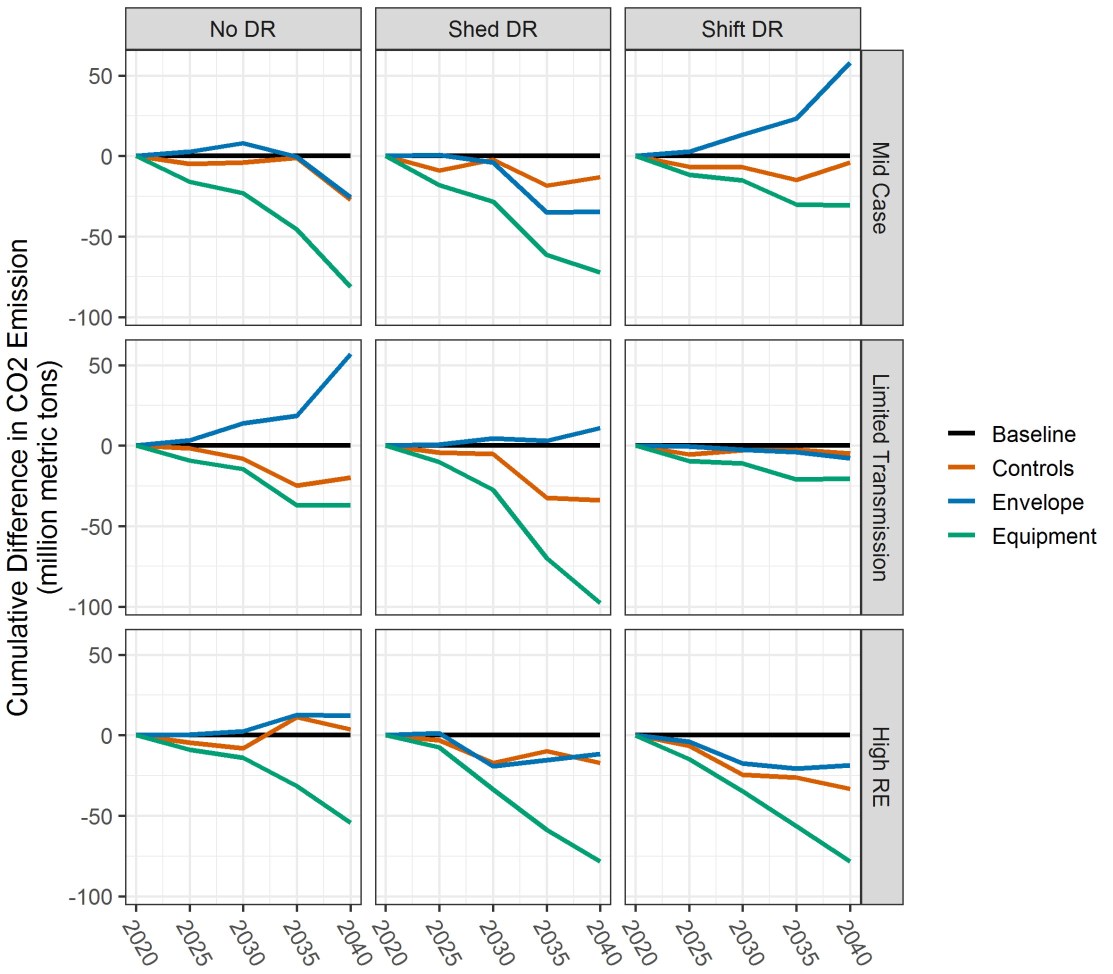

ERCOT
Baseline
Controls
Envelope
Equipment
Mid Case
Limited Transmission
High RE
Cumulative Difference in CO2 Emission (million metric tons)
25
0
-25
-50
2020
2025
2030
2035
2040
No DR
Shed DR
Shift DR


ERCOT
No DR
Shed DR
Shift DR
Mid Case
Limited Transmission
High RE
Cumulative Difference in CO2 Emission (million metric tons)
25
0
-25
-50
-75
2020
2025
2030
2035
2040
Baseline
Controls
Envelope
Equipment

CONUS



Baseline
Controls
Envelope
Equipment
Mid Case
Limited Transmission
High RE
Cumulative Difference in CO2 Emission (million metric tons)
40
0
-40
-80
2020
2025
2030
2035
2040
No DR
Shed DR
Shift DR



No DR
Shed DR
Shift DR
Mid Case
Limited Transmission
High RE
Cumulative Difference in CO2 Emission (million metric tons)
50
0
-50
-100
2020
2025
2030
2035
2040
Baseline
Controls
Envelope
Equipment