Challenges and Opportunities
Economy-Wide Decarbonization Pathways in California

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Abstract

Aiming to achieve a deep decarbonization target by mid-century, California has made continuous efforts in developing a portfolio of policy strategy that combines economy-wide targets with sector-specific requirements, and technology-specific mandates. The economy-wide emissions targets focus on the mid-term (2030) and mid-century (2050) goals thus provide flexibility in clean energy technology development pathways. The extent of the flexibility, however, is constrained by the complementary measures proposed to develop low-carbon solutions in certain sectors. Therefore, it is critical to evaluate different mitigation strategies to improve the understanding of challenges and opportunities for California. To capture the technology details while examining the economy-wide policy impact, we employ an integrated top-down bottom-up modeling framework (USREP-EleMod) that combines a recursive dynamic multi-sector computable general equilibrium model with an hourly dispatch and capacity expansion electricity model. Ongoing results show a substantial carbon price increase over the years as a consequence of the stringent economy-wide GHG emissions reductions of 40% by 2030 and 80% by 2050. By 2030, the expected price is close to \$220 per tCO_2 and rises above \$400 per tCO_2 by the end of the time horizon. Because of this,

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renewable natural gas (RNG) starts to become competitive against natural gas (NG), and gradually grows to meet carbon-free fuel demand from different sectors in particular the industrial sector. By 2050, total NG consumption falls by 2.8 Quads whereas total RNG increases by 1 Quad. In the electricity sector, we observe that the generation mix heavily relies on solar and wind resources to meet the carbon-free target by 2045. However, we also note that the electricity sector increases the use of RNG and CCS technologies as a substitute for conventional NG Combined Cycles and Combustion Turbines.

1 Introduction

California is the second-largest energy-consuming state in the U.S. In 2017, California used 7.8 quads of energy (see Table 1), just after Texas. About 16% of in-state energy supply is from carbon-free energy sources, including solar, wind, nuclear, hydro and geothermal (most of which are being converted to electricity). Nearly half of all energy consumed in the state comes from petroleum products. Much of this is used by the transportation sector, which accounts for about one-third of current total energy consumption.

Table 1: Energy Consumption Estimates by End-Use Sector, California, 2017[2]

Sector	Trillion BTU
Residential	1,416
Commercial	1,473
Industrial	1,818
Transportation	3,175
Total Consumption	7,881

In 2016, carbon-free electricity accounted for about 50% of total electricity generation in the State, which included large hydro, solar, wind, and nuclear – wind and solar generation combined represented 17% approximately of the total in-state generation. In addition, annual electricity demand is expected to

[2] https://www.eia.gov/state/seds/sep_sum/html/rank_use.html

increase in the future due to greater air conditioning usage during hotter summers and load growth because of greater EV deployment across the State.

In terms of emissions, California has seen a decrease of GHG emissions over the past years due to the implementation of several policies aimed at decarbonizing the State's economy (especially after year 2000). As seen in Figure 1, emissions from the electric power sector, commercial and residential sector, industrial sector have decreased with respect to 1990. However, transportation-related emissions (which account about 40%) have seen in increased 2014 and 2015, and emissions from agriculture and other uses (about 8% of the total) have dramatically gone up since 1990.[3]

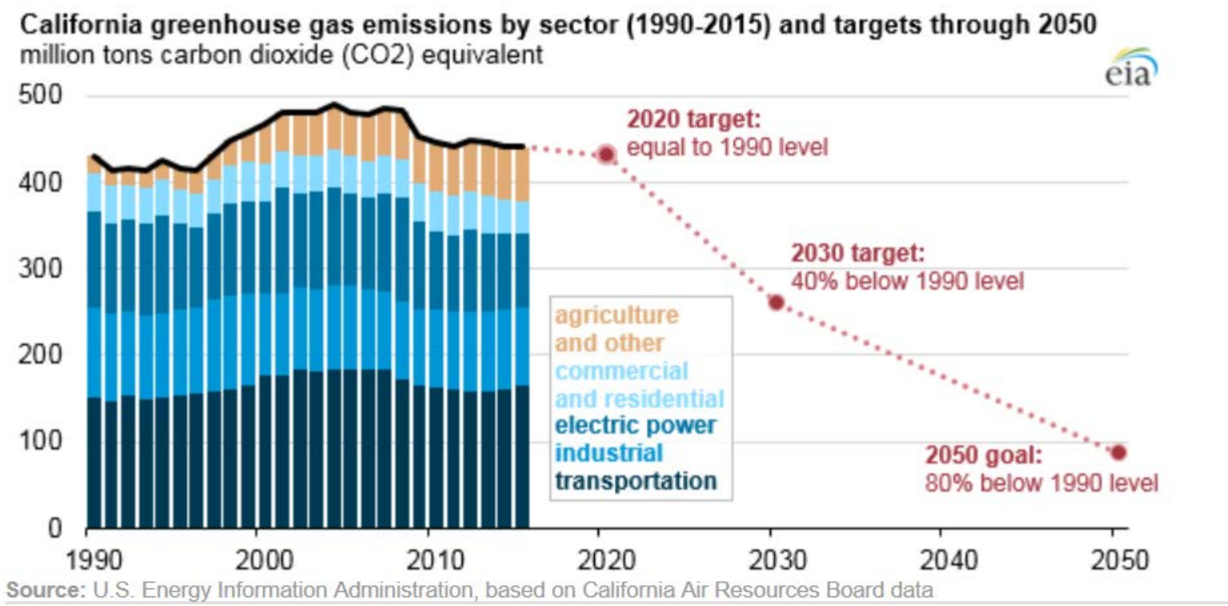

Figure 1: California GHG Emissions by Sector, 1990-2015, and Emissions Reduction Targets Through 2050 (MMTCO_2e).

As also noted in the above figure, California has been proactively developing a portfolio of policies aimed at deeply decarbonizing its economy by midcentury. They include a mix of economywide targets, sector-

[3] https://ww2.arb.ca.gov/ghg-inventory-data

specific requirements, and technology-specific mandates, with focus on the near-term (2030) and mid-century (2050) time horizons. Some of these key requirements include the following:

- Economy-wide emissions reduction target of 40% from 1990 levels by 2030, and 80% by 2050;[4,5]
- A cap-and-trade program with increasingly stringent compliance levels through 2031;[6]
- Energy efficiency improvements (double) of natural gas and electricity end uses by 2030 from a 2015 baseline;[7]
- 60% electricity renewable portfolio standard (RPS) by 2030;[8]
- Federal CAFE standard for light duty vehicles at 54.5 miles per gallon (MPG);[9]
- Deploying five million zero emissions vehicle ZEVs by 2030;[10] and
- 100% net zero-carbon electricity by 2045.[11]

This paper analyzes several scenarios to evaluate California's potential pathways for meeting 2030 and 2050 emissions reduction goals, looking at clean energy technology options (in particular EVs deployment and Renewable Natural Gas), emissions reduction potential, cost to the economy, and impact on the State's electric power system in particular its generation mix and electric load increase because of EVs deployed at scale. We introduce renewable natural gas (RNG), an innovative carbon-neutral fuel that diverts methane from being released into the atmosphere. We treat it as a perfect substitute for natural gas and

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[4] Cal. Stats. 2016, ch. 249, https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB32.

[5] Governor's Exec. Order No. S-3-05 (June 1, 2005), http://static1.squarespace.com/static/549885d4e4b0ba0bff5dc695/t/54d7f1e0e4b0f0798cee3010/1423438304744/California+Executive+Order+S-3-05+(June+2005).pdf.

[6] Cal. Code Regs., tit. 17, §§ 95801-96022 (2019), https://www.arb.ca.gov/cc/capandtrade/capandtrade/ct_reg_2018_unofficialv2.pdf.

[7] Cal. Stats. 2015, ch. 547, https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201520160SB350.

[8] Cal. Stats. 2018, ch. 312, https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201720180SB100.

[9] "2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards," 40 C.F.R. Parts 85, 86, and 600; 49 C.F.R. Parts 523, 531, 533, 536, and 537, https://one.nhtsa.gov/staticfiles/rulemaking/pdf/cafe/2017-25_CAFE_Final_Rule.pdf.

[10] Governor's Exec. Order No. B-48-18 (January 26, 2018), https://www.ca.gov/archive/gov39/2018/01/26/governor-brown-takes-action-to-increase-zero-emissionvehicles-fund-new-climate-investments/index.html.

[11] Cal. Stats. 2018, ch. 312.

pay particular attention to the potential development of RNG as it can use existing gas infrastructure by repurposing natural gas-fired plants.

2 Modeling Approach

To evaluate California's emissions reductions policies, we employ an integrated model that combines two paradigms used by policy and decision makers, namely a top-down and bottom-up approach that combines a multi-region multi-sector dynamic general equilibrium model of the U.S. economy (MIT USREP) with a chronological dispatch and capacity expansion electricity model (MIT EleMod). The MIT USREP model (Yuan et al., 2017, 2019b) portrays an economy with all sectors interrelated through markets where prices and quantities are determined simultaneously and provides a consistent framework that captures direct and indirect impacts of decarbonization. The MIT EleMod model (Tapia-Ahumada et al., 2014, 2015) explicitly takes into consideration hourly demand and hourly supply of wind and solar by geographic region which provide a fine spatiotemporal representation of the electricity system. The method to integrate both models is based on the decomposition algorithm laid out in Böhringer and Rutherford (2009). The first implementation of the approach in a large-scale computable general equilibrium model of the U.S. economy is documented in Tuladhar et al. (2009). The description of the USREP-EleMod integration approach to convergence in the electricity market is provided in Yuan, Tapia-Ahumada and Montgomery (2019a). With a brief description of model integration in the electricity market, this paper focuses on the key convergence mechanism for the emissions market in USREP-EleMod in order to implement an economy-wide emission constraint.

2.1 The Top-Down Model

The top-down component of the integrated model is the MIT US Regional Energy Policy (USREP) model, a multi-region multi-sector energy-economic general equilibrium model of the US economy (Rausch et al., 2010, 2011, 2014, 2015, Yuan et al., 2017, 2019a, 2019b). USREP is built on a state-level economic dataset of the US economy, called IMPLAN (IMPLAN, 2008) covering all transactions among businesses, households, and government agents for the base year in 2006. For the purpose of energy and environmental policy study, we improve the characterization of energy markets in the input-output dataset prepared by IMPLAN by replacing its energy accounts with physical energy quantities and energy prices from Energy

Information Administration State Energy Data System (EIA-SEDS, 2009) for the same benchmark year 2006. The final dataset is rebalanced using constrained least-squares optimization techniques to produce a consistent representation of the economy.

The standard version of USREP aggregates 509 commodities in the IMPLAN dataset to five energy sectors and six non-energy sectors. The energy sectors include coal (COL), natural gas (GAS), crude oil (CRU), refined oil (OIL) and electricity (ELE). The non-energy sectors include energy-intensive industries (EIS), agriculture (AGR), commercial transportation (TRN), personal transportation (HHTRN), services (SRV) and all other goods (OTH). In each sector, output is produced using inputs of labor, capital, energy and intermediate material goods. Primary energy production sectors (crude oil, shale oil, coal, natural gas) use depletable natural resources (crude oil, coal, and natural gas). The model also includes primary energy production sectors that use renewable, non-depletable resources (wind and biomass). Agriculture and biomass production use land. Production is modeled assuming constant-elasticity-of-substitution (CES) functions that is constant returns to scale. Firms operate in perfectly competitive markets and sell their products at a price equal to marginal costs. In each region, a single government entity approximates government activities at all levels - federal, state, and local. Government consumption is paid for with income from tax revenue net of any transfers to households.

Figure 2: USREP Regions

USREP represents the US by twelve geographic regions (see Figure 2), namely Alaska (AK), California (CA), Florida (FL), New York (NY), Texas (TX), New England (NENGL), South East (SEAST), Lakes-Mid Atlantic (LMATL), South Central (SCENT), North Central (NCENT), Mountain (MOUNT), Pacific (PACIF) to account for variations in energy consumption and production across the country. The regions correspond roughly to electricity power pool regions in which electricity produced in that region can serve any household or industry in that region. In each region, we model nine households that differ in the income level as well as the composition of income sources from wages income and rents from the ownership of capital and natural resources. Households of different income levels consume different bundles of goods.

The investment sector in USREP is specified based on the IMPLAN dataset to account for investment demand by private and public entities. The investment sector produces an aggregate investment good equal to the level of savings determined by the representative agent's utility function. The accumulation of capital is calculated as investment net of depreciation according to the standard perpetual inventory assumption. USREP is a recursive-dynamic model, and hence savings and investment decisions are based on current period variables. Capital is assumed fungible across regions and labor is assumed immobile across regions.

To represent historical changes in energy and economic structure, the model is calibrated up to 2016 based on information from Energy Information Administration (EIA)'s Annual Energy Outlooks (AEO). To establish a reference case consistent with official projections, we calibrate the model to match GDP growth through 2050 in EIA's AEO2018 Reference case (EIA, 2018) by updating regional labor productivity growth rates. Policies affecting the US energy system and end-use energy efficiency, such as the regional RPS for electric power generation and national CAFE standards (and separate CAFE standards for California) for vehicle transportation are represented in our reference case to reflect regulations currently on the books. Detailed description of USREP is available in Yuan et al. (2019a).

2.2 The Bottom-Up Model

The bottom-up component of the integrated model is a capacity expansion and economic dispatch model intended to capture the long-term adaptation of a system to the penetration of intermittent renewable generation in the US (Tapia-Ahumada et al., 2014, 2015). There are a wide range of electricity sector models with different levels of detail, covering timeframes that range from milliseconds to years or decades. Capacity planning considers investment in power plants with lifetimes of 20 to 30 years or more, and therefore focuses on years to decades (Figure 3). On the other end are concerns about stability of the grid, and network flows at minutes, seconds, and milliseconds.

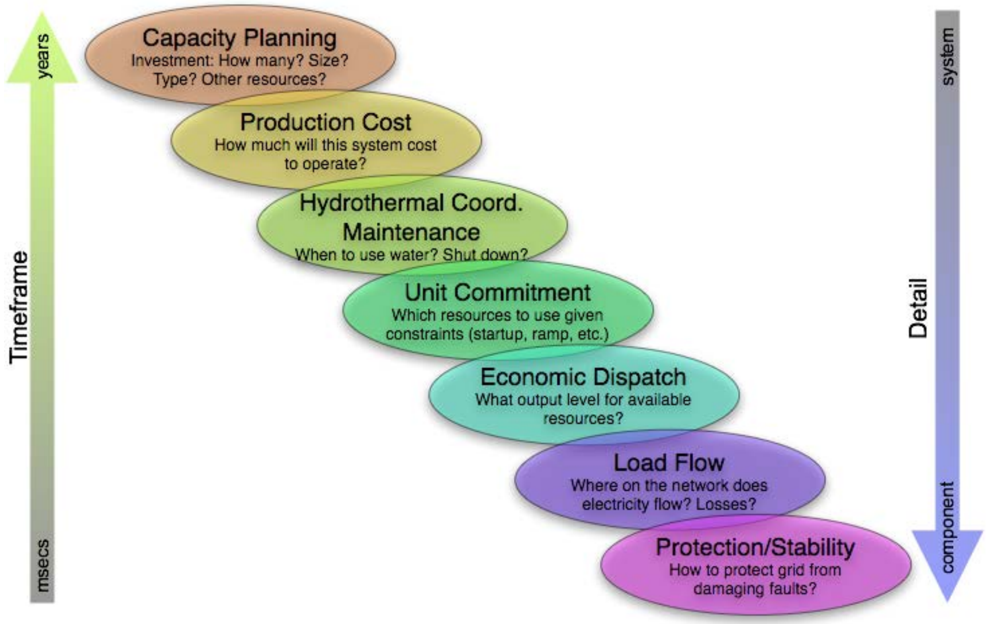

Figure 3: Hierarchical Decision-Making Process in Power Systems (Palmintier, 2013)

To understand future low carbon pathways within electric systems, it is necessary to look at periods of years to decades, with a major focus on what types of electricity generation will be needed to meet low carbon constraints. Intermittent renewables make these analyses more difficult as the decision to invest in wind, solar, nuclear or gas depends on the differential costs of dealing with the great variability of net demand brought about by the intermittency and variability of renewables.

The electric power system model (EleMod) is formulated at the same regional level as in USREP. Following the approach proposed by Perez-Arriaga and Meseguer (1997), EleMod determines the most cost-effective electric generation expansion and operation subject to technical and policy constraints, such as environmental limitations, short-term operating reserves and long-term adequacy requirements in order to maintain acceptable reliability levels. The model incorporates hourly regional load demands, hourly regional wind and solar profiles estimates, resource estimates for wind and solar taking into consideration geospatial limitations, and several technology categories such as utility-scale storage, fossil-fuel based technologies including gas-fired and coal-fired plants, and nuclear plants. In the model, existing regional transmission interties are approximated and electricity trade among regions is possible, except among the Texas, Western, and Eastern interconnects.

EleMod is formulated as a linear programming (LP) problem, minimizing the total cost of electricity generation considering capital investment costs, fixed and variable O&M, and other operational costs such as fuel-related costs, start-up costs and non-serve energy cost (Equation 1).

$$Min\ Cost = \sum_{r}\left[\left(C_r^{fixCap} + C_r^{fixOM}\right) + \left(C_r^{varOM} + C_r^{varFuel} + C_r^{varCO2}\right) + C_r^{StUp} + C_r^{NSE}\right] \quad (1)$$

EleMod is deterministic with a recursive-dynamic structure. Optimal solutions are computed sequentially for every two-year period, adding new capacity as needed to meet growing demand, replace retired units, or meet new policy constraints. It includes three decision timeframes defined as capacity expansion planning, operational commitment planning and operational hourly dispatch decisions.

As Equation 2 show, the model relies on annualized costs of producing electricity in a region r, considering annualized investment costs for each conventional fossil-based technologies n ($c_{r,n}^{fixInv}$), wind class c ($c_{r,c}^{fixInv\_wind}$) and solar renewables ($c_r^{fixInv\_solar}$), and pumped hydro storage ($c_r^{fixInv\_phs}$). Accordingly, main decisions variables include not only operational decisions such as daily connected power and hourly production, but also generation investments to install for fossil fuel technologies ($K_{r,n}$), wind and solar ($K_{r,c}^{wind}, K_r^{solar}$) and pumped hydro storage (K_r^{phs}).

$$\begin{aligned} C_r^{fixCap} &= \sum_{n} K_{r,n} \cdot c_{r,n}^{fixInv} + \sum_{c} K_{r,c}^{wind} \cdot c_{r,c}^{fixInv_{wind}} \\ &+ K_r^{solar} \cdot c_r^{fixInv_{solar}} + K_r^{phs} \cdot c_r^{fixInv\_phs} \quad \forall r \end{aligned} \quad (2)$$

In the particular case of renewables, their hourly profile estimates are incorporated based on historical and/or numerical weather prediction models time series. Wind hourly profiles are taken from National Renewable Energy Laboratory (NREL) data and aggregated at the regional level of the model. These are far less variable than a single site as they integrate over fairly large regions. However, there are still large swings in wind resource availability hour-by-hour, from near full capacity to little or no availability, and also monthly and seasonal variations among regions. Solar hourly profiles are simulated using NREL's System Advisor Model at state level, for various latitude locations and then aggregated at regional level. In general, solar profiles show the strong diurnal pattern of availability with no resource during night time, and higher availability in summer months than in winter, with some day-to-day variation reflecting cloudiness and regional time zone differences. Both wind and solar generation can be curtailed depending on technical constraints and system's oversupply conditions.

For hydro generation, the model currently does not endogenously optimize existing hydro power dispatch. We represent variation in their profiles at regional scale to approximate the electricity production coming from non-intermittent renewable resources. Based on historical records using USGS data (UCS, 2012) as described in Boehlert et al. (2016), we established wet, medium, and dry annual hydro supply conditions and for this paper we simulate a medium scenario.

Fossil fuel-based generation options include 12 conventional technologies. Their representation requires simplified cost and performance characteristics, minimum loading requirement, availability factors, forced outage rates, and heat rates for thermal plants. As noted earlier, costs include fixed and variable O&M, capital, start-up, and fuel. There is also a capacity reserve requirement to ensure long-term reliability of the system to unexpected peaks in demand, assumed to be between 10 and 18% depending on the region. Existing installed capacity per technology is represented in the base year 2016 as the total capacity for each technology in each region based on EIA form 860 and the EIA/AEO Reference Case.[12][13] We have generally assumed that technology costs, in the reference case, are those used by the EIA/AEO (2017) and ATB NREL (2019).[14]

Finally, we assume a prescribed annual demand path for electricity and fuel prices projections based on the EIA/AEO (2018). The most relevant ones being gas, coal, and nuclear fuel costs which rise slowly over time.

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[12] See Form EIA-860 detailed data at https://www.eia.gov/electricity/data/eia860/

[13] See EIA/AEO 2018 Reference Case electricity and renewable fuel tables at https://www.eia.gov/outlooks/archive/aeo18/supplement/excel/sup_elec.xlsx

[14] See details in https://atb.nrel.gov/electricity/2019/files/2019-ATB-data.xlsm

2.3 The Top-Down Bottom-Up Integration

The method to integrate the top-down general equilibrium model and the bottom-up chronological model is based on the decomposition algorithm laid out in Böhringer and Rutherford (2009). The first implementation of the approach in a large-scale computable general equilibrium model of the US economy is documented in Tuladhar et al. (2009). The description of the USREP-EleMod integration approach to achieving convergence in the electricity market is provided in Yuan, Tapia-Ahumada and Montgomery (2019b). To analyze an economy-wide carbon policy, we extend the approach to achieving convergence in the emissions market and provide detailed steps in this section.

2.3.1 Electricity Market

In USREP, the electricity sector is exogenized by converting a CES production function to a linear input-output representation parameterized based on electricity generation and input demand simulated by EleMod. In EleMod, a quadratic programming (QP) problem is formulated to incorporate demand response from USREP. The quadratic formulation maximizes the total surplus of the electricity market, i.e. consumer surplus and producer surplus taking into account overall costs of producing electricity by power suppliers, subject to system operational, security and policy constraints. In Equation 3, p_r^0 and d_r^0 denote a set of reference electricity price and demand in region r. ε_r^0 denotes demand elasticity. d_r and $Cost_r$ are regional electricity supply and total system cost determined by EleMod in response to a demand curve characterized by p_r^0, d_r^0, and ε_r^0.

$$Max\ Welfare = \sum_r \left(p_r^0 \cdot d_r \cdot \left(1 - \frac{(d_r - 2 \cdot d_r^0)}{2 \cdot d_r^0 \cdot \varepsilon_r^0} \right) - Cost_r \right) \tag{3}$$

Iterations between the USREP and EleMod involve passing back and forth electricity supply, fuel demand and prices information until both models converge. Figure 4 illustrates the iterative process and the information that each model needs to exchange in order to reach general equilibrium conditions.

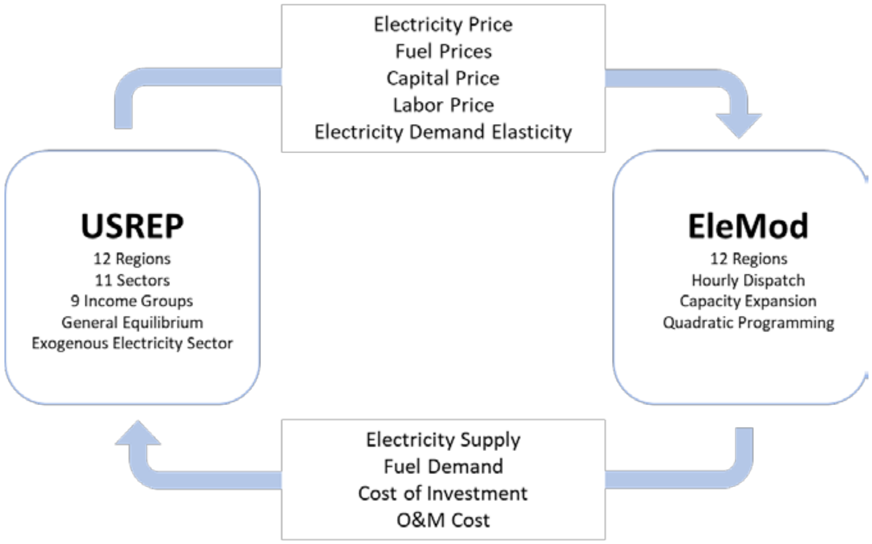

Figure 4: Coupling the TD and BU models – Information Exchange

For each year in the reference case, we feed the regional electricity supply and fuel prices based on EIA/AEO projection to EleMod which in turn determines generation by technology type, generation input demand (fuel demand, capacity investment, O&M costs) and electricity supply price comprised of generation cost, RPS compliance cost, cost of operating reserve and marginal reserve requirement. EleMod passes electricity supply, generation input demand and electricity supply price to USREP. While calibrating USREP to the electricity supply, electricity input demand as well as electricity supply price, we impose a zero-profit condition for the electricity sector by allocating the electricity sector profit/loss to household.[15] In such a sequence, we run the models in a two-year step to 2050 and achieve consistency between the models in electricity supply, generation input demand and electricity supply price.[16]

[15] Lacking information on ownership of the electricity sector, we allocate electricity profit/loss to households in proportion to capital income. The alternative is to treat electricity profit/loss as a collective investment gain/loss that contributes to or draws from the regional investment fund. Different treatment of profit/loss has different welfare implication.

[16] Rather than running iterations between USREP and EleMod in the reference scenario, we simplify the model linking process by calibrating USREP to EleMod without sending feedback in prices of fuel supply, capital and labor supply back to EleMod.

In the counterfactual scenario, the TD-BU model runs iteratively as illustrated in Figure 4. To a new policy regime, EleMod responds with changes in electricity supply, generation input demand and electricity supply price as a result of maximizing the total surplus of the electricity market characterized by reference electricity supply, price, and demand elasticity. We pass the updated electricity supply and generation input demand to USREP which produces a general equilibrium response in prices to both the change in policy regime and the changes in electricity supply and generation input demand. We then pass the changes in prices of electricity demand, fuel supply, capital and labor supply to EleMod and update the reference electricity price, fuel prices, fixed O&M cost and variable O&M cost, respectively.[17] In addition, we update the reference electricity supply in the quadratic objective function to be consistent with the reference electricity price. To speed up the convergence, we derive the electricity demand elasticity in USREP and update the elasticity parameter in the quadratic objective function in EleMod. The iteration between the TD and BU model continues until both models agree on electricity price.

Iteration between the models is important because demand for resources – fuels, capital, labor, and materials – in the electricity model must be communicated in a consistent way to the macro model to capture the market response given the limited supply of those resources in each time period. Likewise, the changes in prices must be communicated back to the electricity model to ensure consistency in economic dispatch decisions based on the updated generating technology costs. Given the different temporal resolution and databases of the two models, this is a nontrivial task.

2.3.2 Emissions Market

For carbon policy evaluation, it is straightforward to implement a carbon tax in the TD and BU model, however an economy-wide carbon constraint with emission trading between the electric and non-electric sectors requires convergence in endogenous carbon price determined by the TD and BU model. To achieve this, we extend the approach to electricity integration to incorporate carbon market response in the BU

[17] Since fuel prices are not calibrated in the reference case, we pass the percent change of fuel supply prices relative to the reference case from USREP to EleMod. Despite an omission in fuel prices convergence, this approach maintains consistency in fuel price response to generation fuel demand changes.

model. Specifically, we build an economy-wide carbon market in EleMod as an instrument to implement an emissions trading scheme between the electricity and non-electricity sectors. In EleMod, to meet a fixed emission cap, each additional reduction of the electricity sectoral emissions is equivalent to each additional non-electricity sectoral emission supply therefore the non-electricity emissions supply curve corresponds to the marginal abatement cost curve of the electricity emissions. Given exogenous electricity sectoral emissions, USREP represents the non-electricity emissions demand that captures the marginal abatement cost of the non-electricity sectors. With the non-electricity emissions supply associated with marginal abatement cost of the electricity sector and the non-electricity emissions demand associated with marginal abatement cost of the non-electricity sectors, we construct a market for the non-electricity emissions where the supply is represented in EleMod and the demand is modeled in USREP. This market is built in EleMod where the QP objective is augmented to include demand response to non-electricity emissions.

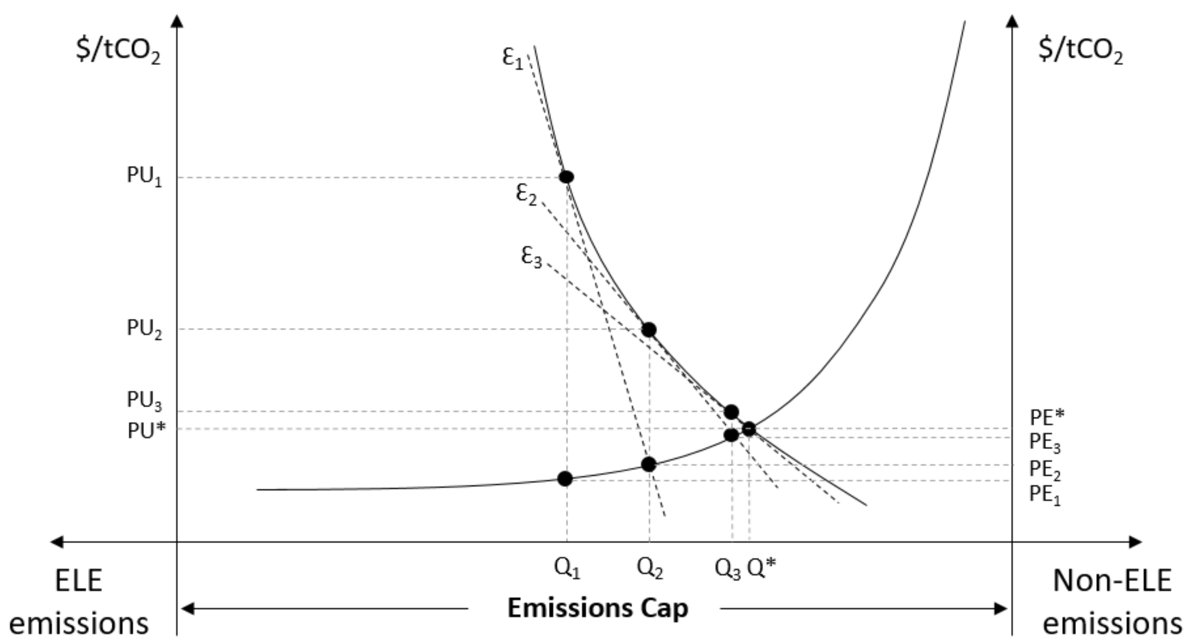

Figure 5: Non-Electricity Sector Emissions Market

The non-electricity emissions market is introduced to EleMod as an instrument to implement an economy-wide emissions trading scheme between the electricity and non-electricity sectors (see Figure 5). D and S denote the demand and supply curve, respectively. In each iteration, the equilibrium non-electricity emissions, marginal abatement cost associated with the electricity and non-electricity sectors, and demand elasticities are denoted by E, PE, PU, and Ɛ, respectively, with an iteration subscript. Price and quantity denoted with an asterisk indicates a converged solution where PU* equals to PE* at the non-electricity emissions level Q*.

Figure 5 illustrates an iterative process that involves passing the non-electricity emissions and carbon prices from USREP to EleMod, solving EleMod to establish an optimal level of the non-electricity emissions hence electricity emissions and pass the electricity emissions to USREP for another round of iteration until both USREP and EleMod agree on a set of endogenous carbon prices generated based on the marginal abatement supply curve of all sectors in the economy. The iterative process ends with convergence in carbon prices from USREP and EleMod. To speed up the carbon price convergence, we derive the non-electricity emission demand elasticity in USREP and update the elasticity parameter in the quadratic objective function in EleMod. The algorithm usually achieves good convergence within 6-7 iterations.

3 Scenarios

To examine the contribution of clean energy technologies on the mitigation pathways as well as cost to the economy taking into account resource adequacy and electric grid capacity, we construct scenarios that captures both the short-term economic response and the long-term adaptation and transmission of energy system to evaluate California's potential pathways to meet the midterm and mid-century decarbonization goals. These are designed to examine both policy costs and technology pathways in the State.

(1) (**REF**) The **Reference** Scenario reflects California's GHG emissions trajectory based on a limited set of policies established prior to 2015, drawing from the reference scenario from the E3 California Pathways model.[18] Key policies include:

18 https://www.ethree.com/projects/deep-decarbonization-california-cec/.

- Sales-weighted average LDV fuel economy of 35 MPG by 2020, 40 by 2025, 43 by 2030 and 46 by 2050;[19]
- 35% Renewable Portfolio Standards (RPS) by 2020, declining to 33% with retirements post-2030;[20]
- Deployment target of 5 million zero emissions vehicles in service by 2030;[21]
- Low-carbon fuel standards (LCFS) with 1.9 billion gallons of gasoline equivalent (GGE) biofuels by 2030.[22]

(2) (**DCT2030**) The **Deployment of Current Technology** scenario evaluates how the mix of commercially available energy technologies, deployed at-scale, may be used to meet many of the state's current low carbon policies. Key change in policies relative to the **Reference** scenario include:

- Economy-wide GHG emissions reductions of 20% by 2020 and 40% by 2030 from the 1990 level;
- State's RPS raised to 50% by 2026, 60% by 2030;
- State's Clean Energy Standard of 100% by 2045.[23]

(3) (**ATI2050**) The **Accelerated Technology Innovation** scenario builds on DCT2030 and evaluates the value of technology innovation on meeting California's long-term economy-wide emissions targets, and the state's 2045 target for carbon-free electricity, considering technologies that are not commercially available today, as well as conventional technologies deployed at-scale. Key policies include:

- Carbon free electricity generation by 2045;
- RNG feedstock as a perfect substitute for natural gas;
- Economy-wide GHG emissions reductions of 80% by 2050 from the 1990 level.

(4) (**CC**) The **Carbon Charge** scenario employs an economy-wide carbon charge that replaces all existing regulations and policies from the previous scenarios, including the 2017 extension of the state's cap and

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19 https://www.energy.ca.gov/2017_energypolicy/.

20 http://www.cpuc.ca.gov/RPS_Homepage/.

21 https://cafcp.org/content/workshop-governor%E2%80%99s-executive-order-b-48-18.

22 https://www.arb.ca.gov/fuels/lcfs/lcfs.htm.

[23] California's Clean Energy Standards is modeled as an electricity-only cap on carbon emissions. The model implements less stringent targets that start at 20% in 2020 and rise to 82.5% in 2045 and 95% by 2050.

trade program through 2030. The charge is set at a level needed to achieve the 80% emissions-reduction by 2050 and its associated revenue is returned back to households in a lump-sum fashion.

4 Results

In this section, we keep our focus on the role played by RNG in sectoral mitigation and the dynamic transition of the electricity system that is under several stringent policy measures. These results present the challenges to meet the proposed decarbonization targets as well as the opportunities created by innovative clean energy technologies that bear potential to achieve the mitigation ambitions, especially for the commercial transportation, refining and energy-intensive industries for which there are no clear pathways based on commercially available technologies.

Even with the CAFE and LCFS policies in place for low-carbon energy development for the transportation sector and a stringent RPS policy for the electricity sector, achieving the economy-wide emissions reduction targets is costly, starting at \$150/tCO_2 in 2020 and growing to \$220/tCO_2 by midterm (2030) and rising above \$400/tCO_2 by mid-century (2050) (see Table 2).

Table 2: Carbon Prices in California (2018\$/tCO_2)

	2020	2022	2024	2026	2028	2030	2032	2034	2036	2038	2040	2042	2044	2046	2048	2050
DCT_ATI	154	196	225	225	217	218	220	216	216	263	302	300	301	302	392	612

Carbon price alters the economic competitiveness of the low-carbon alternates compared to the conventional fuel sources. RNG in the study is considered as a low-carbon fuel that has zero life-cycle emissions. We treat RNG as a perfect substitute for natural gas and assume RNG costs twice as much as natural gas. Given its cost competitiveness relative to natural gas, RNG is not deployed in the REF scenario. In the DCT2030 and ATI2050 scenarios, RNG starts to become competitive against natural gas in 2026 and grows gradually to meet the increasing demand for the economy-wide emissions reduction requirement.

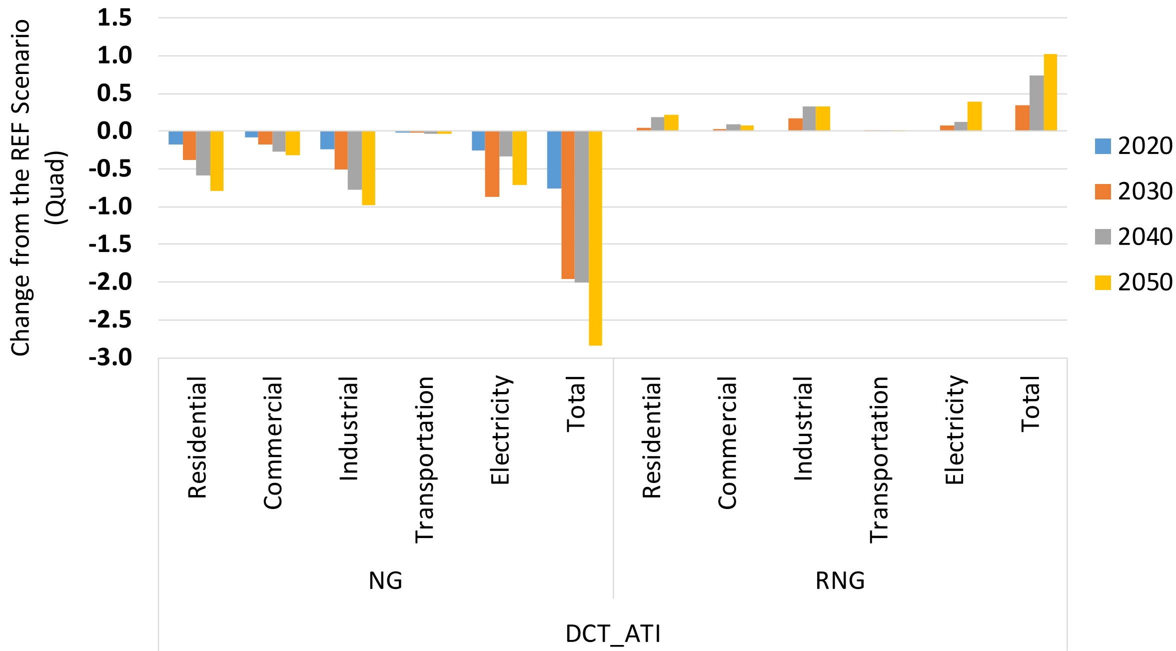

Figure 6: Change in Natural Gas and RNG Consumption by Sector (Quad)

Figure 6 shows the reductions in natural gas consumed in all sectors accompanied by the increases in a smaller magnitude in RNG consumption. In 2030, the industrial sector consumes half of total RNG supply. The electricity sector increases the consumption of RNG from about a quarter of total RNG supply in 2030 to about 40% in 2050. The residential and commercial building sectors quadruple RNG consumption over the ATI2050 period of 2030-2050. Compared to the REF scenario, total natural gas consumption falls by 2.8 Quads by 2050 whereas total RNG consumption increases by 1 Quad. Although RNG makes limited contribution by midterm (2030) its potential to cut emissions by displacing natural gas in various sectors by mid-century (2050) provides opportunities in developing mitigation strategies for long-term goals. Promoting early investment in low-carbon fuels like RNG could expedite the growth of its production, reducing the cost of long-term mitigation.

The electricity sector is a key component of ongoing California's decarbonization policies. The 60% renewable electricity target by 2030 and carbon-neutral electricity goal by 2045 reflect the aggressive policies that the State has adopted in order to reduce the sector's emissions and also support the decarbonization efforts of other end-use sectors. For this paper, we have introduced, in addition to wind and solar resources, other clean energy technology options such as Natural Gas CCS and Renewable

Natural Gas (RNG) based CTs and CCs which are expected to provide flexibility and reliability for the transition of the Californian energy system.

Figure 7 shows the electricity capacity mix evolution for the REF and DCT_ATI cases. In order to meet its 60% RPS target by 2030, CA has to rely on wind and solar resources but also Gas-CCS and RNG-Gas technologies. In our REF case, the low RPS requirement and the favorable economic conditions, make solar the technology the top choice to meet the surge of EVs by 2030.

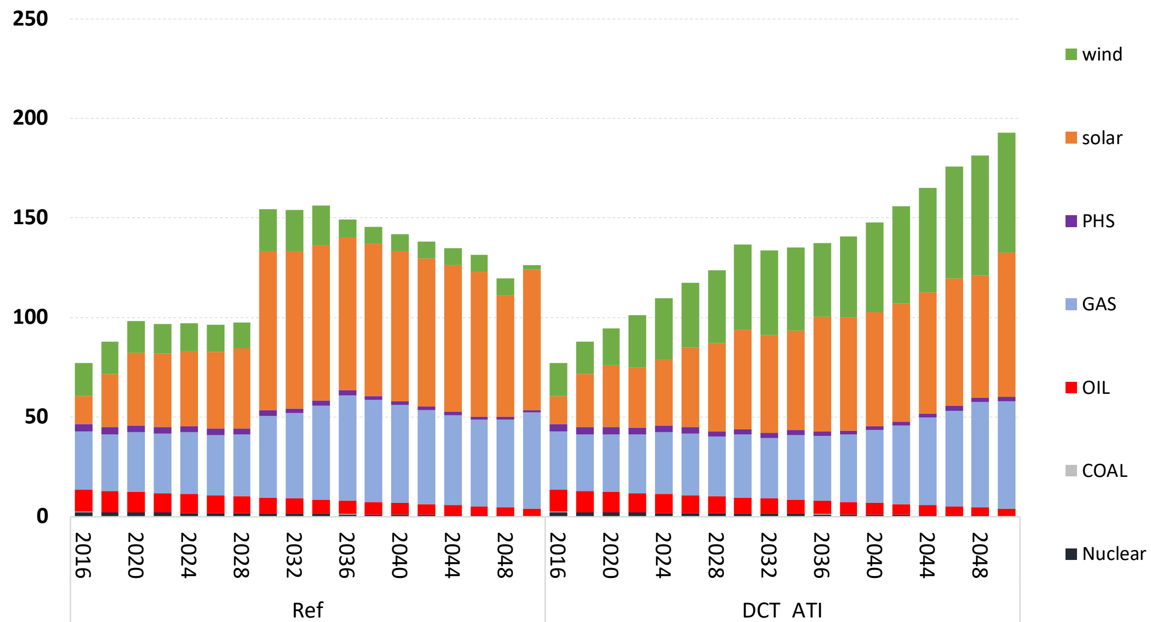

Figure 7: Evolution of Cumulative Power Capacity in the REF and DCT_ATI Scenarios (GW)

Figure 8 shows the annual generation per technology for the REF and DCT_ATI cases. We note that the combination of RPS 60% target by 2030 and the carbon-neutral goal of 95% by 2050 makes cleaner options to be part of the energy mix in particular Gas-CCS and RNG technologies. Also, we note that California relies on clean energy imports from neighboring regions. This is shown in the figure as the difference between electricity demand (black dots) and the stacked columns or also in Figure 8 which illustrates energy trade disaggregated by neighboring regions. Finally, our results show marginal increment of storage systems, as probably costs are too expensive and also because California heavily relies on energy trade which provides flexibility to the system.

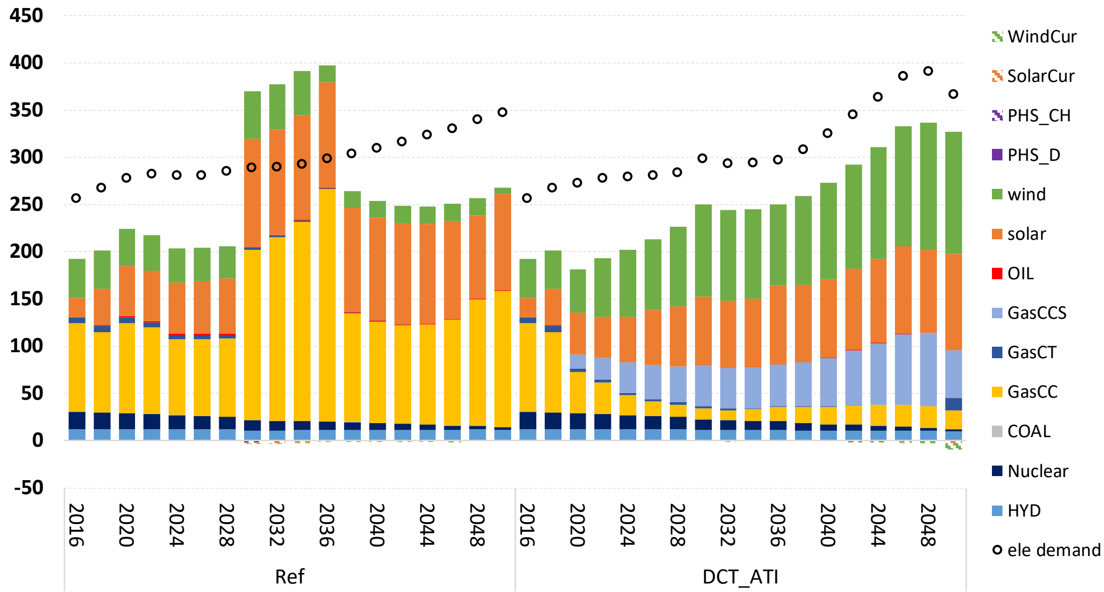

Figure 8: Evolution of Annual Electric Generation in the REF and DCT_ATI Scenarios (TWh)

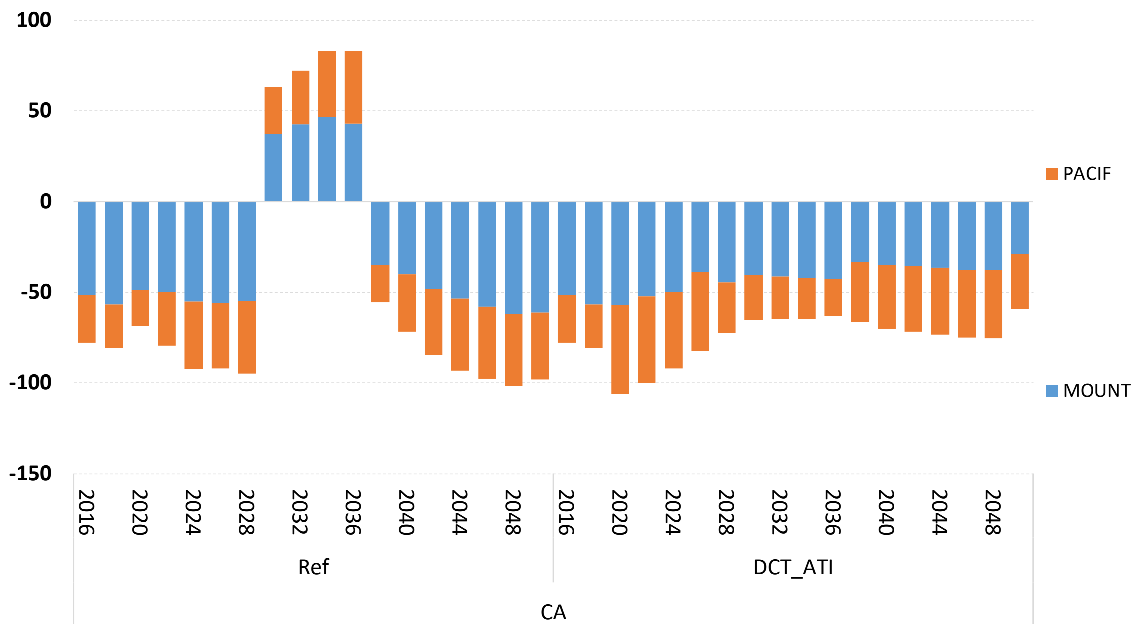

Figure 9: Energy Trade between California (CA) and Mountain (MOUNT) and Pacific (PACIF) regions, Imports to CA (-), Exports from CA (+) (TWh.Year)

These results highlight the need of California to keep relying on gas technologies in order to manage the increasing operational issues arising from an ever-increasing penetration of intermittent renewables. Both, natural gas and RNG are needed in the State to ensure reliability and provided much needed flexibility through technologies that use these fuels, as they can provide load-following capabilities, quick start-ups and ramp times (see Figure 10).

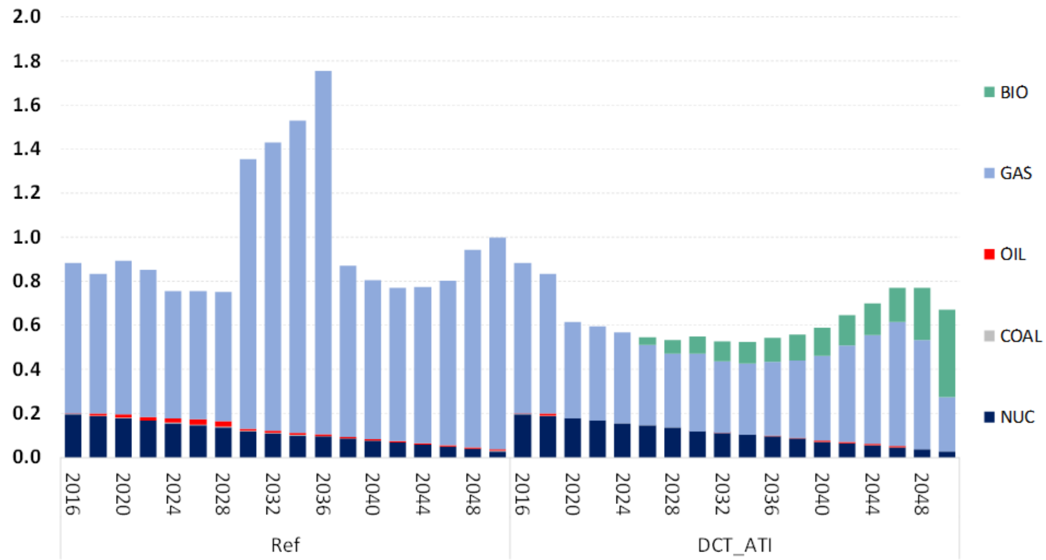

Figure 10: Fuel Demand from Power Sector in the REF and DCT_ATI Scenarios (Quad)

Achieving the economy-wide targets with complementary measures results in consumption loss as well as gross state product (GSP). Figure 11 shows consumption loss ranges from 0.1% in 2020 rising to 0.25% by midterm (2030) and about 1% by mid-century (2050). Relative to the REF scenario, GSP decrease by half a percent in 2020, 0.6% percent by midterm (2030) and 1.25% by mid-century (2050).[24]

As mentioned earlier in the section, early investment in low-carbon fuels such as RNG would reduce the cost of emissions mitigation in the long run. Designing a mitigation pathway that takes into account the

[24] The economic cost estimates do not include health benefits from emissions reduction.

potential of innovative clean energy technologies is crucial in balancing the needs to archive mitigation goals while minimizing the cost of the economy.

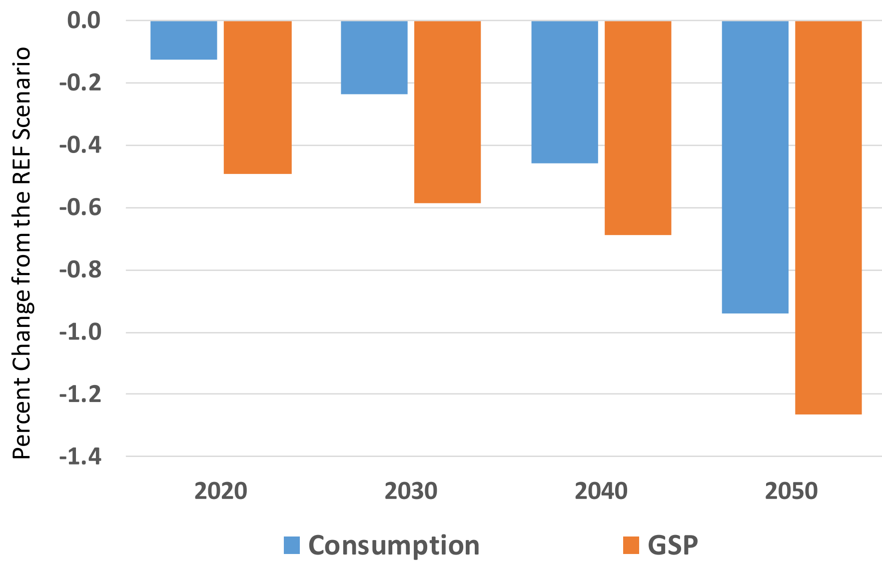

Figure 11: Impact on Consumption and Gross State Products in the DCT_ATI Scenarios (Percent Change from the REF Scenario)

5 Conclusion

California's aggressive long-term decarbonization targets (80% economy-wide reduction by 2050 and carbon-free electricity by 2045) will require further technology innovation. The electricity sector will play a key role as it will support the decarbonization of other end-use sectors such as transportation and buildings. The transportation sector in particular (accounting 40% of total emissions) will need to rely on the massive deployment of electric vehicles; increasing vehicle fuel efficiency; use of cleaner alternative fuels, etc. In the case of other sectors, the use of RNG for example will be critical to meet carbon-free requirements in addition to providing needed flexibility because of the increasing deployment of variable intermittent renewable resources. In the case of the electricity sector, RNG and CCS technologies will be needed to enabling the growth and integration of wind and solar at scale.

Our results suggest the following:

- In the reference scenario (REF) –based on the set of policies mostly established prior to 2015– state-wide carbon emissions result in about 4% emissions increase in 2030, and 6% in 2050 (compared to 2020). The effectiveness of RPS and fuel efficiency standards ZEVs is mostly seen in the years before 2035, after which emissions start increasing because of the economy and electricity demand growth.
- In the near-term scenario (DCT2030) –based on a mix of already commercially available energy technologies, a 60% RPS target, and an economy-wide 40% emissions reduction target by 2030– RNG see some deployment as it becomes competitive relative to NG. By 2030, 40% of total RNG supply are consumed by the industrial sector. Emissions reductions are due to decline in primary energy consumption energy (mostly transportation sector). The electricity sector relies mostly on solar and wind, although we see an increase in gas capacity needed to provide long- and short-term reserves to allow the integration of more renewables into the system. In terms of generation, we note the take up of Gas-CCS and continuing reliance of electricity imports from neighboring regions.
- In the long-term scenario (ACI2050) –based on an economy-wide 80% emissions reduction target by 2050 and carbon-free by 2045 of the electricity sector– we note that the stringency of the policies adopted results in rising marginal costs of abatement expected price is close to \$220 per tCO_2 and by the end of the time horizons above \$400 per tCO_2. RNG gradually grows to meet carbon-free fuel demand from different sectors, in particular the electricity sector. By 2050, total NG consumption falls by 2.8 Quads whereas total RNG increases by 1 Quad. In addition to wind and solar, the electricity sector increases the use of RNG and CCS technologies as a substitute of conventional natural gas Combined Cycles and Combustion Turbines.

These results present the challenges and imply the opportunities for alternative mitigation pathways to be explored. The macro impacts of the mitigation policies currently proposed suggesting that designing a mitigation pathway take into account the potential of innovative clean energy technologies is crucial in balancing the needs to archive mitigation goals while minimizing the cost of the economy.

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