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Path to 100% Renewables for California

WÄRTSILÄ WHITE PAPER

Meeting California's goal of 100% renewable electricity by 2045 while also ensuring affordable and reliable power is a tremendous challenge. This white paper explores a new path that would enable California to meet its goal of 100% clean electricity by 2040 — five years ahead of schedule — slashing greenhouse gas emissions and air pollution along the way. Compared to current plans, this path optimizes the number of wind farms and solar installations built in the state, saving billions of dollars and alleviating land-use and grid construction pressures. The proposed pathway features flexible thermal generation that can run on carbon-neutral fuel produced with excess solar and wind energy. Together with energy storage, flexible generation can ensure affordable, reliable electricity supply and a net-zero-carbon future.

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Executive Summary

California has ambitious goals for decarbonization, including a Renewable Portfolio Standard (RPS) that relies heavily on solar, wind and battery storage. The RPS requires that by 2045 at least 60% of electricity will come from solar, wind and other carbon free sources, while the remainder can be supplied from carbon neutral sources. Yet the RPS still allows for fossil-thermal generation in 2045 and beyond to cover grid losses. This study explores an Optimal Path for California to decarbonize the electricity sector completely, and compares it to alternatives, including the current Integrated Resource Plan (IRP).

The Optimal Path builds out renewables and battery storage faster than the IRP, or California's Current Plan, and during the final years of the study period leverages power to gas (PtG) to produce renewable fuels using excess solar and wind energy that would otherwise be curtailed. As fossil fuels are phased out, thermal assets convert to renewable fuel to form a large, distributed long-term energy storage system with durations of weeks, not hours, providing seasonal balancing and security of supply during extreme weather events. Benefits of this approach include reaching RPS goals by 2040, five years ahead of schedule, and net-zero carbon by 2045. The Optimal Path leveraging power-to-methane is accompanied by the following features relative to the current (IRP) plan;

- Reach RPS target by 2040, and fully decarbonize by 2045
- 124 Million tons less CO2 emitted during 2020-2045
- 8 BUSD lower cost
- Significantly less NOx and particulate emissions (2020-2045)
- Requires 2/3 of the land for solar and wind development relative to the current RPS plan
- Allows for consideration of flexible thermal capacity today on a strategic basis, while respecting the falling share of fossil generation in accordance with the goals of decarbonization
- Enables closing of the OTC plants in 2023
- Avoids GW's of thermal capacity (and natural gas infrastructure) from becoming "climate stranded" while maintaining reliability in a cost-effective manner

An alternate Optimal Path was also considered leveraging power to hydrogen instead of methane. Many of the advantages listed for power to methane hold true for power to hydrogen. A hydrogen alternative has allure because it is truly carbon free, but still faces challenges. Challenges include lack of hydrogen infrastructure.

For the state of California to realize the benefits of power to gas as defined in this study the following policy recommendations are required;

- Formal recognition of all renewably sourced carbon-neutral and carbon-free fuels as "renewable fuels" for RPS compliance purposes (beyond just biofuels).
- Close OTC plants according to original retirement schedules (no extensions)
- Deployment of the optimal mix of new generation sources, described as the Optimal Path throughout the study, which includes solar, wind and energy storage as well as strategic amounts of fast-start flexible thermal generation (Table 5).

Introduction

California is a global leader in clean energy. Current plans include a renewable portfolio standard (RPS) that sets a 60% carbon-free target by 2030, then transitioning to 100% clean energy by 2045. The 2045 goal requires all MWh for retail sales within the state to be met with zero or net-zero carbon energy sources.

California (CA) has set ambitious goals but several key challenges exist that are addressed throughout this study. These challenges are primarily related to minimizing the cost of power while maintaining security of supply with the increased variability in energy production from clean energy sources such as solar, wind and hydro. California has amazing solar potential, but the solar output varies during the day and is zero at night. In order to maintain reliability through the coming years legacy thermal plants (once-through cooling, or OTC facilities) have already been given retirement extensions, allowing them to emit carbon beyond their original retirement dates.

Seasonally solar production is maximized in summer months and minimized in winter due to differences in solar intensity and day length. Wind in California also follows seasonal patterns with maximum output occurring in mid-year (Figure 1). Unlike solar, wind also generates at night. Hydro power is also available, but has seasonal patterns related to rainfall and is subject to multi-year patterns related to drought conditions (Figure 1).

California is reliant on these three dominant carbon-free energy sources (solar, wind, hydro) to meet it's clean energy targets, and must carefully consider how to build out its electrical system to optimize utilization of these resources, maintain reliability, and to minimize both cost and environmental impact along the way. Key to this process is the design and implementation of storage systems, both short-term and seasonal (e.g. Jenkins et al. 2018).

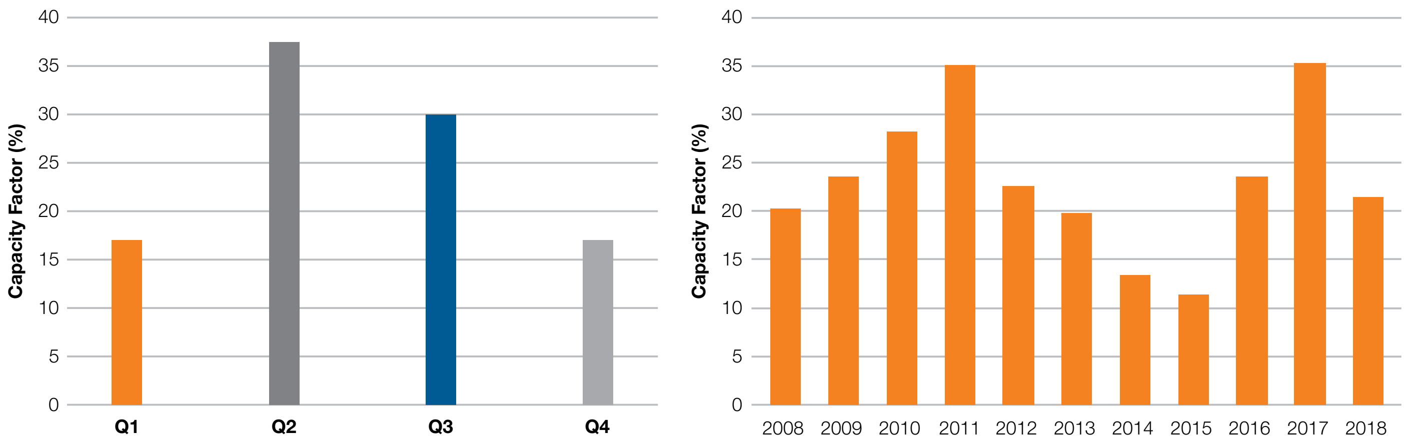

Figure 1. Wind capacity factors by quarter for California, left (CEC, 2019a), Annual California hydro capacity factor, right (CEC, 2020).

California hydro production is dependent on drought conditions. A multi-year drought left hydro production in 2015 at less than one third of peak year productions in 2011 and 2017. This emphasizes that the power system needs to be dimensioned so that it can handle these dry years.

This study compares three potential pathways for CA to meet its climate goals in the electric utility sector, with a focus on energy storage systems, cost and environmental impact.

The **first pathway**, called **Current Plan**, follows the existing Integrated Resource Plan (IRP) process through 2030 and extrapolates to 2045 under the assumptions and guidelines of the RPS (high electrification scenario). This pathway is heavy on solar and some wind, and traditional energy storage, and as per the RPS does not reach full carbon-neutrality by 2045. It does not reach carbon neutrality because the RPS allows fossil-generation to cover grid losses, which are approximately 8% of the total annual load for the state of California.

The **second pathway**, called **Optimal Path**, optimizes the entire system until 2045, and explores the power-to-gas (PtG) process as a long-term storage alternative, both power-to-methane (PtM) and power-to-hydrogen (PtH) - read more on this later in the Power-to-Gas section. The Optimal Path achieves RPS goals five years ahead of schedule (2040 instead of 2045) and reaches total carbon-neutrality by 2045.

In the **third** pathway called **Current Plan without Fossil Thermal,** California reaches carbon-neutrality by 2045 without any combustion of fuels other than biomass and biogas.

Following the current RPS, all scenarios ensure that by 2030 at least 60% of energy provided to consumers in California is carbon-free and provided directly by solar, wind and hydro.

Analytical Approach

This power system Study has been conducted utilizing PLEXOS® Energy Simulation Software. Plexos has a robust simulation capability across electric, water and gas systems focusing on full user control, transparency and accuracy across numerous constraints and uncertainties. This software is widely used by system operators (including CAISO), utilities and consultants for power system analysis as well as system planning and dispatch optimization.

Plexos is capable of long-term capacity expansion optimization applied in this study. Capacity expansion models find the least cost generation capacity mix for a power system for the future. That is, the software selects the best fit technologies among the given candidates to satisfy the future electricity demand while respecting real-life constraints related to power plant operations and transmission. To properly calculate costs and emissions, the software solves the hourly dispatch of power plants throughout the studied period while making new capacity additions.

The model used in this study is based on the Plexos model used by the California Independent System Operator (CAISO) and Western Electricity Coordinating Council (WECC) to support the 2019 IRP as well as the IRP 2019 modelling datasets (CPUC 2019a, b). These sources provide necessary inputs for the expansion optimization, including existing generation capacity with their parametrization, system demand now and in the future as well as financial inputs from fuel prices to the investment cost of new generation capacity.

The modelled power system covers California, North-West (Oregon, Washington, Idaho etc.) region, and South-West (Arizona, Nevada, New Mexico etc.) region, with their load, generation capacity and transmission constraints being accounted for between the regions. The neighbouring states are important to incorporate in the model because of California's dependency on imported electricity. More information regarding demand and capacity can be found in the Appendix.

The software can select new generation capacity additions from several potential technologies during the expansion optimization. These include solar, wind, biomass, geothermal, Reciprocating Engines, Gas Turbines (GT), Combine Cycle Gas Turbine (CCGT), Lithium-Ion storage, pumped hydro, and Power to Gas (PtG) fuel synthesis systems. Performance, cost and parameterization of all potential new-build decisions are presented in the Appendix.

This expansion optimization approach was applied to all studied future scenarios. Each scenario was modelled across a 25-year horizon by explicitly solving 2022, 2026, 2030, 2035, 2040 and 2045 dispatch. The model optimizes the capacity needed and the power system operation for these years. Selecting specific model years as opposed to every year across the horizon made the simulation tractable, while within each year the model was run at two-hour time resolution.

For accurate insights in California, the reported results are isolated for the state of California even though the neighbour states were also modelled and optimized. Results include capacity additions, costs, generation across all fuel classes, overgeneration or curtailed renewable energy, CO_2 emissions, other air pollutant emissions such as NO_X and particulates, and land-use.

NEIGHBOURING STATES HAVE RENEWABLE TARGETS OF THEIR OWN

At present California is reliant on neighbouring states for approximately 32% of all electricity used by Californians (CEC, 2019b). Neighbouring states can absorb excess energy (overgeneration) from Californian renewable energy sources (RES) such as wind and solar and provide needed flexibility to California via the Energy Imbalance Market (EIM). Questions arise over the ability and willingness of neighbours to provide this flexibility service when they are all moving towards similar RPS standards as California (Figure 2). In this study it was assumed that all the neighbouring states would decarbonize their power systems by 2045 and thereby large quantities of fossil fuel based balancing power would not be available for California from them.

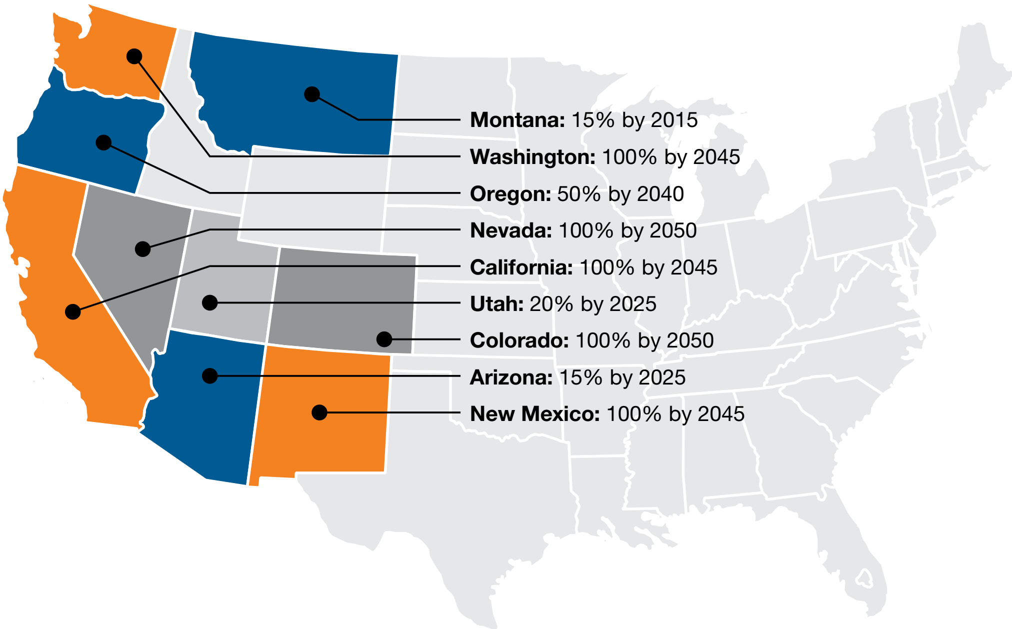

Figure 2. Current clean energy targets for States in the Western United States. These are expected to continue to become more and more stringent.

Summary of Scenarios

The scenarios – or pathways – are summarized in Table 1

	Current Plan – the state's current plan	Optimal Path	Current Plan without Fossil Thermal
Full RPS compliance date	2045	2040	2045
Fossil fuels in use after 2045?	Yes	No	No
Net-Zero carbon by 2045?	No	Yes	Yes
OTC retirement date extensions?	Yes	No	Yes
Thermal investments limited	Yes (selected OTC capacity replacement with thermal and peakers for firm capacity)	No (thermal added as per system optimization but still respecting other RPS constraints)	Yes (selected OTC capacity replacement with thermal and peakers for firm capacity). No fossil fuel thermal allowed in 2045
Existing CCGTs retire at the age of 35 years	Yes	Yes	Yes

Table 1. Main features of the scenarios.

Power-to-Gas (Power-to-Methane, PtM)

Unique to the Optimal Path (Table 1) is allowance for power-to-gas (PtG), which here is defined as the process of using excess RES energy, MWh that would otherwise be curtailed, to produce renewable fuels. The first such fuel to consider is methane, produced through the power-to-methane, or PtM process. PtM produces carbon-neutral CH4 (methane) via a three-step process.

1. Direct Air Capture (DAC) of CO_2 from the atmosphere as a source of carbon
2. Electrolysis of water as a source of hydrogen
3. Methanation to combine carbon and hydrogen into CH4

The final molecule, CH4 (methane) can be stored and transported in existing natural gas infrastructure and used in households, industries and power plants by any thermal technology that can burn natural gas. Carbon is recycled from air, so combustion of PtG methane is net-zero, or carbon-neutral, with no increase in atmospheric CO_2 levels.

While PtM, or power to fuels in general, is not currently used at mass-scale, they are a major avenue for deep decarbonization, particularly in the transportation sector. The processes of electrolysis and methanation are decades old technologies with numerous commercial applications. Direct air capture (DAC) of carbon is the newest technology involved with the PtG process, with several large-scale projects under development. For example Carbon Recycling International is developing a large DAC facility in China that will produce 180,000 tons per year of liquefied natural gas (LNG) and methanol (Carbon Recyling International, 2019). Carbon Engineering is actively developing a 1 million ton per year DAC carbon capture plant in Texas for enhanced oil recovery, where CO_2 taken from the air will be pumped into the ground for permanent sequestration, and help to enhance oil production (Rathi, 2019). The California Low Carbon Fuel Standard (LCFS) was amended in 2019 to include DAC, allowing companies to net carbon sequestered from air from the carbon footprint of fuels sold into the California market.

Power-to-Gas (Power-to-Hydrogen, PtH)

Power-to-hydrogen is an alternate PtG pathway. Power-to-hydrogen requires only electrolysis, where electrolyzers use excess renewable energy to produce hydrogen (from water) for direct use as a fuel. Hydrogen production with PtH is less expensive than PtM and more efficient as there is no need for carbon DAC or methanation. In addition, hydrogen as a fuel is carbon free. Complexities arise as there is, unlike the existing infrastructure for methane, no comparable hydrogen infrastructure. Thermal power plants designed to burn methane typically cannot burn 100% hydrogen. Existing gas storage facilities, pipelines, compressor stations and distribution lines typically cannot handle 100% hydrogen without expensive upgrades, if not complete replacement. Still, hydrogen is an efficient and carbon-free alternative to renewable synthetic hydrocarbons and is worth investigating. Power plant technology manufacturers seem to understand this as many of them are in the process of developing technologies that are fuelled by 100% hydrogen.

Why Power-to-Gas?

Renewable fuels from PtM or PtH processes are not economic relative to low-cost fossil fuels prevalent in the United States. However, in a 100% carbon-neutral power system, where fossil fuels are banned, PtG and its use in existing or new built thermal power plants is considered a form of long-term storage (e.g., (Blanco & Faaj, 2018)). The thermal fleet coupled with gas storage and delivery systems becomes a gigantic distributed "battery". Fuel produced by PtG can be stored indefinitely and is the equivalent of fully charged "cells" in a Li-Ion battery storage system. Thermal power plants become the "inverters", taking stored renewable energy and converting it to MWh. In power system operations renewable energy will serve the majority of load, traditional storage (e.g., batteries) will handle day to day balancing, and PtG coupled with the thermal fleet provides longer term balancing (e.g., seasonal) and reliability (e.g., generating MWh when unforeseen weather leads to days or weeks of little to no solar that cannot be managed with traditional, shorter term storage).

Scenario findings

The first portion of findings will observe and compare the results of California's Current Plan and the Plexos optimized Optimal Path for the state. The third scenario, Current Plan without Fossil Thermal, is further studied in a separate section.

Optimal Path minimizes capacity buildout

"Our grid needs to go on a diet and get leaner and greener" - NRDC (Chen, 2017)

The installed generation and storage capacity for California is depicted in Figure 3 for the Current Plan and the Optimal Paths. All three scenarios meet the RPS target of 60% energy from clean energy sources by 2030 and meet load and other requirements of the High Electrification scenario all through the period. Old CCGT´s retire at age of 35. For the Current Plan the capacity additions are mainly solar and battery storage, although wind and small amounts of geothermal and biomass are added as well.

The Current Plan requires 263 GW of capacity in 2045 while in the Optimal Paths with PtM and PtH require 237 and 231 GW of capacity respectively. (Figure 3). The Optimal PtH pathway installs almost twice as much power to gas capacity than the PtM pathway, an artefact of PtH production capacity being less expensive, and the PtH fuel production being more efficient than PtM.

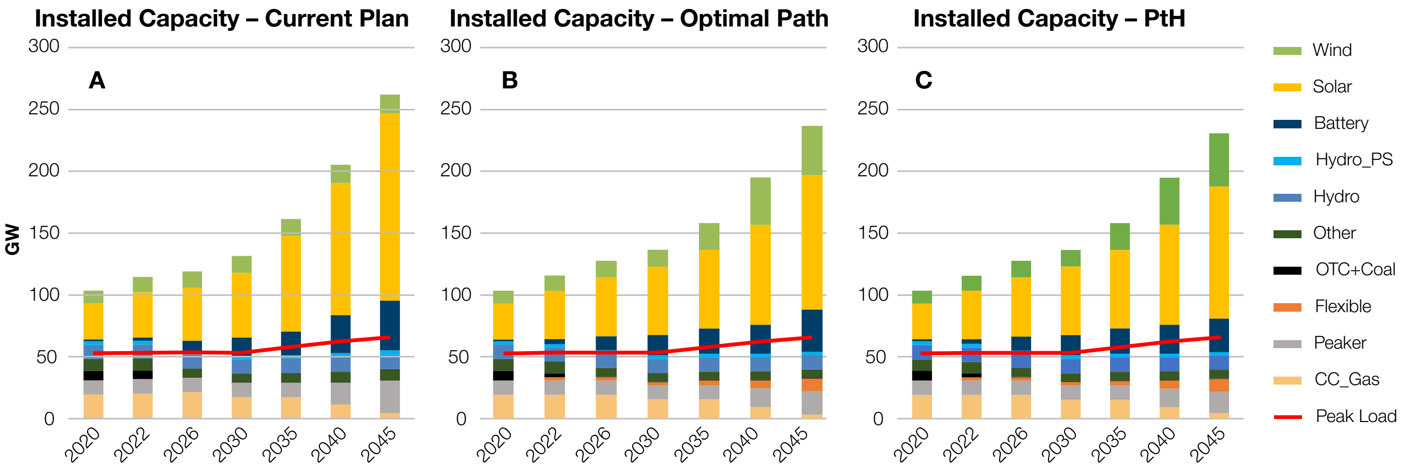

Figure 3. Capacity mix for Current Plan (A), Optimal Path PtM (B) and PtH (C) 2020-2045.

Optimal Path minimizes carbon emissions and reaches net-zero by 2045

"The report finds that limiting global warming to 1.5°C would require…'net zero' around 2050." (The Intergovernmental Panel on Climate Change, 2018)

The Optimal Path has a reduced carbon footprint across the entire horizon relative to the Current Plan (Figure 4). This is due to OTC retirements occurring on schedule (no delays) and earlier replacement of inefficient, inflexible thermal capacity with a wider array of clean energy sources, storage and flexible thermal. The addition of greater amounts of wind in the Optimal Path (Figure 3B & 3C vs. 3A) also allows for additional renewable generation at night, displacing MWh that would otherwise be generated with thermal in the Current Plan.

In the Optimal Path carbon emissions reach net-zero in 2045, while the Current Plan does not reach zero at all (as per the IRP). This is because the IRP allows for grid losses to be produced with fossil fuels even in 2045. The cumulative carbon reduction with the Optimal Path, using either PtM or PtH, is approximately 125 million tons of CO_2 (Figure 4) compared to the Current Plan, corresponding to annual equivalent CO_2 emissions of approximately 27,000,000 cars (assuming 4.6 tons per year of CO_2 from a vehicle as per the EPA, 2020a)

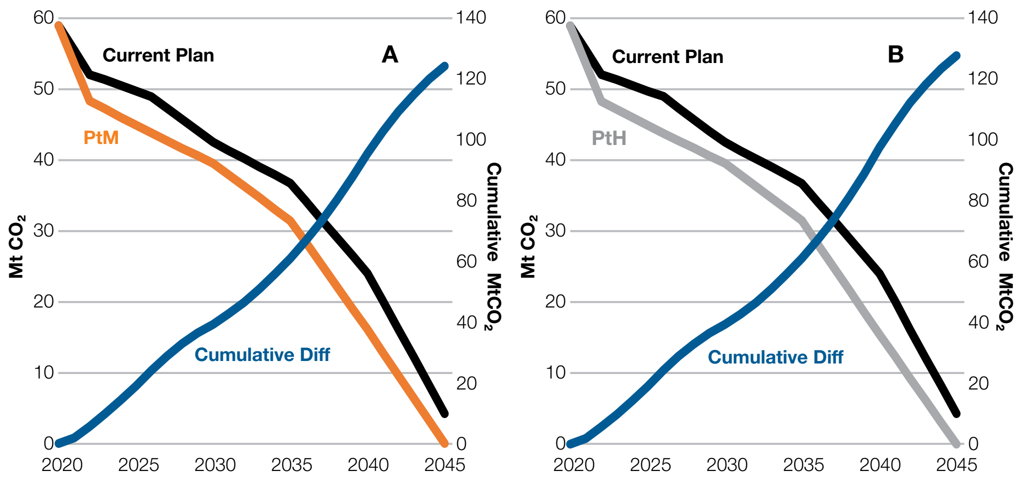

Figure 4. Annual CO_2 emissions for Current Plan and Optimal Path PtM (A) and PtH (B) across 2020-2045, and the cumulative emissions savings with Optimal Path.

Optimal Path minimizes emissions of NO_X and Particulates

"NO_2 along with other NO_X reacts with other chemicals in the air to form both particulate matter and ozone. Both of these are also harmful when inhaled due to effects on the respiratory system." US EPA (2020b)

Fuel combustion emits hazardous pollutants independent of CO_2 generation. To that end it is of interest to understand the contribution of PtG in 2045 in the Optimal Path to emissions of Nitrogen Oxides (NO_X) and particulate matter (PM10), and to explore the trajectories of these emissions across scenarios.

Annual flow rates were calculated using thermal generation (MWh by year) and the following rates on a "per MWh" basis for modern gas plants.

NO_X (as NO_2)	0.08 Lb/MWh
PM10	0.10 Lb/MWh

These values are indicative of gas generation in general and not meant to represent any specific technology.

All pollutants in 2045 are significantly reduced relative to 2020 (Figure 5). In both the Current Plan and Optimal Path thermal generation is all gas and provides less than 10% of all electricity in 2045. Current Plan NO_X and PM10 levels are reduced by 86% relative to 2020 levels. In comparison the Optimal Path levels are reduced 82% relative to 2020 levels. The emissions reductions are similar except for one major difference: The Optimal Path is net-zero carbon and in compliance with IPCC recommendations related to climate change in 2045, the Current Plan is not.

Values in Figure 5 are for the PtM pathway but are assumed similar for the PtH pathway. A lack of publicly available emission rates from CTs or ICEs on 100% hydrogen makes calculation difficult, but hydrogen burns hotter than CH4 and produces greater amounts of NO_X per unit of fuel burned. Therefore, the values presented for PtH pathway are assumed at a minimum to be similar to that from PtM.

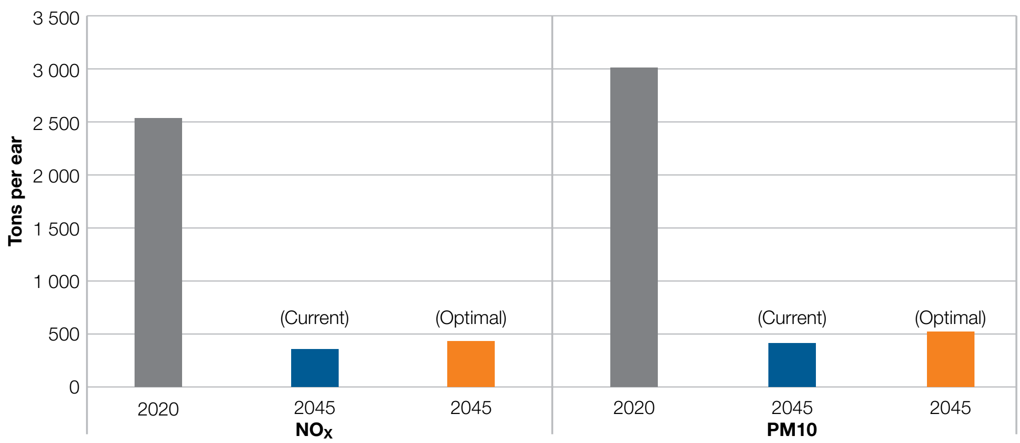

Figure 5. NO_X and PM10 emission rates (metric tons/year) in 2020 and 2045 for Current Plan and Optimal Path.

Optimal Path minimizes curtailment of solar and wind

"Solar and wind developers need to be able to sell nearly all the electricity they produce to repay their investors and make money."- NRDC (Kwatra, 2018)

A major difference between the Current Plan and Optimal Path is a dramatic reduction in curtailment of solar and wind across the horizon and in particular at the end of the period when the Optimal Path becomes 100% carbon-neutral (Figure 6). In the middle phase of the transition, more flexible thermal capacity is available in the Optimal Path to support renewables and to reduce curtailment. Towards the end of the horizon (2045) the PtG capacity acts as additional load to be served specifically by over-generation of solar and wind. Therefore, by design the Optimal Path maximises the use of renewables.

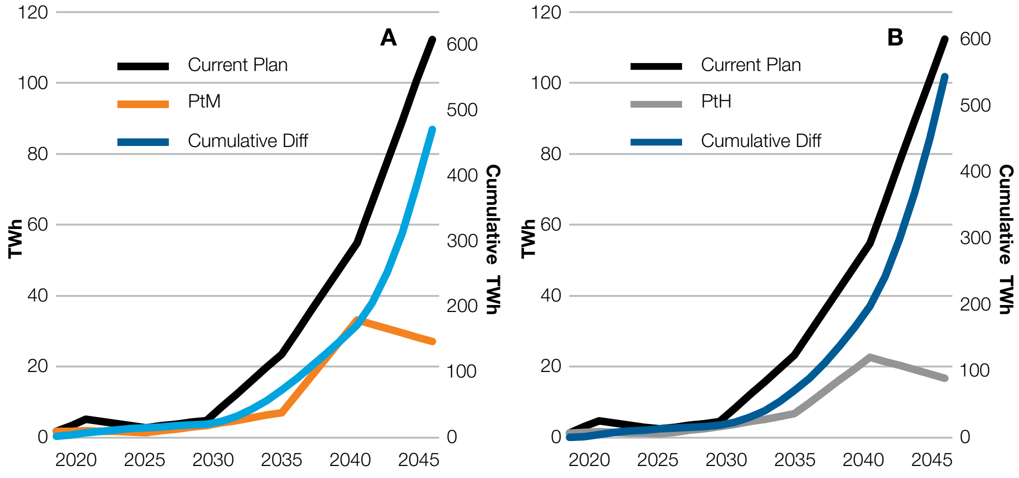

Figure 6. Annual curtailment (overgeneration) of solar and wind for the Current Plan and Optimal Path (left scales), and cumulative difference of curtailment (right scales), for PtG (A) and PtH (B).

Optimal Path minimizes land use

"Habitat loss—due to destruction, fragmentation, or degradation of habitat—is the primary threat to the survival of wildlife in the United States." (National Wildlife Federation, 2020)

Deep decarbonization by necessity means large volumes of solar and wind capacity to provide energy, either directly or indirectly through storage mechanisms. Solar and wind, however, require a lot of land. Solar on average needs approximately 5 acres per MW (Green Coast, 2019) while wind requires roughly 0.75 acres per MW (Gaughan, 2018). Every solar or wind project will have to undergo rigorous environmental impact assessments, permitting and grid connection. The more sites and land needed for renewable development, the greater the risk of delays. The Optimal Path using either PtM or PtH requires approximately 300 square miles less land for renewable development (Table 2).

	Optimal Path PtM	Optimal Path PtH	Current Plan
GW Solar (Residential)	34	34	34
GW Utility-Scale Solar	76	73	118
GW Wind	40	43	16
Land Use (Utility-Scale Solar), sq. miles	594	570	922
Land Use (Wind), sq. miles	47	50	19
Total Land Use utility-scale solar & wind (sq. miles)	641	621	941
Additional Land needed vs Optimal Path	-300	-320	

Table 2. Calculated land use for the Optimal Path and Current Plan.

Optimal Path minimizes total cost to decarbonize the electric utility sector in California

"Californians are paying Billions for power they don't need" - LA Times (Penn & Menezes, 2017)

At present Californians pay some of the highest prices for electricity in the nation (Daniels, 2017). As California moves towards aggressive decarbonization, the state faces the challenge of doing so in the most cost-effective manner. As with any optimization problem, adding more choices, or more degrees of freedom, often results in better solutions than those obtained with a narrower range of choices. The results for the Optimal Path and especially the introduction of PtG demonstrate this concept, as the Optimal Path allows the simulation to unlock the value of thermal capacity in a 100% carbon-neutral future. The Optimal Path PtM provides lower cost than the Current Plan across the horizon 2020-2045 (Figure 7), yielding a net savings of 8 Billion USD. The Optimal Path PtH provides initial savings but then added costs towards 2045 as all thermal capacity in CA must be retired and replaced with new capacity capable of burning 100% hydrogen, in order to be in line with CA clean energy goals. Total saving is however 3 Billion USD compared to Current Plan, excluding the cost of the hydrogen grid.

Total generation cost includes OpEx (fuel and other variable costs), CapEx (capital costs and other fixed costs), interchange costs (costs of purchased imports, revenues from exports, and associated wheeling charges), and estimated transmission expansion costs. The costs do not include any carbon taxes. In the year 2045, the levelized cost of electricity for the Optimal Path is 50 $/MWh (PtM) and 54 $/MWh (PtH), in comparison to 51 $/MWh for the Current Plan. Note: CapEx of the existing power system (in 2020) is not included, but CapEx of all new plants installed during the period is included. This gives a false impression of costs increasing rapidly.

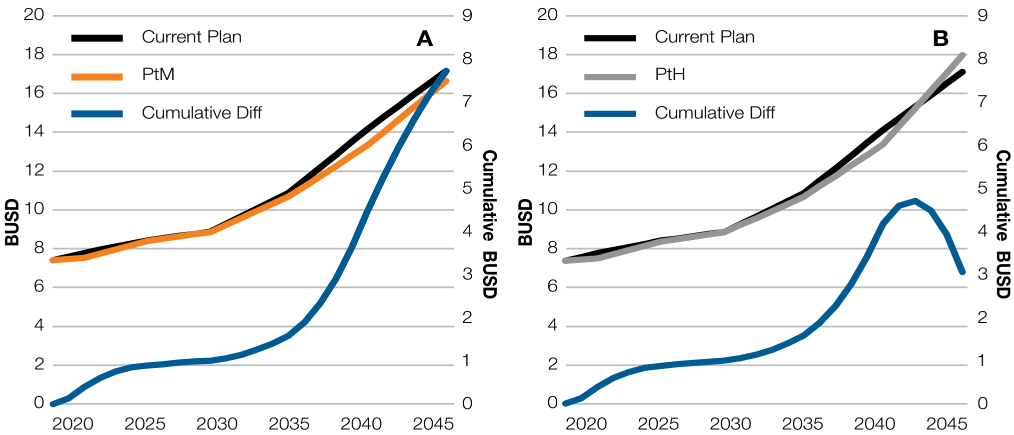

Figure 7. Annual total generation cost of Optimal Path and Current Plan, and cumulative savings of Optimal Path versus Current Plan via PtM (A) and PtH (B). Note: 2020 cost is only OpEx while the cost after 2020 includes both CapEx and OpEx of the new investments.

Optimal Path maximizes storage capacity through use of power-to-gas

"The optimised mix of short-term battery storage and long-term power-to-gas (PtG) storage leads to the least cost system solution for 100% RE" (Breyer, Fasihi, & Aghahosseini, 2019)

The major differentiating factor of the Optimal Path is the use of PtG as a long-term storage, to manage weather periods during which solar, wind and possibly hydro output are out of phase with demand. Traditional energy storage systems, ranging from Li-Ion batteries to pumped hydro, rarely exceed durations of 12 hours while seasonal weather-related events in renewable dominated systems can easily lead to far longer periods of diminished renewable outputs. Storage must cover the differences, and a diversified portfolio of storage optimized for different timescales is an optimal choice as shown in the cost, carbon trajectory and land use considerations outlined in previous sections.

Some advocate for pumped hydro as a long-term storage solution. Pumped hydro was included as a capacity choice in the simulations that the model could choose if it was an optimal candidate for new-build. Price and performance for pumped hydro was provided by the IRP documentation. Across all four scenarios pumped hydro was installed between 285 GWh (same in optimal path PtM and PtH pathways) and 333 GWh (Current plan without thermal). Therefore, pumped hydro is included as new build capacity in all scenarios. However, in the current plan without thermal, the majority of energy storage selected by the model was battery storage (1624 GWh). This is due to batteries having a lower cost ($/kW) and higher round trip efficiency than pumped hydro. For the Optimal path (both PtM and PtH) the model selects renewable fuels as the preferred long-term storage option.

POWER-TO-GAS PRODUCTION AND USE IN OPTIMAL PATH

Throughout the year excessive wind and solar electricity is used to power the direct air capture (DAC), electrolysis and methanation (collectively "PtM") for production of renewable methane. Production is maximized in mid-year when solar and wind outputs typically peak. Thermal generation using this carbon-neutral fuel is used mostly in the winter months (December through February) with some sporadic generation in late summer and fall (Figure 8). The renewable gas storage (Figure 8) is charged with gas during spring and early summer to provide fuel for fall (Sept-October) and winter (Dec through Feb) carbon-neutral thermal generation.

The renewable capacity and PtG process are dimensioned so that enough carbon neutral fuel can be produced for Californian power system annual needs. In the Optimal Path California is therefore self-sufficient on carbon neutral fuel for power system balancing.

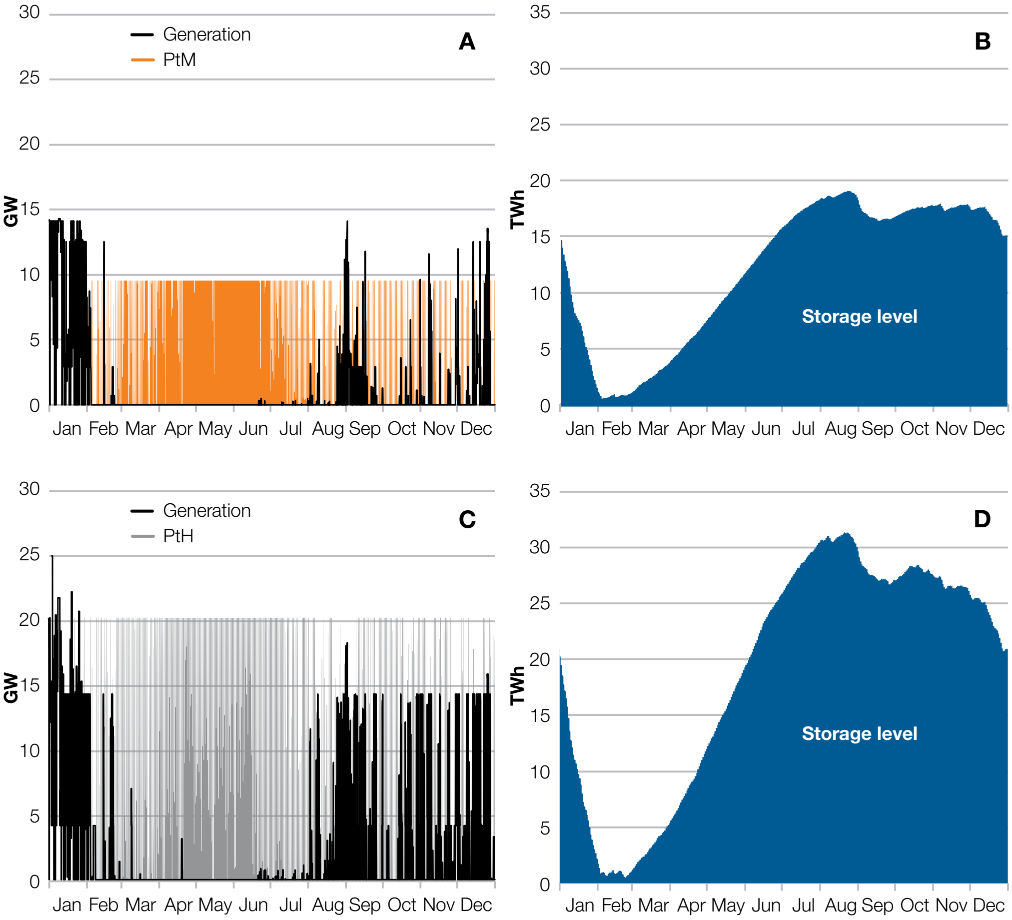

Figure 8. Power-to-gas (PtG) utilization in 2045, Optimal Path. Annual hourly thermal generation and electricity consumption (GW) of PtM and PtH (panels A & C respectively); Annual storage levels of renewable gas from PtM and PtH (Panels B & D respectively).

RENEWABLE GAS VOLUMES RELATIVE TO EXISTING UNDERGROUND GAS STORAGE FACILITIES IN CALIFORNIA

The simulation model could generate and store renewable methane without any limitations. Results (Figure 8 A, B) showed a difference between upper and lower bounds of gas volumes in the storage to be approximately 18 TWhfuel which is equivalent to 61 billion cubic feet of gas. The underground gas storage capacity serving California, as of 2017, consisted of 12 facilities with a total capacity just shy of 400 billion cubic feet of gas, designed to store methane "over daily to seasonal time scales" (California Council on Science and Technology, 2018). Therefore, under the Optimal PtM pathway the renewable methane capacity required for 100% carbon-neutrality would use roughly 15% of existing long-term underground gas storage capacity in the state. Hydrogen storage (TWh) is approximately 80% greater than methane by volume (Figure 8 D vs B) and should also fit within the underground storage capacity in the state of California, but further research is needed to determine if these chambers can safely store hydrogen. Even if they can store hydrogen there is a lack of infrastructure (pipelines) to convey this fuel to distributed generation assets.

RENEWABLE GAS AND EXISTING THERMAL AS LONG-TERM ENERGY STORAGE

In 2045 in the Optimal Path, the accumulation of methane through the PtM process across the spring/summer months leads to an 18 TWh "bank" of stored, renewable energy (Figure 8B). Assuming a generic thermal plant heat rate of 8 MBtu/MWh (42.5% efficiency), 18 TWhfuel x 42.5% = 7.65 TWhelectric. That is, the 32 GW of thermal capacity installed in California in 2045 in the Optimal Path PtM would be able to generate 7,650 GWh of electricity, giving a full power duration of approximately 240 hours (10 days). The amount of stored hydrogen in Optimal Path PtH is 32 TWh

(Figure 8D), 80% greater than the TWh in Optimal Path PtM. Therefore, the same 32GW of installed thermal capacity using hydrogen would have a duration of approximately 18 days.

The PtM fuel storage need is approximately 15% of the total underground gas storage in California, or rather the existing storage capacity is 6.7 times greater than the fuel volumes needed for the Optimal Path. If the existing underground gas storage capacity in California was filled with renewable gas from the PtG process, the 32 GW x 240 hours would instead have a duration of 1,600 hours (67 days). There is potential for California to optimize stored gas volumes for reliability purposes. Similar can be envisioned for hydrogen, assuming hydrogen infrastructure is in place to move hydrogen from storage facilities to power plants.

Overall the combination of long-term renewable carbon neutral fuel storage coupled with thermal capacity has direct parallels with battery storage (Figure 9).

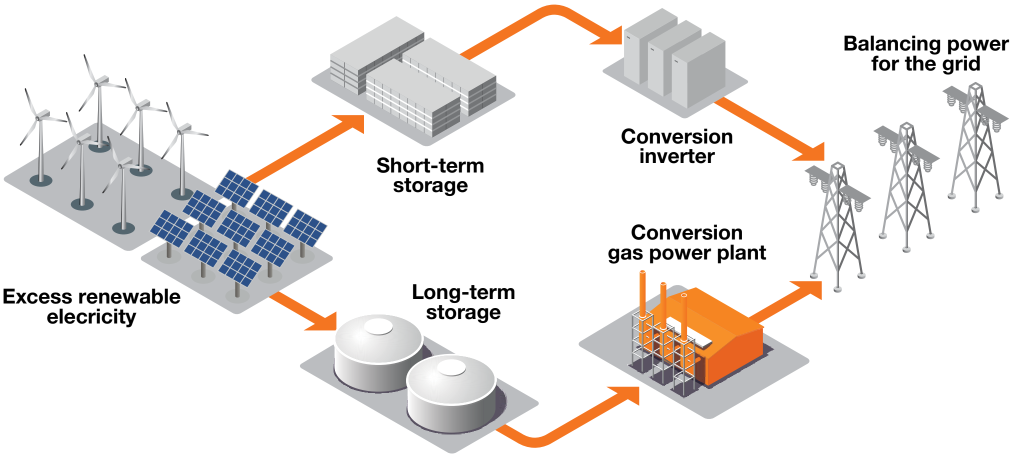

Figure 9. Renewable energy can be stored in short term batteries or converted to renewable PtG fuels for long term storage.

THERMAL GENERATION IN 2045

In 2045 in the Optimal Path, gas-fired generation remains in the system but operates in short bursts using renewable fuels. This capacity not only acts as long-term energy storage but also provides flexibility and firm capacity. The contribution to system reliability is an essential role for this capacity minimizing overbuild of wind, solar and battery storage (which all have low effective load carrying capabilities).

The gas-fired capacity and the electricity generation is presented in Table 3A for the Optimal Path PtM. There are three types of gas capacity in the system. Firstly, some older inflexible CCGTs that provide electricity for longer stretches during low renewable winter months. Keeping these older assets in the systems makes sense as permitting new ones can be challenging and the cost of building new ones is relatively high. Secondly, peakers, mostly simple cycle CTs, which ensure adequate firm capacity for system reliability, but rarely operate due to their poor efficiency. Thirdly, flexible gas fired generation participates in daily and seasonal renewable balancing while providing firm capacity for system reliability. Flexible gas generation is here considered as medium speed reciprocating engines, which have start times of 1 to 5 minutes, minimum down times of 5 minutes and no restrictions on minimum run time, and unlimited starts per day with no maintenance penalties. Combined with high efficiency (heat rates on the order of 8000 Btu/kWh), flexible thermal generation can provide balancing power as needed with the least amount of operational restrictions relative to any other form of thermal capacity. Similar trends are shown for the Optimal Path PtH case (Table 3B), only the capacity factor of CCGTs and flexible generation are increased due to the lower cost of synthetic renewable hydrogen versus methane (both in terms of capital cost to install hydrogen production assets, and the higher efficiency of electrolysis alone versus that of electrolysis plus DAC and methanation).

	CCGT	Peaker	Flexible
Generation GWh	4698	593	6716
Installed Capacity MW	3168	19075	10143
Capacity Factor %	16.9	0.4	7.6

Table 3A. Methane thermal capacity operational data for Optimal Path in 2045.

	CCGT	Peaker	Flexible
Generation GWh	9906	1573	11101
Installed Capacity MW	4504	17193	10606
Capacity Factor %	25.1	1.0	11.9

Table 3B. Hydrogen thermal capacity operational data for Optimal Path in 2045.

Current Plan without Fossil Thermal

The final studied scenario assumes that fossil gas-fired generation is forbidden and must retire from the system by 2045. This is an alternative way to decarbonize the system instead of using PtG, and currently the mainstream political approach in many areas, including California. Furthermore, one should note that the fossil gas-fired capacity cannot be retained for reliability purposes in this case as there is no acceptable fuel available.

The installed capacity for 2045 is depicted in Figure 10 together with the Current Plan and Optimal Path. Removing gas-fired capacity from Current Plan leads to major battery storage additions that are needed for two purposes: to provide long-term storage and to maintain system capacity reserve margins for security of supply. As battery storage is added to the system it initially has high effective load carrying capability (ELCC). When battery storage capacity exceeds 50% of the peak load it flattens net load peaks cross longer durations, in which case it is difficult to ensure every storage device is fully charged at critical peak times with enough duration to sustain the peak. As more storage is added to the system, it's marginal ELCC is reduced, leading to much larger storage for provision of adequate capacity margin.

This scenario is relying on solar and battery storage, both heavily overbuilt, in order to provide security of supply during all types of weather conditions. Much of the storage capacity is added for ensuring system reliability. The capacity factor of storage is 3% versus 17% and 15% for the Optimal Path with PtM and Current Plan respectively. Consequently, the generation cost of the system increases dramatically: the levelized cost of electricity in 2045 is 128 USD/MWh, which is more than double compared to the Current Plan and the Optimal Path. Nevertheless, the system reaches zero carbon in 2045 by utilizing mainly solar and batteries, so it is technically possible. Other studies have reported that complete removal of thermal capacity in California would lead to dramatic cost increases (Energy and Environmental Economics, Inc., 2019).

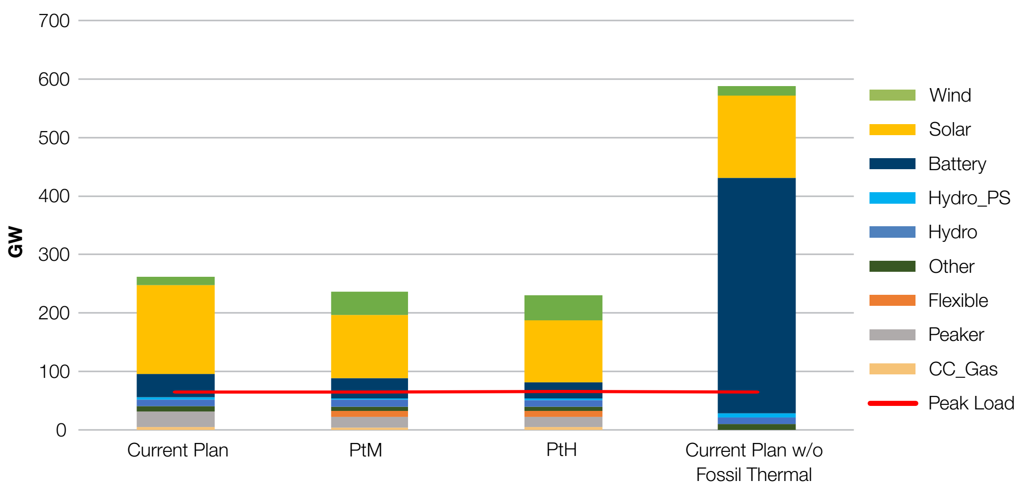

Figure 10. Installed capacity in 2045 for all scenarios. Note: the necessary overbuilding of battery storage if thermal generation is banned from the system.

Optimal Path maximizes generation from carbon-free sources

The generation by technology type for each scenario is presented in Figure 11, including the generation of storages and electricity exchange with other states. The total load includes state-wide electricity demand with grid losses, as well as pump & battery storage charging and PtG loads with their losses. Thus, this graph shows the annual generation balance.

The figure also depicts the actual Californian electricity demand, including the state-wide electricity demand and storage and PtG losses. In 2045, electricity demand is higher in the Optimal Path as the PtG process consumes electricity. Excess renewable energy that would have been curtailed in the alternate scenarios is utilized by the PtG process and stored as long-term energy in the form of fuel. Figure 11 clearly indicates how the Optimal Path has a greater diversity of energy sources, and the fact that the thermal power plants do not run much but enable construction of a smaller and more efficient power system.

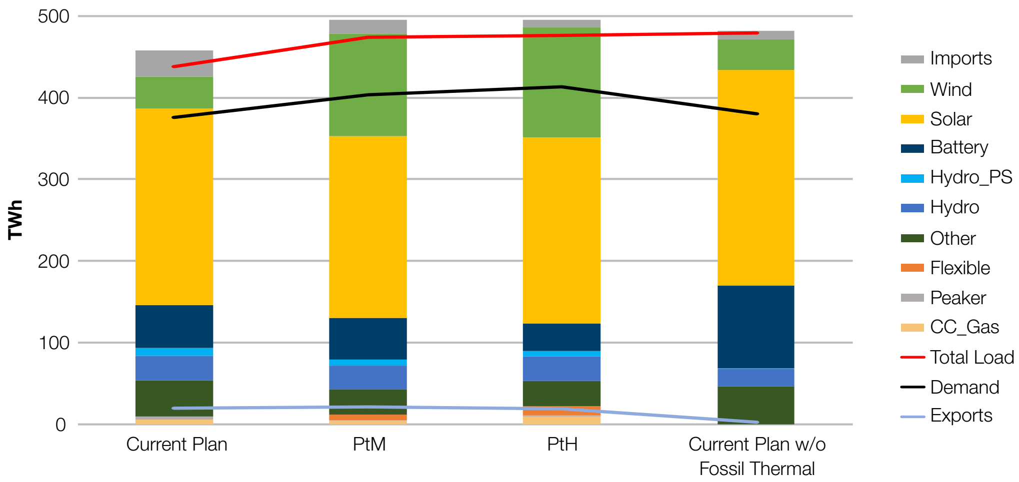

Figure 11. Generation (TWh) in 2045 for the scenarios.

Summary and Final Recommendations

California is leading the world in environmental stewardship by embarking on an aggressive path of decarbonization. Decarbonizing the electric power sector will require new ways of thinking and new approaches to simultaneously meet carbon goals and minimize land use, emissions and cost. The California IRP meets some but not all these goals. Through consideration of carbon-neutral pathways utilizing renewable power to gas, this analysis shows that net-zero carbon can be reached by 2045 while simultaneously minimizing land use, emissions and costs (Table 4).

		Optimal Path		Current Plan	
		PtM	PtH	IRP	w/o Fossil Thermal
Capacity	GW Solar	109	107	152	141
	GW Wind	40	43	15	16
	GW Storage	37	30	44	410
	GW Thermal Old	14	0	14	0
	GW Thermal New	18	32	17	0
	GW Other	7	7	9	9
	GW Hydro	12	12	12	12
	Total GW (Capacity)	**237**	**231**	**263**	**588**
	PtM GW (load)	**10**	**0**	**0**	**0**
	PtH GW (load)	**0**	**20**	**0**	**0**
Storage	GWh Pumped Hydro	285	285	326	333
	GWh Batteries	158	108	189	1624
	GWh Renewable Fuels	7650	13 617	0	0
	Total GWh storage in system	**8093**	**14 010**	**515**	**1957**
Curtailment	Curtailed Wind (TWh)	4	4	4	7
	Curtailed Solar (TWh)	23	13	108	61
	Total Curtailment (TWh)	**27**	**17**	**112**	**68**
Carbon	Mton (2020-2045)	824	820	948	935
	Mton CO_2 in 2045	0	0	4	0
Cost	**2045 Energy Cost ($/MWh)**	**50**	**54**	**51**	**128**
Land	Land for Utility-Scale Solar (Sq. miles)	594	570	922	806
	Land for Wind (Sq. miles)	47	50	19	18
	Land needed for Solar & Wind (Sq. miles)	**641**	**620**	**941**	**824**

Table 4. Summary of results from scenarios.

THE OPTIMAL PATHWAY EXHIBITS THE FOLLOWING FEATURES:

The Optimal Pathway (both PtM and PtH) have the following common attributes;

- Meets current RPS compliance 5 years ahead of schedule and full net-zero compliance in 2045
- Enables closure of OTC plants by 2023
- Minimizes cumulative CO2 emissions between now and 2045
- Minimizes the needs to permit and build new grid connections to renewable generation sites
- Reduce land use requirements for renewable development by hundreds of square miles
- Dramatically reduce solar & wind curtailment and maximize value of renewables
- Maximizes reliability by providing weeks of long-term energy storage

In both the PtM and PtH pathways early closure of the OTC plants allows for early installation of more than 10 GW each of solar and battery storage, supplemented by approximately 2.5 GW of flexible thermal. This ensemble of flexible capacity and carbon-free solar provides a greater carbon reduction across the whole modelling horizon as well as lower cost than the current IRP plan.

The PtM pathway provides 8 BUSD savings over the Current Plan and uses off the shelf technology for power generation. Flexible thermal can be installed as needed without fear of the assets being stranded in 2045, as they can transition at any time from fossil gas to renewably sourced methane from the PtM process. The PtM pathway leverages existing gas storage and pipeline/distribution systems, and provides for 8 TWh of reliable, fully dispatchable renewable energy storage. The Optimal Pathway with PtM reaches true carbon-neutrality for the state of California by 2045.

The Optimal PtH pathway has allure because hydrogen production is more efficient than PtM and hydrogen fuel is truly carbon free. The results indicate greater energy storage potential with hydrogen relative to methane and a 3 BUSD savings over the Current Plan. The savings are reduced relative to PtM because all thermal generation installed in CA to run on gas (methane) must be retired and replaced with all new thermal generation designed to burn 100% hydrogen. The costs/savings reported for PtH do not include the cost of modification of existing gas infrastructure or the need for new build hydrogen infrastructure such as pipelines, compressor stations and distribution systems needed to support hydrogen power generation.

The path to the decarbonized power system for California in 2045 is dependent on decisions made now. For example, the passage of Senate Bill (SB) 100 that led to the current RPS, is already guiding how utilities invest today. Investors and power system planners need assurance that technologies necessary to reach the goals will have support at the policy and legislative levels. Elements of renewable PtG are being planned or already in use to decarbonize the residential and transportation fuel supplies for the state of CA. But there is no policy level mechanism through which electric utilities can be assured that California will recognize carbon-neutral renewable methane (from PtG process) coupled with flexible thermal assets as “renewable generation”. Such a policy would allow utilities to strategically install flexible thermal as needed while also assuring these assets would contribute positively towards the ideal net-zero power system and enable California to follow the Optimal Path outlined in the study.

Flexible thermal should center around technologies that allow for distributed installation, with project sizes under 100 MW in most cases, without starting costs and restrictions on the number of starts per day, start times of 5 minutes or less, minimal to no restrictions on minimum run or down times, low gas pressure requirements to avoid compressor losses, zero water consumption, and minimum unit turndown of 10-20%. These flexibility features – used by Plexos for flexible gas generation in the study – allow units to thrive in energy markets exhibiting high net load and price volatility, such as California, in ways less flexible thermal cannot. Flexible generation can immediately shut down when renewables are available, minimizing overgeneration, use of fuels and carbon emissions.

POLICY RECOMMENDATIONS:

The Optimal Pathway as described in this work, either through power to methane or power to hydrogen, enables California to achieve its clean energy goals faster than currently planned and at a lower cost than currently projected, while also ensuring reliability. For the state to take full advantage of these benefits, the following policy considerations must be addressed.

- California must formally recognize thermal plant operation on renewable fuels, including synthetic methane and hydrogen produced with excess renewable energy, as renewable generation for the purposes of meeting clean electricity mandates. This would provide regulatory certainty which in turn will encourage research, development and deployment of power-to-methane and power-to-hydrogen technologies, enabling the fastest, least-cost Optimal Path to 100% clean electricity.
- Retirement of once-through-cooling power plants by 2023. To ensure adequate firm capacity over the next few years, the California Water Control Board is considering extending the licenses for some of the state's once-through-cooling power plants. However, the addition of flexible thermal along with renewables can replace the legacy thermal assets while ensuring reliability and adherence to California's clean power goals.
- California should allow for replacement of legacy thermal capacity with optimal proportions of renewable, lithium-ion and other forms of traditional energy storage, as well as strategic amounts of fast-start, flexible thermal capacity. This is outlined in the Optimal Path scenario of this study, capacity additions for Optimal Path displayed in Table 5. Flexible thermal is critical for reliability and will transition to renewable fuels in the future.

	Unit	2021	2022	2023	2024	2025
Solar	MW	2165	2165	2165	2165	2165
Wind	MW	519	519	519	519	519
Battery storage	MW	1692	1692	1692	1692	1692
Battery storage	MWh	6768	6768	6768	6768	6768
Flexible gas	MW	0	2421	0	0	0

Table 5. Annual capacity additions by technology type for Optimal Path

The policy goals above allow for and facilitate the Optimal Path outcomes provided in this work, allowing California to meet RPS goals five years ahead of schedule and reach true carbon neutrality by 2045, with decreased emissions and lower costs the entire way.

Appendix

MODEL INPUTS AND NODE INFORMATION

In this study, the model contains three nodes, California, North-West (Oregon, Washington, Idaho etc.), and South-West (Arizona, Nevada, New Mexico etc.). Each of these nodes have their generation technologies modelled by several aggregated power plants. The technologies include solar PV, wind, geothermal, bio, hydro (reservoir, run-of-river), combined cycle and open cycle gas turbines, engines, steam turbines (coal and gas-fired), nuclear, pump storage, and battery storage. Initial capacity mixes for NW and SW regions are presented in Figure 12. For California, initial mix in 2020 is depicted in Table 3 (the installed capacity figures in results section).

For the technologies, several characteristics are modelled, including size of plant, minimum stable generation, heat rate at 100% and 50%, fuel price, VO&M, FO&M, start cost, ramp rates, maintenance and forced outages, and firm capacities. These metrics are well-established and documented for both existing thermal assets and new-builds. For the Optimal path with hydrogen, it was assumed that the same new build technologies are available as for gas (methane) with the same costs and performance. Variable renewable generation (wind and solar) are represented by their hourly generation profiles for a full year in order to capture their variability and low and high generation periods.

The model has capacity reserve margin requirements as well as an operational reserves requirement that captures the additional reserve requirements for wind and solar PV balancing. The requirements are due to the weather forecast error and its impact on predicting wind and solar generation as well as the short-term variability of these resources. The technologies are modelled with a constant firm capacity except battery storage, of which effective load carrying capacity decreases when the amount of installed battery capacity increases.

According to the IRP (CPUC 2019a,b) solar and wind have low marginal ELCC when the states penetration is high, i.e., installing additional capacity adds only a little new firm capacity. The same applies to battery storage: once the installed 4-hour battery capacity is approximately 50% of peak load, ELCC drops down to 7%. This low ELCC necessitates buildout of significantly more capacity than is needed to serve load and showcases the need for dramatic overbuild of capacity to meet load and reliability without firm, dispatchable resources.

The demand for each node is modelled as hourly profiles for a full year. For the future years, the load growth follows CEC Pathways High Electrification load forecast, which assumes, for example, increasing electrification in transportation sector and buildings. The forecast also assumes additions in behind the meter solar generation that is included in the model with solar PV profiles. Annual demand assumption without storage load and losses and rooftop solar for California and the neighbour regions are depicted in Figure 12.

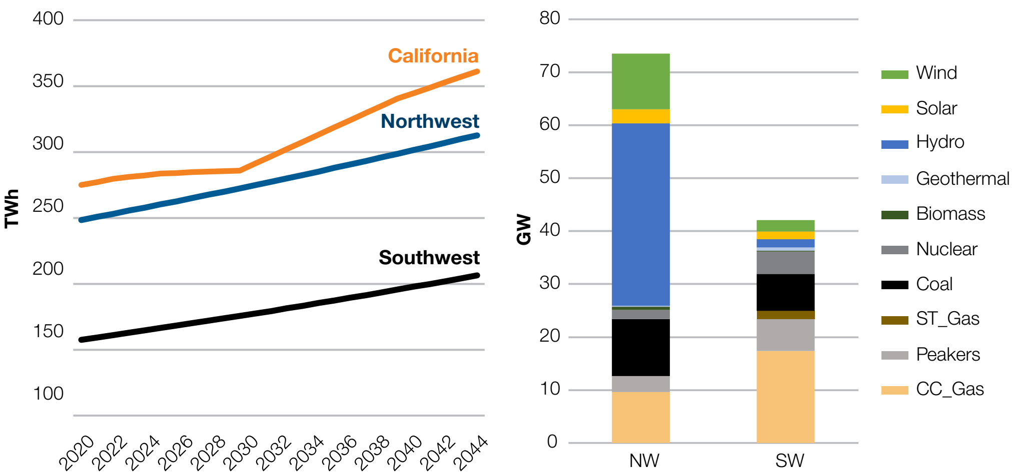

Figure 12. Electricity demand by regions (left) and Initial Installed capacity in NW and SW Regions (right).

California's RPS targets are modelled by gradually increasing the target so that it reaches 60% in 2030 and 100% in 2045. Up until the end of 2030, RPS eligible sources are wind, solar, bio, geothermal and small-scale hydro. After 2030, nuclear and large-scale hydro are also considered RPS eligible.

To meet future demand and RPS targets, the model can choose the technologies to add to the power system. The potential technologies with their price assumptions are given in Table 6. Battery storages have also FO&M that is 1.5% of CapEx and PtG has a FO&M that is 4% of CapEx. The software can also add 12-hour pump hydro with a CapEx of 2879 USD/kW and a FO&M of 14.64 USD/kW-year. Economic life and WACC assumptions are in Table 7.

Transmission expansion is not optimized in the study. Instead, the cost of expansion is estimated after the generation expansion optimization using CAISO's transmission capability and cost estimates produced for the IRP modelling. The estimation assumes that location with available transmission capacity is utilized first, after which renewable generation additions are done by starting from locations with the lowest transmission expansion cost.

Renewable Energy Sources (RES) and storage technology price learning curves used in this study are displayed in Figure 13 in more detail.

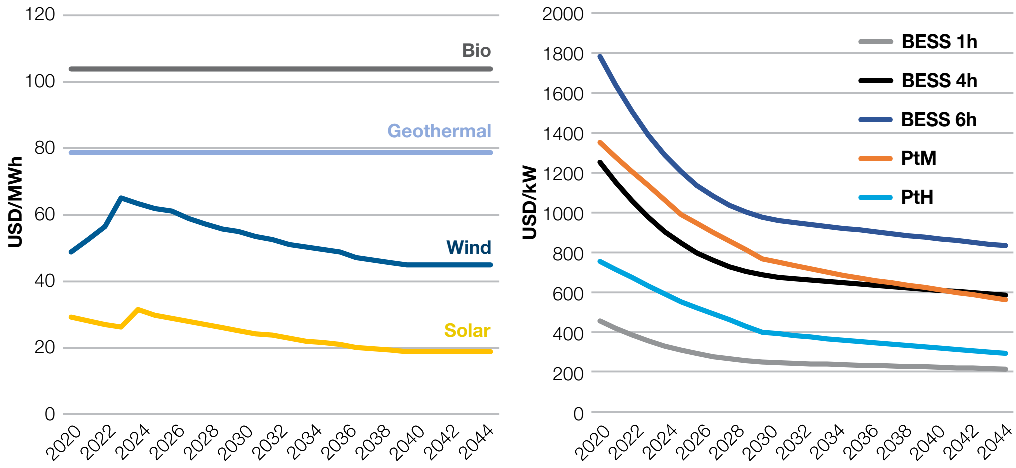

Figure 13. Levelized Cost of Energy for Renewable Energy Sources (left) and storage technology price (right) learning curves. Source: IRP dataset, Bloomberg NEF Source: IRP dataset, LUT.

	Heat Rate MMBtu/ MWh	VO&M Charge $/MWh	Start Cost $/MW	FO&M $/kW,a	CapEx $/kW
Open Cycle Gas Turbine (CT)	9.92	3	70	13.7	950
Combine Cycle Gas Turbine (CCGT)	6.98	2.65	60	11.1	1250
Reciprocating Internal Combustion Engine (ICE)	8.02	5	0	13.7	1250

Table 6. Inputs for new build thermal candidates (assumed to be the same for methane and for hydrogen).

	Renewables	Battery Storage	Pump Hydro	Thermal
WACC, %	6.4	9.13	9.13	5.84
Economic Life, years	20	20	50	20

Table 7. Economic life for generation/storage and WACC assumptions.

The fuel and carbon price for this study are those used in the CAISO IRP. California's fuel and carbon price in 2020 are displayed in Table 8. Based on market forecast a gradual increase for gas and carbon prices are assumed.

Fuel	Price
Coal	2 USD/MMBtu
Gas	4.3 USD/MMBTu
Uranium	0.7 USD/MMBtu
Carbon Price	15.2 USD/t CO_2

Table 8. Fuel and carbon price inputs for the study. Source: CAISO IRP dataset.

THE MODELLING SOFTWARE

Plexos is a simulation software for studying and dispatching of a power system. The software uses mathematically based optimization techniques to realistically represent the operation of a real-life power system.

Plexos is an optimal tool for the capacity expansion studies of high variable renewable generation system because it is able to:

- Modelling the variability of wind and solar in detail is important for representing the low solar and wind periods required to properly model the system reliability
- Including the technical parameters needed to capture the inflexibilities of thermal generation. Such parameters include ramp rates, starts costs and profiles, minimum stable generation and minimum up and down times.
- Allowing the representation of weather forecast uncertainty in operational reserve provision

A Plexos model is a combination of power system data and advanced mathematical formulation, which captures the characteristics of the studied system. Figure 14 shows the power system data used in a model. This data, combined with the mathematical formulation, is a Plexos model, representing the power system with each of its techno-economic detail. The formulation basically models system features, such as the characteristics of power plants (e.g. efficiencies, dynamic features), the nodes and lines in the electrical grid, ancillary service requirements, and supply-demand balance.

The model is fed to a solver that produces the results shown in the figure (right side of Figure 14). The solver optimizes the power system. In a long-term expansion model, the optimization objective is to find the optimal (lowest cost) generation capacity additions to supply the future electricity demand. Due to the complex nature of the power system capacity optimization modelling some simplifications and compromises are typically needed. But it is noteworthy to mention that these simplifications should not severely impact the end results, which means that all compromises need to be carefully investigated and chosen.

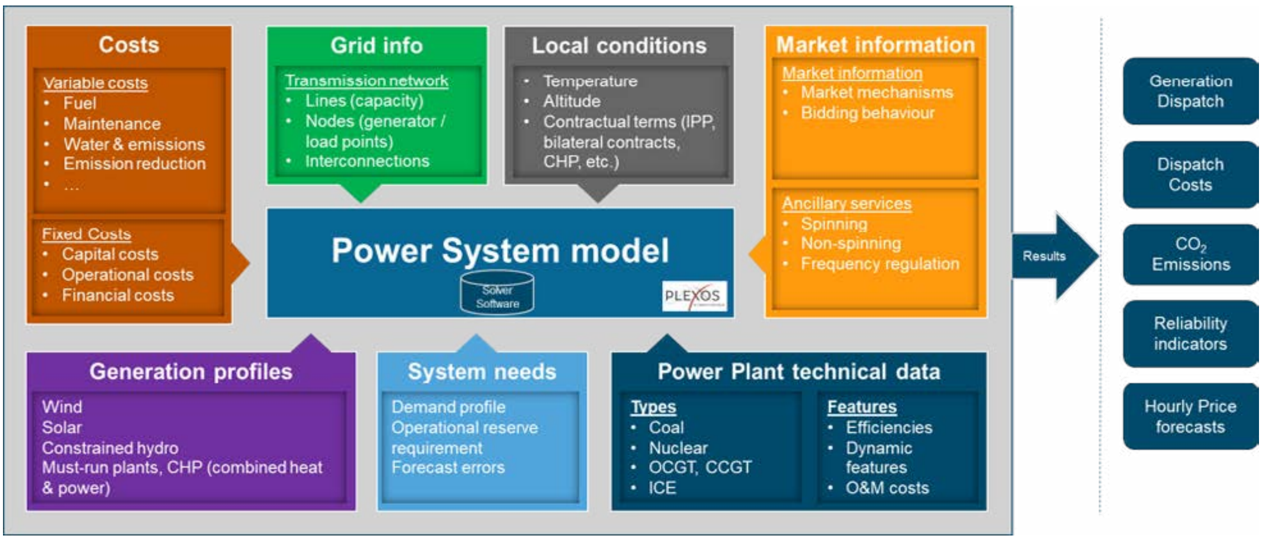

Figure 14. Plexos power system model (requires major computing power).

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