LA100

The Los Angeles 100% Renewable Energy Study

LA100: THE LOS ANGELES 100% RENEWABLE ENERGY STUDY

EXECUTIVE SUMMARY

LA DWP Los Angeles Department of Water & Power

NREL Transforming ENERGY

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Executive Summary

Executive Summary Authors

Jaquelin Cochran,[1] Paul Denholm,[1] Meghan Mooney,[1] Daniel Steinberg,[1] Elaine Hale,[1] Garvin Heath,[1] Bryan Palmintier,[1] Ben Sigrin,[1] David Keyser,[1] Devonie McCamey,[1] Brady Cowiestoll,[1] Kelsey Horowitz,[1] Henry Horsey,[1] Anthony Fontanini,[1] Himanshu Jain,[1] Matteo Muratori,[1] Jennie Jorgenson,[1] Matt Irish,[1] George Ban-Weiss,[2] Harvey Cutler,[3] Vikram Ravi,[1] and Scott Nicholson[1]

[1] National Renewable Energy Laboratory, [2] University of Southern California, [3] Colorado State University

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Foreword

I am very pleased to offer a few words of congratulations and reflections on this groundbreaking report, the **Los Angeles 100% Renewable Energy Study (LA100)**. LA100 explores pathways the nation's second-largest city could take to achieve a 100% clean energy future, and is one of NREL's most momentous achievements in fulfilling our mission to transfer knowledge and innovations to address the nation's energy and environmental goals.

The scale of this undertaking cannot be overstated. As Lauren Faber O'Connor, the chief sustainability officer for the City of Los Angeles, said: "What excites me most about the 100% renewable energy study we are partnering with NREL on is its unprecedented nature. We don't like to shy away from challenges, and neither does NREL."

With world-class research partners from the University of Southern California, Colorado State University, and Kearns & West, NREL formed a dream team of experts in topics ranging from building loads and bulk power systems to life cycle greenhouse gas emissions, jobs and economic development, environmental justice, and more.

The team entered uncharted waters in exploring this energy transition, as a single method or model would not suffice for a study of this scale, scope, and rigor—so they created an entirely new methodology that impressively integrated more than a dozen tools—and made vigorous use of our supercomputer.

Just as important as the science, I am proud that LA100 took important steps toward involving the local community in the energy conversation, engaging with the study's LA-based Advisory Group throughout the project to ensure the research reflects what matters most to the people who live and work in Los Angeles.

And unlike many other studies of high-renewable systems, LA100 made reliability a fundamental requirement for the future grid—ensuring a renewable system will still mean a reliable system in the face of extreme events like wildfires or heat waves that today can leave entire communities without power for weeks at a time.

The study's results show that a reliable, 100% renewable electricity supply is indeed achievable for LA by 2045 or even a decade sooner. Equally exciting is how the results point to new research priorities—from R&D to advance the development of commercially available storable hydrogen fuel, to improvements in how we model and prioritize energy equity.

The LA100 study lights a new path for other jurisdictions to replicate, build upon, and scale up this type of analysis for their own energy system transformations. And I am certain the team's years of hard work will have a ripple effect, as the study offers invaluable insight into how the United States can achieve national-scale goals for a 100% carbon-free power sector.

I salute all those who had the vision to engage in this ambitious effort and will watch with anticipation as the LA100 study benefits not only Angelenos, but the entire nation.

Sincerely,

Martin Keller

Director of the National Renewable Energy Laboratory

Having reliable, low-cost electricity is at the heart of everything we do—from making breakfast to doing our jobs, maintaining our health, connecting with loved ones, getting around town, and even having fun. And what happens *before* we flip on the light switch—how our utilities get the electricity supply they deliver to our homes and businesses—has a fundamental impact on our future. It affects the air we breathe, how much of our income goes toward electricity bills, the job opportunities available in our communities—and how we leave the planet for future generations.

The choices our utilities make in delivering our power have important implications—and the systems that generate the electricity we rely on are changing to incorporate more renewable energy technologies, which have become significantly less expensive in recent years. Transitioning to higher amounts of renewables in the power system is an important part of addressing climate change—which the City of Los Angeles recognizes to be the most significant issue facing the global environment today.

To combat climate change while capturing health and economic benefits, the City of Los Angeles has set ambitious goals to transform its electricity supply, aiming for a 100% renewable energy power system by 2045, along with a push to electrify the buildings and transportation sectors.

To reach these goals, and assess the implications for jobs, electricity rates, the environment, and environmental justice, the Los Angeles City Council passed a series of motions in 2016 and 2017 directing the Los Angeles Department of Water and Power (LADWP) to determine the technical feasibility and investment pathways of a 100% renewable energy portfolio standard.

Renewable energy technologies draw upon resources that can be easily replenished, like wind, solar, geothermal, and hydropower, rather than finite or **nonrenewable** resources like natural gas and coal.

With great ambition comes great need for actionable data and analysis—so LADWP partnered with the National Renewable Energy Laboratory (NREL) on the **Los Angeles 100% Renewable Energy Study (LA100)**, a first-of-its-kind objective, highly detailed, rigorous, and science-based study to analyze potential pathways the community can take to achieve a 100% clean energy future.

As a U.S. Department of Energy research lab with decades of experience in energy systems analysis, NREL offered unbiased, best-in-class expertise and modeling capabilities to help Los Angeles navigate its clean energy transition—and joined forces with partners from the University of Southern California, Colorado State University, and Kearns & West to tap into additional expertise.

> This document explores the high-level conclusions from NREL's extensive modeling, research, and stakeholder engagement through the multiyear LA100 analysis.
>
> Additional results by scenario and topic, links to download each chapter of the full report, a glossary of terms, and an interactive data viewer can be found on the study website at: **maps.nrel.gov/la100**

Community Driven, Community Tailored: The LA100 Advisory Group

In coordination with the Office of Los Angeles Mayor Eric Garcetti, LADWP established the LA100 Advisory Group in 2017.

The Advisory Group includes representatives from environmental groups, neighborhood councils, academia, customers, city government, business and workforce groups, and renewable energy industry organizations. Its role is to guide the LA100 study in understanding and planning for issues related to feasibility, reliability, public health, and equitable local economic development, including job opportunities and local hiring programs.

LADWP held 15 quarterly Advisory Group meetings from June 2017 through March 2021. These discussions with the Advisory Group helped NREL to further tailor its analysis to LA's needs, bridging the relationship between research and community concerns.

Members of NREL, LADWP, and the LA100 Advisory Group touring LADWP's Pine Tree Wind and Solar Farm. *Photo by Dennis Schroeder, NREL 50703*

Informing Decisions on the Road to 100%: Study Objectives

The LA100 study aims to inform the City of LA, LADWP, and other stakeholders of possible pathways to 100% renewable energy, and the implications of these pathways for the people who live and work in LA. With guidance from the Advisory Group, NREL evaluated a range of future scenarios to equip LA decision makers to address these questions:

- What are the **pathways and costs** to achieve a 100% renewable electricity supply while electrifying key end uses and maintaining LADWP's current high degree of reliability?
- What are the benefits for **greenhouse gas (GHG) reductions** and **public health**?
- How might the **economy** respond to such a change?
- How can communities shape these changes to prioritize **environmental justice**?

NREL modeled and analyzed different projections for LADWP's customer electricity demand, local solar adoption, power system generation, and transmission and distribution networks, and worked with local LA institutions to examine changes to air quality and the

> LA100 is the most comprehensive, detailed analysis to date of an entirely renewable-based electric grid as complex and large as the LADWP power system.

potential for jobs and economic development. As a result of these integrated modeling activities, LA100's findings shed light on the options and tradeoffs among different approaches to achieving 100% renewables for LA. Along the way, LADWP learned how to use NREL's high-tech tools and datasets for their own analyses, so they can convert the findings into workable, achievable plans.

Complex Questions, Complex Analysis: LA100's Pioneering Approach

LA100 presented an analytical undertaking of unprecedented scale and complexity. The real-world impact of approaching 100% renewables cannot be analyzed using just one method or model—so LA100 took a new approach. The study uniquely integrated diverse capabilities across the lab and its study partners, including detailed electricity demand modeling, power system investments and operations analysis, distributed energy resources and distribution grid modeling, economic impact analysis, life cycle GHG analysis, and photochemical air quality modeling, among others.

The multidisciplinary team used NREL's high-performance computer to:

- Run millions of simulations of thousands of **buildings** to examine how adoption of new design elements, equipment, or appliances could change how much and when people use electricity
- Explore opportunities to electrify different **transportation** modes and assess when and where people might charge electric vehicles (EVs)
- Use sophisticated aerial scans and customer adoption models for each and every roof in LA to see how much **rooftop solar** could be installed
- Apply state-of-the-art **utility planning tools** at unprecedented scale to examine costs and benefits of a wide range of technologies, including solar photovoltaics (PV), wind, concentrating solar power, geothermal, biofuels, batteries, hydrogen storage, and demand response
- Perform detailed analysis of both the **distribution and transmission network** to ensure new resources will not overload lines
- Simulate how different technologies, including **energy storage**, could be used to ensure electricity demand is met every hour of every day of the year.

Crucially, the study also addressed a suite of questions vital to the public and policymakers, including considerations for environmental justice—how these investment pathways differ in terms of cost and impacts to the local economy, jobs, GHG emissions, air quality, and public health. Finally, the study created dynamic tools to visualize the results in the name of promoting transparency, public engagement, and robust discussion of how LA can achieve its vision for the future. These resources are available on the LA100 website at: **maps.nrel.gov/la100**

What Makes the LA100 Study So Complex?
Watch this video to learn more.

https://youtu.be/-u4uB5H2u5g

Unprecedented Scope, Unparalleled Detail: What It Takes to Model 100% Renewable Electricity Systems

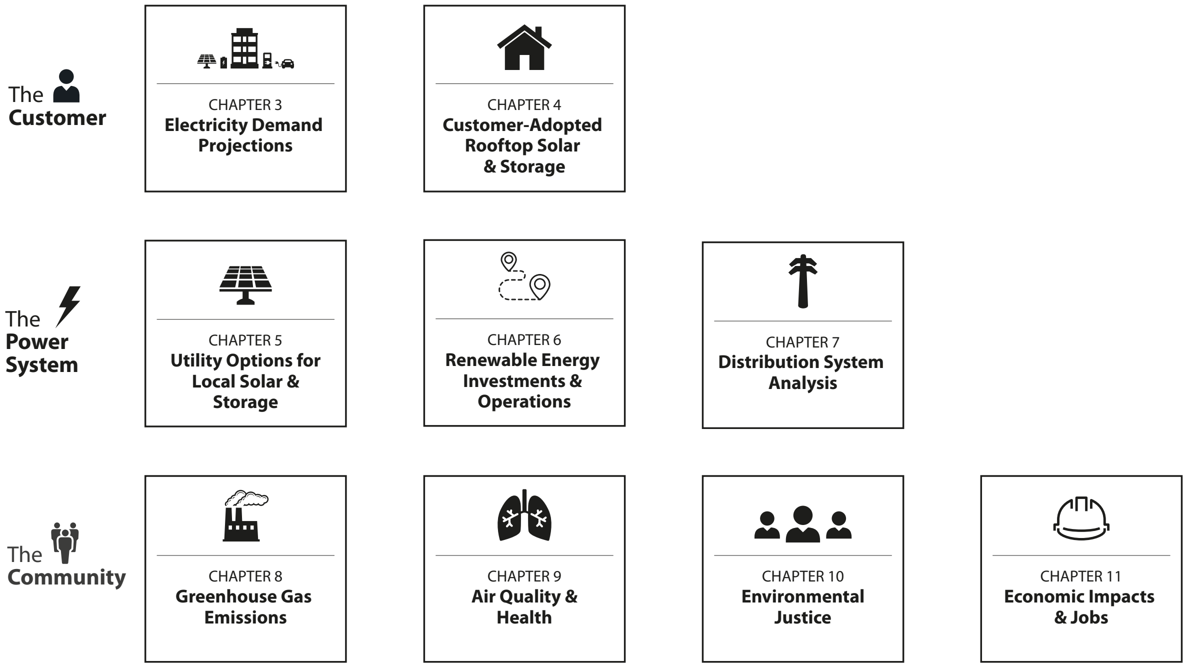
LA100's uniquely integrated modeling activities aimed to identify where, when, how much, and what types of infrastructure and operational changes would achieve reliable electricity at least cost, taking into consideration factors such as renewable energy policies and requirements, technological advancement, fuel prices, and electricity demand projections.[2]

Because of the large scope of the LA100 study, there is no single model in existence that can perform all the analysis required. The temporal, geographic, and

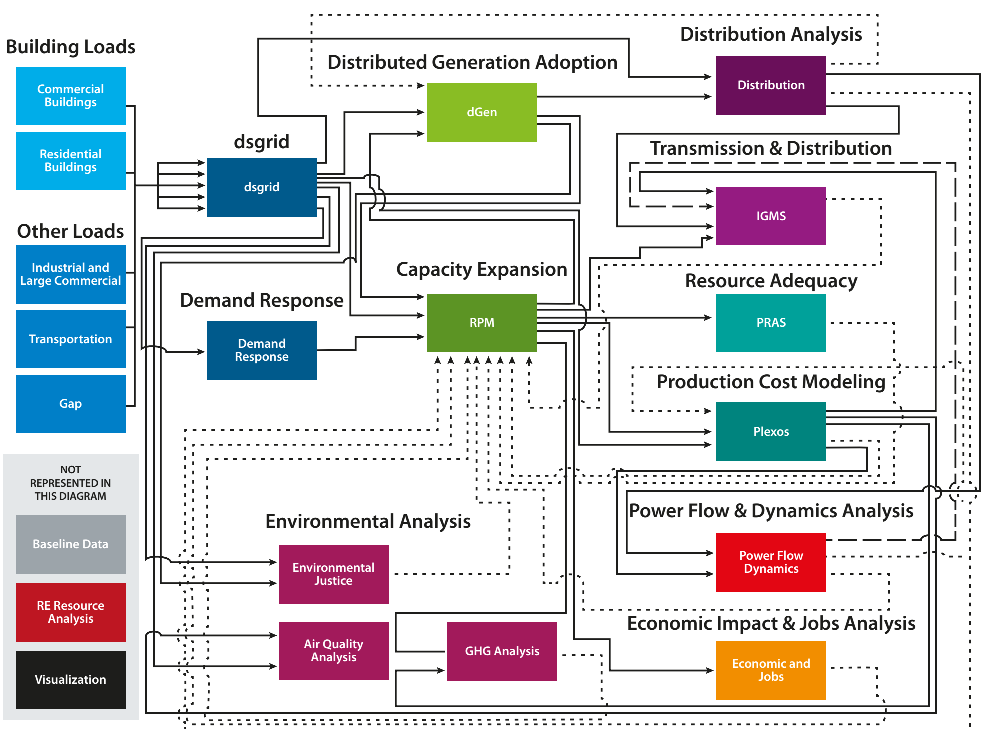
[1] This analysis was performed based on electricity demand projections generated prior to the COVID-19 pandemic. It does not account for changes that occurred during the pandemic, nor does it consider potentially longer-lasting impacts, such as changes in work patterns.

sectoral scope of this study required an approach with multiple steps—and about a dozen individual tools or models of various types. The full report (**maps.nrel.gov/la100/report**) details the data sources and requirements for all the modeling steps necessary to conduct the study.

LA100 required pushing existing tool sets to new levels of sophistication, as there has never been a 100% renewable energy study of a U.S. utility system the size of LADWP that considers all the elements shown here.



Overview of the modeling components of the LA100 study, including where each is referenced in the full report



50 terabytes of load data

More than **100 million** simulations

Detailed view of the LA100 study data flow, beginning with Building and Other Loads on the left. Solid lines represent data flow; dashed lines represent feedback to inform the modeling.

What LA100 Does and Does Not Address

The value of this study is in providing a deeper understanding of the challenges and tradeoffs in achieving a 100% renewable power grid, as opposed to identifying specific costs, technologies, or project sites. For example, for Angelenos interested in achieving 100% renewable energy without biofuels by 2030, the study addresses the types of characteristics of generation and storage that could maintain reliability, and what technologies are likely to be available at an earlier timeframe. For Angelenos interested in minimizing the cost of deep decarbonization, the study explores costs and greenhouse gas emissions at various combinations of renewable energy deployment and electrification of transportation and building end uses. The goal is not to predict outcomes or to provide a detailed plan that identifies specific project sites and their costs, but to allow Angelenos to make long-term policy goals informed by a better understanding of both feasibility and costs and benefits.

Importantly, the study does not present recommendations. The goals and specific implementation pathways are decisions that LADWP will make with input from community members after reviewing the study findings. For example, the study does not recommend or evaluate alternative retail rate structures, customer incentives, or efficiency programs to identify policies or programs that could be needed to realize LA100's electrification, efficiency, or demand response projections. Without identifying these programs, the study cannot analyze the cost or rate design implications of such programs. However, NREL has provided information to LADWP on the overall amount of assumed electrification, energy efficiency, and demand response to enable LADWP to assess potential costs associated with various programs. Similarly, the study does not address tradeoffs in electricity rates and rate of electrification.

LADWP's Pine Tree Wind and Solar Farm. *Photo from LADWP*

Map by Billy Roberts, NREL

7,880 megawatts (MW)
generation capacity

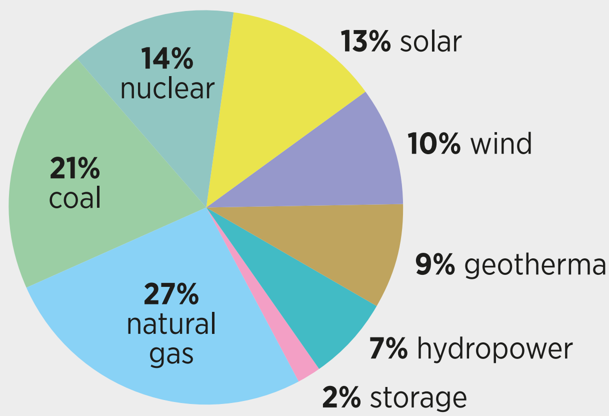
>3,600 miles of transmission lines to move electricity in

>10,400 miles of distribution lines to deliver power to customers

LADWP by the Numbers

CUSTOMER ENERGY CONSUMPTION

2019 GENERATION MIX



The Nation's Largest Municipal Utility: About LADWP's Power System

LADWP, the nation's largest municipal water and power utility, was established more than 100 years ago to deliver reliable, safe water and electricity to LA, and currently serves more than 4 million residents, translating to 1.5 million customers.

Most of the load within LADWP territory resides within the Los Angeles Basin—a term that is used often in the LA100 study—surrounded physically by the San Gabriel and Santa Ana mountains and the San Joaquin Hills, along with the Pacific Ocean. However, LADWP owns portions of two high-voltage direct-current (DC) lines along with a series of alternating-current (AC) lines, which are used to tap into valuable energy resources in the Pacific Northwest, Rocky Mountains, and Desert Southwest.

Exploring Possible Futures: LA100 Scenarios

NREL worked with the LA100 Advisory Group to frame the sets of questions addressed in the study, including:

- As more Angelenos adopt energy technologies like EVs and air conditioning, how might that change **total demand for electricity** throughout LA?
- What could LA's future grid **look like**? Does reaching 100% mean big changes locally—like building new transmission lines or power plants?
- How can LA make sure that the new system is **reliable** under extreme events like fires and heat waves?
- What about **impacts** on jobs, the local economy, air quality, public health, and environmental justice?
- And what might all of this **cost**?

To help address these questions, we designed scenarios that help us explore different options for how LA might achieve its clean energy future.

A **scenario** is one possible pathway toward a clean energy future.

Each scenario has the same end goal—100% renewable energy—but **how** the goal is achieved varies across the scenarios.

Exploring different scenarios helps us understand the potential impacts and tradeoffs among the different choices LA could make in reaching 100% renewable energy.

One such difference between the scenarios focuses on the customer. How does your demand for electricity change, for example, if you make your windows more efficient, or buy an air conditioner or EV?

Assessing the Impact of Customer Choices: Electricity Demand Projections

The LA100 study looks at three possible futures for customer electricity demand.

- The **Moderate** projection assumes moderate (above-code) improvements to energy efficiency and moderate electricity demand growth due to electrification of consumer products like cars and stoves, and moderate improvements to energy efficiency.
  - **What does this projection mean for the future power system?** While this future projects the least change compared to today's electricity demand, it is not a business-as-usual case: it projects about 1 million light-duty EVs on LA's roads by 2045, more use of electric and heat-pump technologies in the buildings sector, and a continued focus on energy efficiency through all sectors of the economy.
- The **High** projection assumes a bigger effort to decarbonize buildings and transportation. This projection assumes that almost all appliances and heating and other equipment in buildings switch from natural gas to electric, and that 80% of passenger cars on the road by 2045 are plug-in electric, and that 12% of demand is shiftable. The high energy efficiency target means that customers buy almost exclusively the most efficient building materials and appliances.
  - **What does this projection mean for the future power system?** In this future, we see much more electricity use compared to today, but the demand for electricity is also flexible—for example, we see more EV charging during the day when it's sunny and solar panels are generating lots of electricity.
- The **Stress** projection represents all the electrification of the High projection, but with lower efficiency and demand response improvements compared to Moderate, which would otherwise help manage the electrification-driven growth in electricity demand.
  - **What does this projection mean for the future power system?** In this future, we see big growth in electricity demand in the evening when people come home to plug in their vehicles after the sun sets, but this doesn't align with when renewable energy availability is highest. This projection helps us understand the value of energy efficiency and aligning customer demand with available renewable energy supply.

Three possible futures for **customer electricity demand**

Moderate energy efficiency, electrification, and demand flexibility, e.g.:

- 30% of passenger cars on the road in 2045 are plug-in electric
- Residential building equipment and appliance sales are distributed across all efficiency levels
- 80% of new and retrofit equipment is 5 years ahead of California's Title 24 commercial building energy-efficiency code-minimum
- 75% of residents have access to residential charging; 25% access to workplace charging

High energy efficiency, electrification, and demand flexibility, e.g.:

- Appliances, heating within buildings switch from natural gas to electric
- Residential building equipment and appliance sales are at highest efficiency available
- 80% of passenger cars on the road in 2045 are plug-in electric
- 60% of residents have access to residential charging; 50% access to workplace charging to encourage more daytime charging
- Demand is more flexible in its timing

Stress grid conditions—high electrification but low energy efficiency and demand flexibility, e.g.:

- All the electrification of High
- But timing of demand is not aligned with renewable generation
- Energy efficiency adoption is lower than Moderate (matches LADWP's 2017 Strategic Long-Term Resource Plan 10-year efficiency goals)
- 90% of residents have access to residential charging; 15% access to workplace charging to restrict daytime charging

Defining the 100% Target

Against these different trajectories of customer electricity demand, we also evaluate a variety of clean energy options for how to supply the electricity to meet this demand. These are the scenarios that explore different options for what infrastructure LADWP might choose to build to meet its 100% clean energy targets. We look at four possible scenarios.

It's important to remember that scenarios are not prescriptions or predictions—LADWP will not choose one scenario as its marching orders. Instead, the scenarios help illuminate how making different decisions could impact LA's future in a variety of ways—from costs, to environmental concerns, to the local economy.

The four scenarios that are evaluated against the different demand projections include SB100, Limited New Transmission, Transmission Focus, and Early & No Biofuels.

The **SB100** scenario is based on current California law, Senate Bill 100, which requires that 100% of electricity sales be renewable or zero carbon by 2045. This is the only scenario in which the 100% target is based on the electricity that serves the customer, not what gets generated. This means that a small portion of generation—the equivalent of transmission and distribution losses on the grid—can come from non-renewable sources such as natural gas. Another feature of this scenario is the use of renewable electricity credits (RECs), which are a market-based mechanism to help meet renewable energy targets. This allows natural gas generation to help meet the 100% target if offset by the purchase of RECs.

- **What does this scenario mean for the future power system?** These aspects of the SB100 scenario allow for 10%–15% of power generation to be derived from natural gas. As a result, this scenario allows some of the existing natural gas plants to stay active in 2045, which reduces the amount of new investments needed.

But what if LA wants *all generation* to come from renewable energy? The other three scenarios don't allow any natural-gas generation to help LA meet its 100% target. And those scenarios differ by what infrastructure LADWP is able to build.

Early & No Biofuels meets LA's 100% clean energy goal 10 years earlier than the other scenarios, in 2035. This scenario assumes higher levels of customer rooftop solar adoption and prohibits the use of biofuels because of concerns about sustainability. This is different from the other scenarios, which do allow biofuels to replace natural gas as a transition fuel until renewable-electricity-derived fuels, like hydrogen, become widely available for purchase.

This scenario instead builds infrastructure to produce hydrogen gas from renewable-based electricity, and uses that fuel in combustion turbines. This scenario minimizes the use of these hydrogen-fueled power plants to only when wind and solar power are insufficient to meet customer demand, just as the biofuel plants are used in other scenarios.

- **What does this scenario mean for the future power system?** The combination of the earlier transition and added restrictions on which technologies can help meet the 100% target means this scenario relies on higher-cost and less mature technologies, and yet is also quicker to realize the clean energy transition and reduce GHG emissions.

Transmission Focus assumes lower barriers to building new transmission lines and upgrading existing ones. This scenario reaches its target in 2045 and also does not allow natural gas or nuclear generation starting that year.

- **What does this scenario mean for the future power system?** More generation can be built out of state, and electricity can more easily travel without congestion within the city, helping to optimize the use of locally situated power plants.

Limited New Transmission prohibits building new transmission lines that are not already planned. This scenario reaches its target in 2045 and does not allow natural gas or nuclear generation starting that year. This scenario also assumes higher levels of customer rooftop solar adoption.

- **What does this scenario mean for the future power system?** Limiting new transmission encourages more clean energy to be built locally in LA. Still, even this scenario relies on building solar and wind outside the city, where those resources are cheaper and more abundant—and can be served by existing and planned transmission capacity.

> To explore LA100 results by scenario and demand projection, visit the LA100 website: **maps.nrel.gov/la100/key-findings/scenarios/**

LA100 SCENARIOS SNAPSHOT

SB100

Evaluated under Moderate, High, and Stress Load Electrification

- 100% clean energy by **2045**
- Only scenario with a target based on retail sales, not generation
- Only scenario that allows up to 10% of the target to be natural gas offset by renewable electricity credits
- Allows existing nuclear and upgrades to transmission

Early & No Biofuels

Evaluated under Moderate and High Load Electrification

- 100% clean energy by **2035**, 10 years sooner than other scenarios
- No natural gas generation or biofuels
- Allows existing nuclear and upgrades to transmission

Transmission Focus

Evaluated under Moderate and High Load Electrification

- 100% clean energy by **2045**
- Only scenario that builds new transmission corridors
- No natural gas or nuclear generation

Limited New Transmission

Evaluated under Moderate and High Load Electrification

- 100% clean energy by **2045**
- Only scenario that does not allow upgrades to transmission beyond currently planned projects
- No natural gas or nuclear generation

What We Learned: High-Level Findings

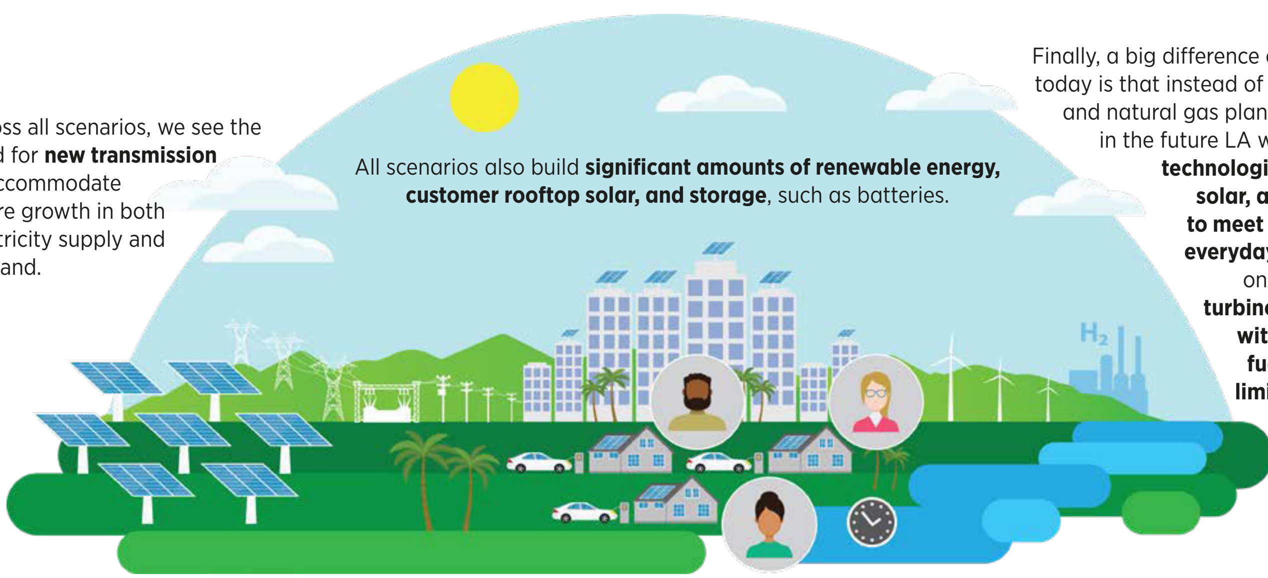
Looking across the scenarios, the LA100 study reveals key insights about what a high-renewable-energy future could look like in LA—and beyond.

- On the road to achieving 100% renewables by 2045, all LA100 scenarios include significant deployment of renewable and zero-carbon energy by 2035, accounting for 84%–100% of energy and a decline of 76%–100% GHG emissions from power plant operations in 2035 compared to 2020, depending on the scenario. Each of the scenarios builds new wind, solar, batteries, and transmission, coupled with operational practices that make more efficient use of these investments.
- By 2045, electricity demand (both annual consumption and peak demand) is likely to grow. High levels of energy efficiency can offset this growth in the buildings sector due to hotter climate, population growth, and electrification. It is the electrification of the transportation sector that propels overall growth in electricity demand.
- Also by 2045, with the incentives evaluated in the study, customers are likely to drive significant growth in rooftop solar: 3–4 gigawatts (GW), including up to a third of customers in existing single-family homes, based on favorable economics to the customer. LADWP might also deploy an additional 300–1,000 MW of non-rooftop, in-basin solar. The distribution grid can manage this growth in local solar—along with the projected growth in electricity demand.

While almost all parts of the distribution grid will need some upgrades, the LA100 study estimates that, after correcting deferred maintenance on the existing system, a modest number of equipment upgrades would be sufficient to manage growth in demand and local solar. These distribution upgrade costs represent a small fraction of the total cost of the clean energy transition.

Additional results by scenario and topic, links to download each chapter of the full report, a glossary of terms, and an interactive data viewer can be found on the study website at: **maps.nrel.gov/la100**

- Electrification of vehicles and buildings leads to substantial improvements in air quality and associated benefits to health—widespread across both disadvantaged and non-disadvantaged communities. LA100's results indicate that realizing these health benefits is principally a matter of achieving high energy efficiency and electrification, independent of any particular renewable energy pathway for the power sector.
- Also regardless of the pathway, economic impacts to the city of the 100% renewable energy transition are projected to be small relative to the overall size of LA's economy—so while the transition could create thousands of clean energy jobs annually, the clean energy investments alone are not anticipated to notably impact LA's economy overall.



Scenario	Total Clean Energy (Renewable, Hydro, and Nuclear) Penetration Achieved 2035 vs. 2045		Present Value of Cumulative (2021–2045) Costs* at Alternative Discount Rates (Billion 2019$)			Cumulative (2020–2045) Life Cycle GHG Emissions, All Sectors (MMT CO_2e)	Reduction in Annual Life Cycle GHG Emissions in 2045 Compared to 2020, All Sectors	Cumulative (2021–2045) Monetized Emissions Costs of GHG Emissions at Discount Rates of 2.5% and 5% (Billion 2019$)		Annual Mean Value** of Avoided Health Impacts in 2045 Only (Undiscounted, 2019$) Compared to 2012	Average Annual Employment from LADWP Power-Sector Spending (2026–2045) by Location of Investment: In-basin / Out-of-basin / Total		
	2035	2045	0%	2.5%	5.0%			2.5%	5.0%		In	Out	Total
SB100 MODERATE	90%	90%	$57B	$40B	$28B	570 MMT	54%	$61B	$16B	$900M	4,900	3,000	7,900
Early & No Biofuels MODERATE	100%	100%	$87B	$59B	$42B	510 MMT	61%	$55B	$14B	Very similar results to SB100 – Moderate, likely***	8,200	4,200	12,400
Transmission Focus MODERATE	90%	100%	$67B	$46B	$33B	540 MMT	59%	$58B	$15B		6,400	3,500	9,900
Limited New Transmission MODERATE	91%	100%	$62B	$43B	$31B	540 MMT	59%	$59B	$15B		6,700	3,000	9,700
SB100 HIGH	84%	88%	$61B	$42B	$30B	460 MMT	79%	$50B	$13B	Very similar results to Early & No Biofuels – High, likely***	5,500	3,500	9,000
Early & No Biofuels HIGH	100%	100%	$86B	$59B	$41B	390 MMT	88%	$43B	$11B	$1,400M	8,700	4,500	13,200
Transmission Focus HIGH	89%	100%	$72B	$49B	$35B	425 MMT	86%	$46B	$12B		7,200	4,300	11,500
Limited New Transmission HIGH	90%	100%	$67B	$46B	$33B	420 MMT	87%	$46B	$12B		7,600	3,900	11,500
SB100 STRESS	85%	87%	$69B	$47B	$34B	480 MMT	77%	$53B	$14B		6,500	3,700	10,200

$0 – $90B | 0 – 600 | $0 – $63B | $0 – $1,500M | 0 – 15,000

*Costs, as measured in the study, represent costs of expanding and operating of the power system from 2021. Present values calculated with a discount rate of 0% are equivalent to an undiscounted value.
**95% confidence interval of values of avoided health impacts in 2045 compared to 2012 is SB100 – M is (-$480M–$3,000M) and of Early & No Biofuels – H is (-$470M–$4,400 M).
***Because the contribution to emissions reductions from the power sector is small (ranging from 0.8%–1% for NOx among LA100-evaluated reductions), it is reasonable to qualitatively estimate the results stated.

Comparison of scenarios across select metrics analyzed in LA100

Major Trends Across All Pathways to 100%

1. **Reliable, 100% renewable electricity is achievable—and, if coupled with electrification of other sectors, provides significant greenhouse gas, air quality, and public health benefits.**

- While achieving a reliable, 100% renewable electricity power system is a significant undertaking requiring substantial investments, the LA100 analysis identifies multiple pathways to get there.
- Wind and solar resources—enabled by storage—are fundamental to providing the majority of energy required to meet future load: **69%–87%** depending on the scenario.
- New in-basin, renewable firm capacity—resources that use renewably produced and storable fuels, can come online within minutes, and can run for hours to days—will become a key element of maintaining reliability (represented in the figure below as hydrogen- and renewably [RE]-fueled combustion turbines and fuel cells).

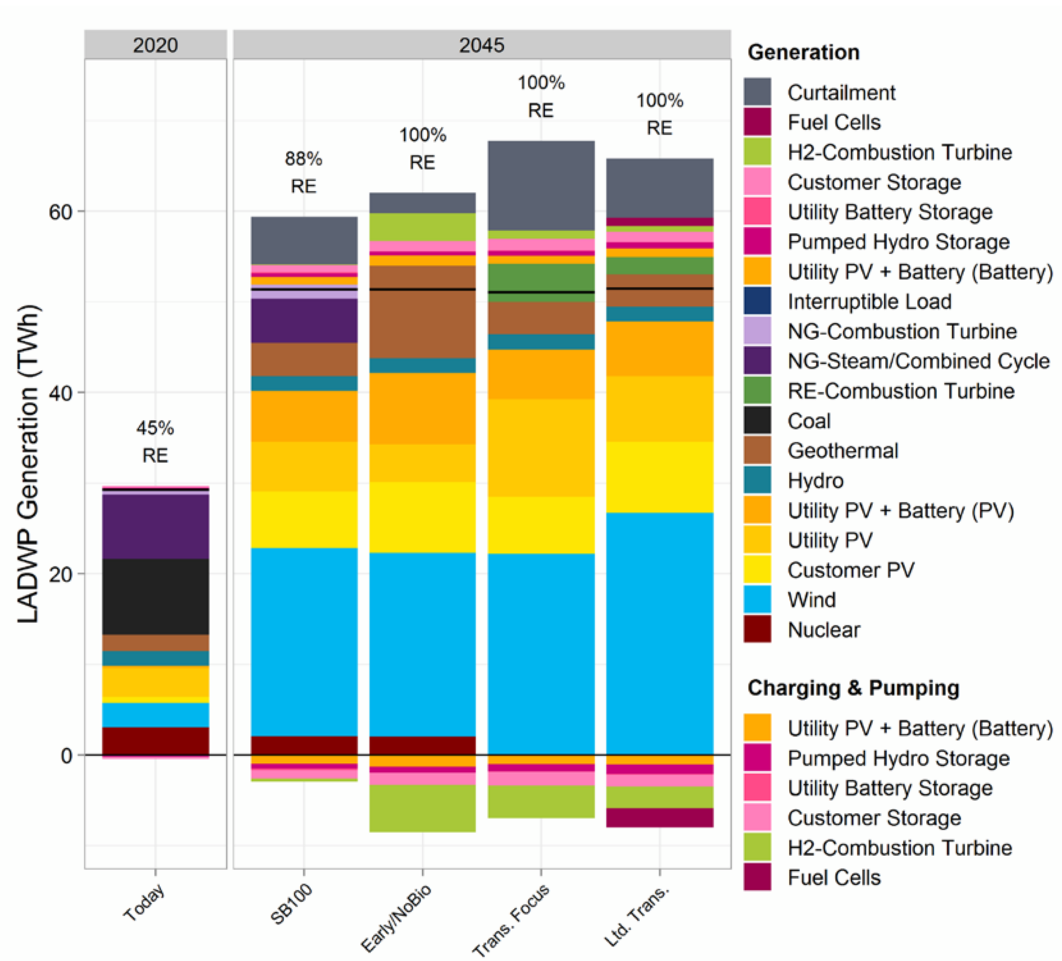
Customer-oriented actions that help complement a renewable energy transition include:

Energy efficiency → helps offset climate- and electrification-driven load growth and potentially higher electricity rates; lowers energy burden for low-income residents

Greater electrification → contributes to higher public health and GHG benefits; helps reduce per-unit electricity costs

Customer demand flexibility → helps contain costs of adding electrification and achieving 100% renewable energy; also supports reliability

- Decarbonizing the power sector through renewable deployment helps create the enabling conditions for decarbonization of the buildings and transportation sectors through electrification. While the power sector itself contributes few non-GHG air pollutant emissions in a 100% renewable future, the electrification of combustion sources in other sectors enables more significant emissions reductions, and thus improved health for Los Angeles residents.



Annual generation mix in 2045 for all High load scenarios compared to 2020

The percent RE refers to percent of generation that is carbon neutral (renewable and nuclear). Negative values indicate the amount of electricity consumed by the plants (e.g., to charge a battery, pump hydro, or produce hydrogen fuel). Load (solid line) is customer electricity consumption exclusive of charging. Curtailment includes available energy that is curtailed to provide reserves.

2. **All communities will share in the benefits of the clean energy transition—but improving equity in participation and outcomes will require intentionally designed policies and programs.**

   - Disadvantaged communities (as defined by CalEnviroScreen scores) could expect to see many benefits in a clean energy transition, including reduced local and regional air pollution, improved indoor air quality from electrification, reduced vulnerability to climate change and improved health outcomes.
   - Ensuring prioritization of these neighborhoods, however, is not an inevitable result of the power-system transition. A just, equitable clean energy future would require intentionally designed decision-making processes and policies/programs that prioritize these communities (see the text box below).

3. **Net economic assessment shows that achieving the LA100 scenarios will not affect LA's overall economy in any meaningful manner.**

   - Using SB100 – Moderate as a reference scenario, the net impact to employment within the city (reflecting combined positive and negative impacts of economic activity measured in LA100, from 2026 to 2045) ranges from a low of 3,600 fewer jobs annually under the Early & No Biofuels – Moderate scenario to 4,700 additional jobs under the SB100 – Stress scenario. While there may be slight positive or negative impacts, these changes are small in relationship to the 3.9 million jobs and $200 billion in annual output of LA's economy as a whole, so they have an almost negligible impact.
   - Specific to jobs associated with LADWP expenditures as measured in LA100, both in and outside of the LA Basin, higher expenditures on new infrastructure and operations of both existing and new infrastructure (exclusive of the distribution grid) correlate with higher numbers of jobs. The number of gross annual jobs (onsite and ripple effect) supported by these expenditures ranges from an average of 7,900 jobs per year in SB100 – Moderate to 13,200 jobs per year in Early & No Biofuels – High.

Example Actions to Support Prioritization of Environmental Justice

Participation in decision-making: Identifying barriers to procedural justice can inform improvements to who is included in decision-making, how decisions get made, and what resources are needed to enable parity of participation.

Energy infrastructure: LA100 shows strong potential for electrification, efficiency, demand response, and rooftop solar in environmental justice neighborhoods—but the modeling does not capture real-world experiences and barriers to adoption. Actions to prioritize environmental justice include improved input modeling data on characteristics significant to environmental justice (e.g., household size, access to smart energy devices) and more comprehensive representation of benefits, such as improved resilience to extreme weather events through energy efficiency upgrades.

Jobs: Identifying workforce needs for each energy technology identified in the study has important implications for potential future hiring and training needs. The City of LA could facilitate programs for in-demand occupations that may be hard to fill and for other high-quality jobs. The City of LA could also include in clean energy program design some of the workforce objectives sought by the community. For example, some have requested solar installations within disadvantaged communities as a way to support clean energy jobs that do not require long commutes.

Maintaining support for electrification: Electrification of transportation, building end uses, and the Ports of Los Angeles and Long Beach provide significant air quality and related public health benefits. Hence, a prioritization of disadvantaged communities as first immediate beneficiaries of localized air quality improvements would include a focus on electrification. But electrification can be hindered by increasing electricity rates. Toward the end of the 100% renewable energy transition, the cost of fully decarbonizing the power sector, if reflected in increased rates, could lead to public pressure to reduce the pace of electrification. Further analysis could consider options that maintain decarbonization and improved health as a goal, but with a better understanding of the interaction among the costs of power system decarbonization, pace of electrification, and rate design.

Neighborhood-level health impacts: Quantifying neighborhood-level impacts could be an important component of further analysis after LA100 with regard to achieving outcomes beneficial to disadvantaged communities. For example, the design and evaluation of any EV incentives could be coupled with analysis of local air quality benefits, especially in neighborhoods along roadways that suffer high local pollution. As another example, LA100 results suggest value to reliability in building new, state-of-the-art combustion turbines at current thermal generating station sites fueled by renewable-electricity-derived fuels (such as hydrogen) and operated less frequently compared to natural gas today. One step that LADWP and the City of LA can consider to prepare for this change is to establish expectations of anticipated neighborhood environmental impacts (based on local-scale air quality modeling), monitor these impacts, and revise operating protocols as needed.

4. LA can get started now, with many no-regrets options that achieve significant emissions reduction (76%–99%) by 2030.

- The LA100 study finds many no-regrets options. On the customer side, the study shows significant benefits from electrification in terms of improving GHG emissions, air quality, and health, and emphasizes the critical role of customer demand flexibility to reduce per-unit electricity costs and contribute to reliability.
- When it comes to the LADWP power system, the no-regrets options include new wind, solar, batteries, and transmission—deployed in or out of the LA Basin, and coupled with smart-grid operational practices that make more efficient use of these investments. LADWP can also address existing distribution maintenance needs to enable changes on the customer side, which were assumed to have already occurred as the starting point for LA100.

Key Distinctions Between Pathways to 100%

1. The LA100 scenarios show similar cost increases until approximately 80%–90% renewable energy. The pathways diverge with differences in the technologies deployed to meet the last 10%–20% of energy demand that cannot be easily served by wind, solar, and conventional storage technologies—and to maintain reliability in the face of extreme events.

- In-basin renewable capacity that can come online within minutes and run for days serves a critical role: it provides energy during periods of lower wind and solar generation, extremely high demand, and unplanned events like transmission line outages.
- Today, the cheapest option for this type of peaking capacity is a storable renewable fuel used in a combustion turbine. Biofuels are commercially available today and could serve as a transition fuel until commercially available, electricity-derived fuels become more widespread.
- If the City of LA does not want to use biofuels, LADWP can produce its own clean fuel in the form of hydrogen (produced from renewable electricity).
    - This option is not yet commercially available at scale, so building the necessary infrastructure could represent a significant portion of total costs associated with the clean energy transition.
    - In the Early & No Biofuels scenario, hydrogen technology represents a 20+% increase in cumulative (2021–2045) costs compared to cases that allow biofuels.
- The resources used to help meet this last 10% and maintain reliability can produce local air emissions, particularly when based on combustion generation.
- However, even accounting for future growth in energy demand, these new resources would be used much less often than current natural-gas plants, resulting in lower emissions—both in the power sector and economy-wide.

2. The combination of higher energy efficiency, electrification, and demand flexibility, while associated with increased total costs, offers both greater benefits and reduced per-unit electricity costs compared to alternative scenarios.

- While LA100 does not represent a complete analysis of tradeoffs (e.g., it does not address costs of demand-side equipment, employment benefits from energy efficiency, and impact to overall energy expenditures, among others), the benefits as measured within the study are significant. For example, comparing a scenario with Moderate and High electrification levels, while the High electrification version has higher total costs, it offers lower per-unit costs, higher GHG and air pollutant emissions reductions, and higher public health benefits (see the figures on the next page).
- In addition, comparing SB100 – Stress to SB100 – High shows the value of energy efficiency and demand flexibility (as the scenarios are otherwise the same). SB100 – Stress has an 8.5% higher annual electricity consumption and 17% higher peak demand compared to SB100 – High. The combination of efficiency and demand flexibility assumed in the High version reduces the cumulative (2021–2045) costs of that scenario by 13%.

This study is unique for a 100% renewable energy analysis in that it includes vulnerabilities to many types of events (heat waves, fires, earthquakes, among others).

Keeping the lights on was a foundational part of this study, as the City of LA recognizes the critical role of a reliable power grid—especially in a future with more consumer products, like cars, electrified. A 100% renewable grid cannot compromise on reliability, particularly when electricity is playing a greater role in heating, cooking, and transportation.

Increasingly, studies of the evolving grid, regardless of the contribution of renewables, are examining the impact of climate change on demand for electricity, and the vulnerability of the grid to increased temperatures and climate-change-driven natural disasters, whether they be wildfires or earthquakes.

Minimizing climate vulnerabilities requires careful planning and use of a mix of resources, including continued deployment of the cleanest resources that can maintain reliability (which today include combustion-based resources), while aggressively pursuing lower-emitting technologies, such as hydrogen fuel cells.

Scenario	Cumulative (2021–2045) Costs* per MWh (2019$)	Reduction in Annual Life Cycle GHG Emissions, All Sectors, in 2045 Compared to 2020	Reductions in Annual Emissions from LA100-Influenced Sources in 2045 Compared to SB100 – Moderate	Annual Mean Value** of Avoided Health Impacts in 2045 (Million 2019$) Compared to SB100 – Moderate	Annual Mean Avoided Incidences in 2045 Compared to SB100 – Moderate
Early & No Biofuels MODERATE	$93/MWh	61%	2% NO_x; 1% $PM_{2.5}$	$9M	**1 prevented** premature death **0 change** in cardiovascular hospital admissions **0 change** in asthma ER visits
Early & No Biofuels HIGH	$83/MWh	88%	63% NO_x; 39% $PM_{2.5}$	$500M	**53 prevented** premature deaths **23 fewer** cardiovascular hospital admissions **19 fewer** asthma ER visits
	$0 – $100			$0 – $500M	

*Annual per-MWh costs do not equal rates—these costs represent the revenue requirement (per unit of generation) to cover the annualized costs associated with expenditures measured in LA100.
**95% confidence interval of values of avoided health impacts in 2045 compared to SB100 – M is: Early & No Biofuels – M ($1M–$24M) and Early & No Biofuels – H ($19M–$1,400 M).

Scenario	Cumulative (2021–2045) Costs* per MWh (2019$)	Reduction in Annual Life Cycle GHG Emissions, All Sectors, in 2045 Compared to 2020	Reductions in Annual Emissions from LA100-Influenced Sources in 2045 Compared to SB100 – Moderate	Annual Mean Value** of Avoided Health Impacts in 2045 (Million 2019$) Compared to SB100 – Moderate	Annual Mean Avoided Incidences in 2045 Compared to SB100 – Moderate
SB100 MODERATE	$62/MWh	54%	n/a	n/a	n/a
SB100 HIGH	$61/MWh	79%	63% NO_x; 39% $PM_{2.5}$	$490M	**53 prevented** premature deaths **23 fewer** cardiovascular hospital admissions **19 fewer** asthma ER visits
	$0 – $100			$0 – $500M	

*Annual per-MWh costs do not equal rates—these costs represent the revenue requirement (per unit of generation) to cover the annualized costs associated with expenditures measured in LA100.
**95% confidence interval of values of avoided health impacts in 2045 compared to SB100 – M for SB100 – H is ($18M–$1,400M).

Comparison of costs and benefits between two different electrification levels for the Early & No Biofuels (top) and SB100 (bottom) scenario. The High electrification level offers higher benefits and lower per-unit electricity costs.

3. Accelerating the target year to 2035 increases both costs and benefits.

- All else equal, an earlier target year means LADWP must make the necessary investments to achieve 100% renewable electricity more quickly. This results in earlier accumulation of debt, ultimately leading to greater costs over the timeframe of this study (2021–2045).
- However, benefits also accrue more quickly, though not necessarily at the same rate as costs. The earlier LADWP achieves a zero-GHG-emission or 100% renewable system, the earlier the avoided emissions accumulate. Reducing emissions earlier has value in terms of reducing the magnitude of the effects of climate change. Similarly, new renewable energy jobs accrue more quickly.
- The Early & No Biofuels scenario accumulates both the costs (from annualized payments for renewable technologies) and benefits (GHG emissions, renewable energy jobs) of this transition due to the 10-year head start.
- If the earlier target is pursued, success would also require an accelerated schedule for renewable energy procurement, permitting, siting, and workforce training, among other activities that are outside the scope of the study but are essential components of implementation.

"Life cycle" GHG emissions consider all phases of both the generation facility and its fuel: plant construction; plant operation including fuel combustion (if applicable) and other operations and maintenance (O&M) as well as emissions from the acquisition, treatment, and transport of fuels, when applicable; and finally plant decommissioning and disposal.

4. Technology restrictions result in higher costs when it comes to meeting the last 10%–20% of energy demand—but almost no additional air quality or public health benefits.

- The costs, GHG emissions, air quality, and public health trajectories across scenarios (within any given electrification level) are similar until each scenario reaches approximately 90% renewable and zero-carbon electricity. After 90%, the costs diverge for different scenarios, but the overall benefits plateau.
- SB100 remains around 90% renewable and zero-carbon electricity through 2045 due to how this scenario is defined. But all the other scenarios move from 90% to 100% renewable electricity by 2045—and they exhibit sharp increases in costs in the last 10%.
- The additional benefits of restricting technology eligibility in terms of air quality and public health,

Scenario	Reduction in Power-Sector Life Cycle GHG Emissions in 2045 Relative to 2020	
SB100 HIGH	68%	**Annual Health Impacts Metrics* Compared to SB100 – High, 2045 Only**
Early & No Biofuels HIGH	93%	**1 prevented** premature death **0 change** in cardiovascular hospital admissions **0 change** in asthma ER visits **$6M** annual mean value* of these avoided health impacts

*95% confidence interval of values of avoided health impacts in 2045 of Early & No Biofuels – H compared to SB100 – H is -$1M–$17M

Comparison of GHG emissions and health impacts in 2045 between SB100 – High and Early & No Biofuels – High as measured in the selected scenarios analyzed in the study, are minimal when electrification levels are constant because natural gas consumption across all scenarios is significantly reduced or eliminated compared to today. Because changes to the power sector only contribute 0.8%–1% of the NOx emissions reductions among LA100 scenarios compared to 2012, and 10%–18% of the particulate-matter emission reductions, it is clear that changes to energy efficiency and electrification levels (for vehicles, buildings, and the Ports of Los Angeles and Long Beach) are the predominant cause of health benefits.

Looking Ahead: Addressing Uncertainty, Prioritizing Future Decisions

1. **Identifying alternative options for firm, in-basin capacity likely represents the largest opportunity to reduce the costs of the transition and points to the highest priorities for R&D: hydrogen and extended demand response.**

   - All LA100 scenarios build in-basin combustion-based resources to help meet the last 10%–20% of electricity demand that is not easily met by low-cost wind, solar, and batteries. The timing of building these new resources can be cost-effectively delayed somewhat with a combination of energy efficiency, local solar and storage, new transmission, and technologies and techniques to increase the capacity of existing, in-basin transmission. But delays in deploying these *other* options could accelerate the need for new in-basin resources.

Demand response—the change in the amount or timing of electricity use in response to a price or other signal from the utility—is most often used today to reduce system peaks and thereby reduce the need for additional power plants or transmission lines. Demand response may also be used to shift demand for electricity to times when more renewable energy is available.

   - The fuel for new in-basin resources varies by scenario. Several scenarios use biofuels, which are commercially available and serve as a net-zero-carbon transition fuel while technologies such as hydrogen-based fuels mature.
   - Alternatives to biofuels include renewable electricity-derived hydrogen fuel, or hydrogen derivatives, such as synthetic methane or ammonia. There is considerable uncertainty regarding hydrogen's long-term cost and commercial availability, as well as generator modifications needed to use these fuels. There is also uncertainty as to how long it will take to develop infrastructure for transportation and storage. To reduce hydrogen costs, the City of LA could partner with industry as part of economy-wide decarbonization where hydrogen-derived fuels are used to power industry, non-electrified transportation, and serve as feedstocks for chemicals and materials that currently rely on fossil fuels.
   - Across the scenarios, allowing fuel flexibility (biofuels inclusive) allows LADWP to start now without committing to hydrogen infrastructure. Allowing RECs (to continue limited use of natural gas) could mitigate risk; limiting use of RECs to a few percent could provide the needed reliability benefits and still provide nearly all the GHG, air quality, and public health benefits associated with the transition to 100% renewable electricity.
   - In addition to fuel flexibility and RECs to mitigate uncertainty in the use of hydrogen and biofuels, one alternative yet to be deployed and tested at scale is multi-day demand response. Such a program could be initiated now to enable more rapid roll-out should the City of LA proceed with biofuel or hydrogen options and find those paths infeasible or cost-prohibitive.
   - Such a program would require a detailed analysis of the customer base to identify customers with flexible loads, and the necessary compensation needed to reduce these loads for extended periods. Exploring this option would likely require pilot programs and new rate designs that compensate customers for reduced energy consumption, as these types of programs do not exist at scale in the United States outside of very large industrial customers.

2. **What if LA wants to pursue an earlier target?**

   - The LA100 study did not evaluate achieving 100% renewable energy prior to 2035. However, in 2030 the scenarios achieve a decline of 76%–99% GHG emissions from power plant operations compared to 2020, and an overall renewable and zero-carbon energy contribution of 77%–99% of energy, depending on the scenario—so significant progress can be made in the next decade if LA starts now.

- A faster transition to 100% renewables would likely require deployment of technologies at a higher cost, reflecting both technology maturity and commercial availability. The costs could be particularly high for firm capacity resources needed to fully replace natural gas, given the current role of natural gas in responding to extreme events. We assume this complete transition is feasible by 2035, but we have not evaluated the supply chain and other aspects of feasibility that would be required to effect this change in less than 10 years.
- Availability of this type of firm capacity resource (e.g., hydrogen production, renewably fueled combustion turbines, fuel cells) would benefit greatly from a robust RD&D program at the financial scale of national and international initiatives rather than a single city's budget.
- Expediting regional transmission development would likely require state- and federal-level support.

3. **This study marks an important but not final analysis in LA's pivot towards a clean and equitable energy future.**

- LA100 establishes a methodology that could serve as a foundation for additional and updated analyses that could help reassess costs, benefits, and tradeoffs over time. Continued analyses are needed to understand how to improve implementation, monitor results, and adjust decisions.
- In particular, using current-generation, forward-looking models to anticipate implications for environmental justice does not capture real-world experiences and barriers to adoption. Therefore, effectively prioritizing environmental justice in implementation, per the City Council motion, would require ongoing monitoring and adjustments.
- In addition, aspects related to customer demand (efficiency, electrification, demand response, and customer solar and storage) also represent high-priority areas for ongoing analyses. The changes on the demand side occur, to a large degree, outside of LADWP's immediate control and planning, but can be substantially impacted by rate structures, incentives, or local policies, and have significant potential to affect the costs and benefits of the 100% renewable transition.

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Diving Deeper: Key Findings by Topic

The LA100 study aims to inform the City of LA, LADWP, and other stakeholders of possible pathways to 100% renewable energy, and the implications of these pathways for the people who live and work in LA—including implications for environmental justice, GHG emissions, air quality and public health, the economy, and reliability.

Here, we dive into high-level findings for each topic addressed in the study. Additional detail, figures, and supporting data can be found on the Results by Topic section of the LA100 website (**maps.nrel.gov/la100/key-findings/topics/**) and in Chapters 3–11 of the full report (available at: **maps.nrel.gov/la100/report**).

The Customer

Electricity Demand Projections: Explores how electricity is consumed by customers now, how that might change through 2045, and potential opportunities to better align electricity demand and supply

Local Solar and Storage: On the customer side, explores the technical and economic potential for rooftop solar in LA, and how much solar and storage might be adopted by customers; on the LADWP side, identifies and ranks locations for utility-scale solar (ground-mount, parking canopy, and floating) and storage, and associated costs for integrating these assets into the distribution system

The Power System

Renewable Energy Investments and Operations: Explores pathways to 100% renewable electricity, describing the types of generation resources added, their costs, and how the systems maintain sufficient resources to serve customers

Power System Adequacy and Reliability: Describes how the LA100 scenarios were evaluated to ensure LADWP can balance demand for electricity with supply, even after failures of transmission and generation equipment or during extreme events

Distribution Grid Impacts: Summarizes future growth in distribution-connected energy resources and provides a detailed review of impacts to the distribution grid of growth in customer electricity demand, solar, and storage, as well as required distribution grid upgrades and associated costs

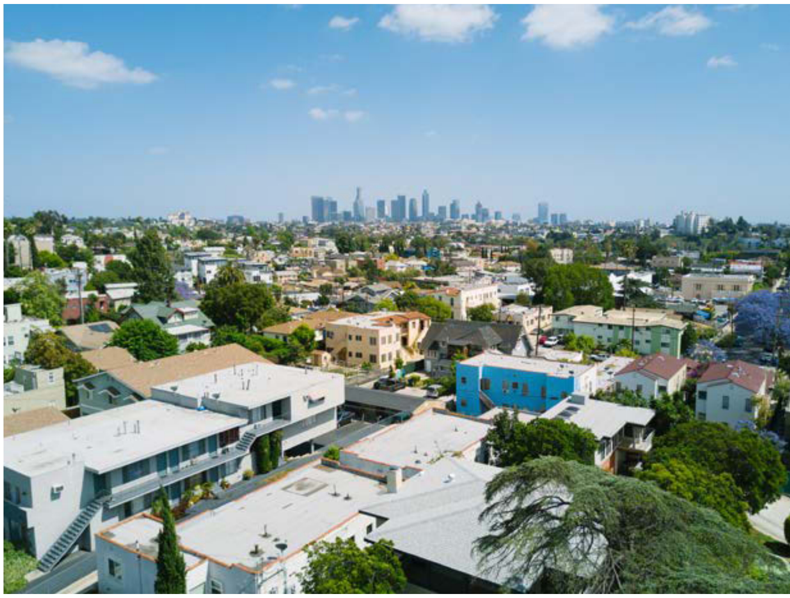
The Community

Greenhouse Gas Emissions: Summarizes GHG emissions from the power, buildings, and transportation sectors, along with the potential costs of those emissions

Air Quality and Public Health: Summarizes changes to air quality (fine particulate matter and ozone) and public health (premature mortality, emergency room [ER] visits due to asthma, and hospital admissions due to cardiovascular diseases), and the potential economic value of public health benefits

Environmental Justice: Explores implications for environmental justice, including procedural and distributional justice, with an in-depth review of how projections for customer rooftop solar and public health benefits vary by census tract

Jobs and the Economy: Reviews economic impacts, including local net economic impacts and gross workforce impacts



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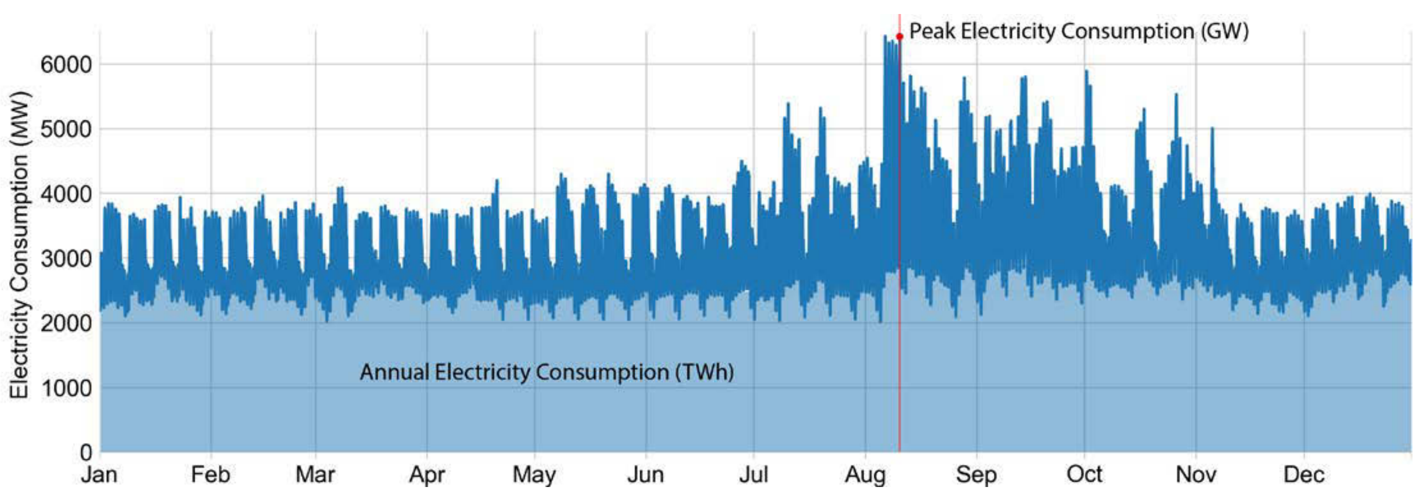
Electricity Demand Projections

LA100's electricity demand projections explore how electricity is consumed by customers now, how that might change through 2045, and potential opportunities to better align electricity demand and supply.

Find additional information on this topic on the LA100 website (**maps.nrel.gov/la100/key-findings/topics/electricity-demand-projections**) and in Chapter 3 of the full report (**nrel.gov/docs/fy21osti/79444-3.pdf**).

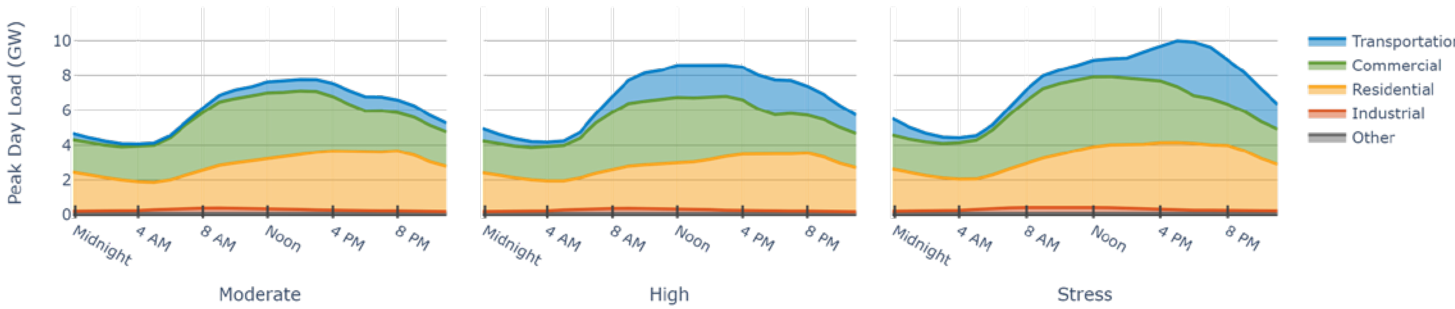
How might LA electricity demand evolve over the study period in response to technological change?

- **All demand projections assume significant technology-driven change based on LA's and California's historical track records and future ambitions regarding energy efficiency and electrification.** The Moderate projection includes the least change as compared to today's electricity demand. However, it is not a business-as-usual case: it projects about 1 million light-duty EVs on LA's roads by 2045, more use of electric and heat pump technologies in the buildings sector, and a continued focus on energy efficiency through all sectors of the economy.
- **Weather-correlated cooling demand is an important driver of LADWP systemwide peak demand in all projections and all model years.** LADWP is a summer-peaking system. In our modeling results, in all projections through 2045 the system-wide peak day occurs in early August, on the hottest weekdays of the modeled weather year. Historically, the LADWP system peak day has hit on various days in August or September. Cooling loads in buildings are a nonlinear function of outdoor air temperature—hotter temperatures mean not only increased cooling demand, but also increased energy needs to deliver the same amount of cooling.
- **With high electrification of the light-duty vehicle fleet, system peak days are still driven by cooling loads, but EV charging may influence the timing of the peak by 2045.** Although LA100 peak demand always hits on an August day with high cooling loads, the timing of the 2045 demand peak is significantly different across our three projections. The Moderate projection shows the same peaking pattern as today—peak demand occurs around 4 p.m.—but the High and Stress projections, which both include significant light-duty vehicle electrification, show peak demand occurring at 2 p.m. and 7 p.m., respectively (see the first figure on the next page). In those projections, the time of system peak is influenced by where, and therefore when, EV charging takes place. The High projection assumes more workplace charging, which is better aligned with solar generation. The Stress projection continues today's trend of mostly residential charging starting in the evening hours.



The key metrics of peak electricity demand (measured in GW) and annual electricity consumption (measured in terawatt-hours, TWh) illustrated with an example profile from LA100 modeling results

The figure shows the resulting system peak demand in context with a full year of demand data. The magnitude and timing of peak electricity demand drives power system planning, because there must be enough generation capacity available to meet that demand at that time (and at other near-peak times), with some power in reserve to manage forecast errors and outages on the power system. The amount and timing of electricity use throughout the whole year is important as well—how much total energy needs to be delivered, and how well those needs align with wind, solar, and other generation resources.

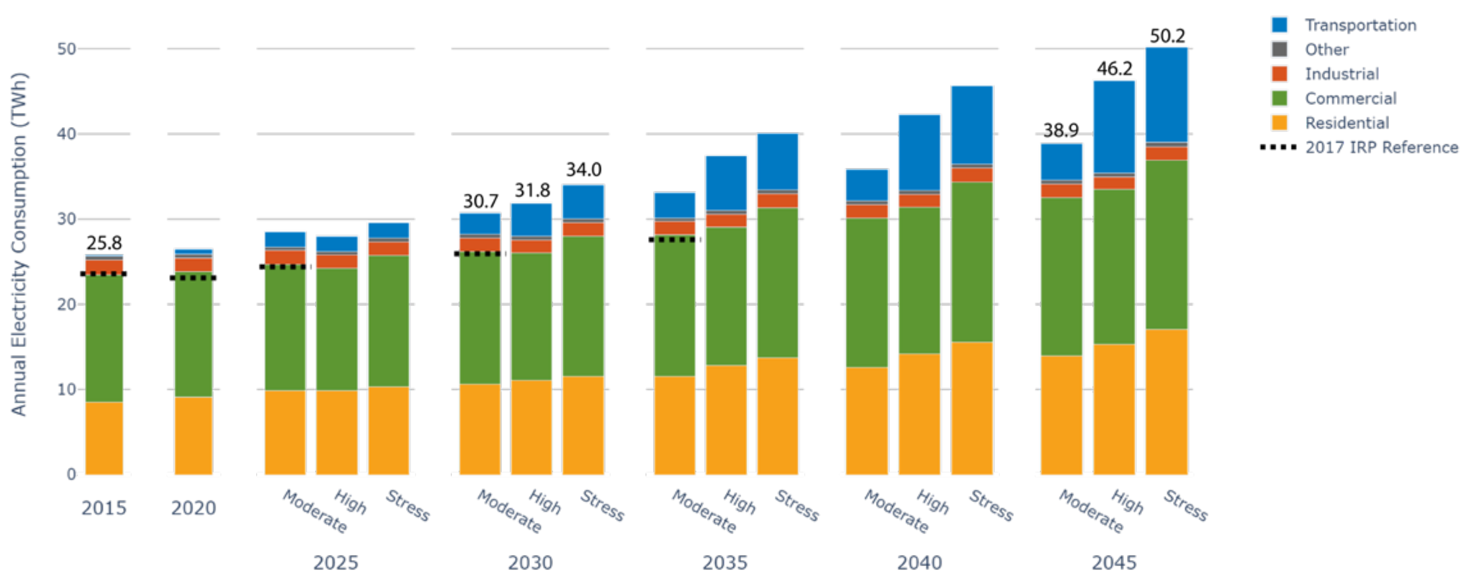


Peak demand profiles in 2045

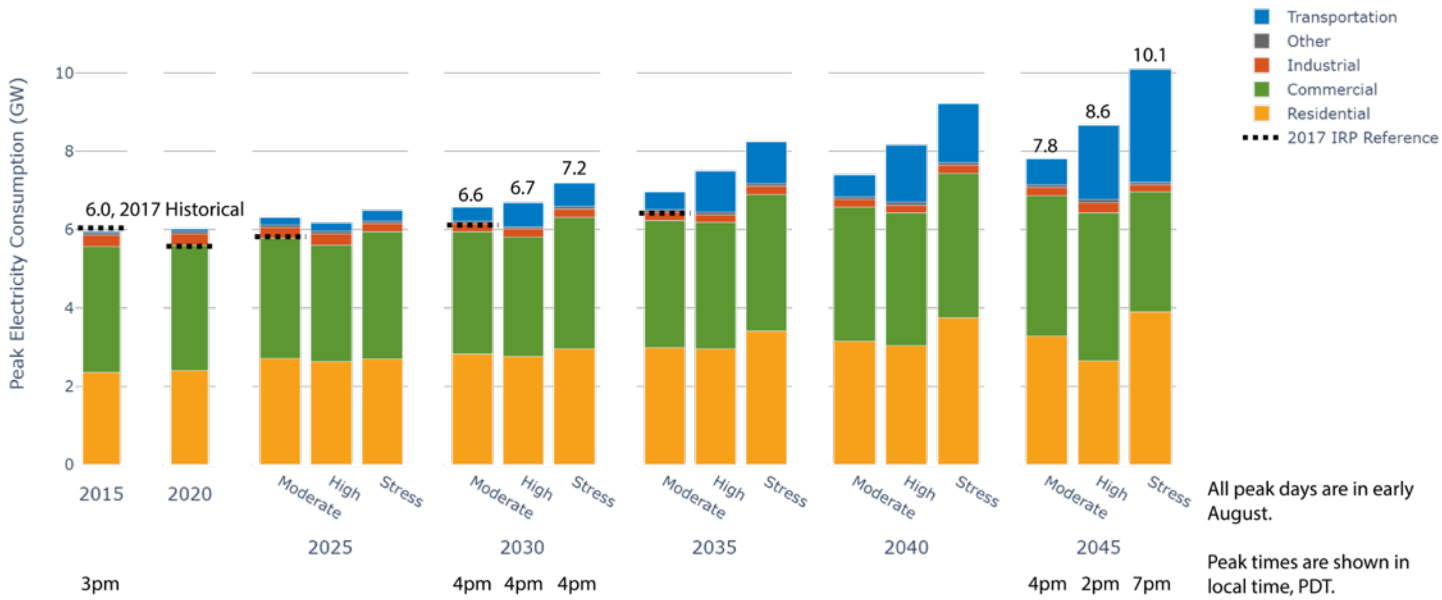
- **High levels of energy efficiency and electrification would drive significant change in the buildings sector that is difficult to see in peak demand and annual energy consumption metrics.** The High projection significantly mitigates increases in electricity use due to electrification through 100% sales shares of the highest efficiency equipment models in the residential sector and efficiency adoption up to 15 years ahead of Title 24 codes in the commercial sector.
- Key public infrastructure such as the water system, school buses, and transit buses are expected to use significantly more electricity; however, these will remain small loads from a systemwide perspective.
- All projections show higher annual energy consumption, driven most prominently by EV charging, but also with contributions from economic growth, the water system, miscellaneous electric and process loads in buildings, and building electrification. Demand grows at compound rates of 1.6% (Moderate), 2.3% (High), and 2.6% (Stress) (see the figure below).
- **Peak electricity demand also grows in all projections, but at a rate slower than annual electricity consumption.** This reflects the tendency of electrification to add load at all times, not correlated with system peak, and results in an overall demand profile that is less peaky than what we see today (see the first figure on the next page).

What strategies can be used to better align electricity supply and demand?

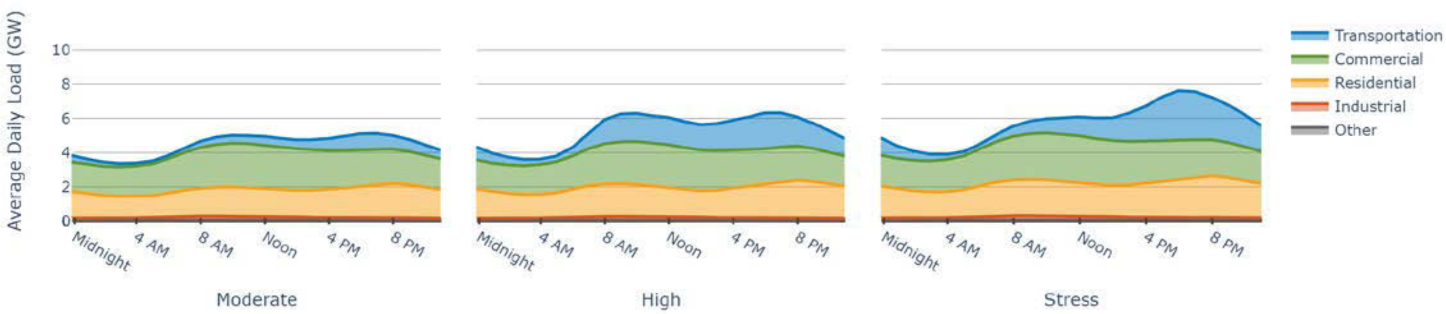
- **EV charging can be better aligned with solar generation by ensuring access to workplace charging infrastructure.** EVs in the High projection have 50% access to workplace charging and 60% access to home charging, whereas the Stress projection assumes 15% access to workplace charging and 90% access to home charging. This results in charging profiles that on average are more (High projection) or less (Stress projection) aligned with solar generation in the daylight hours (see the second figure on the next page).



Annual electricity consumption by projection-year and sector



Peak electricity demand by projection-year and sector



Average daily profiles for 2045 by projection-year and sector

- With high electrification of the light-duty vehicle fleet, schedulable EV charging may be able to provide significant demand response opportunities even if LADWP's incentive levels and marketing efforts are modest.
- If demand response technology becomes plug-and-play and LADWP provides a wide range of well-marketed and sufficiently incentivized demand response programs, up to 18% of peak demand and 12% of total annual demand could be avoided or shifted from high- to low-price times.
- While it is clear where demand response could potentially be moving, exactly what level of transformation will be achievable is highly uncertain. There are open questions concerning infrastructure buildout, precise technical capability, and human behavior and preferences. Market structures and business models are also active areas of innovation.

Important Caveats

- LA100 demand projections relied on state and local planning documents for projections of population and economic growth, and those assumptions were held constant across the scenarios.
- None of the component demand models are currently capable of capturing relationships between, e.g., income and demographic factors, and decision-making and habitual behaviors that drive energy use outcomes. Nor were income and demographic factors available in detailed parcel- and customer-level data used to spatially disaggregate modeling results.
- Technology adoption was modeled exogenously, based on various planning documents, state and local policies and goals, and engineering judgement. The overarching goal of demand scenario construction was to provide a small number of demand projections that approximately bracket possible outcomes from a power system (total and peak load) perspective. Notably, the City of LA's 2019 electrification and efficiency targets were released mid-project—we were able to incorporate most, but not all, of the demand-side goals; namely, we were not able to include electrification of medium- and heavy-duty vehicles.
- LA100 models different electrification scenarios for the Port of Los Angeles, but electrification of the Los Angeles International Airport is not captured, nor is industrial decarbonization. There are also many commercial premises in Los Angeles that do not map to standard commercial building types—as with industrial manufacturing (including refining, which could be impacted by high electrification of the transportation sector), demand for those premises was projected to continue largely as is.
- LA100 captures average monthly temperature increases from climate change but does not capture heat island effects or extreme weather events such as heat waves.
- The LA100 demand response analysis used the best data and modeling methods available at the time, but there is more to learn. We limited demand response shifting to within a day and did not evaluate multiday strategies that could help reduce the need for power system capacity in managing longer-term events.

Local Solar and Storage

LA100 evaluates the growth of "local" solar and storage systems that are sited within Los Angeles. The study considers two types of local solar and storage systems: customer adopted (rooftop solar) and procured by LADWP (in other locations within the city).

Find additional information on this topic on the LA100 website (**maps.nrel.gov/la100/key-findings/topics/local-solar-and-storage**) and in Chapters 4 (**nrel.gov/docs/fy21osti/79444-4.pdf**). and 5 (**nrel.gov/docs/fy21osti/79444-5.pdf**) of the full report.

How much potential exists for rooftop solar?

- **Rooftop solar potential in Los Angeles is significant and represents the largest in-basin generation resource.** The city has over 13 GW of solar rooftop technical potential, and over half is in the residential sector.
- **Opportunity for rooftop solar on multi-family buildings is substantial, and a potential contributor to environmental justice.** Development on multi-family buildings is currently limited due to classic owner-tenant barriers to adoption. The study identifies 2,060 MW of technical potential for multi-family building rooftop solar and 337 MW for ground-mount solar.

How did LA100 model the potential for local solar?

LA100 uses geospatial data to assess the potential for siting solar on millions of building rooftops, ground-mount sites, parking canopies, and floating locations within Los Angeles.

The study first estimates technical potential, or the theoretical upper bound on what could be deployed, and is not a reflection of the amount of distributed solar capacity that is economic or likely to occur.

LA100 scanned hundreds of thousands of rooftops in Los Angeles to assess their potential for solar using lidar (light detecting and ranging) data, which allow us to measure the topographical height of a building and infer a roof's degree of shading, angle, orientation, and developable area. These characteristics are important for understanding how solar energy would be generated throughout the day.

For each parcel of land identified for possible ground-mount, parking canopy, or floating solar deployment, the study ranks its suitability based on a least-cost algorithm that considers project size, cost of land acquisition, land ownership, distance to grid.

How much rooftop solar is economic?

- **By 2045 rooftop solar would be an economic choice for nearly all households and businesses.** Fundamental drivers of rooftop solar value are strong, including projected continued declines in solar costs, increasing retail rates, and increasing electricity demand due to electrification of building end uses and vehicles. Economic potential for the twin customer solar projections of Early & No Biofuels and Limited New Transmission – High is 9.9 GW in 2045, followed by SB100 – Stress at 9.3 GW (see the first figure on the next page). To estimate customer adoption of solar, we simulate the amount of rooftop solar capacity that would be economic for LADWP customers to adopt in each year. This includes determining not only whether it is economic to adopt solar, but also the best match of solar capacity to the building's energy consumption.

How is customer rooftop solar compensated?

LA100 evaluates two options:

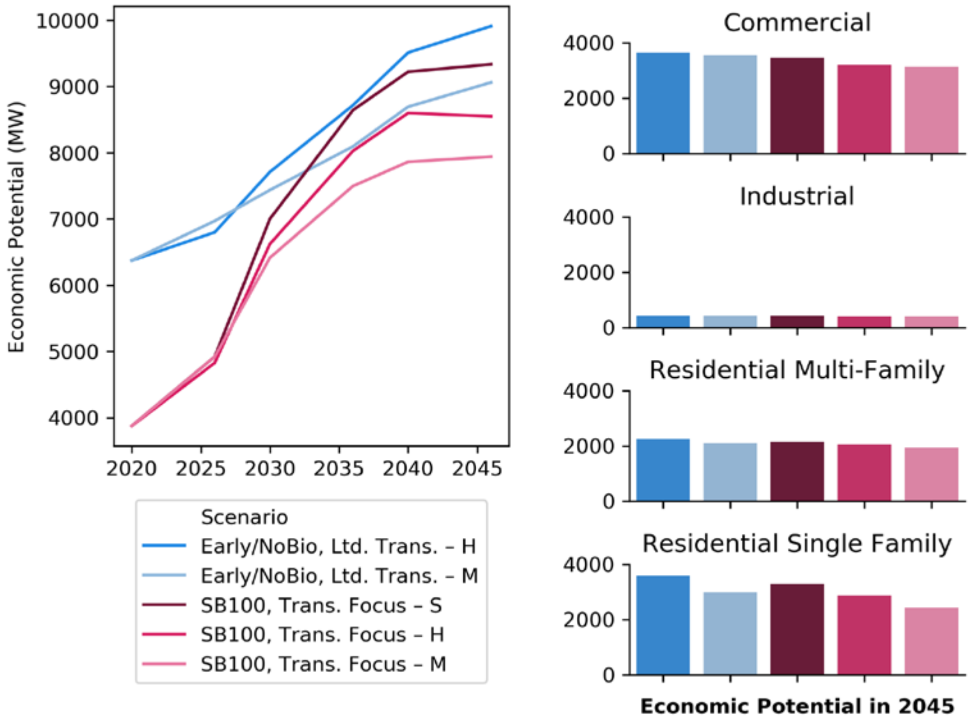
Net metering: All customer solar generation is valued at the retail electricity price, a continuation of LADWP's current solar program.

- Used in Early & No Biofuels and Limited New Transmission scenarios

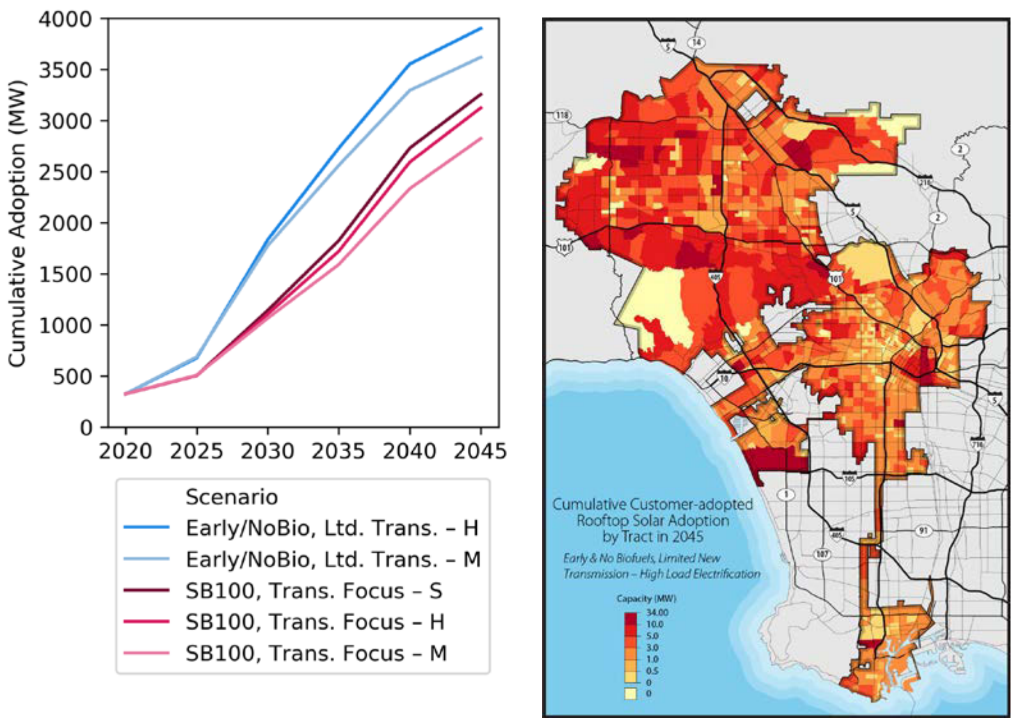
Net billing: Self-consumed customer solar generation offsets retail purchases, and non-self-consumed generation (i.e., exported to the grid) is valued relative to other sources of generation at that time, i.e., at wholesale rates.

- Used in SB100 and Transmission Focus scenarios

- **Compensating non-consumed generation at wholesale rates lowers the overall economic potential**, but by 2045, results in similar amounts of overall potential as most technical potential is economic at that point. Much of the gap between the two compensation types is bridged by 2030.
- **Increased load electrification is a significant driver of rooftop solar potential**. As demand for electricity increases with new loads, rooftop solar potential similarly increases to offset the new demand. However, the compensation mechanism for rooftop solar (net billing or net metering) is a larger driver of rooftop solar overall.



Total economic potential (GW) by year (left) and by sector in 2045 only (right) for LA100 scenarios



Rooftop solar adoption projection by scenario (left); Adoption by tract in the Early & No Biofuels – High and Limited New Transmission – High scenarios in 2045 (right)

How much rooftop solar and storage is adopted in the LA100 scenarios?

- **LA100 projects that customers adopt between 2.8 GW and 3.9 GW of rooftop solar by 2045, including 22%–38% of all existing single-family homes, up from 6% in 2020.** Customers are projected to adopt between 34% and 40% of the total economic potential for rooftop solar capacity. Looking at cumulative adoption over time, initially scenarios with higher daytime compensation encourage earlier adoption, but over time, the scenarios begin to converge and are influenced by overall levels of customer electricity demand.

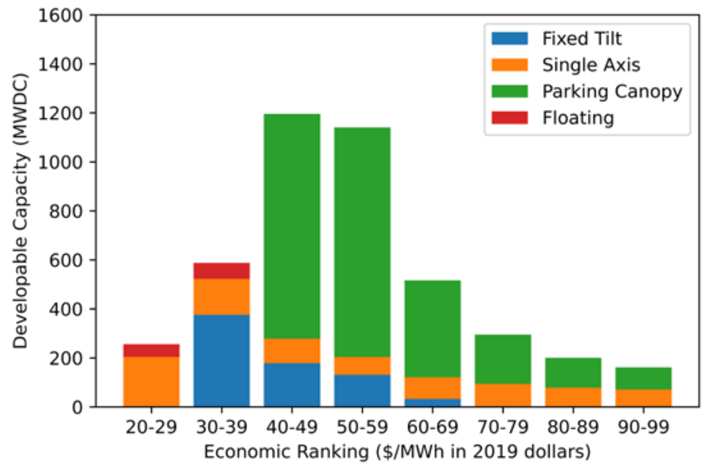
- **LA100 also projects customer-adopted storage based on historical trends of adoption** within LADWP and California. Using a linear trend, NREL projects that in 2045, 91% of residential solar systems purchased that year are co-adopted with storage and 64% of non-residential systems, resulting in 1.1–1.5 GW adopted.

How much potential exists for non-rooftop local solar?

- **5,700 MW_{PV} and 1,599 $MW_{Battery}$ of non-rooftop local solar technical potential exists within the LADWP in-basin service territory for ground-mount (solar-only and solar-plus-storage), parking canopy, or floating solar projects.**
- Of this total, 850 MW of capacity exists for projects >10 MW, 2,100 MW for projects >1 MW, and the remainder for projects <1 MW.
- Significant opportunity for local solar in LA exists in the city's parking lots. Parking canopy solar makes up the majority (58% or about 3,900 MW) of LA's local solar potential.
- Though LA is urban, ground-mount solar makes up a considerable portion (40%, or about 2,200 MW) of the city's local solar opportunity.

How much local solar is economic?

- **A site development cost ranking analysis of this potential indicates that about 4,400 MW or about 80% of the non-rooftop local solar potential can be built at or below $100/megawatt-hour (MWh) based on 2019 capital costs (see the figure on the right).** These estimates do not include any existing or future federal or state incentives.
- Single-axis tracking and floating solar sites are most highly ranked, but the largest potential overall for lands <$100/MWh is parking canopies (61%).
- Land acquisition costs are assumed to be zero for parking canopy and floating solar sites, making many of them competitively ranked compared to ground-mount installations on non-government-owned lands.
- Both land acquisition costs and distance to 34.5kV distribution interconnection lines (as described in more detail on p. 39) play an important role in determining cost-optimal locations for siting local solar in LA.
- The additional distribution grid upgrade costs for integrating this non-rooftop local solar and storage (beyond the changes already required for load and customer rooftop solar) are generally low enough to not limit non-rooftop deployment.



Solar PV-only site cost ranking of non-rooftop local solar sites with 2019 economic ranking <$100/MWh

Important Caveats

- The potential role of evolving electricity prices has not been explored. This analysis starts from existing LADWP tariffs and does not consider changes to their structure or design. For instance, at high levels of renewable deployment, retail prices might evolve to better align needs of the overall power system during periods of scarcity.
- This study assumes strong uptake from low-income households. Existing solar adoption in Los Angeles is currently skewed to mid- to-high-income single-family homes. Research indicates that economic factors, specifically, savings on electricity bills, are a significant factor in solar adoption for all sectors. This study presumes that, when it is economic to do so, low-income households adopt solar at equal measures as high-income ones. However, we do assume a lower rate of adoption among multi-family and renter-occupied buildings.
- Customer adoption of distributed storage is in an early stage. As such, well-calibrated customer adoption models are currently not widely available. Among other factors to be further understood by further research are how customers respond to utility and/or price signals to charge and discharge from the grid, and the degree to which distributed solar is coupled with storage.
- The non-rooftop local solar analysis does not consider the full range of land use and zoning challenges that can influence the feasibility of developing a solar project.

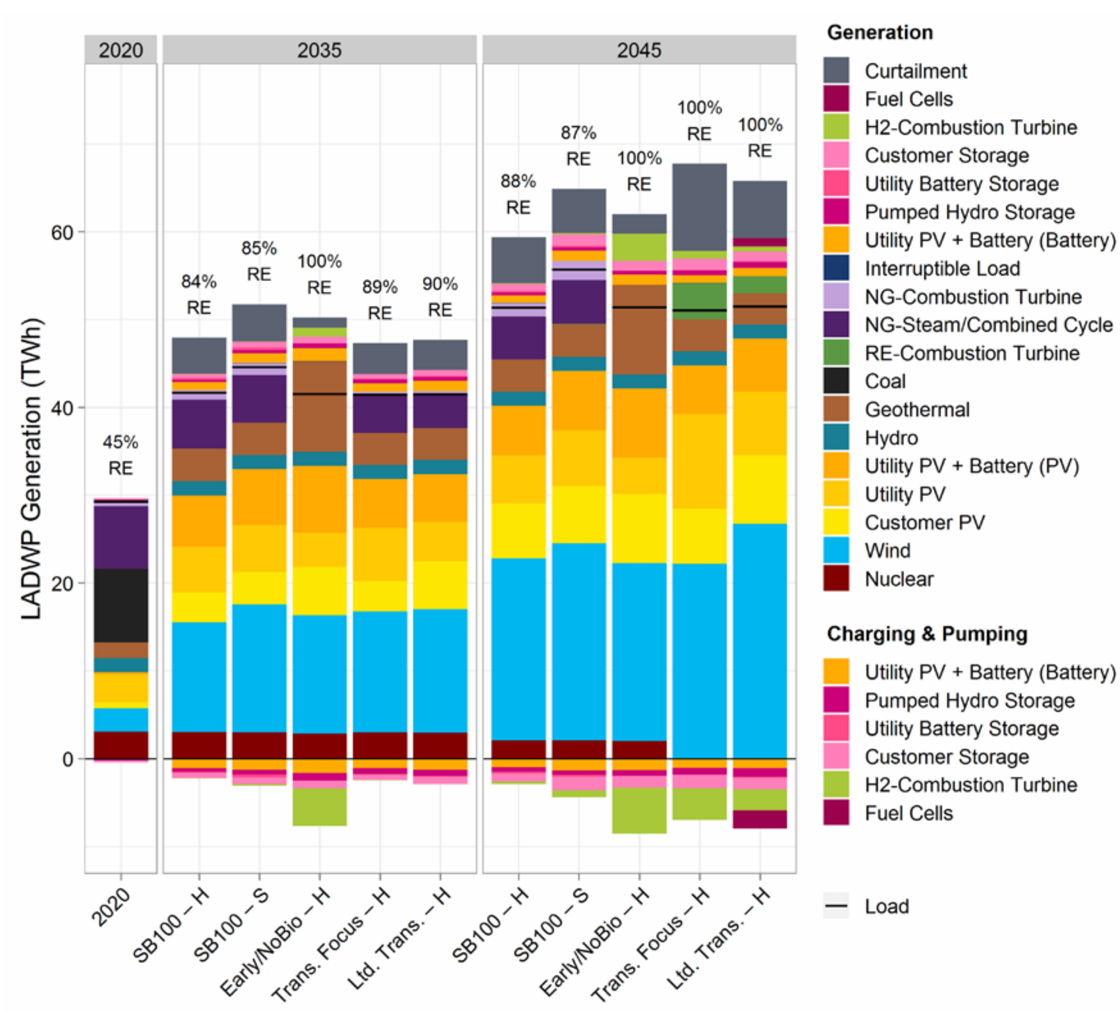
Renewable Energy Investments and Operations

LA100 explores pathways to 100% renewable electricity, describing the types of generation resources added and their costs.

Find additional information on this topic on the LA100 website (**maps.nrel.gov/la100/key-findings/topics/renewable-energy-pathways/**) and in Chapter 6 of the full report (**nrel.gov/docs/fy21osti/79444-6.pdf**).

How can the target be met? Technology pathways to achieving 100%

- **Due to costs and access to high-quality resources, wind and solar resources are responsible for providing the majority of the energy required to meet load irrespective of the broader set of options leveraged to achieve a 100% renewable power system.** Across the scenarios analyzed, wind and solar account for 69%–87% of total energy generation by 2045.
- **Diurnal storage resources (resources with storage durations of less than 12 hours) increase the utilization of wind and solar assets by shifting surplus energy from mid-day to evening, nighttime, and morning hours.** However, due to periods of low renewable resources, diurnal storage assets combined with wind and solar generation are insufficient (at reasonable cost) to achieve a reliable, 100% renewable electricity supply.
- **New in-basin renewable firm capacity—resources that use renewably produced and storable fuels, can come online within minutes, and can run for hours to days—is a key element of maintaining reliability at least cost given the assumed retirement of natural gas generators, existing transmission constraints, and challenges in upgrading existing or developing new transmission.**



Progression of the annual generation mix from 2020 through 2045 for all High and Stress load scenarios

The percent RE refers to percent of generation that is carbon neutral (renewable and nuclear). Negative values indicate the amount of electricity consumed by the plants (e.g., to charge a battery, pump hydro, or produce hydrogen fuel). Load (solid line) is customer electricity consumption exclusive of charging. Curtailment includes available energy that is curtailed to provide reserves.

Why can't LA just rely on lots of rooftop solar and battery storage to reach 100%?

The solar resource in LA is great. But putting solar on every available rooftop in LA would not be enough—even accounting for future energy efficiency upgrades.

Solar is only available during daylight hours, and even if it is paired with batteries for energy storage, it remains insufficient to meet load reliably.

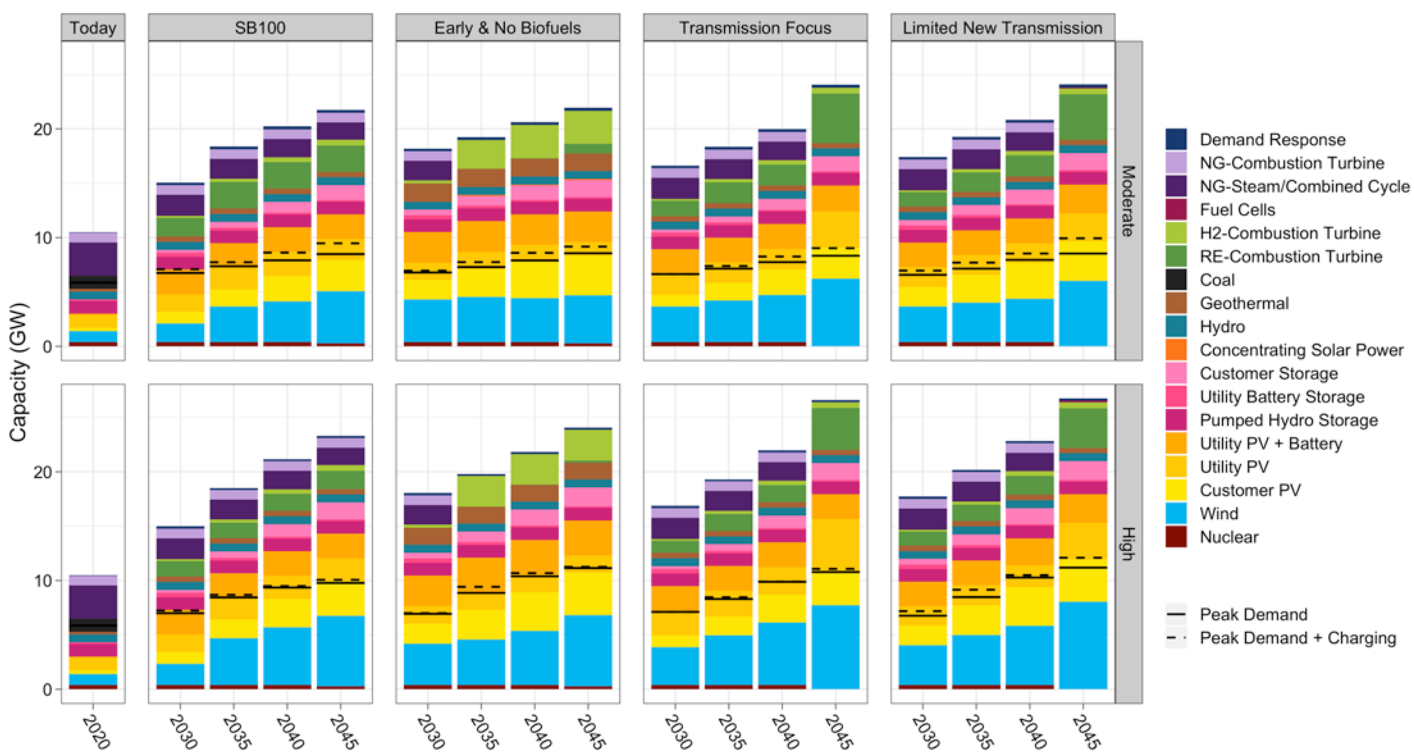
While batteries are getting cheaper, they're not projected to be cost effective to store energy for more than 10 hours at a time.

This means LA would still have challenges in meeting demand during periods of high demand and low solar supply, as the LA100 scenarios see in the fall and winter months.

Furthermore, it's often cheaper to build in the desert, which lets LA take advantage of economies of scale and the ability to track the sun.

So, even in sunny LA, a balanced mix of resources is needed to achieve 100% renewables at lowest cost while maintaining reliable service.

- **Achieving a 100% renewable or clean power system requires rapid and sustained deployment of variable generation (wind and solar), diurnal storage, and firm capacity technologies.** Across the High load scenarios, the average annual deployment for combined wind, solar, and batteries ranges from approximately 470–730 MW/yr over the study period (2021–2045), representing a substantial acceleration of procurement of new resources.
- **LADWP's unique AC and DC transmission infrastructure (existing and planned upgrades) enables the utility to access the high-quality and abundant renewable resources outside of the LA Basin and bring energy from those resources to the city.** Across all scenarios explored, out-of-basin generation resources produce the majority of electricity used to meet load (74%–89% of total energy generation by 2045), consistent with today. As electrification significantly increases LA's demand for electricity, the total energy generated from out-of-basin sources is expected to increase to almost double the 2020 value, while the total transmission



Evolution of the capacity mix over time. Top row shows Moderate load projections for each scenario; bottom row shows High load scenarios (the Stress load scenario is not shown).

Utility PV + battery assumes co-located solar and storage with shared loosely DC-coupled inverter capacity. Capacity represented is the capacity of the inverter (i.e., the maximum output). The size of the solar relative to the battery is chosen by the capacity expansion model used in the study, but is generally on the order of a 2:1 ratio (e.g., 10 MW PV + battery has a 10 MW solar array with 5 MW of battery storage).

capacity into the basin is projected to increase little by 2045 in all but the Transmission Focus scenario. Reliability is maintained by making strategic upgrades to in-basin transmission assets, siting new out-of-basin resources diversely across separate corridors, developing new in-basin firm capacity resources, and demand response. This allows LADWP to operate its transmission network more flexibly and minimizes the risk presented by a failure of any transmission line.

- **Although in-basin solar generation has the advantage of being more resilient to transmission congestion and outages, most LADWP-procured solar in the LA100 study is built outside of the LA Basin due to lower costs and the ability of existing and new transmission to support of out-of-basin resources.** All scenarios assume that customers adopt 2.8–3.9 GW of rooftop solar by 2045 (see Chapter 4 of the full report for details: nrel.gov/docs/fy21osti/79444-4.pdf). Although technically eligible locations within the city for ground-mount and other utility-scale solar could support an additional 4.8 GW of PV at a levelized cost of less than $100/MWh, the LA100 scenarios build only a fraction of this potential due to the overall lower costs and higher performance of out-of-basin solar resources. Nevertheless, these locations could serve as alternative siting for in-basin generation should customer-adopted solar not materialize or if LADWP chooses to site solar locally for other reasons.
- **The Early & No Biofuels – High scenario generates 98% carbon-free electricity by 2030.** Even though the 100% target is almost met, significant new capacity occurs between 2030 and 2035, primarily to replace retiring natural gas plants with a portfolio of technologies that can meet the final 2% of energy needs during time periods of low wind and solar quality that had previously been served by natural gas.

What are the costs of achieving the 100% target?

- **The estimated total cumulative costs of new investments needed to achieve the 100% target across the suite of scenarios explored range from $57 billion to $87 billion (2019$) depending on the scenario and load projection.** See the text box on the next page for what is and is not included in these costs. Costs increase over time across all scenarios due to the accumulation of costs of procured capacity and generation (and the associated debt or power purchase agreement [PPA] payments), increasing load, and increased stringency of the renewable energy targets.

Why do the LA100 scenarios build new but rarely used renewably fueled combustion power plants?

All LA100 scenarios build significant amounts of renewably fueled combustion turbines in the LA Basin. Much of this capacity is deployed at sites currently used for LADWP's natural-gas-fueled power plants.

But these new plants aren't run very often in most scenarios, so why would LADWP invest in building them in the LA basin?

These renewably fueled combustion turbines are built primarily as peaking plants for reliability—similar to how the grid is operated today, with many peaking plants that don't run very often.

The study builds these plants to address three challenges of reliably reaching 100% renewable energy:

1. The challenge of addressing the **seasonal mismatch of supply and demand**. Demand peaks in August and September, but wind and solar generation peaks earlier in the year.
2. The **risks associated with relying on transmission lines to bring wind and solar energy to the city**. Fires and earthquakes could affect these transmission lines, so LA needs to have energy that can be stored locally that can produce electricity for extended periods of time when needed.
3. The **limitation of the city's local transmission network**—it is difficult and expensive to upgrade transmission infrastructure that could help import renewable energy through the north side of the LA system to other locations in the city.

So, to achieve 100% renewables cost effectively, LA100 scenarios deploy combustion turbines that can be powered with renewably derived fuels. The fuels include biofuels, which are available today, or fuels derived from hydrogen, which are produced from 100% renewable electricity.

These new plants run during times of really high demand, or periods where there just isn't much wind or solar available. They also run more often in simulations that evaluate extended outages of transmission lines.

Ultimately, they form an insurance policy to keep the lights on when things go wrong, including bad weather, hot weather, and fires that take down transmission lines.

How does the LA100 study treat costs?

The LA100 study captures costs associated with developing and operating a reliable power system through 2045 specific to the changes evaluated in the study—population growth, greater electricity demand due to a hotter climate, growth in electric vehicles, and achievement of a 100% renewable power system, among other changes.

However, the cost estimates in LA100 represent only a portion of total cost for LADWP.

For the **bulk power system**, costs include total operational costs (of all generation, storage, and transmission infrastructure) and capital costs (and associated financing costs) for all new investment. Costs associated with debt on existing capital assets or existing contracts (procured prior to 2021) are not considered.

To be clear, the capital costs reported are not costs additional to a business-as-usual scenario—rather, they represent the total costs of new investment related to the changes described above and the cost of bulk power operations.

For the **distribution system**, only upgrade costs required to accommodate load growth and increased local solar and storage are included. Distribution costs do not include the costs of upgrades to manage deferred maintenance, operations and maintenance, or potential costs to acquire land for some substation expansions. Customer-adopted solar costs are listed as equivalent PPA for consistency.

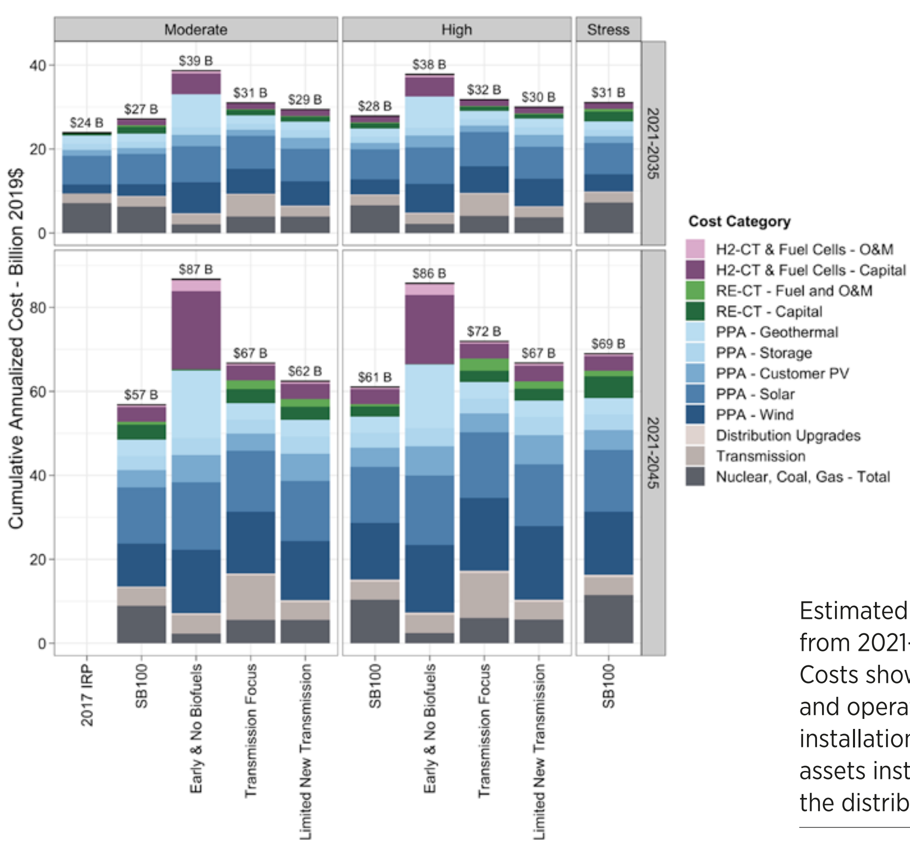
All costs and monetized benefits are adjusted for inflation and are presented in "real" terms (constant 2019$).

Costs Included

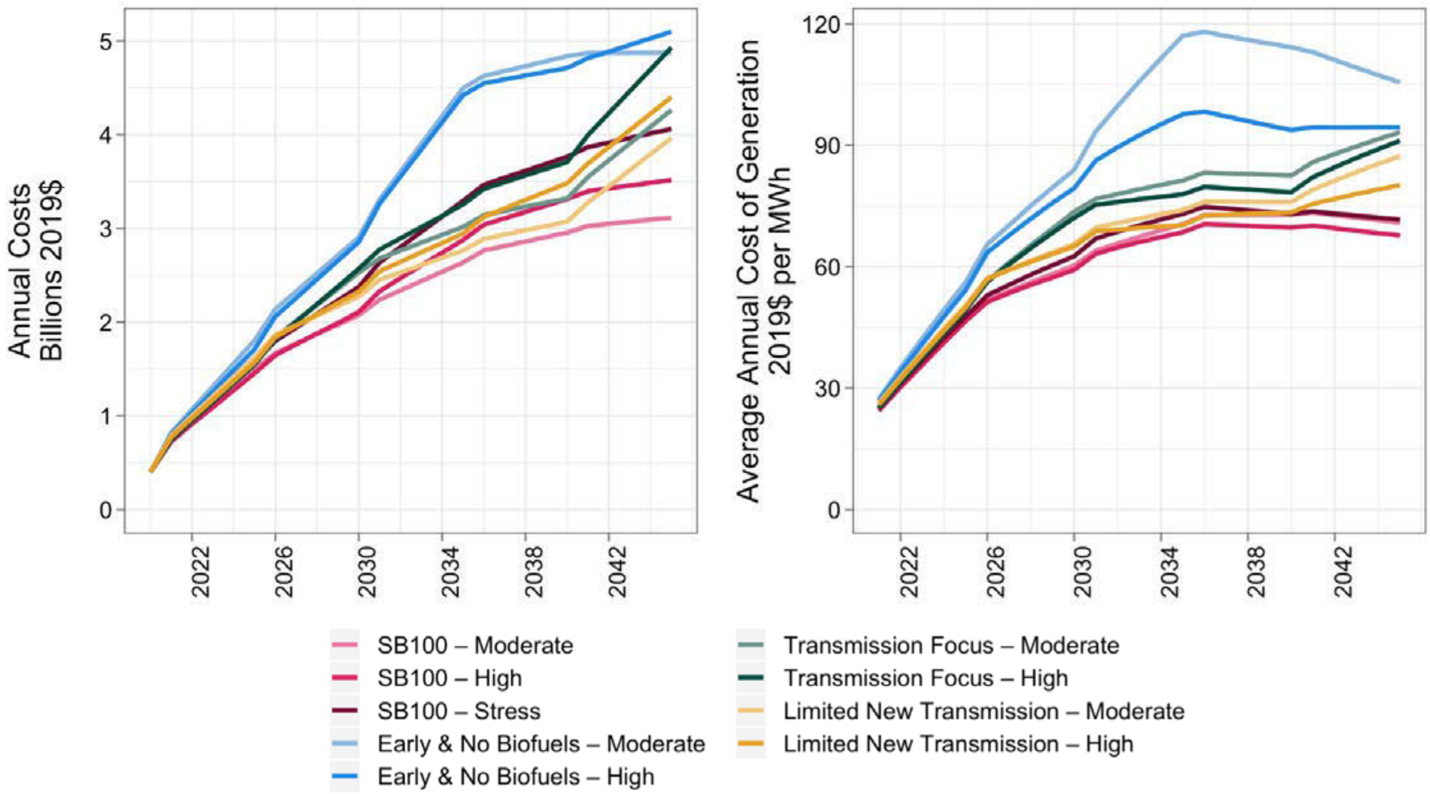
- Costs of new capital investments:
    - LADWP-procured renewable energy generation and storage
    - Customer rooftop solar and storage
    - Transmission
    - Distribution upgrades to accommodate customer electricity growth and distributed energy resources
- Cost of operation and maintenance of all bulk assets (generation, storage, transmission, and distribution) through 2045, including fuel costs associated with both non-renewable and renewable thermal generation

Costs Not Included

- Investments made prior to 2021 (i.e., servicing LADWP's debt)
- Capital investments needed for today's distribution grid to address current distribution maintenance needs
- Future operating costs for the distribution grid
- Distribution upgrade costs beyond equipment and labor, including land acquisition costs for substation expansion, new substations, or circuit reconfiguration.
- Costs associated with customer programs, for example, to support energy efficiency or encourage demand response



Estimated cumulative annualized system costs incurred from 2021–2045 by scenario, load level, and cost type. Costs shown include bulk power system investment and operations costs and customer rooftop solar installation costs, but do not include debt payments on assets installed prior to 2021 or normal maintenance of the distribution system.



Estimated annual and average annual costs of generation over time. Annual costs (left) represent the total costs observed in a given year (operations, PPA payments, annualized capital costs from LA100 resources installed in current and earlier years). Average annual costs of generation (right) do not equal rates—these costs represent the revenue requirement (per unit of generation) to cover the annualized costs associated with expenditures measured in LA100.

- The cost of achieving the 100% target is highly dependent on A) what technologies are assumed to qualify as "renewable," B) the availability of financial compliance mechanisms such as RECs, C) how quickly the target is achieved, and D) the evolution of load. Each of these points is elaborated below.

A. **The eligibility of technologies has a significant impact on costs.** One of the largest drivers of the cost difference of Early & No Biofuels compared to the other scenarios is the exclusion of biofuels, which is currently the only storable renewable fuel that can be purchased in sufficient quantities to serve as firm capacity. Because of this exclusion, the Early & No Biofuels scenario meets firm capacity with a higher-cost solution: increased out-of-basin geothermal capacity coupled with in-basin hydrogen combustion turbine capacity. In the case of the Early & No Biofuels – High scenario, we estimate that treating biofuels as eligible could reduce cumulative costs through 2045 by approximately 21%, while substantially reducing the risk of relying on less mature technologies, such as hydrogen production, storage, and use in fuel cells or combustion turbines.

B. **Similarly, the eligibility of alternative compliance mechanisms, such as RECs, is an option to further mitigate the cost and uncertainty of meeting the 100% target.** RECs effectively allow an ineligible technology (primarily natural-gas generation) to contribute to the generation mix if offset with a purchased certificate. In the SB100 scenario, we estimate that disallowing the use of RECs in the year 2045 would increase cumulative costs by approximately 2% in 2045, rising to approximately 18% when including cumulative costs over the financial lifetime (2074) of the new investments.

C. **The speed of the clean energy transition also impacts costs, though less so than technology eligibility.** The speed of the transition to a 100% power system impacts costs in two ways. First, costs for renewable technologies are expected to decline through 2045, so installing these technologies by 2035 comes at a higher cost compared to closer to 2045. For example, the study's cost assumptions for battery storage decline around 20% between 2035 and 2045. Second, LADWP must incur those costs earlier, which results in more costs accumulated more quickly. We estimate that extending the compliance target to 2045, assuming the use of unbundled RECs for up to 10% of compliance through 2044, reduced cumulative costs by approximately 17% through 2045.

D. **Modernizing load through increased energy efficiency and load flexibility helps mitigate the costs of achieving a 100% system.** Comparing the SB100 – High scenario to the SB100 – Stress scenario, the latter of which includes identical levels of electrification, but greater annual load (8.5% higher) and peak load (17% higher) due to lower levels of efficiency and demand response, shows that the efficiency and demand response assumed under the High scenario reduces costs by 14% cumulative through 2045.

What are the primary factors driving the cost of achieving a 100% renewable system?

Renewable energy is declining in cost. In fact, renewables in places like southern California, with very good solar resources, are often cheaper than new coal and gas generation on a per-unit energy basis. Battery prices have also fallen significantly. So utilities like LADWP are building new wind, solar, and batteries when they need new electricity supply. Given these lower cost projections, what accounts for the costs associated with the LA100 scenarios?

First, demand for electricity will rise in the future due to more electric vehicles and hotter temperatures. So LA needs to build new renewable supply to serve this load. Second, the LA100 scenarios retire fossil plants and replace some of them earlier than LADWP would otherwise. Third, the cost of reaching 100% renewable energy gets more expensive closer to the target.

To understand why the costs get higher as the system approaches 100%, we need to consider how power systems meet peak demand. For any power system, meeting peak customer electricity demand costs more than it does during normal hours. Most of the year, power is produced using plants that operate every day. But when electricity demand peaks—like during a heat wave when all air conditioners in the city cycle on simultaneously—power system operators need to rely on so-called peaking plants that are needed for only a few hours a year. That means a substantial portion of the total generating capacity, although necessary, is not used very often.

Similarly, a big driver of costs of 100% renewable power systems comes from meeting the last 10% of energy needs with renewable energy. To get to a 90% renewable target, the LA100 scenarios build wind, solar, batteries, and other technologies that are used every day. But there are times of the year when additional power is needed—like during one of those heat waves, or during times with low wind and solar resources.

To account for the last 10% of energy needs to get to a 100% renewable grid, the study builds plants that are used infrequently. And because they are not needed very often, the cost per unit of electricity is much higher compared to a plant that produces electricity throughout the year. So getting to 100% means adding new renewable resources sufficient to meet demand in each and every hour of the year, including some very difficult hours.

And these hours can get expensive because renewable peaking technologies are less mature and have higher costs compared to natural gas plants. So not only are costs incurred for replacing existing peaking units, but these units are being replaced at higher costs.

Now that we have reviewed why costs increase for any 100% renewable energy system, let's examine why we see differences in costs across the scenarios evaluated in the LA100 study.

The first reason is that each scenario allows a different set of technologies to be eligible to serve as peaker plants. The SB100 scenario is the cheapest because it has the fewest restrictions on eligibility, even allowing up to 10% of electricity generated to be supplied by natural gas. This means that LA doesn't need new renewable supply to meet the last 10%—existing natural gas plants can continue to be used.

In contrast, the other three scenarios must generate all electricity from renewable energy. And the highest-cost scenario, Early & No Biofuels, must meet the 100% target without biofuels, which is currently the only renewable fuel widely available for purchase in the market. Instead, this scenario builds more generators that use clean hydrogen. The cost of the hydrogen option is more expensive compared to biofuels because all the infrastructure that is needed to produce, transport, and store it is less mature.

Another reason for the higher costs of the Early & No Biofuels scenario is it also achieves the 100% goal faster. That means LA would need to start paying for new sources of power earlier. Furthermore, because the necessary investments need to occur prior to the 2035 target date, there is reduced opportunity to realize the benefits of expected cost reductions of the key renewable and storage technologies compared to a 2045 target.

Costs are one factor in considering options to get to 100% renewable energy—the benefits vary, too. But understanding drivers of cost increases can help identify possible options to reduce costs. These options could include reducing the need for peaking capacity through multi-day demand response programs, or charting a pathway to 100% renewable energy that allows investments to be continuously reevaluated as costs change.

- **Wind, solar, and battery storage are near-term, no-regrets options to achieve a significant fraction of renewable energy generation.** The LA100 scenarios show similar cost increases through approximately 80%–90% renewable energy. Beyond 90%, the costs are highly dependent on technology choices, which vary in their maturity today. To maintain optionality for a 100% renewable electricity system and to reduce the cost of serving demand in the hours with the lowest wind and solar availability, possibilities include:
  - Fuel flexibility to serve as backup for emergencies or as a hedge against uncertainty related to prices or market availability of fuels
  - Automated demand response, such as through investments in information and communication technologies and customer education and outreach, to reduce the need for new supply capacity
  - Power market participation to enable imports of low-cost renewable electricity for storage (and increase revenue through sales)
  - Advanced transmission technologies, such as flexible AC transmission systems, to make more effective use of existing transmission capacity.

Important Caveats

- **The Early & No Biofuels scenario assumes the ability to quickly scale up hydrogen infrastructure.** While the required hydrogen technologies exist today and have been deployed at smaller scale to support oil refineries and ammonia production, they have not been deployed at scales needed for a large power system, in particular the infrastructure needed to transport and store the hydrogen fuel in sufficient quantities needed for reliability.
- **Because of the unique challenges in building new transmission infrastructure, the costs and feasibility of transmission upgrades are among the most uncertain inputs to modeling of pathways to 100% renewable energy.** Simplifications were made to represent transmission infrastructure and upgrade costs in the capacity expansion and production cost modeling stages. We assume that transmission upgrades include adding capabilities to utilize existing and new capacity more fully, meaning they can be operated closer to their thermal limits. These capabilities may include dynamic line ratings, flexible AC transmission, and use of fast-responding inverter-based resources and demand response to manage contingency events. The costs of some of these capabilities are uncertain, and not fully captured in the study.
- **The evolution of the power system outside of LADWP could impact LADWP's opportunities.** For example, faster decarbonization across the West could affect locations for out-of-basin renewable generation and transmission, as well as increase periods of surplus generation and transmission congestion. Coordinated planning and market participation could also present new opportunities to reduce the costs of the 100% renewable transition.
- **The potential role of the customer has not been fully explored.** The LA100 study assumes significant changes to the traditional role of the customer, with loads (particularly EV charging) providing an important source of flexible load and demand response, including provision of operating reserves in response to contingency events. However, most of the demand for electricity is still assumed to be inflexible. Changes to utility tariffs, communication technologies, and networked end-use devices could allow customers to dramatically change energy usage—at a scale not yet tested—to offset in-basin firm capacity and transmission upgrades.
- **The study does not fully assess the feasibility of the accelerated deployment; in particular, the study does not evaluate the availability of manufacturing supply chains and labor forces or detailed construction schedules for the resources identified in each scenario.** However, despite the levels of deployment observed representing a large acceleration in procurement for LADWP, these changes remain small in the context of existing and expected growth in national and international renewable energy and storage industries. As a result, we expect these rates to be able to be supported over a 25-year planning horizon. In addition, leveraging some limited flexibility in the timing of retirement of existing and addition of new resources could alleviate many risks associated with the rapid construction and integration of resources along the identified investment pathways.

Power System Adequacy and Reliability

Ensuring a reliable future power system is foundational to the LA100 study. All LA100 scenarios were evaluated to ensure that LADWP can balance demand for electricity with supply, even after failures of transmission and generation equipment or during extreme events.

Find additional information on this topic on the LA100 website (**maps.nrel.gov/la100/key-findings/topics/reliability**) and in Chapter 6 of the full report (**nrel.gov/docs/fy21osti/79444-6.pdf**).

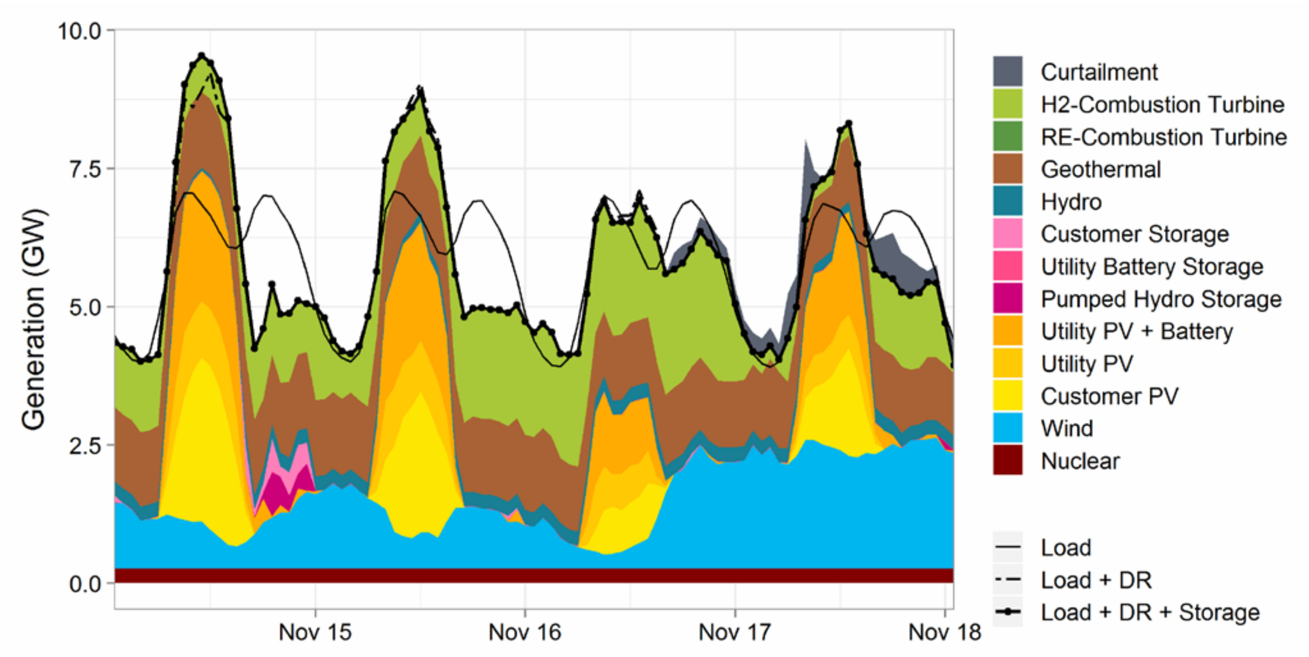
How is reliability maintained in a 100% renewable power system?

- **All modeled scenarios achieve the 100% renewable or clean energy targets while maintaining resource adequacy.** While wind and solar technologies provide a large fraction of the energy needs, all scenarios rely heavily on diurnal storage (storage with less than 12 hours of capacity), demand response, and renewably fueled generators to provide operational flexibility and operating reserves. In addition, renewably fueled generators capable of operating for extended periods over multiple sequential days ensure load balancing on consecutive days or weeks with low wind and solar resource availability.
- **The role of energy storage is particularly important in all scenarios.** Storage technologies such as pumped hydro storage and batteries address the majority of the daily mismatch of supply and demand. Seasonal storage (e.g., hydrogen technologies) is relied on primarily to address seasonal mismatches in supply and demand, and to replace various services currently provided by in-basin natural gas generators that are expected to retire. Storage is also an important source of operating reserves. The use of storage introduces new complications in guaranteeing that the system can respond, including careful state-of-charge monitoring and ensuring replacement reserve capacity is available during extended outage events.
- **Maintaining sufficient in-basin firm capacity resources allows the future systems to continue uninterrupted operation during infrequent but impactful long-duration transmission outages.** Analysis of the performance of the 2045 Early & No Biofuels – High system under 215 long-duration transmission outage events demonstrated that the ability to increase generation from in-basin firm capacity allows load to be met under the large majority of outages explored, including a majority of the more extreme (critical N-1-1) outages.
- **Maintaining reliability will require new methods and approaches to planning and operating the power system.** Increased reliance on wind, solar, and storage will require improved ability of LADWP to forecast resource supply, demand, and the overall state of the system. This includes monitoring either directly (or indirectly) distributed resources and creating the proper signals and incentives to optimally utilize customer-sited storage, controlled EV charging, and demand response. New software, controls, communication, and monitoring will be required across the entire system to better coordinate the operation of generation, transmission, and distribution resources across multiple timescales. This will be particularly important to maximize the use of wind and solar delivered from outside the LA Basin and to decrease the use of expensive in-basin dispatchable generation assets traditionally used to provide reliability services.

Balancing Supply and Demand: Every Hour, Every Day

- **In a 100% renewable future, a mix of generation sources will be needed to make sure energy supplies are sufficient to meet demand.**
- The LA100 study simulates every hour of the year for each scenario, so we can demonstrate how LADWP could provide reliable service at all times. Wind, solar, and storage can work together to shift times of high renewable output to periods of high demand. This is supplemented with non-weather-dependent (dispatchable) renewable resources, including hydro, geothermal, and generators with storable fuels.
- During the periods of lowest wind and solar output, there is greater dependence on dispatchable resources. This includes natural gas in the SB100 scenarios, where emissions from natural gas are offset by RECs.

- In cases with no natural gas (such as Early & No Biofuels – High, as shown in the figure below) energy is served from resources using liquid or gas fuels produced by renewable energy during periods of lower demand and higher renewable output.



Hourly generation for low variable generation days in the Early & No Biofuels – High scenario in 2045

How does the LA100 study define reliability?

Wherever possible, the LA100 study team uses terms and standards that are commonly used in the electric industry. In the United States, the main organization that defines reliability is the North American Electric Reliability Corporation (NERC). Reliability encompasses two elements—adequacy and operating reliability.

Adequacy, or resource adequacy, represents the ability of LADWP to have enough generation—at the right locations and the right availability—to keep the lights on. This ability also requires LADWP to have sufficient transmission to deliver that power to all customers. This ability also includes ensuring that the supply is available on the hottest summer days, and even when "reasonable" (i.e., not extreme) outages occur. All power plants and transmission lines occasionally fail, and an adequate system has sufficient spare capacity to come online and replace capacity that fails or need to be taken out for maintenance. An important element of maintaining adequacy is estimating the availability of variable resources such as solar and wind throughout the year, and in particular during times of expected system stress. Another element is understanding the role of energy storage.

The LA100 study uses a mix of modeling tools to assess the adequacy of the system. First, a capacity expansion model is used to identify a mix of resources that should provide enough spare capacity to meet load during all hours of the year. The adequacy is then tested by simulating the resulting system on an hour-by-hour basis, ensuring that demand is always met on all points of the system, with sufficient spare capacity to withstand significant outages that can last for days.

The second component (**operating reliability**) essentially ensures that the lights stay on even when unexpected things happen. There is some overlap between the adequacy and operating reliability. Adequacy is intended to ensure that sufficient capacity is available when things go wrong, such as a resource outage. Operating reliability means that the system can still operate in the seconds and minutes after the outages. The LA100 study evaluates several aspects of operating reliability. First, it checks to ensure there are adequate operating reserves, or capacity that can quickly respond to an outage within seconds or minutes. Next, it simulates actual outages of hundreds of components in the LADWP system, ensuring that the supply of energy is maintained and equipment is not damaged by overloads.

For additional details, see Chapter 6 of the full report (nrel.gov/docs/fy21osti/79444-6.pdf).

Sunrise and Sunset: Addressing System Ramping Requirements

- **The generation mix must address the large drop in solar generation that occurs at sunset with resources that can rapidly increase output.**
- A growing concern in power systems with increasing wind and solar deployment is the need to vary output from the power plants serving the net load—meaning the load not being served by these variable renewable resources. In particular, decreases in solar output occurring before sunset require generators to rapidly increase output to meet load.
- Although projected maximum ramps in net load more than double by 2045 compared to 2020, these ramps are manageable because of the deployment of batteries and other fast-response resources.
- In the LA100 scenarios, the maximum 3-hour ramp rates are often nearly twice the current 3-hour ramp rates. The High load electrification scenarios have somewhat lower ramp rates because of higher levels of demand response, which shifts load to before the challenging sunset period.
- In today's system, load ramps are typically met by changing the output of gas-fired generators. In LA100 scenarios, this ramping is frequently met by storage and other resources that can vary output much faster than fossil-fueled generators.

Rapid Response: Operating Reserves

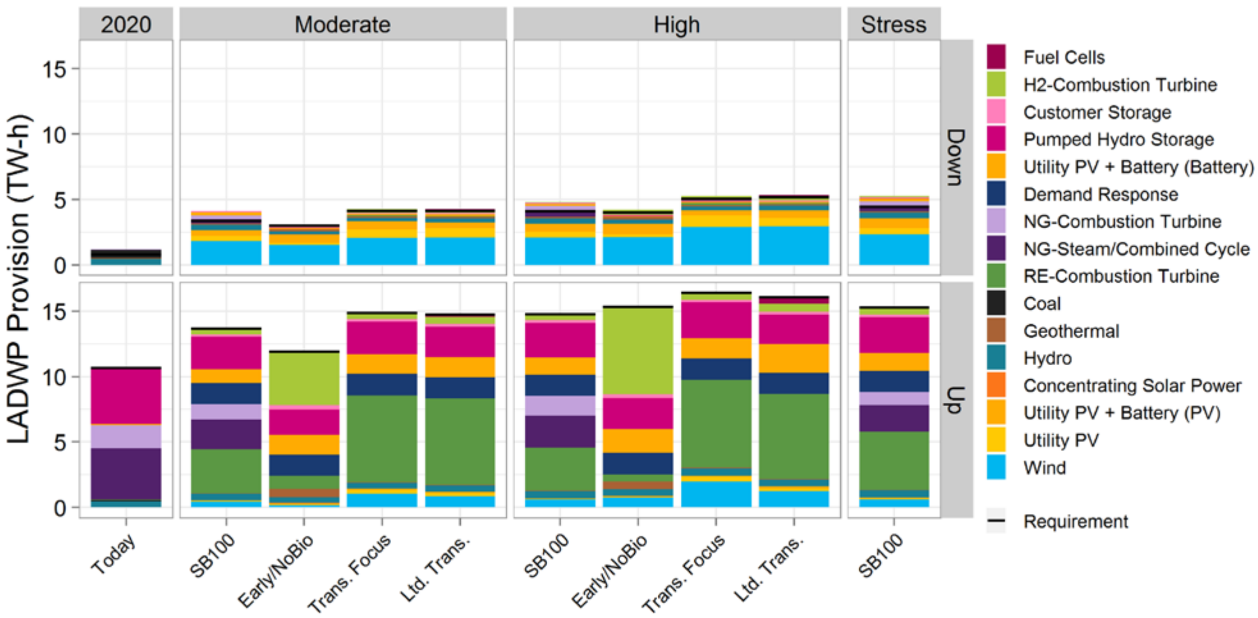
- **Operating reserve requirements are expected to increase in a 100% renewable system.** Storage is an important source of operating reserves; however, this technology introduces new complications in planning to ensure that storage is sufficiently charged, and that replacement reserve capacity is available during extended outage events.
- Ramping requires generators to vary output to respond to normal variations in electricity demand, wind, and solar generation. But even faster response is sometimes needed for events like when a large generators or transmission line fails. This rapid response is provided by operating reserves, which in the current system are typically provided by natural-gas-fired generators that operate at partial output and are able to increase output, along with LADWP's Castaic pumped storage plant. **Increased amounts of wind and solar on the system will likely increase the amount of reserves required.**
- LA100 simulations consider the requirement to provide multiple types of operating reserves. Due to its rapid response, battery storage is an important source of operating reserves. During many periods, PV and wind are an important source of reserves, as these resources can be "backed down" below what the weather conditions would allow, and then increase output at a rate that exceeds most conventional generators. Demand response is also used as a source of rapid response, as is currently used in many parts of the United States. In many cases, combustion turbine resources are still used to provide some reserves, particularly during periods of peak demand when they are online to provide energy. **However, the use of demand response, storage, wind, and solar to provide reserves helps minimize the use of combustion-based resources, further reducing emissions and the use of costly fuels needed to keep the plants running at reduced output.**

Hot Years, Cloudy Years, and Everything In Between: Analyzing the Impact of Multiple Weather Years

- Weather variability can have a substantial impact on the ability to meet electricity demand. **Analysis of all scenarios under 7 years of weather data demonstrates that each scenario has sufficient capacity to withstand year-to-year weather variability.**

When Things Don't Go as Planned: Transmission Reliability After Contingency Events and Extended Transmission Outages

- **Contingency analysis reveals that planned transmission upgrades, continued use of in-basin capacity and new fast-responding resources can help maintain operational reliability.** However, the contingency analysis also identifies a significant number of elements on the transmission network that may require additional upgrades to those already planned, depending on implementation of other measures to improve transmission system capabilities (see text box on next page). Overall, there will be increased need to carefully monitor power flow on various elements of the transmission system and ensure resources are scheduled to ensure an outage will not cause excessive overloads.



Annual reserve provision for all scenarios in 2030, broken down by reserve direction (upward or downward) and type of providing generator

Reserves represent capacity that is available to increase output. One terawatt-hour (TW-hr) of reserves is equal to a 110 MW power plant that is standing by at zero output but able to increase output any time during an entire year. This plot includes three types of upward reserves: spinning contingency reserves, which respond to large power plant and transmission line failures; regulating reserves, which respond to random variations in demand within seconds; and flexibility reserves, which respond to random variations in wind and solar output occurring over timescales of multiple minutes. We also include downward reserves (regulation and flexibility).

How can LA get more transmission for less?

The LA100 scenarios require squeezing all possible capacity out of existing and new transmission capacity. This will require new approaches that may include:

Additional DC or flexible AC transmission systems (FACTS). AC power cannot typically be steered. This means that the system is inherently limited by its weakest component. This also means that there is always under-utilized transmission capacity—transmission elements that could actually carry more power, but attempting to deliver more power on this element would overload other elements. LADWP already utilizes both DC transmission and phase-shifting transformers that allow various degrees of control over power flow. Additional deployment of DC or FACTS devices can allow the system to increase the flow on the elements that are operating below their thermal limits, essentially allowing greater overall system capacity.

Dynamic line (and equipment) ratings. The actual capacity of transmission elements (transformers, lines, protection equipment) is typically rated on a limited set of conditions, largely based on how hot they will get on summer days. Cooler weather or windy conditions can cool some transmission elements (primarily overhead lines). This means that they could sometimes carry more power than their “normal” ratings. Dynamic line rating schemes might even consider the ability of transmission elements to carry power more than steady-state conditions would normally allow for a short period of time (such as under peak demand conditions) in anticipation of cooling later in the day. Even if contingencies occur under hot weather conditions (where there are reduced benefits), the information provided by active equipment monitoring can be combined with FACTS devices to optimize power flow and maximize system reliability.

Rapid and dynamic response to contingency events. Contingency analysis often applies a uniform threshold rating for what is considered an overload. However, the actual impact of an overload to an element on the transmission system is a function of both the increase in power (current) and the amount of time of the overload. The impact will vary by element type, with overhead conductors typically able to handle larger increases in power for shorter time periods, while other components such as underground cables and transformers are more sensitive. Inverter-based resources (including battery storage) or sheddable loads can respond to an event with a few seconds via a variety of control schemes. Under contingency conditions, this could allow for potentially greater very short-term overloads on non-sensitive components of the transmission system. Fast-response resources can reduce the duration of the overload from minutes to seconds, while reducing reliance on partially loaded thermal in-basin capacity providing operating reserves. In-basin capacity will still act to provide energy to replace the batteries or reduce load shed during extended outrages, but can be operating as non-spinning resources, reducing costs and emissions.

- **All LA100 scenarios appear robust to withstand extended transmission outages due to the use of in-basin dispatchable capacity (renewably fueled combustion turbines and fuel cells).** To avoid blackouts, the LA100 scenarios build renewably fueled in-basin capacity and, in some cases, additional transmission lines. We then test the robustness of the system against a set of over 215 combinations of extended transmission outages that could result from fires, maintenance, or any other reason. We evaluate these outages over an entire year for the most difficult scenario, Early & No Biofuels – High. Analysis demonstrates that the ability to increase generation from in-basin firm capacity allows load to be met under the large majority of outages explored, including a majority of the more extreme outage cases.

Important Caveat

- Climate change could impact the ability of LADWP to maintain resource adequacy. The study assumes rising temperatures as part of the projections for customer electricity demand. The study also evaluates the ability of LADWP to serve load during transmission outages, which may become more frequent due to wildfires. However, the study does not consider many other potential impacts of a changing climate, including changes in wind patterns, how increased temperatures could accelerate degradation of transmission equipment and result in more frequent outages, or the impact of fires on output from solar capacity.

Distribution Grid Impacts

The distribution grid must be able to manage changes to electricity demand and local solar and storage. LA100 analyzes the impacts of these changes to the distribution grid, associated upgrade costs, and how to minimize distribution grid impacts.

Find additional information on this topic on the LA100 website (**maps.nrel.gov/la100/key-findings/topics/distribution-grid**) and Chapter 7 (**nrel.gov/docs/fy21osti/79444-7.pdf**) of the full report.

How are distribution-connected resources deployed in the LA100 scenarios?

- **All scenarios examined in the LA100 study include significant quantities of solar and storage connected to the distribution system**, including:
  - 2,800–3,900 MW_{PV} and 1,400–1,700 $MW_{Battery}$ of customer-adopted rooftop solar and storage. Roughly 90% of this customer-adopted capacity is connected to the 4.8kV distribution network.
  - 300–1,000 MW of utility-driven non-rooftop local solar deployment and 200–700 MW of battery storage connected to the 34.5kV subtransmission network.

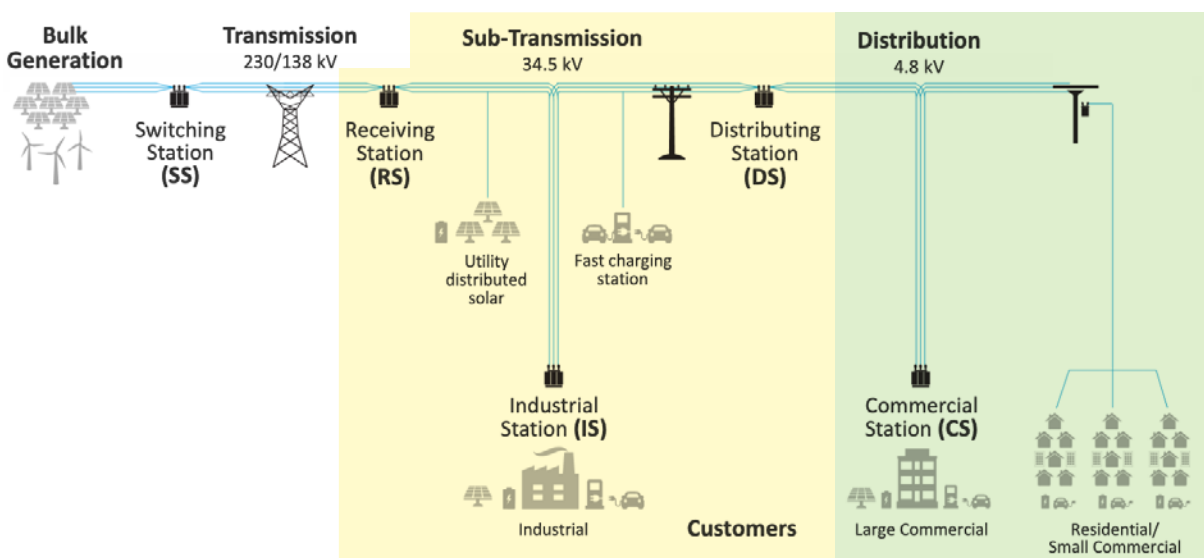
LADWP's distribution system operates at two voltage levels.

1. The **local distribution system (4.8kV)** includes the lines and equipment that connect houses and neighborhoods.
2. The **subtransmission system (34.5kV)** serves as the interface between the transmission and distribution systems and integrates the local distribution system as well as large industrial customers and large solar systems; for example, solar that LADWP deploys within the city.

For this study, the LA100 team built the first complete electric models for LADWP's entire distribution system at both voltage levels and then analyzed the challenges and required changes due to electrification and the adoption of local solar and storage.

The study results assume any existing issues on the distribution system are corrected before exploring the impacts and costs to achieve 100%. This enables the study to isolate the impacts of the LA100 scenarios from deferred maintenance.

- **All scenarios exceed the local solar targets of the Los Angeles Green New Deal by about 1.5–2.4 times.** Most of this capacity is customer-driven rooftop solar.
- **The greatest amount of non-rooftop solar is built in the Early & No Biofuels – High scenario (1,000 MW), with the smallest amount built in the Transmission Focus – Moderate scenario (300 MW).** In all cases, either very high loads or limits on building new transmission drive the development of additional in-basin capacity. Local solar deployment is not strongly impacted by distribution upgrade needs.



Simplified summary of LADWP voltage classes, highlighting the 4.8kV and 34.5kV that are both included in LA100's distribution system analysis

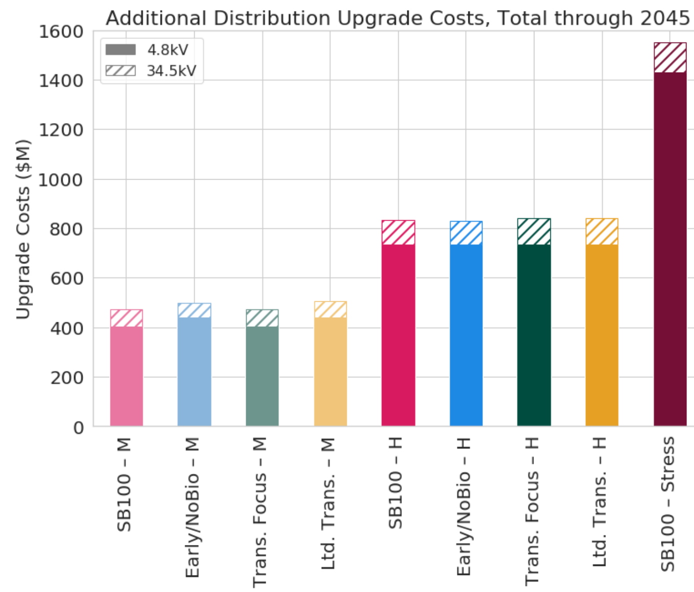
- **The spatial deployment of non-rooftop distribution-connected in-basin solar shows significant regional variation.** Overall, the LA100 scenarios build 6%–18% of the systemwide technical potential capacity for non-rooftop sources; however, many receiving station (RS) regions have zero deployment, some consistently have 10%–80% of technical potential deployed across all scenarios, and other regions have 60%–99% of capacity deployed in only a few scenarios.

- **Non-rooftop solar regional variation is influenced by in-basin transmission congestion as well as small differences in electric losses across regions that make particular regions closer to high load areas more attractive for siting.** As a result, we find parking canopy solar an attractive solution for serving demand in denser regions of the city.

- **To a lesser degree, the spatial deployment of rooftop in-basin solar also varies by RS region, mostly as a function of incentive level (see Chapter 4 of the full report: nrel.gov/docs/fy21osti/79444-4.pdf).** Specifically, rooftop adoption varies from 5%–31% of technical potential capacity with moderate rooftop adoption and up to 11%–39% with high rooftop adoption, with similar patterns among RS regions.

How might the changes envisioned by the LA100 scenarios impact the distribution grid in terms of upgrades and costs?

- **Distribution grid equipment upgrades are required on most (90%) of feeders/circuits to address overloads and voltage challenges caused by combined load, solar, and storage changes associated with 100% renewable electricity pathways.** However:
  - For the 4.8kV system, the majority of challenges are limited to a fraction of feeders (1.4%–3.4% for 2021–2030, and 4%–23% for 2031–2040) where the maximum power flow is high enough to require splitting into multiple feeders.
  - The remaining problems can be addressed using existing technology—the most common upgrade is increasing the size of service transformers—those that connect the distribution system at 4.8kV or 34.5kV to the lower voltages used by customers.
  - Beyond feeder splitting, there are typically only a modest number of upgrades required per feeder/region (cumulative average [median] of 8–14 per 4.8kV feeder and 22–33 per larger 34.5 kV region, depending on scenario). This represents only a fraction of the hundreds to thousands of pieces of equipment on each feeder/region.



Total distribution system upgrade costs associated with changes modeled in the study, by scenario (2019$). These costs are in addition to upgrades required to manage existing challenges on the distribution system and do not include operations and maintenance or additional costs for land and siting for expanded or new substations. The distribution system costs presented here were updated after other chapters of the study were completed. These are the final distribution system costs.

- **The total cumulative cost (through 2045, after correcting existing challenges) of distribution upgrades due to changes modeled in the LA100 study ranges from $472 million (SB100 – Moderate and Transmission Focus – Moderate) to $1,550 million (SB100 – Stress).**

- **These costs are about 1%–2% of bulk system costs and are also relatively minor compared to the equipment costs for corresponding distributed solar and storage resources. However, these costs do not include a number of additional distribution system costs that are required through 2045.** Specifically, these costs do not include substantial investments required to address current distribution upgrade needs, routine maintenance of the distribution system, distribution operations costs, or land acquisition and other costs that may be required for distribution upgrades, notably for substation upgrades. Collectively, these other costs are likely much higher than these *additional* costs required as a result of load changes and distributed energy resource adoption.

- **The vast majority of these upgrades and costs (85%–92%, depending on the scenario) are incurred on the 4.8kV distribution system, rather than the 34.5kV system.**
- Solar and storage can help reduce maximum net loads (load minus solar and storage) and hence avoid some substation upgrades. This is true even though the storage in this study was dispatched to reduce systemwide operation costs, not to defer distribution upgrades. Modifying the storage dispatch to account for distribution needs could further avoid substation upgrades.
- **When distribution upgrades are designed considering load needs simultaneously with customer-adopted rooftop solar and battery storage, the total upgrade costs are reduced compared to making upgrades sequentially for load and then distributed energy resources.** This was observed on 8%–24% of feeders on the 4.8kV system and accounted for a total savings of 12%–15% systemwide depending on scenario.
- Although the specific locations of solar and storage integration can have a localized impact on distribution upgrades required, in aggregate the total upgrade costs were consistent (within 4%–12%) across five randomized samples of customer solar deployment patterns.
- There are a number of key questions that require additional analysis to answer, including:
    - Might it be better to upgrade the 4.8kV to 12–13kV?
    - To what extent might coordinated control help?
    - What is the value of optimizing distributed resources for the grid?
    - To what extent could resiliency and other value streams change distributed energy resource deployment and distribution needs?

Important Caveats

- The quality of any study's results is limited by the quality of the data. For LA100, we endeavored to obtain and verify the best data available, but these data are still not perfect. Some specific challenges for distribution include inaccuracies in the electrical model itself and challenges and unknowns with disaggregated loads and high spatial resolutions of solar and storage deployment. Still, our estimates should reflect the overall direction of trends and systemwide impacts and opportunities.
- Distribution analysis only estimates infrastructure upgrades needed for the 100% renewable pathways for the years 2030 and 2045 due in part to intensive computational and data needs. In actuality, infrastructure upgrades are continuously needed as loads change and distributed energy resources come online. This will undoubtedly change LADWP's actual upgrade deployment, and the changes in timing may result in different overall results. However, one clear outcome of this work is that simultaneously considering load growth and distributed solar and storage when upgrading the distribution system can save costs compared to sequentially upgrading for one followed by the other.
- These results also only consider infrastructure upgrades needed to address system violations introduced due to load growth, electrification, and solar and storage deployments. They do not include other routine maintenance or capital costs like component replacement due to aging. They also do not include potential additional costs due to extreme weather, cyber, or other disasters. In some cases, these routine upgrades could also introduce opportunities for preemptive upgrades that could save LADWP and its customers money overall.
- The results do not include some considerations beyond techno-economic drivers. For example, with any substation upgrades—such as transformer size increase, the addition of a new transformer/bank, or other reconfiguration—there may also be a need to expand the footprint of the substation, which can be difficult in dense portions of LA. In this case, our study does include equipment costs, labor, and some additional costs for reconfiguration and engineering work; however, we do not include land acquisition, community resistance, or other practical factors that could greatly complicate such a project in reality.
- We do not include a number of technical analyses such as protection, voltage flicker, coordinated controls, and system reconfiguration. It is expected that these will be secondary considerations to the main thrusts of this analysis. However, some of them—notably considerations around reverse power flow—may require updated practices and perceptions in planning and operations that might otherwise present challenges in the transition to 100% renewable energy.
- In short, long-term studies like this one can never perfectly predict the future of load changes, customer adoption, community support/resistance, equipment costs, disruptive technologies, regulations, and other factors. Still, we expect the results presented here accurately capture the tradeoffs among various options and scenarios.

Greenhouse Gas Emissions

The LA100 study's GHG analysis evaluates the net reduction in GHG emissions from the power, buildings, and transportation sources associated with the LA100 scenarios.

Find additional information on this topic on the LA100 website (**maps.nrel.gov/la100/key-findings/topics/greenhouse-gas-emissions**) and Chapter 8 of the full report (**nrel.gov/docs/fy21osti/79444-8.pdf**).

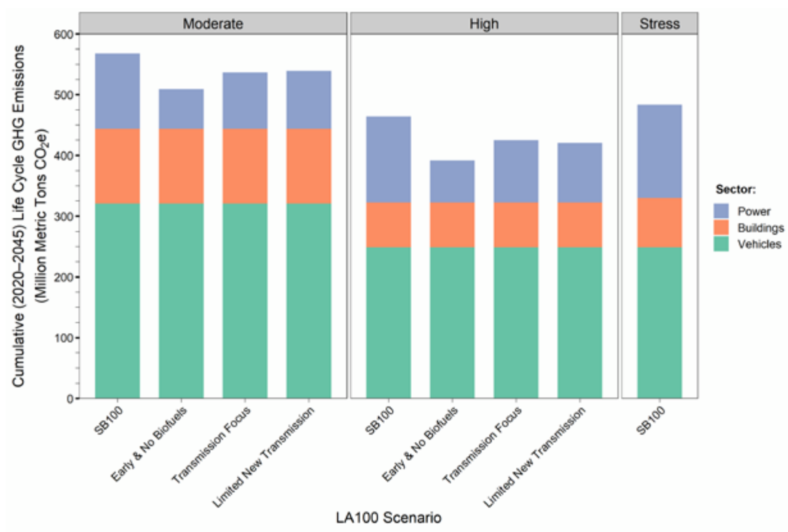
Considering all GHG emissions attributable to power and non-power sectors associated with LA100 scenarios (life cycle GHG emissions), how much do they differ by LA100 scenarios?

- **The Early & No Biofuels – High scenario exhibits the lowest *cumulative* (2020–2045) life cycle GHG emissions attributable to the LA100 scenarios,** at just under 400 million metric tons (MMT) carbon dioxide equivalent (CO_2e). The SB100 – Moderate scenario has the highest, at approximately 570 MMT CO_2e.
- **Fuel use and associated fuel cycle emissions from the vehicles sector account for between 51% (SB100 – Stress) and 64% (Early & No Biofuels – High) of cumulative GHG emissions.** Power sector GHG emissions account for between 13% (Early & No Biofuels – Moderate) and 32% (SB100 – Stress) of cumulative GHG emissions. Fuel use and associated fuel cycle emissions from the buildings sector account for between 16% (SB100 – High) and 24% (Early & No Biofuels – Moderate) of cumulative GHG emissions.
- **By 2045, all LA100 scenarios show significantly lower *annual* life cycle GHG emissions compared to 2020 for the sources analyzed.** The Early & No Biofuels – High scenario is estimated to have the highest reduction of annual life cycle GHG emissions in 2045 relative to 2020 (88% lower). Approximately 20% of the 4 MMT CO_2e/year of 2045 annual life cycle GHG emissions in the Early & No Biofuels – High scenario are from the power sector, 16% are associated with fuel use in the buildings sector, and 64% are associated with fuel use by the vehicles sector (light-duty vehicles and buses).
- **2045 *annual* life cycle GHG emissions are highest in the SB100 – Moderate scenario, at 16 MMT CO_2e/year (54% lower than in 2020).** Approximately 18% of the 2045 annual life cycle GHG emissions in the SB100 – Moderate scenario are from the power sector, 25% are associated with fuel use in the buildings sector, and 57% are associated with fuel use in the vehicles sector.

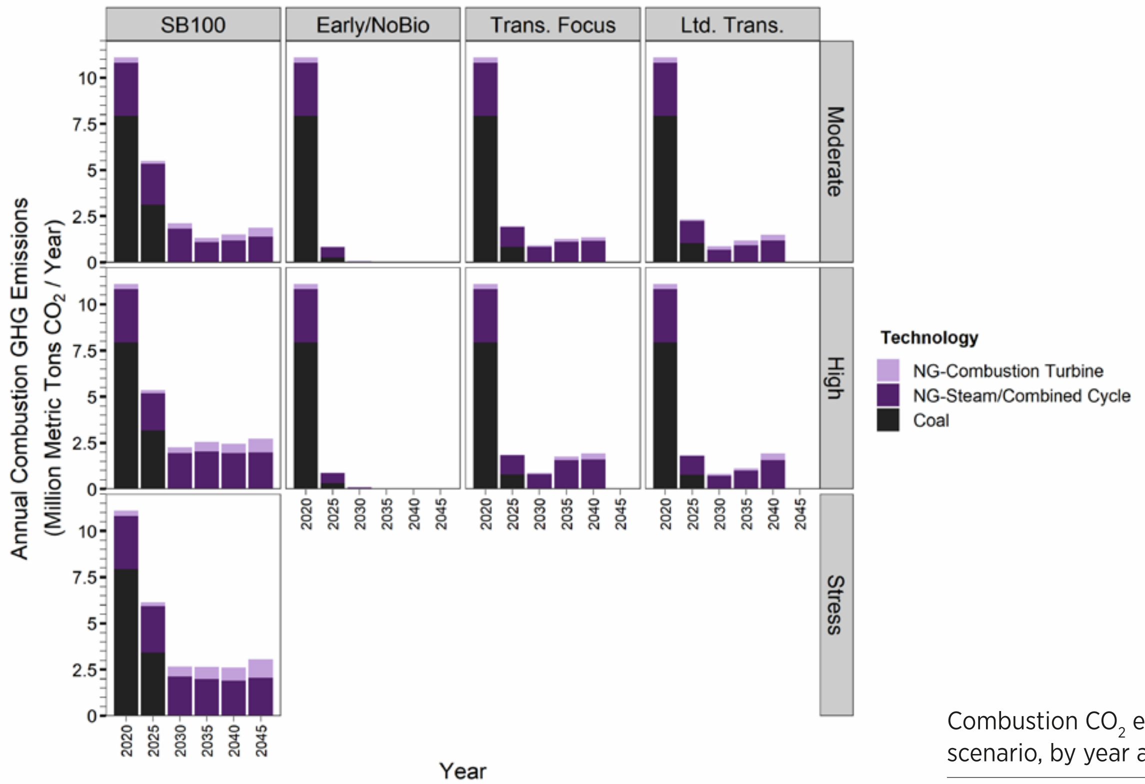
How did LA100 model GHG emissions?

For the **power sector**, GHG emissions are reported in two scopes: combustion-only CO_2 emissions and life cycle GHG emissions. NREL's power sector models report CO_2 emissions from the combustion of fossil fuels. In addition, based on a systematic review of extant literature, NREL has calculated GHG emissions (e.g., CO_2, methane, nitrous oxide and sulfur hexafluoride [SF_6]) attributable to the electricity generation in LA100. These "life cycle" GHG emissions are composed of several "phases" of the life cycle of both the generation technology and fuels. These include not only combustion of fossil fuel (in the operation phase) but also construction and decommissioning of generation assets as well as ongoing non-combustion emissions related to the maintenance of the plant and the extraction, processing, and transport of fuel, where applicable. The latter is known as the "fuel cycle." When weighted by 100-year global warming potentials, GHG emissions are reported in carbon dioxide equivalents (CO_2e).

For **non-power sectors** that are influenced by LA100 scenarios—buildings (residential and commercial) and vehicles (light-duty and buses)—both combustion emissions and fuel cycle emissions are reported. When summing emissions for all three sectors (power, buildings, vehicles), for simplicity, we refer to them together as "life cycle" despite not including all life cycle phases for buildings and vehicles.



Life cycle (power sector) and fuel cycle (buildings, transportation) cumulative GHG emissions associated with each LA100 scenario, by load projection (Moderate, High, Stress), 2020–2045



Combustion CO_2 emissions for each LA100 scenario, by year and technology type

By how much do GHG emissions from LADWP's in-basin electricity generation change under different LA100 scenarios?

- **All LA100 scenarios show significant cumulative (2020–2045) combustion GHG emission declines compared to a hypothetical case where current generation and associated annual emissions are held constant, ranging from an approximately 53% reduction for SB100 – Stress to an 86% reduction for Early & No Biofuels – Moderate.**
- Across all scenarios, combustion GHG emissions from coal generation initially dominate at about 8 MMT CO_2/year, before quickly dropping off after 2025, leaving natural-gas-fired power plants to account for the remaining, if any, combustion emissions from 2030 onward.
- The Early & No Biofuels set of scenarios has the lowest annual life cycle GHG emissions in 2045, at 0.6–0.9 MMT CO_2e/year, or about 80% lower than those of the SB100 set.
- Power sector GHG emissions from life cycle phases outside of fossil fuel combustion (which include construction, decommissioning, and ongoing non-combustion such as maintenance of generator facilities and fuel extraction) account for between 33% and 58% of cumulative (2020–2045) emissions.
- Because Early & No Biofuels reaches the 100% renewable target 10 years earlier, this scenario has the lowest cumulative life cycle GHG emissions for the power sector in the study period, at approximately 65–69 MMT CO_2e, or about half those of the SB100 set.

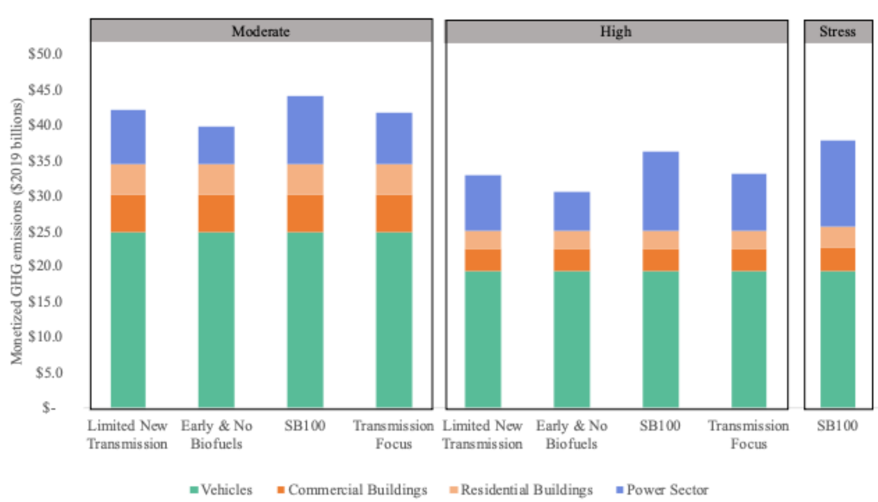
By how much do GHG emissions from non-power sectors (selected transportation and buildings sources) change under different LA100 scenarios?

- **Due to higher levels of end-use electrification, life cycle GHG emissions associated with natural gas consumption in the buildings sector under the High load projection are significantly lower than under the Moderate projection—a reduction equivalent to the annual emissions generated by 5.7 million average U.S. homes' energy usage.**
- Reductions in natural gas usage in residential buildings in the High and Stress load projections equates to approximately 86% reduction in annual GHG emissions from 2020 to 2045 for both projections. The commercial building results are similar.

- Across all three load projections, combustion emissions account for approximately 78% of the cumulative life cycle GHG emissions from fuel use in the residential building sector, with the remaining 22% attributed to the fuel cycle (extraction, processing and transport of fuels), similar to commercial buildings.
- Compared to 2020, the Moderate EV adoption projection reduces annual life cycle GHG emissions from fuel used in light-duty vehicles and buses by approximately 48% in 2045; the High EV adoption projection reduces GHG emissions by approximately 85%. These reductions are equivalent to those generated by the consumption of 1.0 and 1.7 billion gallons of gasoline, respectively.
- The fuel cycle (extraction, processing, and transport of vehicle fossil fuels) accounts for about 31% of the total cumulative (2020–2045) life cycle GHG emissions from light-duty vehicles and buses in both the Moderate and High EV adoption projection scenarios.
- Passenger cars and light-duty trucks account for almost all (99%) of annual life cycle GHG emissions associated with fuel consumption from vehicles considered within the LA100 study, with the two bus fleets contributing negligible annual emissions.

What are the economic costs associated with the GHG emissions from the LA100 scenarios, and what is the relative contribution of each sector?

- **Monetized costs of GHG emissions in LA100 scenarios differ by discount rates: the cost of future emissions in current dollars. Under the 3% central case set by the Interagency Working Group on the Social Cost of Carbon, these cumulative costs of emissions (2020–2045) range from a low of approximately $31 billion under the Early & No Biofuels – High scenario to a high of approximately $44 billion under the SB100 – Moderate—a difference of approximately $13 billion between the scenarios.**
- Cost levels of GHG emissions are primarily driven by electrification rather than by differences among the power sector scenario, and under each scenario, regardless of level of electrification, vehicles are the largest component. The portion comprised by vehicles ranges from a low of 51% under SB100 – Stress to a high of 63% under both Early & No Biofuels scenarios. Costs of GHG emissions from buildings exceed those of the power sector under Moderate scenarios, while the opposite is true under High scenarios.
- Within the power sector, the lowest cumulative GHG costs by 2045 are approximately $5.2 billion under the Early & No Biofuels – Moderate scenario, while the highest ($12.1 billion) are under the SB100 – Stress scenario at a 3% discount rate. Costs of buildings-related GHGs range from approximately $5.7 billion under High electrification to approximately $9.6 billion under Moderate.



Cumulative monetized costs of life cycle GHG emissions (2020–2045) under a 3% (central case) discount rate

Important Caveats

- While accounting for changes to GHG emissions associated with generation technologies, we do not consider GHG emissions from other electric infrastructure (e.g., transmission lines, distribution lines, substations). This caveat is especially important for the Transmission Focus scenario.
- Charging of energy storage technologies occurs through grid electricity, and thus the GHG accounting of power sector emissions captures the emissions associated with operation of energy storage (both batteries and hydrogen produced by electrolysis).
- Greenhouse gas emissions accounting assesses the electric-sector life cycle and changes to fuel use due to efficiency and electrification in residential and commercial buildings and light-duty vehicles and buses. The GHG accounting includes the full life cycle of emissions associated with electricity generation technologies, including construction and operation of the power plants and their decommissioning as well as emissions associated with combustion and the fuel cycle (extraction, processing, and transport of fuels). We do not account for life cycle GHG emissions associated with any changes to infrastructure outside of the power sector (e.g., equipment to electrify buildings or vehicles, charging stations). For vehicles and buildings, only emissions associated with fuel combustion and the fuel cycle (fuel extraction, processing, and transport) are considered.
- GHG emissions from operations are analyzed cumulatively in 5-year timesteps (2020–2045).
- GHG emissions are reported in the aggregate in terms of carbon dioxide equivalent.
- Long-duration storage is assumed to be represented by hydrogen storage combined with fuel cell regeneration.
- Combustion turbines burning hydrogen are assumed to have the same upstream and downstream emissions as conventional natural-gas combustion turbines and the same non-combustion emissions as fuel cells. Hydrogen combustion turbines have no combustion phase GHG emissions because the hydrogen burned is derived from renewable electricity.
- The study reports net GHG reductions but does not create a marginal cost curve for GHG reductions as our analyses of costs and emissions do not align 1-to-1 in scope (i.e., costs include investments unrelated to GHG mitigation).
- While modeling estimates for monetized impact multipliers by discount rate and year account for thousands of different combinations of possible future outcomes as a result of GHG emissions, these are still subject to inherent modeling limitations and not representative of all foreseeable costs.
- Dollar values assigned to GHG emissions over time are from a 2017 study of economic damages of greenhouse gas emissions; future revisions of these figures in response to developments in research and understanding of physical and social science will likely drive changes over time.
- Monetization of GHGs are values that can be modeled and quantified using objective criteria and do not include subjective values such as an individual's willingness to pay for changes in quality of life due to changes associated with GHG emissions.

Air Quality and Public Health

LA100 assesses potential changes to air quality (fine particulate matter and ozone) and public health (premature mortality, asthma, and cardiovascular diseases) from the LA100 scenarios, and the potential economic value of changes to public health.

Find additional information on this topic on the LA100 website (**maps.nrel.gov/la100/key-findings/topics/air-quality-and-health**) and Chapter 9 of the full report (**nrel.gov/docs/fy21osti/79444-9.pdf**).

LA100's air quality and public health modeling resulted from a collaboration with researchers at the University of Southern California and NREL.

Overall, results suggest that the LA100 scenarios could lead to citywide reductions in major air pollutant emissions, including oxides of nitrogen (NOx) and fine particulate matter ($PM_{2.5}$). The largest reductions in emissions derive from changes to non-power sector sources that are affected by the LA100 scenarios (selected transportation and buildings, as well as the Ports of Los Angeles and Long Beach). These reductions in air pollutant emissions due to LA100 are modeled to consequently lead to citywide reductions in $PM_{2.5}$ concentration and an increase in ozone concentration in certain areas within Los Angeles. That ozone concentration increases despite NOx emission reductions can be thought of as temporary "growing pains" that the city experiences on the path toward ozone reductions. Once NOx emissions get sufficiently low, further emission decreases will lead to marked ozone reductions. Health effects are proportional to the concentration changes: where both pollutants contribute to the same health endpoint, the reductions in $PM_{2.5}$ outweigh the slight increases in ozone.

Ozone is a pollutant that is not directly emitted, but rather is formed in the atmosphere following emissions of "precursor" pollutants in the presence of sunlight, most importantly NOx and a grouping of individual pollutants called volatile organic compounds (VOCs).

$PM_{2.5}$ is both directly emitted and is also formed in the atmosphere (e.g., from NOx and SO_2 precursor emissions following different chemical reaction pathways), the latter being the larger contributor to $PM_{2.5}$ concentrations in Los Angeles.

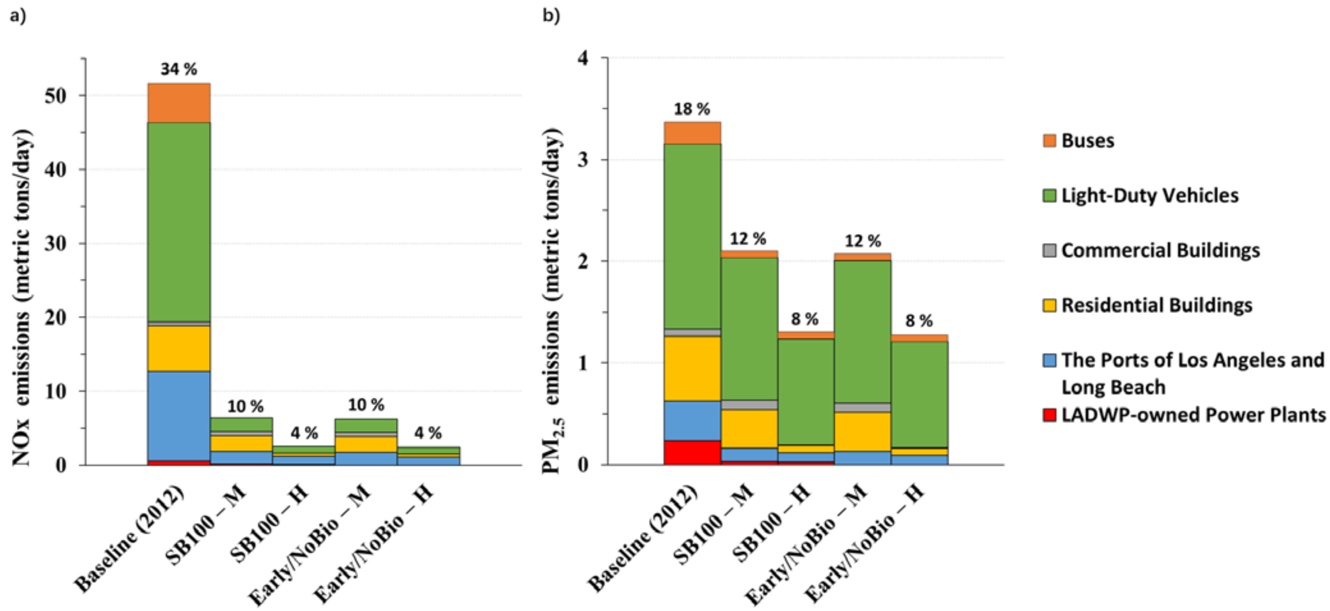
When weighted by the costs of each health effect, the overall changes to air quality from LA100 scenarios could provide hundreds of millions of dollars—and up to nearly $1.5 billion—in monetized benefits in the year 2045.

How do changes due to electrification levels and power plant eligibility in LA100 scenarios affect NOx and $PM_{2.5}$ emissions?

- **All selected LA100 scenarios result in significant reductions in annual primary emissions (directly emitted) for LA100-influenced sources in Los Angeles in 2045 compared to the 2012 Baseline.**
  - SB100 – Moderate (which we use as an LA100 reference scenario for this analysis) leads to an estimated annual reduction in NOx emissions in 2045 of 88% (approximately -35 metric tons/day) and 38% (approximately -1.3 metric tons/day) in $PM_{2.5}$ emissions compared to 2012 for LA100-influenced sources. These reductions are due to changes in the scenarios (i.e., electrification of end-use sectors and changes in power plant fuel use and fuel choice), and due to changes occurring outside the scope of LA100. Reduced emissions from light-duty vehicles and the Ports are the two major contributors to decreases in LA100-influenced NOx and $PM_{2.5}$ emissions.

LA100-influenced sources include the power sector, the Ports of Los Angeles and Long Beach, residential buildings, commercial buildings, light-duty vehicles, and buses.

- **Among the LA100 scenarios (all in 2045), Early & No Biofuels – High has the greatest reduction in annual emissions for LA100-influenced sources: for instance, 62% (4.0 metric tons/day) and 39% (0.8 metric tons/day) lower NO_x and $PM_{2.5}$ emissions relative to SB100 – Moderate, respectively.**
  - These reductions are due almost entirely to electrification of light-duty vehicles and building appliances. Isolating impacts of changes to the power system (both fuel use and fuel type), NOx emissions generated from LADWP-owned in-basin power plants are 84%–88% lower in Early & No Biofuels scenarios as compared to SB100 scenarios, when load levels are held constant. No emissions of $PM_{2.5}$ occur from the power sector in 2045 in Early & No Biofuels because all plants are assumed to burn hydrogen, for which we assume no $PM_{2.5}$ emissions.



Contribution of LA100-influenced sectors to annual average emissions in Los Angeles in 2045 compared to the 2012 Baseline

The percent labels above each column represent the fraction of emissions that are from LA100-influenced sectors out of the total emissions from all sources in the city. The power sector emissions shown represent LADWP-owned power plants located in the South Coast Air Basin.

- **The emissions from LA100-influenced sources as a fraction of all anthropogenic NOx and $PM_{2.5}$ emissions in Los Angeles decrease from the 2012 Baseline (which is 34% for NOx and 18% for $PM_{2.5}$) to the reference scenario in 2045 (10% for NOx and 12% for $PM_{2.5}$ in SB100 – Moderate, for instance), indicating the potentially smaller contribution of LA100-influenced sources to citywide air pollutant emissions and air quality impacts in the future.**
  - The fraction is higher for scenarios with Moderate electrification relative to scenarios with High electrification, but is identical for SB100 and Early & No Biofuels with the same electrification level, which suggests the role of electrification outweighs changes to LADWP power plants in citywide emissions.

How do changes in emissions in LA100 scenarios in turn affect ozone and $PM_{2.5}$ concentrations?

- **Reductions in the emissions of primary $PM_{2.5}$ and precursors to secondary $PM_{2.5}$ (e.g., NOx) result in 6% lower (0.6 µg/m^3) annual-average, daily $PM_{2.5}$ concentrations on average across Los Angeles between 2012 and 2045 under the future reference scenario of SB100 – Moderate.**
- **Simultaneous changes in the power sector and high electrification in end-use sectors in 2045 could yield additional air quality improvements as evidenced by a comparison of Early & No Biofuels – High to SB100 – Moderate, in which citywide $PM_{2.5}$ concentrations decrease by another 0.2 µg/m^3 (2% below SB100 – Moderate levels).**
- Most of the reduction in $PM_{2.5}$ concentration comes from increasing electrification levels (Moderate to High) rather than changes to the power sector. The $PM_{2.5}$ concentration reductions projected under LA100 scenarios are important in the context of the Los Angeles region currently exceeding the federal $PM_{2.5}$ concentration standard by 1–2 µg/m^3. (The federal annual mean $PM_{2.5}$ ambient air quality standard is 12 µg/m^3.)
- **All selected LA100 scenarios in 2045 show *increases* in ozone concentrations for most parts of Los Angeles in summertime.** Ozone concentrations are generally highest in summertime (May to September). The increase from 2012 to 2045 under SB100 – Moderate leads to a citywide ozone concentration increase of 2.2 parts per billion (ppb) (5%).[2]

[2] The metric used by regulatory agencies is the daily maximum 8-hour average of ozone concentration at a specific location, which is what is calculated and reported here. For simplicity, references to “ozone concentration” refer to this metric.

- This increase in ozone concentration occurs despite the reductions in NOx emissions noted above because of the particular ratio of the two ozone precursor pollutants (NOx and VOC) and the nonlinearities of ozone formation chemistry. Currently, with regard to ozone formation chemistry, Los Angeles is generally in a regime whereby VOC reductions can lead to reductions in ozone, yet NOx reductions can lead to increases in ozone (see Chapter 9 of the full report for details: nrel.gov/docs/fy21osti/79444-9.pdf).

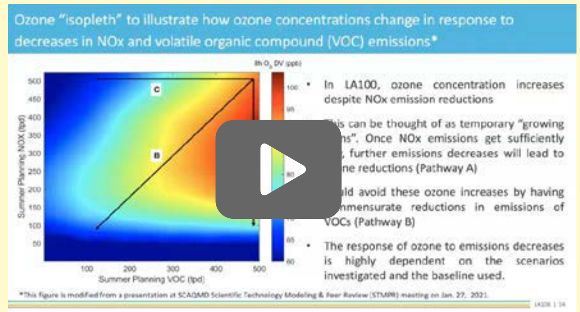
- **Despite the citywide average ozone concentration increase, ozone concentration is simulated to decrease in all LA100 scenarios in 2045 in a portion of the San Fernando Valley where baseline concentrations are the highest, thus yielding benefits to those residents.** This phenomenon indicates that some areas in Los Angeles are shifting from the regime where NOx reductions lead to ozone increases to where reductions in NOx emissions can lead to reductions in ozone.

- **The ozone increases simulated here can be thought of as temporary "growing pains" on the path to reduce ozone in Los Angeles. Once NO_2 emissions become sufficiently low, further emissions decreases will lead to ozone reductions, like we see in the results for the San Fernando Valley mentioned above.**

- **Nevertheless, it should be remembered that reductions in NOx emissions, despite currently leading to ozone increases in most parts of the city, yield immediate benefits given the role of NOx in forming $PM_{2.5}$ and because exposure to elevated levels of NO_2 itself has deleterious health effects.**

Why Does the LA100 Study Show Increasing Ozone Concentration Despite Reduced NOx Emissions?

Watch this video to learn more.



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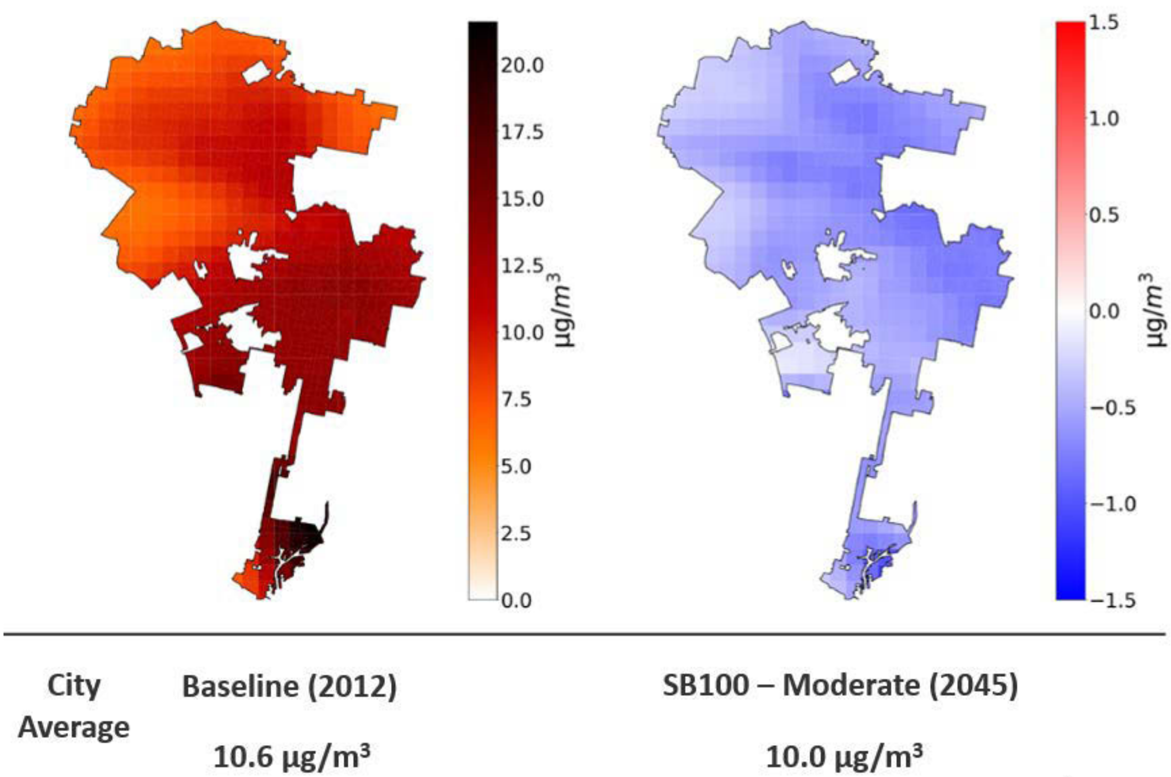


Spatial pattern of $PM_{2.5}$ concentrations in Los Angeles for (left) Baseline (2012), and (right) SB100 – Moderate minus Baseline (2012). Values are averaged over the four simulated months to be representative of annual averages. The figure on the right depicts changes over time from the 2012 Baseline to 2045 for our reference scenario (SB100 – Moderate).

Simulated Los Angeles citywide spatial average of daily maximum 8-hour average ozone in July and annual average daily $PM_{2.5}$ for all evaluated scenarios. Percentages in parentheses show change of future scenarios compared to the 2012 Baseline. Future scenarios simulate the year 2045.

Species (units)	Baseline (2012)	SB100 – Moderate	SB100 – High	Early & No Biofuels – Moderate	Early & No Biofuels – High
Ozone (ppb)	43.8	46.0 (+5%)	46.1 (+5%)	46.0 (+5%)	46.1 (+5%)
$PM_{2.5}$ (µg/m^3)	10.6	10.0 (-6%)	9.8 (-8%)	10.0 (-6%)	9.8 (-8%)

What are the impacts of changes in ozone and $PM_{2.5}$ concentrations on health, including monetization of these benefits?

- **All evaluated LA100 scenarios are modeled to result in reduced incidence of early death (premature mortality) and three diseases (ER visits due to asthma, hospital admissions due to cardiovascular diseases, and heart attacks) in 2045 as compared to the 2012 Baseline.**
- **While the power sector itself contributes few non-GHG air pollutant emissions, electrification of combustion sources in other sectors enables more significant emissions reductions, and thus improved health for residents of Los Angeles.**
- **Compared to the 2012 Baseline, SB100 – Moderate is estimated to result in net health benefits within the city in 2045, including 96 avoided premature deaths, 53 avoided cardiovascular-related hospital admissions, and yet 30 increased asthma-related ER visits.** The increase in asthma-related ER visits is due to a modeled increase in ozone concentrations in the future. **These net health benefits of SB100 – Moderate translate to approximately $900 million in annual monetized health benefits in 2045 for the City of Los Angeles** and exceed approximately $4 billion when including benefits accrued in neighboring counties (in 2019$).
- **Comparing Early & No Biofuels – High to the 2012 Baseline yields the largest health benefits among the scenarios evaluated (for instance, 150 avoided premature deaths in the city), and the total monetized benefits from the improved air quality are approximately $1.4 billion in 2045 for the City of Los Angeles.**
- Comparison of two LA100 scenarios at High load levels with their corresponding Moderate load scenarios (Early & No Biofuels – Moderate versus Early & No Biofuels – High, and SB100 – Moderate versus SB100 – High) helps to isolate the effects of electrification of transportation sources (light-duty vehicles and buses) and building appliances in 2045. **The net health benefits within the city in 2045 from electrifying buildings and transportation end uses include about 52 avoided premature deaths, 22 avoided cardiovascular-related hospital admissions, and 17 avoided asthma-related ER visits. These health benefits translate to an annual average monetized benefit for the City of Los Angeles of approximately $500 million in 2045**, exceeding approximately $1 billion when including the surrounding region.
- Comparing the Early & No Biofuels scenario to SB100 at constant load levels isolates air quality changes resulting from changes to LADWP power plants in 2045, and **it is found that changes to LADWP power plants as a result of LA100 scenarios result in very little change in health effects, i.e., these plants are not large contributors to regional air pollution and related health effects.** Net health benefits from these comparisons are smaller than mentioned above for scenario comparisons that isolate changes to electrification levels, with one avoided death annually and even smaller health benefits for the other health endpoints, translating to an annual monetized value of health benefits of a few million dollars in 2045. Note that all LA100 scenarios have greatly reduced natural gas combustion at LADWP-owned facilities compared to today, and for Early & No Biofuels, natural gas combustion is eliminated. All scenarios use hydrogen in 2045, with Early & No Biofuels exclusively using hydrogen combustion, and at reduced levels of generation compared to natural gas today. This similarity across LA100 scenarios—reduced natural gas generation compared to today—is why air quality and public health changes are small when comparing scenarios at a constant electrification level. The monetized value of the health benefits is dominated by avoided premature mortality in comparison to avoided cardiovascular hospitalizations, heart attacks, or asthma-related ER visits.

- The estimated health benefits are based on just one year (2045) that we considered for our air quality modeling. Cumulative benefits to the city will depend on the pathway adopted to reach to 100% renewable energy, but are likely to be multiples larger.

Important Caveats

- The focus of this analysis is on regional air pollution. It is not an exhaustive environmental hazards analysis. For example, we do not investigate near-source exposures to emissions sources (e.g., power plants, freeways, the Ports), or fuel leaks. We did not investigate the role of transitioning LADWP-owned power plants to 100% renewable energy on near-source exposure to pollutants in 2045. In addition to the pollutants that were considered in this report (ozone and $PM_{2.5}$), many other pollutants are emitted from combustion sources that can affect local air quality. These pollutants could be investigated in future work to develop estimates of additional health benefits to neighboring communities to LADWP's current natural-gas-fired power plants.
- This analysis quantifies benefits based on air quality modeling of just one year (2045), whereas net benefits will be cumulative. The magnitude of cumulative benefits depends on the pathway to 100% renewable energy. These cumulative benefits are likely to be much larger than the 2045 annual benefits, but their quantification will require further analysis of intermediate years. Such analysis could also help to identify pathways that maximize cumulative human health benefits.
- While tempting, it is not appropriate to compare the power system capital costs associated with achieving 100% renewable energy (the various LA100 scenarios) to the health benefits reported in this chapter. The health benefits quantified and then monetized are annual, whereas the power system transformation capital costs are cumulative. Therefore, they cannot be directly compared.
- Furthermore, the health benefits estimated here are just a subset of all health effects that result from exposure to ozone and $PM_{2.5}$. For instance, other respiratory illnesses such a bronchitis are affected by air pollution exposure. In addition, we only model two pollutants' concentrations; many more will be affected by LA100 scenarios. For instance, NOx emissions were modeled for their importance to formation of ozone and $PM_{2.5}$ in the atmosphere, yet exposure to NO_2 also has direct health effects that were not modeled. In these ways, the health benefits and monetized value of those benefits are underestimated compared to those that would be experienced by Los Angeles residents as a result of the LA100 scenarios.
- Note that the contribution of LA100-influenced sources to citywide total emissions could be relatively small in the future, thus changes to air quality are limited.
- Medium- and heavy-duty trucks are one of the largest sources of air pollutant emissions in Los Angeles. LA100 did not include medium and heavy-duty vehicles in the development of scenarios, thus only current regulations were considered in the air quality modeling. If LA100 had developed electrification scenarios (or other zero-emission vehicle pathways) for these vehicles, greater emission reductions than considered here would be included, especially by further reducing $PM_{2.5}$ pollution. Similarly, we do not include any mandates requiring larger penetration of electric vehicles in California that would further reduce emissions and provide air quality benefits outside of what is modeled here. Emissions reductions beyond current regulations from off-road sources are another category of contributors to air pollution that were not explored in LA100 (outside the Ports).
- Air quality results shown here are highly dependent on the ways that the scenarios were defined. Simulated ozone responses to emissions reductions are highly dependent on atmospheric context, and thus the scenarios investigated. This goes for both the LA100 scenarios and the reference scenario used as a point of comparison.
- Air quality modeling results shown here are for the purpose of demonstrating the potential changes in air quality induced by LA100 scenarios, rather than to predict actual air pollutant concentrations in the future. The comparison of air pollutant concentrations between scenarios can illustrate the combined or isolated effect of electrification levels and power plant eligibility in LA100. However, we do not recommend comparing the simulated air pollutant concentrations directly with the National Ambient Air Quality Standards.
- We strove to assess the impacts of emissions changes on air pollutant concentrations in Los Angeles. To avoid including additional confounding factors, we keep the same meteorological year across all scenarios in air quality modeling. The 2045 scenarios are driven by 2012 meteorology, consistent with the selection of baseline year. Thus, the potential effects of changes to the climate are not considered. Climate change is expected to lead to additional changes in air pollutant concentrations through several pathways, such as changes to rates of chemical reactions that are sensitive to temperature, additional emissions from higher evaporation rates of chemicals like petroleum products, etc. Future analysis could consider simultaneous impacts from climate change on air quality and subsequent health impacts.

Environmental Justice

The City of Los Angeles identified environmental justice as both a key motivation for the LA100 study and an intended outcome for the transition to 100% renewable electricity.

LA100 reviews three areas of distributional justice—deployment of customer rooftop solar, air pollutant concentrations (fine particulate matter [$PM_{2.5}$] and ozone), and air-quality-related health impacts (ER visits from asthma, cardiovascular-related hospital admissions, and premature mortality)—as well as additional impacts that affect quality of life in ways not quantified in the study.

Find additional information on this topic on the LA100 website (**maps.nrel.gov/la100/key-findings/topics/environmental-justice**) and Chapter 10 of the full report (**nrel.gov/docs/fy21osti/79444-10.pdf**).

How is customer rooftop solar distributed in Los Angeles under LA100 scenarios?

- **Significant growth in rooftop solar occurs in all scenarios across the city, in both disadvantaged and non-disadvantaged communities (DAC/non-DAC), as identified by the State of California by its CalEnviroScreen score.** There is significant potential for solar in disadvantaged tracts. The distribution of solar between DAC and non-DAC census tracts remains similar to today. In 2020, 35% of customer rooftop solar is sited in disadvantaged communities, rising to 37%–41% by 2045 under the LA100 projections. (For reference, approximately half of the census tracts in LA are DAC.)
- The LA100 study, however, does not capture many distinctions between disadvantaged and non-disadvantaged households that could be important to rooftop solar projections, including homeownership, rooftop quality, income, and access to financing. Therefore, policy actions to prioritize disadvantaged communities could focus on analyzing these types of factors that would lower barriers to realizing potential economic benefits of solar, as well as non-rooftop alternatives such as community solar and virtual net metering.

How do power plant eligibility and electrification levels in end-use sectors affect pollutant concentrations in disadvantaged and non-disadvantaged communities?

- **In the 2012 Baseline, census tracts designated as DAC through their CalEnviroScreen scores by the state of California have, on average, higher mean concentration of $PM_{2.5}$ but lower mean concentration of summertime ozone compared to non-DAC tracts.** In all evaluated LA100 scenarios

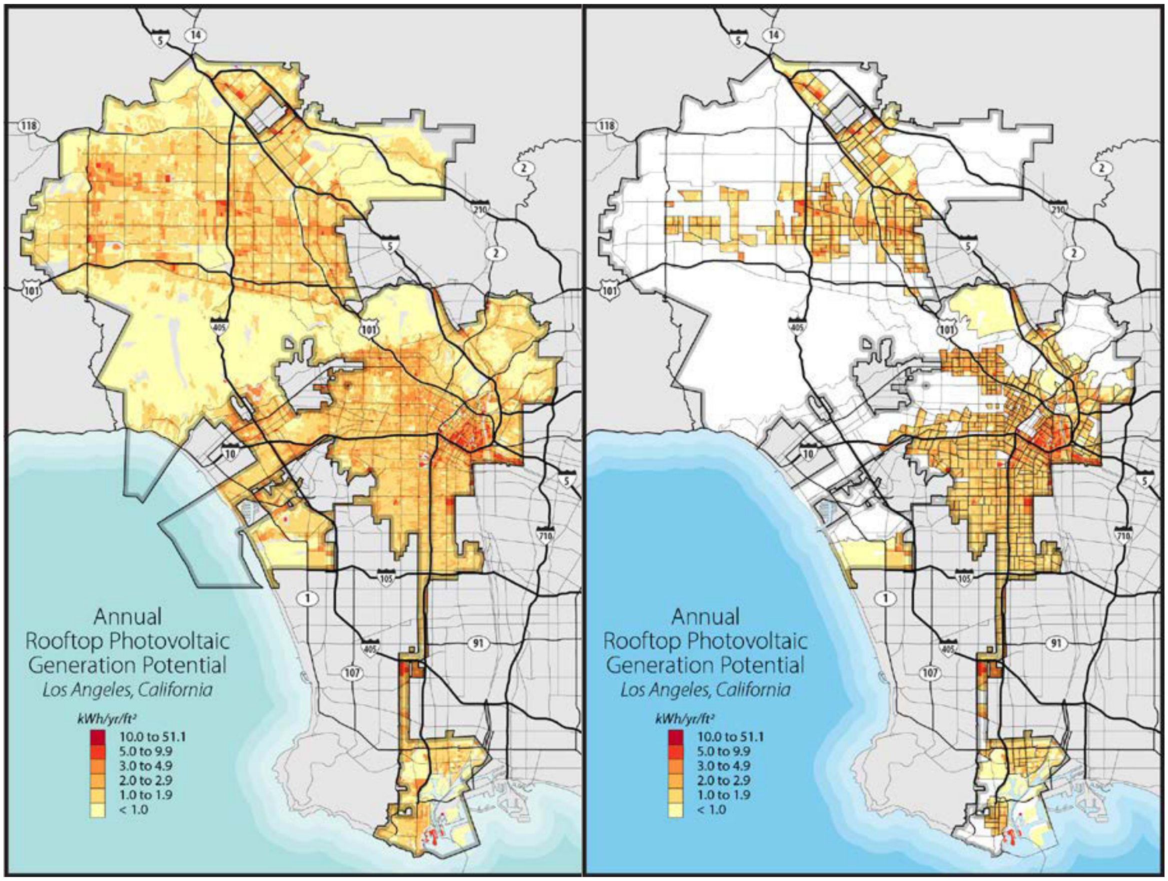
How is environmental justice addressed in the LA100 study?

The LA100 study was guided by definitions of environmental justice codified in California and federal policy and aimed to follow procedural justice and distributional justice principles in its approach to community engagement and analysis of scenario outcomes.

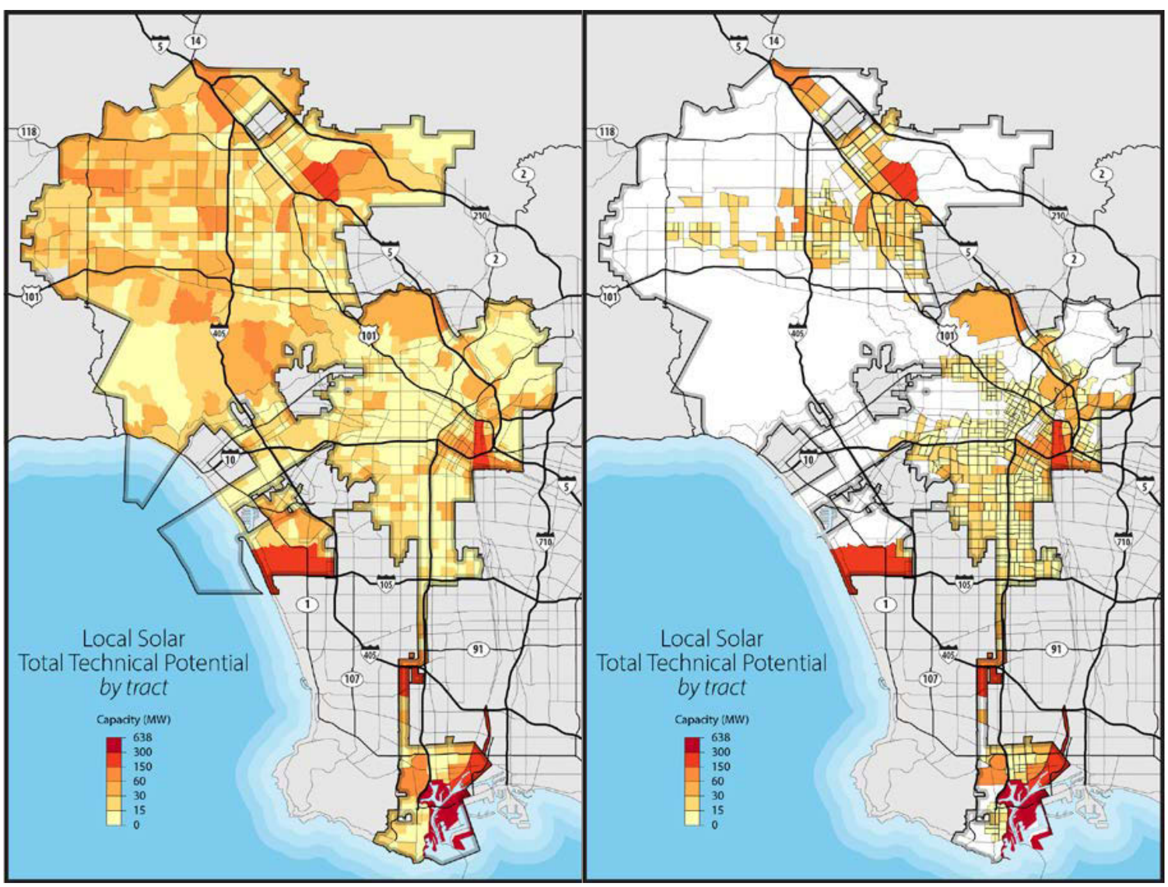
Procedural justice principles motivated the regular release to the Advisory Group of interim study findings, elicitation and inclusion of Advisory Group feedback, updates to LA100 analytical approaches in response to feedback, and hosting and participating in community meetings to inform the public of study findings and gain a better understanding of public priorities for an energy transition. The public has vocalized many priorities; how competing priorities will be evaluated and/or incorporated into implementation plans has not yet been identified. Deliberative polling and participatory budgeting are examples of public engagement that empower citizens in decision-making.

Distributional justice principles guided the analysis of technology deployment and air quality and related public health impacts in relation to disadvantaged community designations, which are based on present-day CalEnviroScreen scores in Los Angeles, as specified in the August 2017 City Council Motion. Half of the city's census tracts are identified as disadvantaged communities, comprising one quarter of the state's total.

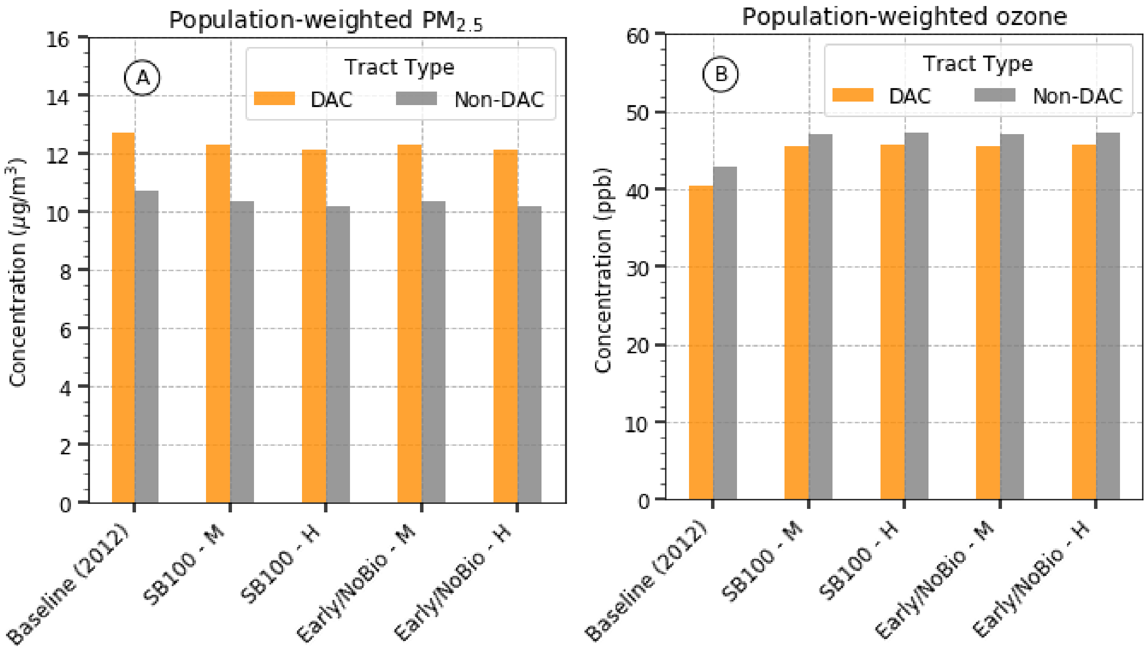
Analysis of distributional justice in terms of technology deployment focuses on customer-sited solar adoption as an example. A full environmental justice analysis of not just customer-solar adoption, but also adoption of building energy efficiency and electrification of electric appliances and vehicles, among others, would require details on policy and program implementation, which were beyond the scope of this study. Nevertheless, the adoption levels of these technologies will be important facets of energy justice outcomes. This initial environmental justice analysis is intended to provide high-level context for LADWP's own ongoing policy and program development, implementation, and evaluation.



Customer rooftop solar generation potential. All LA (left); disadvantaged communities (right)



Local solar technical potential (rooftop and non-rooftop). All LA (left); disadvantaged communities (right)



Population-weighted concentrations of $PM_{2.5}$ (annual average, left) and ozone (summertime averaged daily 8-hr maximum, right) in DAC and non-DAC census tracts

(year 2045), the relative patterns of pollutant concentration experienced by DAC and non-DAC tracts persists; that is, all future scenarios show higher concentrations of $PM_{2.5}$ and lower concentrations of ozone in DAC compared to non-DAC tracts.

- Relative to the Baseline (2012), annual-average, population-weighted concentration of $PM_{2.5}$ decreases by a total of about 0.39–0.56 µg/m³ (3.3%–5.2%) in all LA100 scenarios in 2045 on average throughout LA. **$PM_{2.5}$ concentration reduction is similar for DAC tracts as compared to non-DAC tracts for the evaluated LA100 scenarios.** (Note that by far the largest monetary damages from air-pollution-related health effects result from prolonged exposure to $PM_{2.5}$.)
- By contrast to the $PM_{2.5}$ results, population-weighted, summertime concentrations of ozone increase by a total of about 4.2–5.3 ppb (10%–13%) in all evaluated LA100 scenarios relative to 2012. (While counterintuitive, the scientifically well-established chemistry of ozone formation and the particular composition of LA's atmosphere means that the reductions in NOx emissions from LA100 scenarios lead to increases in ozone concentration given the current composition of the atmosphere in LA; see Chapter 9 of the full report for details: nrel.gov/docs/fy21osti/79444-9.pdf). **Projected ozone concentration in 2045 for DAC tracts increases slightly more compared to that for non-DAC tracts (e.g., +13% in DAC versus +10% in non-DAC in the Early & No Biofuels – High scenario).**

How do health impacts measured in LA100 differentially affect disadvantaged and non-disadvantaged communities?

- **On balance, air pollution-related health effects decrease citywide under LA100 scenarios (see Chapter 9 of the full report for details: nrel.gov/docs/fy21osti/79444-9.pdf). Yet within the citywide benefits, all comparisons among future LA100 scenarios evaluated in the year 2045 yield greater change in health endpoints for DACs as compared to non-DACs for all three endpoints investigated.** The differences between DAC and non-DAC are not large in many cases, and in fact the 95% confidence level was not reached in our statistical analysis in most cases, which means that we cannot say that there is a difference between DAC and non-DAC that might not have occurred by chance. It can at least be said that there is no furthering of environmental justice disparity in terms of air-pollution-related health effects.
- **All LA100 scenarios evaluated indicate improvements in two health indicators—premature mortality and cardiovascular disease—compared to the 2012 Baseline.** Annual premature mortality reduces by an average of 72 deaths per DAC tract and 76 per non-DAC tract in the Early & No Biofuels – High scenario compared to the 2012 Baseline. Cardiovascular-related hospital admissions reduce by a total of 38 in DAC tracts (34 in non-DAC tracts) in the same scenario comparison.

- However, owing to the aforementioned increase from 2012 in ozone concentration in LA100 scenarios, the number of annual asthma-related ER visits increases in both tract categories in the two comparisons made to the Baseline (2012) (Early & No Biofuels – High and SB100 – Moderate). **Asthma-related ER visits are statistically significantly different between DAC and non-DAC tracts for most scenario comparisons, with DAC tracts seeing, on average, greater increases in incidences.**

- **In terms of isolating the contributions of different sectors to the evaluated health effects by comparing the evaluated LA100 scenarios in 2045, the greatest improvements observed are from increased levels of electrification of end-use sectors (such as residential and commercial buildings, transportation), as opposed to differences in power sector generation technology type and fuel use.** The trend observed whereby the greater the electrification, the greater the improvement in health overall, is likely to continue with higher levels of electrification.

What other, non-quantified impacts of LA100 scenarios could be beneficial to disadvantaged communities?

- **Disadvantaged communities near the LADWP in-basin power plants, the Ports of LA and Long Beach, major roadways, and living or working in buildings with electrified water or space heating or other appliances have several types of benefits expected as a result of LA100 scenarios in addition to those quantified and reported above.**

- These benefits include reductions in air-pollution-related health effects from lower concentrations of more local pollutants (in contrast to regional air pollutants like ozone and fine particulate matter) contributed by changes to LADWP in-basin power plants, and electrification of the operation of the Ports and light-duty vehicles on major roadways. The concentrations of these other pollutants, such as nitrogen dioxide and toxic and hazardous air pollutants, were not quantified in LA100 because they involve chemistry, health effects, and near-source scales not modeled. Thus, the health benefits quantified in LA100, in this respect, should be viewed as an underestimate.

All communities would share in the benefits of the LA100 scenarios—but improving equity in participation and outcomes will require intentionally designed processes, policies, and programs.

Disadvantaged communities could expect to see many benefits in a clean energy transition, including reduced local and regional air pollution, improved indoor air quality from electrification, reduced vulnerability to climate change, and improved health outcomes. Ensuring prioritization of these neighborhoods, however, is not an inevitable result of the power-system transition. A just, equitable clean energy future would require intentionally designed decision-making processes and policies/programs that prioritize these communities.

- LA100 did not model indoor air quality, where improvements could be experienced from reduced use of indoor combustion equipment replaced with electric appliances.

- In addition, in various ways, all of the LA100 scenarios should also reduce noise, visual, and odor nuisance from affected sources (like vehicles) and facilities.

Important Caveats

- Analyzing how to prioritize benefits related to technology deployment to environmental justice neighborhoods requires information on future rates and policy and program design and implementation, which will occur after the completion of this study. Nevertheless, the study provides data on potential outcomes, which could help guide policy design. A near-term focus on participatory justice can support a process to design and monitor the policy implementation.
- Due to methodological incommensurability between CalEnviroScreen and our air quality-health impacts modeling approach, our analysis could not follow the approach used in CalEnviroScreen. This is because CalEnviroScreen is a retrospective tool based on sparsely measured data whereas LA100 looks toward the future using highly resolved models that produce sometimes slightly different metrics than those defined in CalEnviroScreen.
- Air quality modeling, and thus the analysis of public health effects resulting from changes to air pollutant concentrations, focused on analyzing both High and Moderate load electrification projections of the SB100 and Early & No Biofuels scenarios. Selection of these scenarios provides a high/low bookend to air pollutant emissions amongst the full set of LA100 scenarios. In addition, when evaluated in carefully selected pairs, analysis of these two scenarios allows for the isolation of changes to the power sector (by holding electrification levels constant) and to electrification levels (by holding power sector eligibility criteria constant). Results for the other LA100 scenarios are likely to fall in between those for SB100 and Early & No Biofuels.
- Owing to a focus on modeling emissions changes to LA100-affected sources (as opposed to all sources of air pollutants in LA), our estimates of concentrations are not predictions of future concentrations in an absolute sense, but rather should only be used in the context of comparing results among the evaluated LA100 scenarios.
- This analysis identifies whether there are statistically significant differences between DAC and non-DAC tracts for the health and air pollutant concentration indicators. However, even when differences between non-DAC and DAC tracts are not statistically different, they may have practical significance, and vice versa (some statistically significant differences are not practically significant). Importantly, health modeling (see Chapter 9 of the full report: nrel.gov/docs/fy21osti/79444-9.pdf) indicates that the city as a whole benefits from the emission reduction measures resulting from LA100 scenarios with regard to exposure to ozone and $PM_{2.5}$ and a subset of their related health effects.
- With the addition of premature mortality, the environmental health endpoints modeled in this study align with those used in CalEnviroScreen. Yet, there are many other environmental health endpoints, and the pollutants that cause them, not modeled in this study, and thus this chapter does not represent a complete environmental health analysis of all of the potential health benefits of LA100 scenarios. In this way, the results reported here underestimate the potential health benefits of LA100 scenarios and their associated monetary benefits. LA100 focused on regional pollutants and did not model pollutants directly emitted that have high local spatial gradients in concentration, nor their associated health effects. For instance, reducing the use of combustion at LADWP in-basin power plants also reduces many pollutants directly emitted, such as NO_2 and a host of hazardous air pollutants, that have more local effects. **Ultimately this study underestimates the potential health benefits of the LA100 scenarios, especially for nearby residents and neighborhoods.**

Jobs and the Economy

LA100 explores the impact of new investments in construction and operation of the future LADWP power system on employment, household income, and gross domestic product within LA.

Find additional information on this topic on the LA100 website (**maps.nrel.gov/la100/key-findings/topics/jobs**) and Chapter 11 of the full report (**nrel.gov/docs/fy21osti/79444-11.pdf**).

LA100's economic modeling was a collaboration between researchers at NREL, the University of Southern California, and Colorado State University.

What are the net impacts of the LA100 scenarios on LA's economy?

- **Net economic assessment shows that achieving LA100 scenarios will not affect LA's economy, on net, in any meaningful manner.** While there may be slight positive or negative impacts, these changes are small in relationship to the 3.9 million jobs and $200 billion in annual output in the LA economy as a whole, so they have an almost negligible impact.
- **Using SB100 – Moderate as a reference scenario, the net economic impacts from 2026 to 2045 within LA range from a low of -3,800 jobs annually under the Early & No Biofuels – Moderate scenario to 4,600 additional jobs under the SB100 – Stress scenario.** As a percentage of the 3.9 million employed in Los Angeles in 2019, these reflect changes of -0.10% and 0.12%, respectively.
- These changes are economy wide and do not differentiate between those within or outside of specific energy technologies or the energy sector. Additionally, the changes do not consider programs such as those that offer retraining or workforce development to facilitate entry into other jobs.
- Assuming equal distribution of costs across all income levels,[3] lower-income households tend to be the most affected regardless of whether results are positive or negative. Under the Early & No Biofuels – Moderate scenario, where impacts are the most negative relative to SB100 – Moderate, average household income changes -0.51% annually for households earning less than $10,000 annually from 2026 to 2045 compared to changes of 0.09% for households earning more than $150,000 annually. Under SB100 – Stress, where impacts are the most positive, income for households earning below $10,000[4] annually increases an annual average of 0.37% while households earning over $150,000 annually increases 0.10%.
- These trends would affect the distributional impacts of income. When results are positive, the positive accruals to lower-income households tend to make income distribution more even within LA, but when results are negative the opposite is true: income inequality increases.

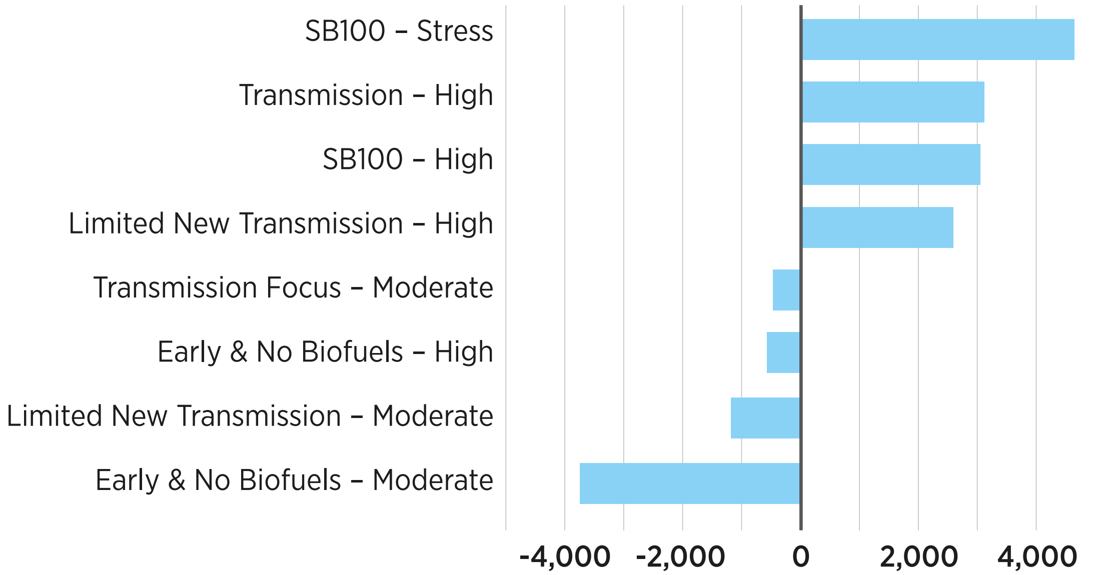
How did LA100 model LA's economy?

The LA100 study used a computable general equilibrium (CGE) model to estimate **net economic impacts** within LA, factoring in both expenditures on construction and operation of infrastructure as well as how this infrastructure may be paid for. These changes can be positive or negative, depending on a number of factors such as how businesses and households change their consumption of different goods and services in response to changes in electricity prices. The model uses changes for all scenarios relative to 2020 prices, although a more accurate representation of changes is to choose a scenario as a reference case and compare other scenarios to this reference. This analysis compares all scenarios with SB100 – Moderate.

The Jobs and Economic Development Impacts suite of input-output (I-O) models was used to estimate **gross economic impacts** of power system investments and operations, both in and out of the LA Basin. This type of model solely considers expenditures made under each scenario, as well as economic activity such as jobs that can be associated with these expenditures. From an employment perspective, this can be thought of as workforce needs.

[3] An equal distribution is used because costs are distributed evenly across households as electricity costs. Households that consume more electricity bear more costs than households that consume less electricity. This assumption is used because the study does not consider whether costs might be distributed differently based on income or tiered based on electricity consumption. These questions are unknown and based on decisions made by those setting rates.

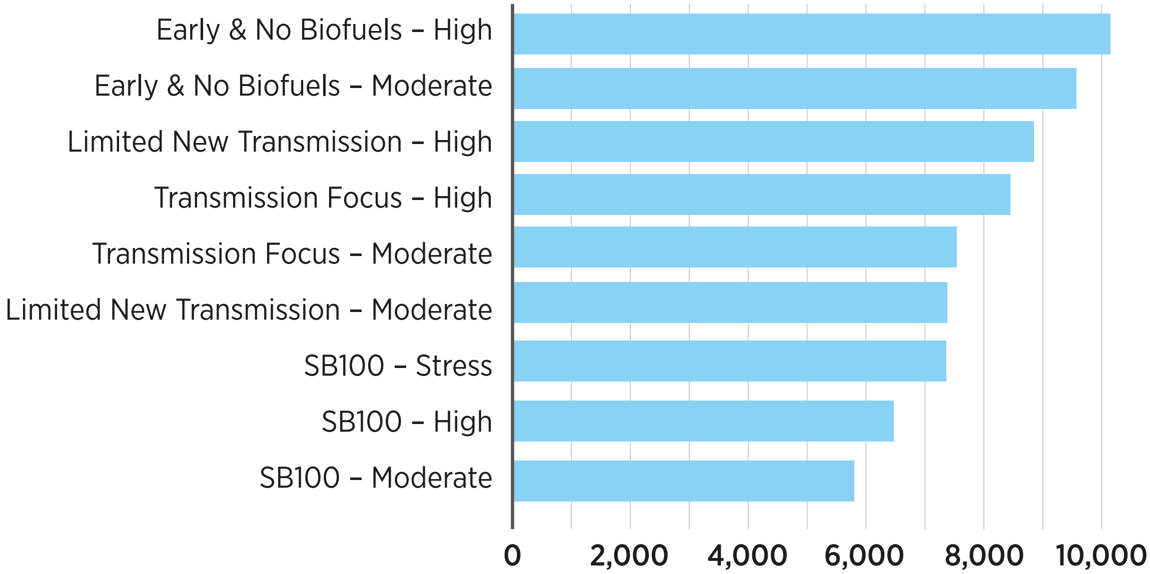
[4] All expenditures are in 2019 U.S. dollars.



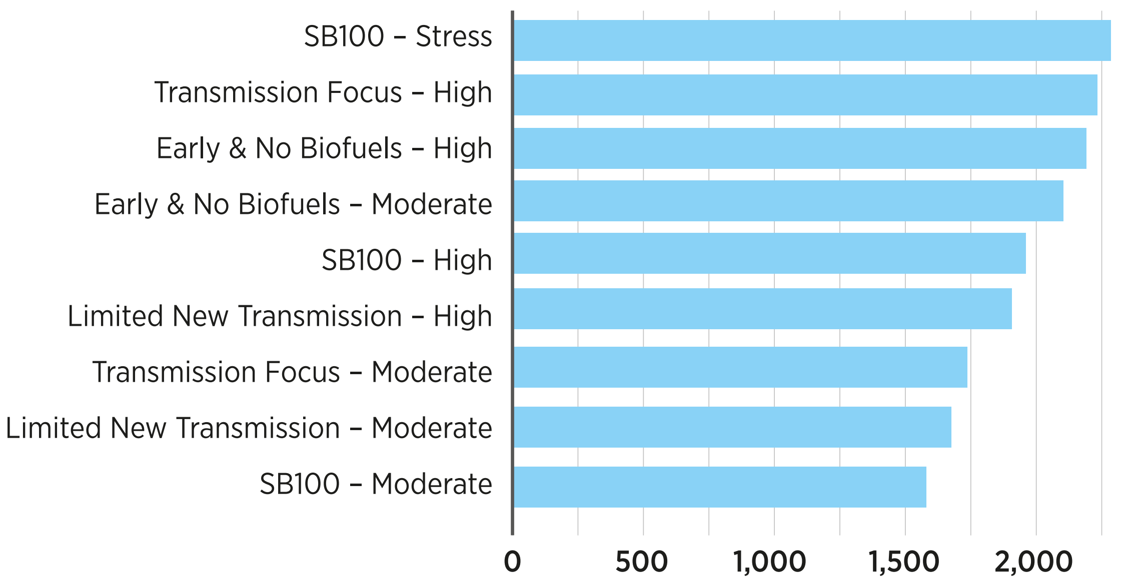
Average annual net job changes in each scenario relative to SB100 – Moderate (2026–2045)

How do the LA100 scenarios impact jobs?

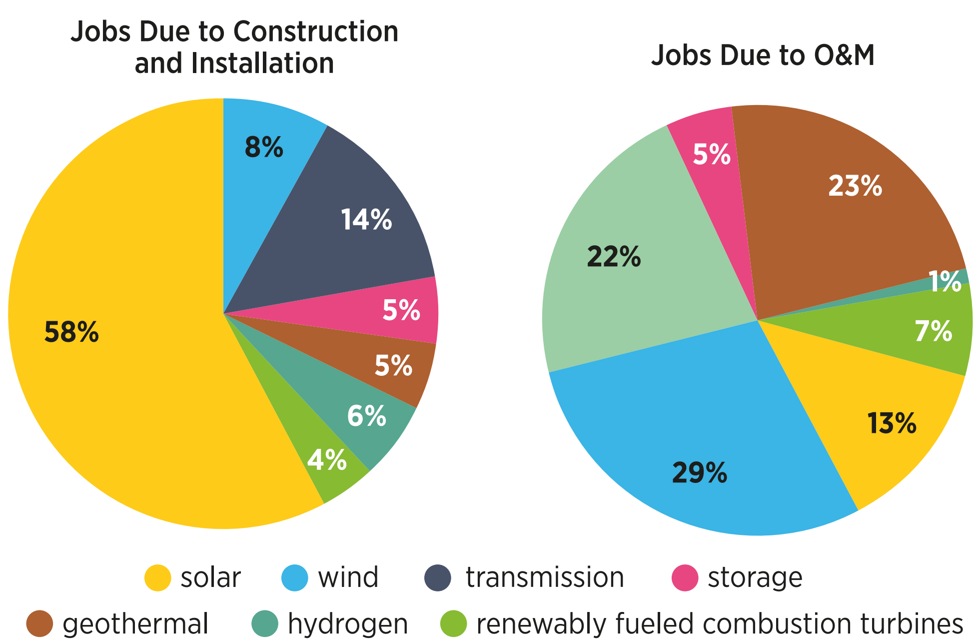
- **Consistent with expectations, higher expenditures on new infrastructure and operations of both existing and new infrastructure correlate with higher numbers of jobs and associated economic activity.**
- Most jobs supported by construction and installation in all LA100 scenarios earn wages that are below the $67,000 annual average for construction and installation workers across all scenarios; 34% of all jobs on average support higher earnings. The gap between the lowest- and highest-earning positions is $19,000.
- Most jobs supported by operations and maintenance (O&M)—71%—support earnings higher than the $52,000 O&M average across LA100 scenarios. The gap between the lowest and highest earnings due to O&M within each scenario supported by each technology is $38,000.
- On average between 2026 and 2045, each scenario supports 8,600 annual jobs due to construction and installation and 2,000 jobs due to O&M.
- The Early & No Biofuels scenarios have the greatest number of gross annual jobs needed to build and operate electricity infrastructure, with the High electrification scenario supporting an annual average of 11,000 and the Moderate electrification scenario supporting 10,400.
- While the Early & No Biofuels scenarios support the largest number of construction and installation positions, the SB100 – Stress and Transmission Focus – High scenarios support the largest number of annual O&M positions, with 2,300 each.
- Among jobs supported by construction and installation, across all scenarios, solar supports the most positions with 58% of the total. Transmission follows, supporting 14% of all jobs. At 4%, renewably fueled combustion turbines support the lowest share of positions.
- Compared to construction and installation, jobs supported by O&M are more evenly distributed across technologies. Wind, which is entirely outside of the LA Basin, supports the largest share with 29%. Geothermal and natural gas follow with 23% and 22%, respectively. Unlike construction, O&M jobs accumulate over time, so timing of the new technologies affects cumulative (and average) employment levels. Geothermal installed early will thus have a larger impact compared to renewably fueled combustion turbines, which are typically installed later. Similarly, natural gas that is online from 2026 to 2040 will support a larger share of O&M-related positions than technologies that are online for shorter periods of time before 2045.



Annual average jobs supported by in- and out-of-basin construction and installation, by scenario (2026–2045)



Annual average employment supported by both in- and out-of-basin O&M, by scenario (2026–2045)



Distribution of employment supported by each technology, averaged across all scenarios

Important Caveats

- All types of economic analysis are solely for the construction, installation, and operation of electricity generation infrastructure. These results do not include jobs associated with energy efficiency or with electrifying demand, such as installing electric water heaters.
- Jobs and earnings are a combination of plant or infrastructure workers and the "ripple effect" of that infrastructure—namely, supply chains and activity associated with those workers spending money in and outside the city of LA (CGE analysis) or LADWP balancing area (I-O analysis), which are determined by data within the IMPLAN model. Higher earnings reflect all of these assumptions. A technology that purchases high-tech manufactured components in California with high-paid workers, for example, will support higher earnings than a technology that imports components and only supports relatively lower-paid wholesalers and retailers. Technologies that purchase more inputs locally will support more jobs than those that import goods and services or have workers who commute in from other states.
- While the net economic analysis includes overall changes in cost, these percent changes are applied evenly across household income groups. There are no assumptions about policies or other rate setting mechanisms that could change how electricity costs are distributed, be those based on income or tiered based on electricity usage.
- Although the net economic impacts of LA100 scenarios in relationship to the economy as a whole are small, the impacts to jobs within specific industries, such as natural gas, may be significant. The study does not identify programs to facilitate transitioning workers to new industries.
- Job estimates are tied to specific energy technologies, while the net economic analysis estimates include all construction and operation in aggregate and are not tied to specific technologies.
- Jobs analysis can be thought of as identifying overall jobs needed to support construction and operations (including supply chain and induced employment), but the study does not identify how these results could translate to specific occupations (e.g., electricians, engineers, grocery workers).
- Job estimates do not necessarily translate to opportunities for LA residents, as employers may hire workers from outside of the region. The analysis does distinguish jobs by the location of the economic activity (in versus out of the LA Basin).
- Jobs by technology include an array of positions that are onsite at generation facilities, throughout the greater supply chain, and those that are supported by workers spending their earnings. Jobs shown for solar, for example, may include a combination of onsite installers, supply chain wholesale workers, hardware manufacturers, and induced retail or health care workers supported by installer and supply chain worker spending.

Next Steps for LADWP and the City of LA

LA100 represents an early but not final set of analyses on transitioning to 100% renewable energy. Here we summarize actions LADWP and the City of LA can consider when implementing next steps. Find additional detail in Chapter 12 of the full report (**nrel.gov/docs/fy21osti/79444-12.pdf**).

The Customer: Further analyses are needed to design, monitor, and evaluate programs to prioritize investments in environmental justice neighborhoods; realize targets for energy efficiency, electrification, and demand response; improve access to clean mobility options; and facilitate customer adoption of rooftop solar and storage.

The Power System: Focus areas for future research include innovative approaches to system planning and operation; storable hydrogen technology and infrastructure development; addressing reliability, resource adequacy, and resilience in the face of climate change; LADWP workforce development; distribution grid evolution; opportunities for advanced coordination and control; and cybersecurity.

The Community: Priorities include quantifying neighborhood benefits and costs of changes; managing end-of-life waste streams for technologies; workforce training for jobs within the industry; and community engagement.

Insights for Other Jurisdictions

Most deep decarbonization and high renewable energy studies identify a strong role for solar, wind, and batteries to decarbonize significant shares of electricity, with resources sited on both the transmission and distribution grids. The LA100 study's findings are consistent with these studies—and emphasize that cities across the nation can get started now (through renewable procurement, permitting, siting, and workforce training) while they work through longer-term, location-specific options for the final 10%–20% of the solution.

Given that renewable and carbon-free generation represents 37% of electricity generated nationally in 2019[5], to achieve deep decarbonization in the power sector, most jurisdictions would need to add significant amounts of renewable energy and deploy nearly all readily available options—wind, solar (local and remote), geothermal, storage, transmission, energy efficiency, and demand response. Jurisdictions can get started on this while considering the more context-specific options for the final 10%–20% of the target. For LA, the in-depth analysis of reliability of this study, combined with LADWP's governance, geography, resources, and load profile, shows value in storable renewable fuel and multi-day demand response for meeting the final 10% of the target.

For other jurisdictions, the final pathway to 100% will vary and depend on interconnectivity, local options, and objectives (e.g., resiliency, jobs, low rates), among other differences.

Regardless of location, undertaking a power system transition of this scale benefits from complex analysis to provide deep insights for electrification, clean mobility, and power-sector decarbonization, coupled with implications for environmental justice, air quality, and economics. The approach taken by LA100 allows consideration of multiple priorities, grounded in a techno-economic understanding of options, addressing not only the practical system-operator concerns but also the issues that motivate broader community participation.

The LA100 study charts a methodology that employs an **unprecedented scale of data and interwoven modeling tools** that can be used to replicate, build upon, and scale up this type of analysis for other questions and jurisdictions.

5 U.S. Energy Information Administration. "Electricity Explained." Accessed March 9, 2021: https://www.eia.gov/energyexplained/electricity/electricity-in-the-us.php

How Does LA100 Compare to Other Decarbonization and Renewable Energy Studies, and What are the Implications of LA100 Results for Other Jurisdictions?

LA100	Other Types of Studies	Implications
100% renewable energy	<100% renewable energy studies	**Getting to ~90% renewable energy:** LA100 has consistent findings with other studies, but the associated costs and feasibility will vary region to region. **Getting to 100% renewable energy:** Everything gets more difficult the closer to 100%, and distinctions about LADWP (e.g., governance, access to resources) become more significant to feasibility of solutions.
100% renewable energy at all times, including contingencies and extreme events	100% renewable energy in normal year	A significant share of costs is due to reliability, thus results (capacity mix, costs) observed in this study could be higher than in a study that allows alternate resources for meeting reliability requirements or planning for extreme events. For example, this study would build more solar, wind, and batteries—and less capacity in renewably fueled combustion turbines—if extreme events were not considered.
100% renewable energy for a city	100% renewable energy studies for a region, nation	Conducting a study at a regional or national level is both harder and easier: harder in that constraints become more difficult to represent, requiring simplification, e.g., transmission and multi-area operations may have to be approximated; and easier in that the same simplifications make it appear easier to find pathways to 100%. Also, regional and national studies have a broader set of available resources and interconnectivity options to choose from. The LA100 study reflects the specific constraints of a city planning for 100% renewable energy.

Learn More and Download the Full Report from the LA100 Website

Additional explanatory content, a glossary of terms, links to download each chapter of the full report, and an interactive data viewer can be found on the study website at: **maps.nrel.gov/la100**

LA100

The Los Angeles 100% Renewable Energy Study

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National Renewable Energy Laboratory
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