DOCKETED

Docket Number:	21-BSTD-02
Project Title:	2022 Energy Code Update CEQA Documentation
TN #:	238924
Document Title:	Holland & Knight Comments - Holland & Knight References (3 of 11)
Description:	N/A
Filer:	System
Organization:	Holland & Knight
Submitter Role:	Public
Submission Date:	7/16/2021 9:47:05 AM
Docketed Date:	7/16/2021

Comment Received From: Holland & Knight
Submitted On: 7/16/2021
Docket Number: 21-BSTD-02

Holland & Knight References (3 of 11)

The attached document is the third of 11 separate uploads that contain the references cited in Holland & Knight's DEIR Comment Letter.

Additional submitted attachment is included below.

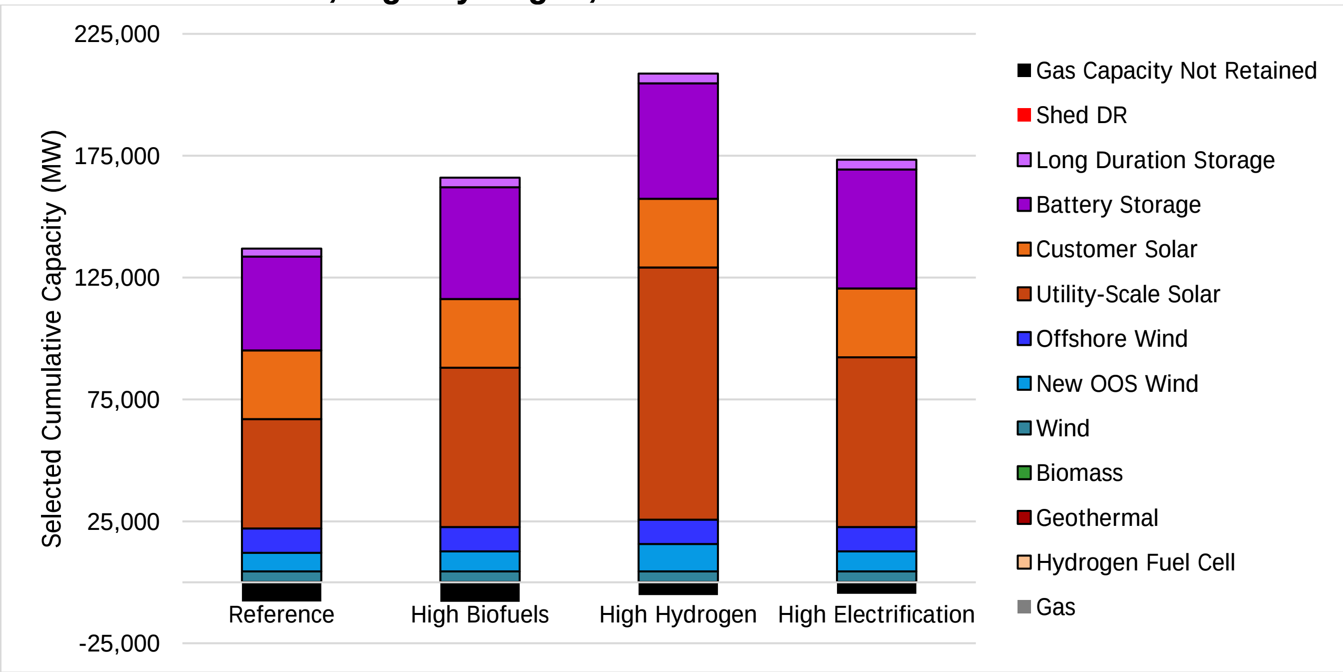
Comment Received From: Holland & Knight LLP
Submitted On: 7/8/2021
Docket Number: 21-BSTD-02

Holland & Knight References (3 of 11)

The attached document is the third of 11 separate uploads that contain the references cited in Holland & Knight's DEIR Comment Letter.

Additional submitted attachment is included below.

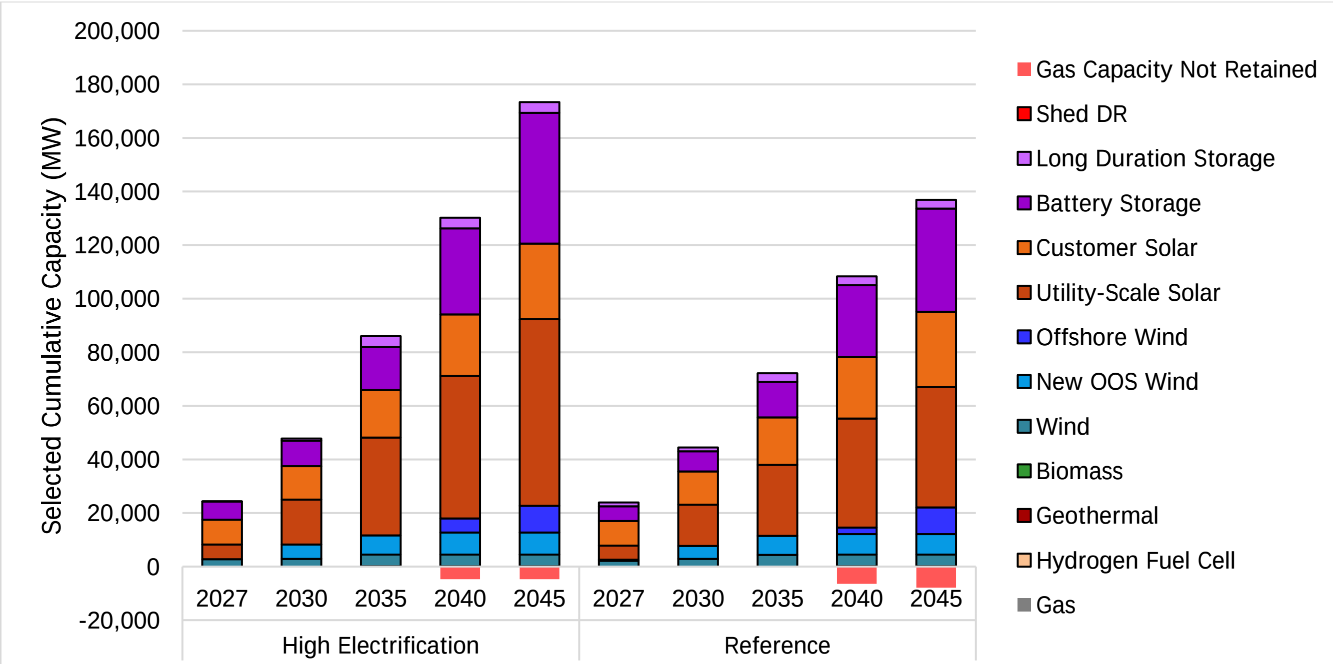
Figure 35: Cumulative Resource Build in 2045 for High Electrification, High Biofuels, High Hydrogen, and Reference Demand Scenarios



Source: CEC staff and E3 analysis

The timing of wind selection does not change between the reference and high electrification demand scenarios, as shown in **Figure 37**. After 2030, the high electrification scenario requires increasing solar and battery capacity each year compared to the reference scenario.

Figure 36: Cumulative Capacity Additions for the Reference and High Electrification Demand Scenarios



Source: CEC staff and E3 analysis

The TRC for the demand sensitivities increase with increased annual loads. However, the average cost per kWh decreases. While increased electricity demand can provide downward pressure on rates, infrastructure associated with hydrogen production or high levels of electrification are not included in this analysis, which could offset part of or all the rate decrease. The scenarios do not include costs associated with electrification, such as distribution upgrades or incentive programs, or other infrastructure required for biofuels and hydrogen, which may impact the relative cost to utility ratepayers. Average costs presented in **Table 13** are directional comparisons of demand scenarios and require additional analysis to include infrastructure costs associated with the demand scenarios.

Table 13: 2045 Annual Electricity Cost Summary for the High Electrification, High Biofuels, High Hydrogen, and Reference Demand Scenarios

$ Billions (2016)	High Elec.	High Biofuels	High Hydrogen[114]	Reference
Nonmodeled Costs	$38	$38	$38	$38
Scenario Fixed Costs	$19	$18	$24	$14
Total Operating Costs	$2.6	$2.4	$3.1	$1.8
Total Revenue Requirement	**$60**	**$58**	**$65**	**$53**
Customer Costs	$6.7	$6.7	$6.7	$6.7
Total Resource Costs	**$66**	**$65**	**$72**	**$60**

Source: CEC staff and E3 analysis

While the previous demand sensitivities focused on different economywide scenarios and varied by total annual electric energy demand, the shape and flexibility of electricity loads can significantly impact cost and resource build. While RESOLVE cannot at this time explicitly model load flexibility, the load shape and resource adequacy requirements can be modified to represent a future with greater load flexibility.

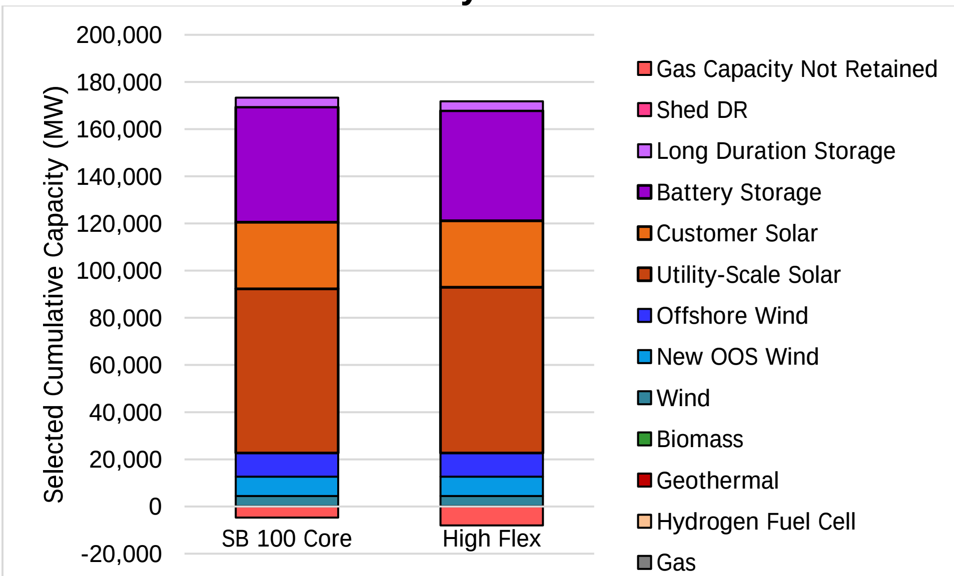
To achieve this, a high-flexibility scenario was created. Load modifiers in the high electrification demand scenario were adjusted to reflect managed charging profiles by electric vehicle drivers based on utility time-of-use rates and building flexibility based on the base case scenario in Lawrence Berkeley National Laboratory's (LBNL's) California Demand Response Study Phase 3.[115] It was also assumed that flexible load could contribute 6 GW to the annual system resource adequacy requirement.

Figure 38 shows the high-flexibility scenario results in 2.2 GW avoided battery storage build and a decrease in economic gas retention by 3.3 GW compared to the SB 100 core scenario, with the same annual electric energy demand.

114 The High Hydrogen demand scenario includes all electrolysis loads for hydrogen production as retail sales.

115 Lawrence Berkeley National Laboratory. July 2020. The California Demand Response Potential Study, Phase 3: Final Report on the Shift Resource through 2030. https://eta-publications.lbl.gov/sites/default/files/ca_dr_potential_study_-_phase_3_-_shift_-_final_report.pdf. The Base Scenario assumed DR-enabling technology prices and performance are frozen at present-day values.

Figure 37: Cumulative Capacity Additions in 2045 for the SB 100 Core and High-Flexibility Scenarios



Source: CEC staff and E3 analysis

The high-flexibility scenario also results in nearly $1 billion of annual cost savings in 2045 compared to the SB 100 core scenario, primarily from avoided storage fixed costs, as shown in **Table 14**. The costs associated with programs to encourage flexible load are not included in this analysis.

Table 14: 2045 Annual Cost Summary for the SB 100 Core and High-Flexibility Scenarios

$ Billions (2016)	SB 100 Core	High Flex
Nonmodeled Costs	$38	$38
Scenario Fixed Costs	$19	$18
Total Operating Costs	$2.6	$2.5
Total Revenue Requirement	**$60**	**$59**
Customer Costs	$6.7	$6.7
Total Resource Costs	**$66**	**$65**
Retail Sales (TWh)	372	372
Average Cost (¢/kWh)	**16.0**	**15.8**

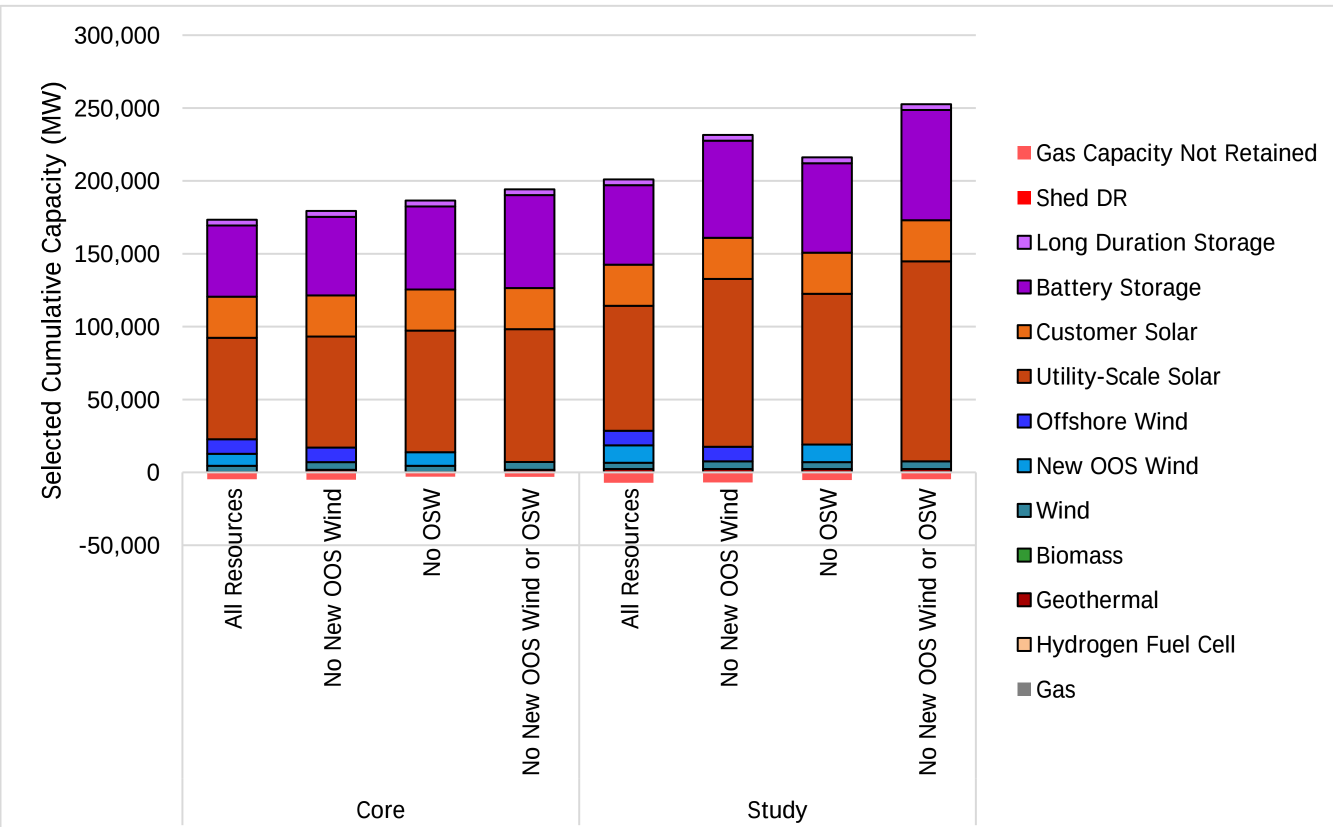
Source: CEC staff and E3 analysis

Resource Sensitivities

Evaluating futures where one or more resource types are not available or are not pursued can provide valuable planning information, especially for resources with long lead times for development. Resource sensitivities were included to evaluate the impact or benefit of pursuing new out-of-state wind resources and offshore wind resources.

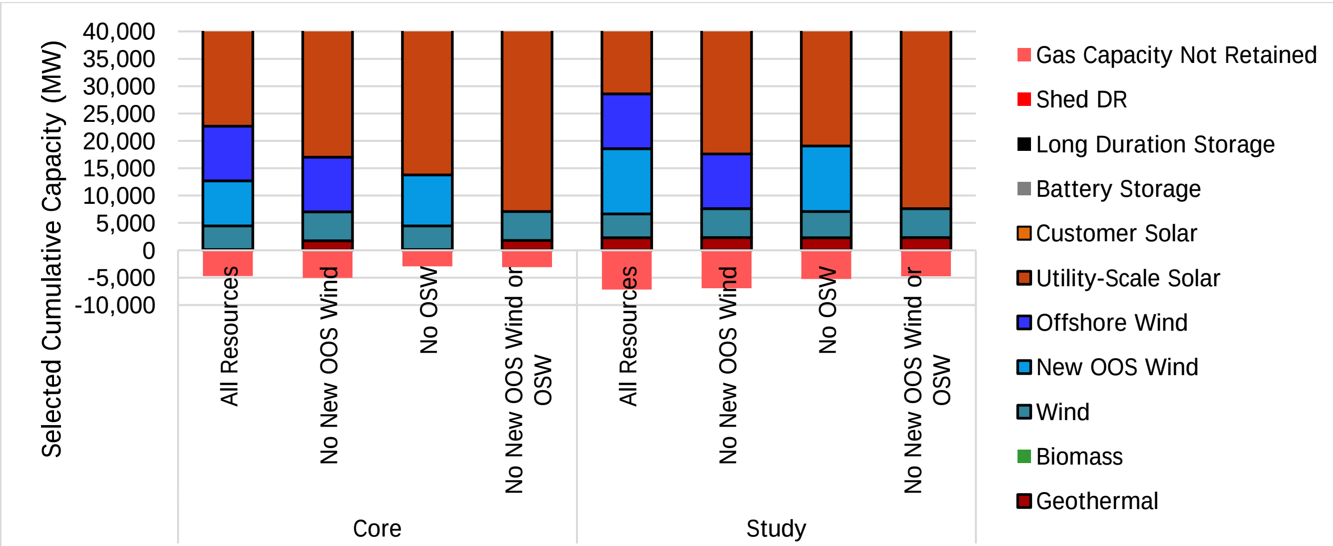
Figure 39 and Figure 40 show resource sensitivities that include “no new out-of-state (OOS) wind,” “no offshore wind (OSW),” and “no new OOS wind or OSW” under the SB 100 core and study load coverages. In nearly all scenarios in which either or both the wind resources are not available or not pursued, the model selects increased geothermal capacity. Utility-scale solar and battery storage meet the remaining energy and capacity needs. The “SB 100 core no new OOS wind or OSW” requires 22 GW more solar capacity and 15 GW more storage capacity than the “SB 100 core all resources scenario.”

Figure 38: Cumulative Resource Builds for the Core and Study Resource Sensitivities in 2045



Source: CEC staff and E3 analysis

Figure 39: Close up of Cumulative Resource Builds for the Core and Study Resource Sensitivities in 2045



Source: CEC staff and E3 analysis

The TRC increases in each of the scenarios where one or both the wind resources are not available or not pursued are not included, as shown in **Table 15**. The primary contributor to increased costs are increased renewable resource and storage costs.

Table 15: 2045 Annual Costs Summary for the SB 100 Core All Resources, No New OOS Wind, No OSW, and No New OOS Wind or OSW Scenarios

$ Billions (2016)	All Resources	No New OOS Wind	No OSW	No New OOS Wind or OSW
Non-modeled Costs	$38	$38	$38	$38
Scenario Fixed Costs	$19	$19	$20	$20
Total Operating Costs	$2.6	$2.7	$2.6	$2.8
Total Revenue Requirement	**$60**	**$60**	**$60**	**$61**
Customer Costs	$6.7	$6.7	$6.7	$6.7
Total Resource Costs	**$66**	**$67**	**$67**	**$68**
Retail Sales (TWh)	372	372	372	372
Average Cost (¢/kWh)	**16.0**	**16.1**	**16.2**	**16.4**

Source: CEC staff and E3 analysis

Study Scenario: Generic Zero-Carbon Firm Resources

Given the uncertainty of a 25-year planning horizon and the relatively conservative criteria for zero-carbon resource cost data used in the core scenarios, the joint agencies included study scenarios to evaluate the potential impact of commercialization of cost-competitive zero-carbon firm resources.

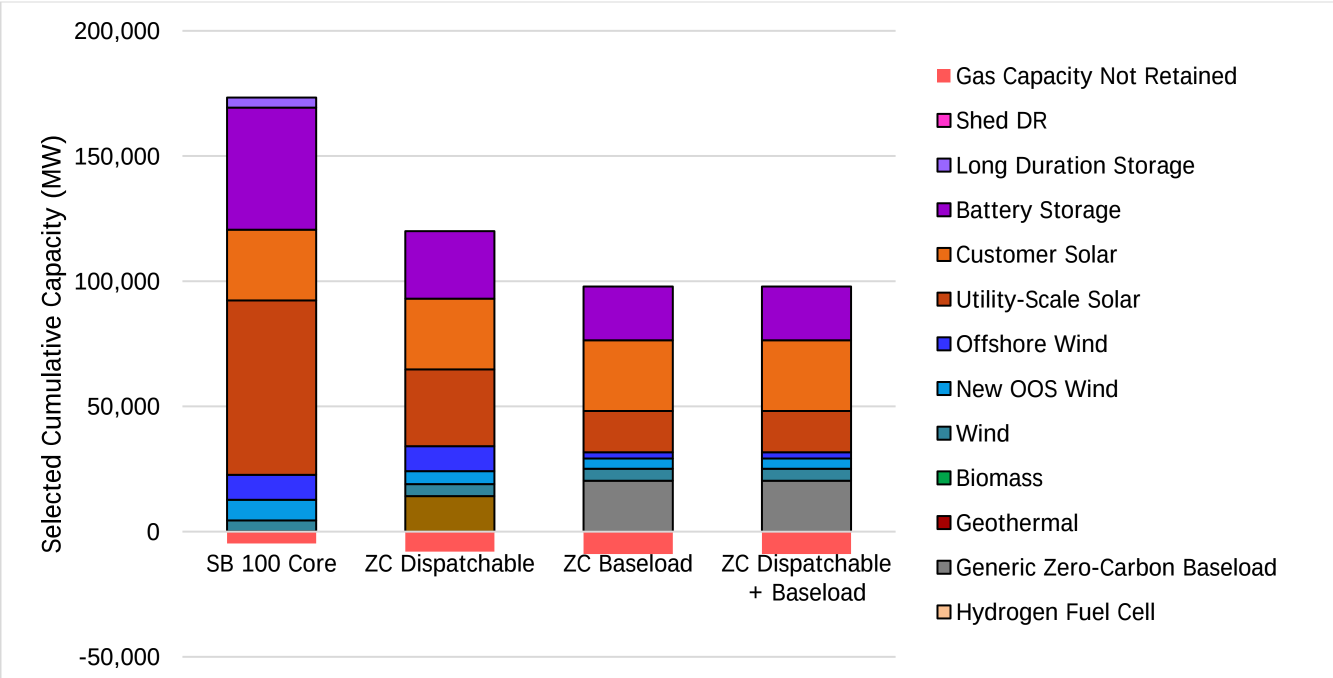
Several zero-carbon firm resources — geothermal, biomass, and hydrogen fuel cells — are already included in the core scenarios as candidate resources. Of these, 135 MW of geothermal is selected in the SB 100 core scenario, up to about 2 GW when new OOS wind or offshore wind are not available to the model. Neither biomass nor hydrogen fuel cells are selected in the core scenarios with the currently assumed cost projections.

The "generic dispatchable" resource and "generic baseload" resource included in these scenarios could represent already included technologies, should cost reductions be achieved, or a wide variety of emerging technologies, such as natural gas with 100 percent carbon capture, 100 percent green hydrogen combustion, or other renewable fuels, should the cost profiles be similar to one of the modeled generic resources.

The "generic dispatchable" resource includes a moderate capital cost and operating cost. The "generic baseload" resource includes a high capital cost and low operating cost. The LCOE of both resources are about $60/MWh when operating at a 90 percent capacity factor.

In scenarios where either the generic dispatchable resource, generic baseload resource, or both are included as a candidate resource, the model selects about 15-20 GW of either or both resources in total, as shown in **Figure 41**. The inclusion of the lower-cost zero-carbon firm resources also significantly lowers the utility-scale solar and battery storage selected in the model. Utility-scale solar selected by 2045 is reduced to 17-30 GW from 70 GW, while battery storage selection is reduced to 21-27 GW from 49 GW. Furthermore, long-duration storage selection is not selected and new OOS wind selected is reduced from 8.2 GW to 4.1-5.2 GW.

Figure 40: Cumulative Capacity Additions for the SB 100 Core and Generic Zero Carbon Firm Resource Scenarios in 2045



Source: CEC staff and E3 analysis

The Evolving Role of Geothermal
While the joint agencies attempt to use the most current publicly available and vetted cost data, there can be significant changes in available data after the modeling has been conducted. The NREL ATB is updated annually, usually with incremental adjustments to cost data. The 2020 ATB update, which was released after modeling for this report was underway, however, included a 30 percent reduction in geothermal cost projects, based on the Department of Energy Geovision Report.[116] This cost-reduction projection places the geothermal LCOE below the LCOE of the generic zero-carbon firm resources modeled in these scenarios. As significant generic zero-carbon firm capacity was selected in the study scenario, it is likely that geothermal would be selected to a much greater extent should the updated cost data be used. Geothermal costs are heterogeneous and can vary widely depending on project location. Coproduction of lithium from geothermal brine may also provide additional revenue streams, effectively lowering the cost of geothermal power, and will be evaluated by the Blue-Ribbon Commission on Lithium Extraction in California.[117]

Each of the generic zero-carbon firm resource scenarios resulted in significant decreases in TRC compared to the SB 100 core scenario, as shown in **Table 16**. Cost reductions are driven by new renewable and transmission fixed costs.

116 NREL ATB 2020 vs. 2019 Changes Reductions in geothermal costs are attributed to trends and predicted advancements in drilling efficiency and enhanced geothermal systems.

117 Ventura, Susanna, Srinivas Bhamidi, Marc Hornbostel, and Anoop Nagar. 2020. Selective Recovery of Lithium from Geothermal Brines. California Energy Commission. Publication Number: CEC500-2020-020. https://ww2.energy.ca.gov/2020publications/CEC-500-2020-020/CEC-500-2020-020.pdf. Assembly Bill 1657 (E. Garcia, Chapter 271, Statutes of 2020), Blue Ribbon Commission on Lithium Extraction in California.

Table 16: 2045 Annual Costs Summary for the SB 100 Core, Generic Dispatchable, Generic Baseload, and Generic Dispatchable + Baseload Scenarios

$ Billions (2016)	SB 100 Core	Generic Dispatchable	Generic Baseload	Gen. Dis. + Baseload
Non-modeled Costs	$38	$38	$38	$38
Scenario Fixed Costs	$19	$13	$14	$14
Total Operating Costs	$2.6	$6.0	$2.8	$2.8
Total Revenue Requirement	**$60**	**$58**	**$55**	**$55**
Customer Costs	$6.7	$6.7	$6.7	$6.7
Total Resource Costs	**$66**	**$64**	**$62**	**$62**
Retail Sales (TWh)	372	372	372	372
Average Cost (¢/kWh)	**16.0**	**15.5**	**15.0**	**15.0**

Source: CEC staff and E3 analysis

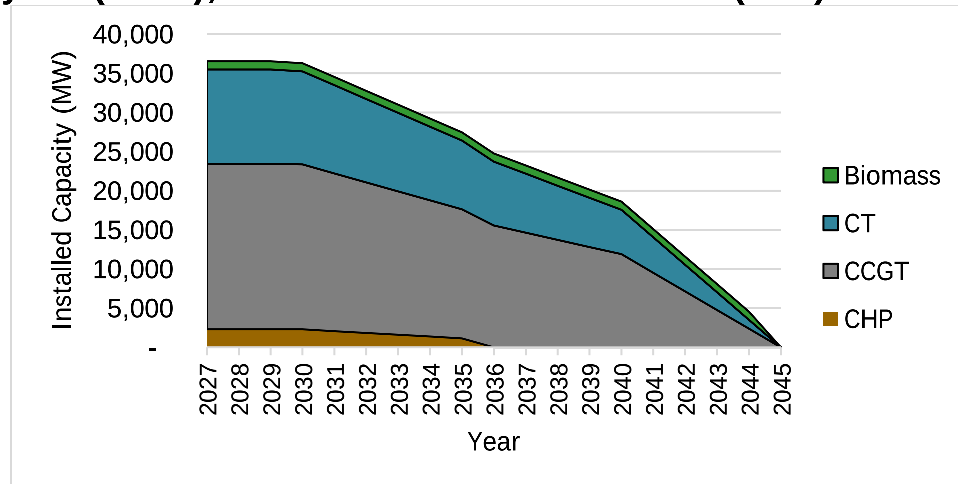
Study Scenario: No Combustion

While SB 100 does not preclude combustion resources from the resource portfolio, studying pathways in which combustion resources are expressly retired can provide insight into what it would take to significantly reduce the contribution to criteria pollutants and toxic air contaminants in California from supply-side electricity generation. To that end, a "no combustion" scenario in which all combustion resources are retired over the planning horizon and no combustion resources are available as candidate resources was included as a study scenario.

In this scenario, all units that use a combustion technology, combustion turbines, combined cycle, combined heat and power,[118] and biomass, retire over the planning horizon, as shown in **Figure 42**. The high-electrification demand scenario was used.

118 All combined heat and power facilities are assumed to retire after 2035 in all scenarios in this report.

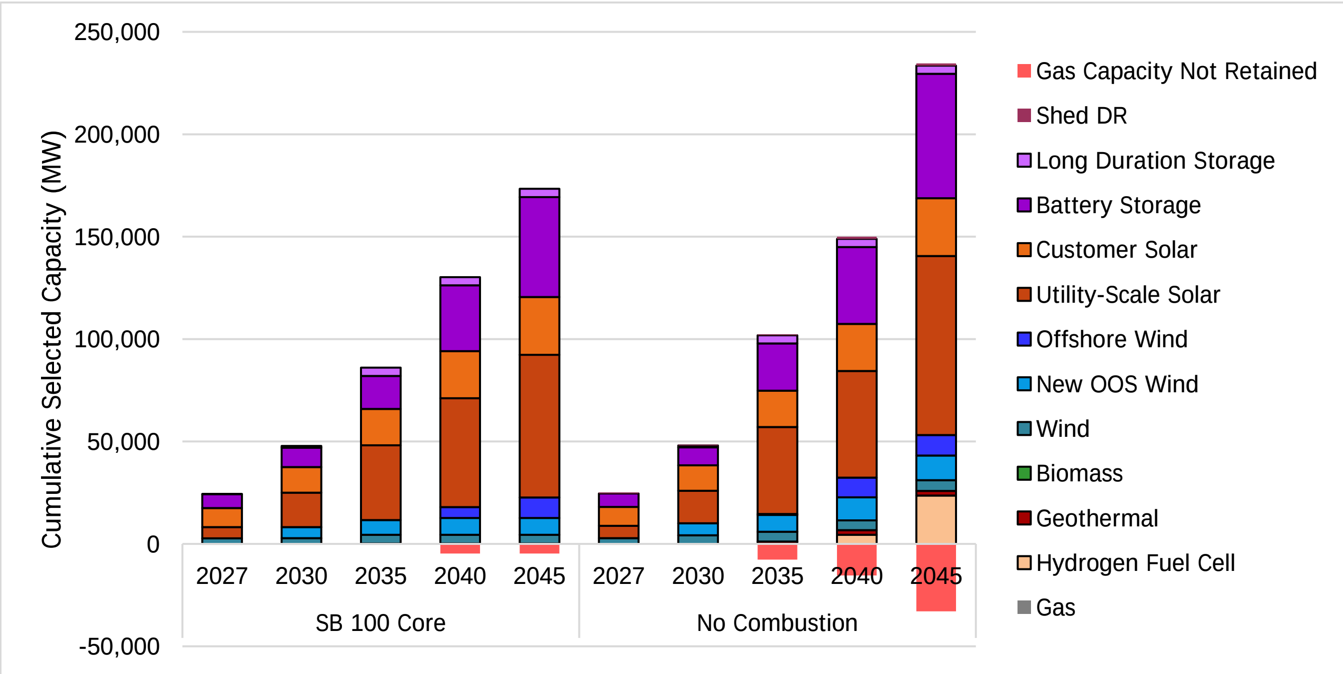
Figure 41: Retirement Schedule for Biomass, Combustion Turbines (CT), Combined Cycles (CCGT), and Combined Heat and Power (CHP) Resources



Source: CEC staff and E3 analysis

With the retirement of all combustion resources, 61 GW of additional capacity is selected compared to the SB 100 Core Scenario. In addition to the resources selected in the SB 100 core scenario, 24 GW of hydrogen fuel cells, the remaining 2.3 GW of geothermal, the remaining 3.8 GW new OOS wind, 18 GW of utility scale solar, 12 GW of battery storage and 1.1 GW of shed demand response were selected, as shown in **Figure 43**.

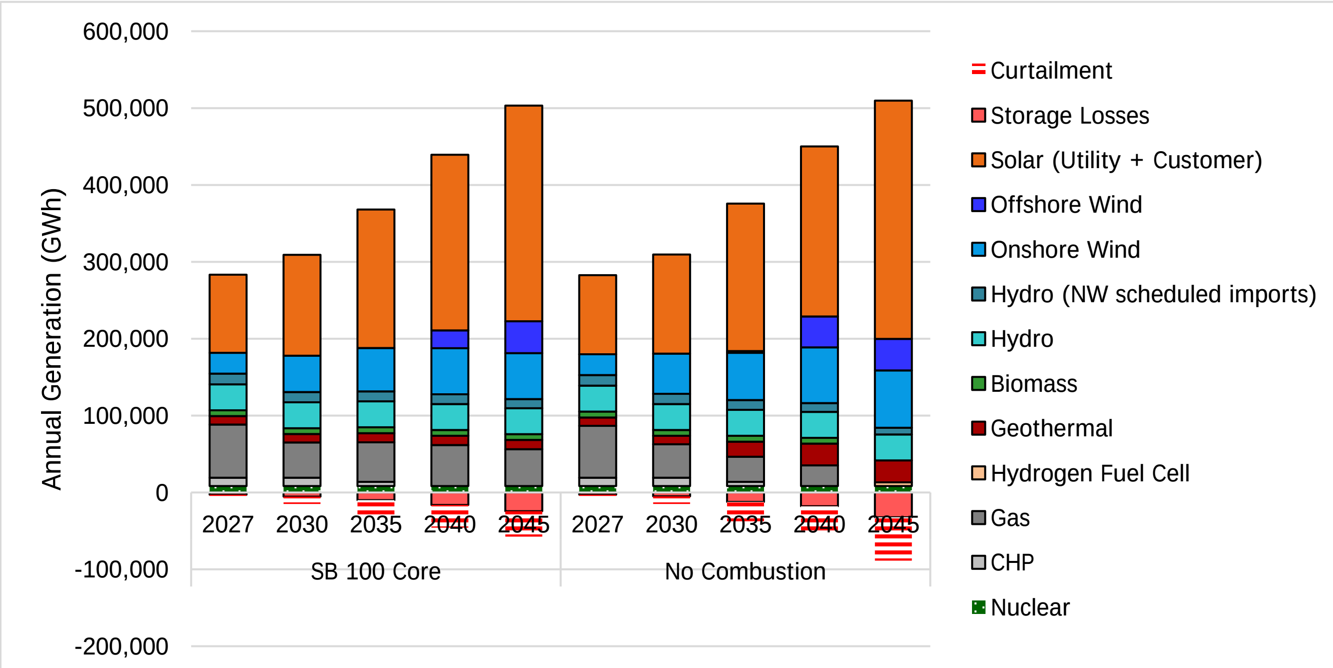
Figure 42: Cumulative Capacity Additions for the SB 100 Core and No Combustion Scenarios



Source: CEC staff and E3 analysis

While significant hydrogen fuel cell capacity was selected, it generates very little energy, as shown in **Figure 44**. The hydrogen fuel cells were selected for the capacity value and function as a peaking resource.

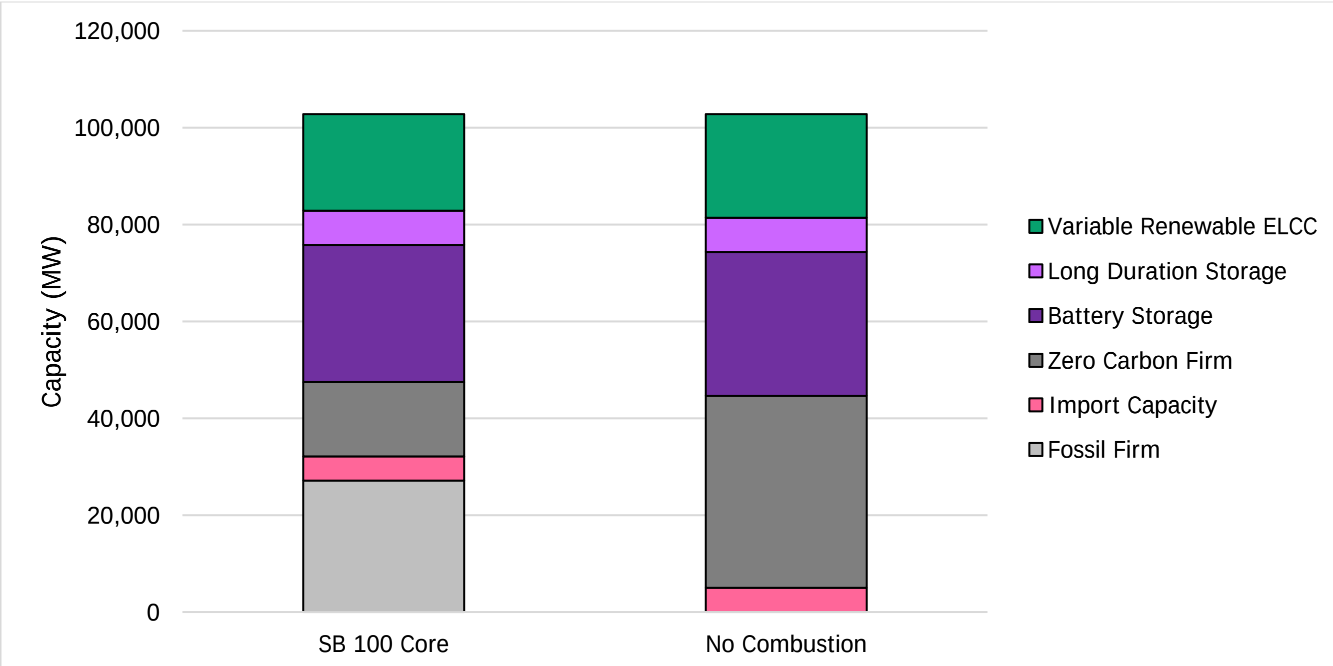
Figure 43: Annual Generation for the No Combustion Scenario



Source: CEC staff and E3 analysis

While fossil firm resources contribute a significant amount to the resource adequacy need in the SB 100 Core scenario, the retirement of these resources requires new resources to be selected to meet the capacity need in the No Combustion scenario. As shown in **Figure 45**, the fossil firm resource contributions are largely replaced by zero-carbon firm, which includes hydrogen fuel cells and new geothermal resources. While there is a resource adequacy constraint in the model (a 15 percent planning reserve margin), a full resource adequacy analysis is necessary to determine whether the portfolios produced meet other established reliability planning standards.

Figure 44: Resource Adequacy Contributions for the SB 100 Core and No Combustion Scenarios



Source: CEC staff and E3 analysis

Given the significant capacity additions in the no combustion scenario, there are increased annual TRC costs compared to the SB 100 core scenario, as shown in **Table 17**. The primary contributors to cost increases are new renewable resources, hydrogen fuel cells, storage, and transmission fixed costs.

Table 17: 2045 Annual Cost Summary of the SB 100 Core and No Combustion Scenarios

$ Billions (2016)	SB 100 Core	No Combustion
Non-modeled Costs	$38	$37
Scenario Fixed Costs	$19	$28
Total Operating Costs	$2.6	$1.8
Total Revenue Requirement	**$60**	**$67**
Customer Costs	$6.7	$6.7
Total Resource Costs	**$66**	**$74**
Retail Sales (TWh)	372	372
Average Cost (¢/kWh)	**16.0**	**18.1**

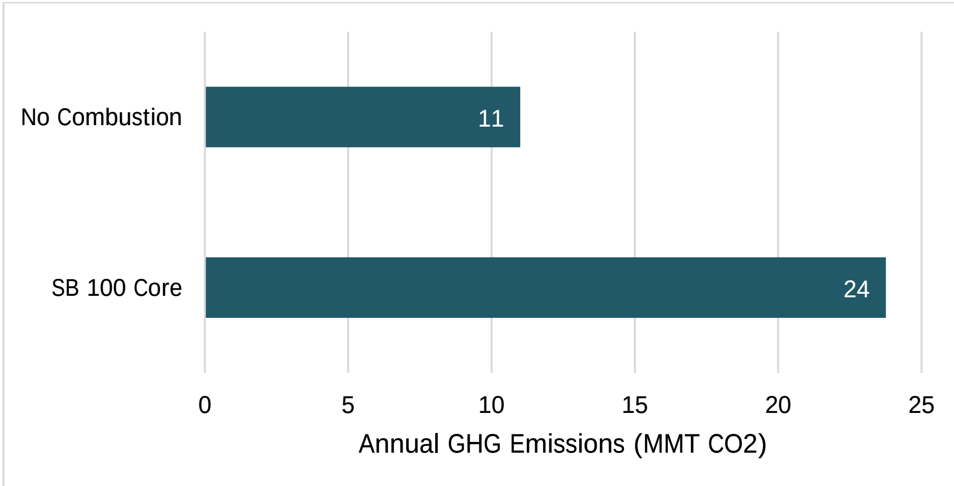
Source: CEC staff and E3 analysis

While all California combustion and virtually all GHG-emitting resources are retired[119] in the no combustion scenario, 11 MMT of GHG emissions attributed to the California electric grid remain, due to unspecified imports,[120] as shown in **Figure 46**.

119 Geothermal resources are not retired and do emit some GHG emissions.

120 As RESOLVE optimizes operations to best reflect energy market dynamics, in periods where the marginal price of energy in California is higher than the price of unspecified imports, unspecified imports are dispatched to California. Implementation of a GHG target in RESOLVE may limit the GHG emissions but may not necessarily reflect market dynamics.

Figure 45: GHG Emissions for the SB 100 Core and No Combustion Scenarios



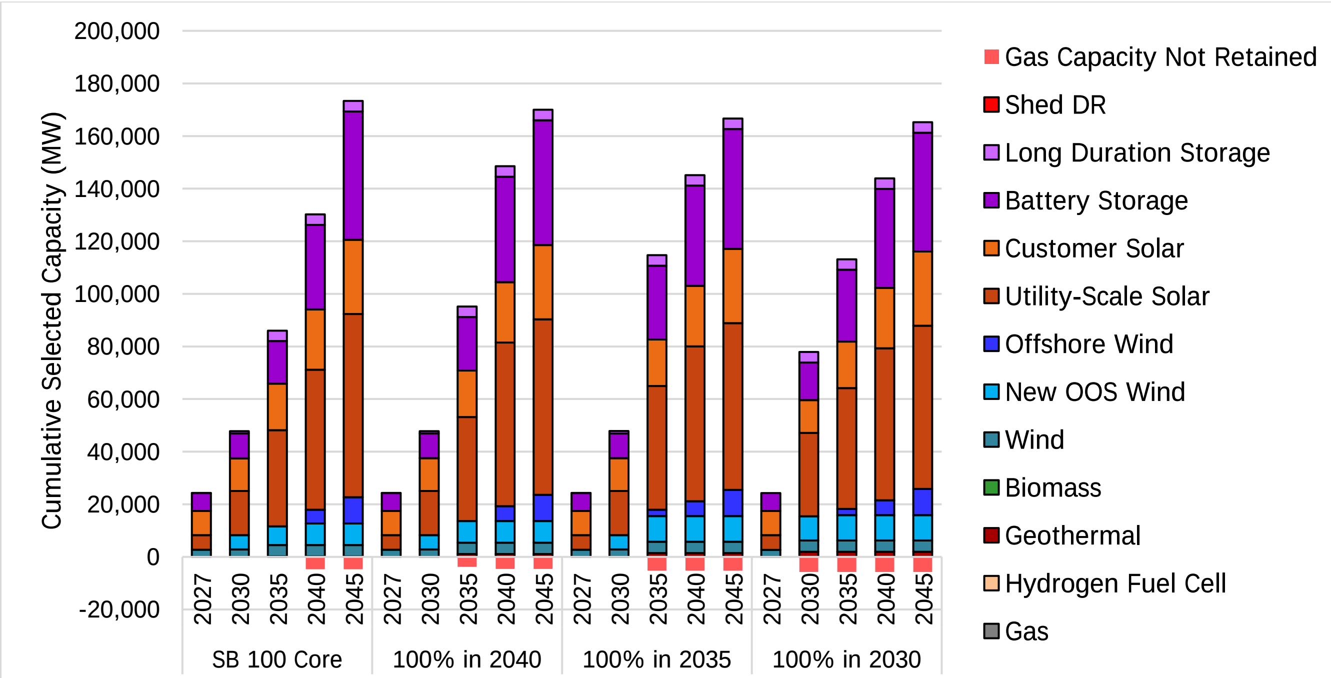
Source: CEC staff and E3 analysis

Study Scenarios: Accelerated Timelines

The final set of study scenarios examines the impacts of accelerating the 100 percent renewable and zero-carbon target to 2030, 2035, and 2040. For each of these scenarios, the SB 100 Core target was accelerated with a linear interim zero-carbon target between 2030 and the target year. After the target year, the 100 percent target is held constant through 2045. The high electrification demand scenario was used for all accelerated timeline scenarios.

In **Figure 47**, each accelerated timeline scenario shows a significant jump in resource build in the 100 percent target year, while the 2045 portfolio remains similar across scenarios. All the accelerated timeline scenarios result in an increase of geothermal resource selection by at least 1 GW. Accelerating the 100 percent target to 2030 or 2035 results in increased new OOS wind selection by 1.3–1.4 GW and decreases in utility-scale solar selection by 6-7 GW and battery storage by 3 GW. Accelerating the target to 2030 or 2035 also results in a 0.5-1 GW of decreased economic gas retention.

Figure 46: Cumulative Capacity Additions for the SB 100 Core (2045 SB 100), 100% in 2040, 100% in 2035 and 100% in 2030 Scenarios



Source: CEC staff and E3 analysis

Each accelerated timeline scenario results in increased annual TRC compared to the SB 100 Core scenario for every modeled year except 2027, as shown in **Table 18**. In general, the TRC shows a significant jump in the year the 100 percent target is set to. By 2045, the TRC for the accelerated scenarios result in less than a 1 percent increase over the SB 100 Core scenario.

Table 18: Annual Total Resource Cost for the SB 100 Core, 100 Percent in 2040, 100 Percent in 2035, and 100 Percent in 2030 Scenarios

TRC ($B)	2027	2030	2035	2040	2045
SB 100 Core	$44.8	$47.0	$50.6	$59.5	$66.3
100% in 2040	$44.8	$47.0	$53.6	$61.5	$66.5
100% in 2035	$44.8	$47.0	$55.8	$61.7	$66.7
100% in 2030	$44.8	$50.1	$55.8	$61.8	$66.8

Source: CEC staff and E3 analysis

Resource Build Rates

Given the magnitude of the capacity additions, the average build rates provide important implications for implementation and achievement of the SB 100 2045 policy goal. Build rates can indicate whether there could be bottlenecks in supply-chain or regulatory and permitting processes, resulting in barriers to procurement.

Over the last decade, California has built on average 1 GW of utility solar and 300 MW of wind per year, with a maximum annual build of 2.7 GW of utility scale solar and 1 GW of wind capacity. **Table 19** shows near-term build rates to 2030 are similar regardless of the electricity demand scenarios and are above the historical 10-year average build rate for utility scale solar and wind capacity.

The long-term build rates to 2045, shown in Table 20, differ significantly for utility-scale solar depending on the demand scenario, ranging from 1.8 GW per year in the reference scenario to 4.1 GW per year in the high hydrogen scenario.

Table 19 Average Build Rates for the High Electrification, High Biofuels, High Hydrogen and Reference Demand Scenarios

Year To	Demand Scenario	Solar (GW/year)	Wind (GW/year)	Storage[121] (GW/year)
2030	High Electrification (SB 100 Core)	1.5	0.8	1.1
2030	High Biofuels	1.7	0.8	0.9
2030	High Hydrogen	1.7	0.8	0.9
2030	Reference	1.5	0.8	0.8
2045	High Electrification (SB 100 Core)	2.8	0.9	2.0
2045	High Biofuels	2.6	0.9	1.8
2045	High Hydrogen	4.1	1.0	1.9
2045	Reference	1.8	0.9	1.5

Source: CEC staff and E3 analysis

Inclusion of diverse wind resources in the portfolio also impacts the average solar and storage build rate, disproportionately from the reduction in wind build rate, with an increase of up to 0.8 GW per year for utility scale solar and 0.6 GW per year for battery storage, as shown in Table 20.

121 Storage in this table is inclusive of new battery storage selected by the model.

Table 20: Average Build Rates for the SB 100 Core, No New OOS Wind, No OSW, and No New OOS Wind or OSW Scenarios

Year To	Resource Sensitivity	Solar (GW/year)	Wind (GW/year)	Storage (GW/year)
2045	SB 100 Core	2.8	0.9	2.0
2045	No New OOS Wind	3.0	0.6	2.2
2045	No OSW	3.3	0.5	2.3
2045	No New OOS Wind or OSW	3.6	0.2	2.6

Source: CEC staff and E3 analysis

Commercialization of cost-competitive zero-carbon firm resources has the potential to significantly reduce average build rates for utility-scale solar and battery storage resources. **Table 21** show that the utility-scale solar build rate reduces to 0.6-1.2 GW per year — on par with historic build rates — and battery storage build rate reduces to 0.9-1.1 GW per year.

Table 21: Average Build Rates for the SB 100 Core, Generic Dispatchable, Generic Baseload, and Generic Dispatchable + Baseload Scenarios

Year To	Resource Sensitivity	Solar (GW/year)	Wind (GW/year)	Storage (GW/year)
2045	SB 100 Core	2.8	0.9	2.0
2045	Generic Dispatchable	1.2	0.8	1.1
2045	Generic Baseload	0.6	0.5	0.9
2045	Generic Dispatchable + Baseload	0.6	0.5	0.9

Source: CEC staff and E3 analysis

Key Takeaways From Preliminary Modeling

SB 100 Is Achievable

This initial analysis demonstrates that supplying 100 percent of retail sales and state loads with renewable and zero-carbon technologies is technically achievable. The modeling suggests the total resource cost of achieving the target is about 6 percent higher than a 60 percent RPS future in 2045, though additional analysis is needed to validate these findings. These costs may be lower if the cost trends for renewables continue to fall faster than projections. Cost reductions and innovation in zero-carbon technologies, as well as load flexibility and energy storage development, can further reduce implementation costs. Moreover, variations on the scenarios studied will develop over time as reliability is examined, technologies develop, and procurement decisions are made.

Increased Resource Diversity Lowers Overall Costs

Portfolio diversity, both technological and geographical, is generally valued by the model. In scenarios where out-of-state or offshore wind are available, the model always selects a significant quantity, if not all, of the resource potential. Furthermore, even a modest amount of load flexibility can reduce battery storage requirements, decrease economic gas retention, and decrease the total resource cost of achieving SB 100. Commercialization of cost-competitive zero-carbon firm technologies could reduce overall system costs and decrease gas capacity retention. If these technologies reach a cost of roughly $60/MWh, they could reduce system costs by an estimated $2 billion annually in 2045.

Gas Capacity Is Retained for Reliability Needs, but Cost Reductions and Innovation in Zero-Carbon Firm Resources and Storage May Reduce Gas Capacity Needs

Natural gas capacity is largely economically retained in the SB 100 core scenario, but fleetwide utilization decreases by half compared to a 60 percent RPS future. The gas fleet is primarily retained because natural gas capacity is the most economic option to provide capacity for reliability needs with the current resource assumptions. Cost reductions and innovation in zero-carbon firm resources and storage resources may reduce economic gas fleet retention.

Further analysis is needed to evaluate costs associated with maintaining an aging gas fleet operating in a high renewables system, including an evaluation of existing gas capacity maintenance costs and the impact of additional gas retirements.

Sustained Record Setting Build Rates Will Be Required to Meet SB 100 in a High Electrification Future

Growing electricity demand is a significant driver of resource build rates in the SB 100 scenarios. The added demand from the various pathways to achieve economywide decarbonization creates a significant resource need, regardless of the SB 100 policy. This added demand has implications for workforce needs, land-use planning, resource supply chains, and regulatory and permitting processes that must be considered for successful implementation of SB 100. Innovation and cost reductions, leading to greater portfolio diversity, may reduce utility-scale solar and storage build rates necessary to meet the SB 100 policy goals.

Goals Beyond SB 100 May Be Achievable but Require Additional Analysis

The study scenarios are beyond the scope of SB 100. However, they provide directional insight to inform the state’s energy and climate planning efforts and contribution toward other environmental and public health goals.

Eliminating all in-state combustion resources results in a significant increase in storage and zero-carbon firm resource selection to replace natural gas capacity. This scenario adds an estimated $8 billion to annual system costs in 2045 compared to the SB 100 core scenario. Further analysis could identify public health benefits, particularly in disadvantaged communities where a disproportionate number of combustion resources are. This analysis may help determine whether the public health benefits outweigh the additional costs.

Accelerating the SB 100 timeline to achieve the 2045 target by 2030, 2035, or 2040 results in increased total resource costs and required additional capacity in the target year. All scenarios resulted in similar annual resource costs and resource portfolios by 2045.

Current SB 100 Analysis Is Directional, and Further Analysis Is Necessary

This analysis is the first step in an ongoing effort to evaluate and plan for the SB 100 policy. As described in the Limitations of RESOLVE section of this chapter, capacity expansion is a powerful and informative tool but is limited by necessary simplifying of assumptions. Further analysis is necessary to determine reliability of the portfolios.

Future work should better capture the effect and value of resources that are either not represented or not well valued in the current modeling framework. Long-duration storage is not fully valued in RESOLVE due to limitations on dispatch. Hybrid resources are not represented in RESOLVE and should be represented in future analysis, as they are increasingly a part of utility plans. Emerging technologies, such as green hydrogen and natural gas with 100 percent carbon capture and sequestration, should be incorporated in future analysis.

The role of demand-side resources load flexibility should also be further evaluated. Significant customer-side solar was assumed in the model, at 39 GW. No additional customer solar was selected by the model in the optimization. Factors outside system costs, such as customer preference and resilience benefits, may affect customer-side resource adoption. Customer storage was also not selected but may provide local capacity and resilience value not captured by the model.

CHAPTER 4: Next Steps and Considerations for Implementation

SB 100 Is an Ongoing Effort

The analysis in the 2021 Report is intended to be a first step in an iterative and ongoing effort to assess barriers and opportunities to implementing the 100 percent clean energy policy established by SB 100. As discussed in Chapter 3, this report includes capacity expansion modeling to provide directional insights into what a 2045 portfolio of renewable and zero-carbon resources may look like, as well as the associated costs and resource build requirements to achieve such a portfolio. These results, however, have not undergone a comprehensive assessment for reliability, which is the suggested next step in the process. From there, the projected portfolio may be adjusted in an iterative manner to ensure reliability for all hours of the year in line with state planning requirements, while meeting clean energy and climate goals.

Additional analytical work is needed to better capture emerging zero-carbon resources and nongeneration technologies; provide higher-resolution insights to address equity concerns, including local public health and economic impacts; and address land use and other environmental implications. Topics for consideration in future SB 100 work are discussed below.

Next Steps for Analysis

System Reliability

In August 2020, California experienced rolling blackouts over two consecutive days. While a sustained west-wide heat wave resulted in the tightness in the electricity supply conditions and contributed to the load shed events, the final root cause analysis[122] that was subsequently released jointly by CPUC, California ISO, and CEC identified the need to comprehensively examine reliability in the near term (by summer 2021) and long term (2022 and beyond) as the state rapidly transitions to the stated goals of SB 100. The final root cause analysis identified the need to reflect the uncertainty of weather, operational characteristics of clean energy resources, and market dynamics into the state's reliability planning processes and studies. While the August events emphasized the need for near-term reliability, the state agencies and balancing authorities recognize the need to incorporate these reliability principles into the 2045 time horizon.

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122 California ISO, CPUC, and CEC. *Final Root Cause Analysis: Mid-August 2020 Extreme Heat Wave*, January 13, 2021, http://www.caiso.com/Documents/Final-Root-Cause-Analysis-Mid-August-2020-Extreme-Heat-Wave.pdf.

The joint agencies plan to evaluate resource portfolios developed in this report for reliability in a multistep process using a production cost model, which will simulate the performance of the portfolio over a year. The first step will evaluate the resource portfolios in all 8,760 hours of the year and highlight potential supply shortfalls in meeting the projected demand. This step will also better capture value provided by some resources, such as long-duration storage, that are not fully captured in a capacity expansion model. After this analysis, the resource portfolio may be adjusted manually, or through revised capacity expansion modeling, to adjust for any operability shortcomings.

The second step will evaluate the revised resource portfolio with a set of probabilistic production cost model runs, which analyzes reliability over a wide range of conditions. This set of runs will explore probabilistic variables, such as loads, renewable energy and hydro availability, and power plant outages to determine the loss of load probability (likelihood of power outages due to insufficient capacity or energy) of the resource mix. A loss of load probability that exceeds, or is significantly under, an acceptable limit will result in additional resource portfolio adjustments and restarting this process at the first step.

Completion of the reliability assessment will provide the joint agencies a more substantiated assessment of pathways to achieve SB 100 while maintaining reliability. This step could be completed as part of the 2025 SB 100 Report or possibly through existing state efforts. The CEC and CPUC are assessing resource availability to complete this modeling ahead of the next report.

Emerging Technologies and Innovation

Additional strategies and technologies have the potential to further enable a high-renewables and decarbonized grid — either by delivering or complementing zero-carbon electricity. State agencies are working together to spur innovation in areas that will be critical to cost-effectively meeting the goals of SB 100.

This collaboration leverages the state's key role in assessing technology gaps and supporting new and innovative technologies through funding of research, development, and deployment programs, including the Electric Program Investment Charge (EPIC) and the Natural Gas Research and Development Program. The state's long-term electricity planning processes inform its approach to innovation for a cost-effective clean energy transition, helping identify technology characteristics that can deliver a decarbonized grid, reduce costs, increase resilience and reliability, and contribute to improved air quality.

Listed below are example technology categories that could significantly impact SB 100 planning if development and adoption barriers are overcome and they can be deployed at scale. Future analyses will be updated to incorporate changes in market conditions, costs, and resource availability of new and existing technologies. Other technologies that could affect a 2045 portfolio, such as natural gas generation with carbon capture and sequestration and emerging nuclear technologies, are not discussed here because of cost uncertainty and limited development potential seen at this time.

Offshore Wind

State agencies are exploring opportunities for the development of offshore wind off the California coast. Offshore wind is an attractive technology from a system planning perspective due to the associated generation potential profile that complements solar, with higher output in the evenings, when electricity demand is high and solar production is low. Offshore wind also complements solar seasonally and can provide more consistent output during winter months when solar production is lower.[123]

While there is a significant resource potential off the California coast — an estimated 112 GW of accessible offshore wind resource — there are also considerable barriers. Among the foremost challenges are significant anticipated transmission requirements and competing coastal uses, including shipping, fishing, recreation, marine conservation, and Department of Defense activities. Together, these factors severely limit the feasible resource potential.

In 2016, the BOEM California Intergovernmental Renewable Energy Task Force, a partnership of state, local, and tribal governments and federal agencies, was created to identify potential sites for offshore wind development off the coast. The task force is conducting a public process evaluating possible sites off the Northern and Central Coasts.

Moreover, because California's offshore resource is in water depths greater than 60 meters, floating turbines are needed.[124] While fixed-bottom offshore wind turbines are a proven technology, floating technologies are relatively nascent, with a total of about 66 MW installed worldwide at the end of 2019. However, the global industry for floating turbines is growing rapidly with almost 6.2 GW of global projects in the pipeline, including 64 MW to be installed in the next year, 1,100 MW under construction and planned to be built by 2025, and 7 GW in development.[125]

The National Renewable Energy Laboratory (NREL) recently published a California-focused study on offshore wind. The study estimated LCOE ranges from $57 per megawatt-hour (MWh) to $68 per MWh for offshore wind coming online in 2030.[126] The first commercial scale floating offshore wind projects are projected to have a higher

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123 National Renewable Energy Laboratory. December 2016. *Potential Offshore Wind Energy Areas in California: An Assessment of Locations, Technology, and Costs*. https://www.nrel.gov/docs/fy17osti/67414.pdf.

124 National Renewable Energy Laboratory. December 2016. *Potential Offshore Wind Energy Areas in California: An Assessment of Locations, Technology, and Costs*. https://www.nrel.gov/docs/fy17osti/67414.pdf.

125 Lee, Joyce and Feng Zhao. August 2020. Global Offshore Wind Report 2020. Global Wind Energy Council. https://gwec.net/wp-content/uploads/2020/12/GWEC-Global-Offshore-Wind-Report-2020.pdf

126 Beiter, Philipp, Walter Musial, Patrick Duffy, Aubryn Cooperman, Matt Shields, Donna Heimiller, and Mike Optis. 2020. *The Cost of Floating Offshore Wind Energy in California Between 2019 and 2032*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5000-77384. https://www.nrel.gov/docs/fy21osti/77384.pdf.

LCOE than fixed-bottom offshore wind turbines due to a higher degree of financial uncertainty, technical challenges, and a less established supply chain and manufacturing process. Floating offshore wind projects in the next 7-10 years are projected to bid at levels competitive with the first fixed-bottom offshore wind projects.

In 2019, the CPUC included offshore wind as a candidate resource in Integrated Resource Planning sensitivity modeling for the first time. Since then, the CPUC collaborated with BOEM and NREL on their report described above. The CPUC will propose that the transmission needs of offshore wind be studied in the next California ISO Transmission Planning Process, kicking off in February 2021. This study will provide improved understanding of the cost of transmission to deliver offshore wind power to load centers in California and, along with the improved assumptions from NREL, will enhance the state's understanding of the possible contribution of offshore wind in meeting the goals of SB 100.

In 2019, the CEC released a funding opportunity that, for the first time, called for research projects focused on offshore wind energy in California. The solicitation sought two types of projects: (1) projects that develop real-time monitoring systems for offshore wind technologies to help increase productivity, reduce O&M costs, support detection and identification of affected species and habitats, and (2) projects that increase understanding of how offshore energy deployments may affect sensitive species and habitats.

Energy Storage

Energy storage technologies — including batteries, pumped hydro, hydrogen, and other emerging technologies — are expected to play a significant role in helping balance the grid as the state implements SB 100. Storage can help bridge the gap between variable renewable generation and grid energy demands (a role played in large part by natural gas plants today) and provide ancillary services and capacity rapidly to support system stability and reliability.

Nearly all newly procured storage by the California utilities, as required by AB 2514, has been four-hour lithium-ion batteries, driven by rapid declines in battery costs.[127] Since 2010, lithium-ion battery costs have dropped by 90 percent and are expected to decline by another 40 percent by 2024.[128] Though lithium ion dominates the global storage market today, increasing demand is allowing competing technologies to enter the market — including advanced battery chemistries, flow batteries, flywheels, thermal energy storage, and other emerging technologies. This trend will be amplified as other states and nations pursue increasingly clean electric grids and electrify transportation.

127 CPUC Energy Storage Web page, https://www.cpuc.ca.gov/General.aspx?id=3462.

128 BloombergNEF, Electric Vehicle Outlook presentation to CEC for the 2020 IEPR Update, June 11, 2020, slides 17 and 20. https://efiling.energy.ca.gov/GetDocument.aspx?tn=233410&DocumentContentId=65926.

One key area of innovation is in long-duration storage technologies. While there are 4.5 GW of pumped hydro energy storage in California, new longer-duration energy storage systems (for example, 100 or more hours of energy storage) are in the development phase and may be deployed within the next decade with the right market signals. Longer-duration storage technologies, such as advanced batteries, thermal energy storage, liquid air energy storage, and compressed air energy storage, can support reliability and further promote achievement of SB 100 goals.

Additional research and innovation will be important to address a range of outstanding issues, including increasing the cycling rate (number of cycles per day) of battery systems; ensuring reliability of systems over the lifetime of these systems; environmental issues associated with the manufacturing supply chain, including reliance on rare earth minerals; management of thermal runaway and fire potential at storage facilities; and end-of-life disposal and recycling of the battery (for example, some technologies rely upon toxic and extreme pH electrolyte materials). Through EPIC, the state is conducting research to advance storage technologies and better understand the storage needs for meeting SB 100.

Hydrogen

Hydrogen technologies — including as a storage resource, use in fuel cells, and direct combustion — can support the cost-effective implementation of SB 100 by integrating more intermittent renewables and providing flexible supply to balance the grid. Hydrogen may improve the economic efficiency of renewable investments and serve as carbon-free seasonal storage, supplying energy when renewable energy production is low and energy demand is high. A recent study by E3 by Mitsubishi Hitachi Power Systems estimates that the hydrogen market in California could be up to 10 GW by 2045, driven primarily by long-duration energy storage.[129]

Some challenges remain for wider adoption of hydrogen production, storage, and use as a direct source of electricity. Production costs are not cost-competitive with other sources of storage and generation, and additional infrastructure is needed to support the transportation and storage of hydrogen. Moreover, gas pipeline systems have been optimized to transport methane; therefore, introducing hydrogen at a large scale requires addressing regulatory and technical barriers that may persist in distributing hydrogen in the existing natural gas pipelines or developing a new hydrogen-specific distribution system. Continued market, policy, and research advances will be needed to propel technologies and strategies needed to overcome these challenges.

The Natural Gas Research and Development Program and the CEC's Clean Transportation Program are investing in hydrogen fueling infrastructure deployment and vehicle demonstration projects to accelerate market growth of fuel cell-electric vehicles.

129 E3. Hydrogen Opportunities in a Low Carbon Future. June 2020. https://www.ethree.com/wp-content/uploads/2020/07/E3_MHPS_Hydrogen-in-the-West-Report_Final_June2020.pdf.

Growth in hydrogen demand from the transportation sector, particularly the heavy-duty sector, will assist in achieving scale in the electricity sector, which is necessary to reduce the costs in production and distribution. Furthermore, EPIC is researching the expanded use of hydrogen in the industrial processing and long-term energy storage markets.

Load Flexibility

Flexible load and other demand-side management technologies and strategies — across transportation, buildings, and industry — will be critical for cost-effective implementation of SB 100 and state electrification goals. Load flexibility enables grid balancing by temporarily aligning demand with the availability of preferred supply resources, including intermittent renewable generation and other zero-carbon resources. Load flexibility supports variable renewable electricity supply by providing fast-response flexible load substitutes for ancillary services. These functions will be increasingly important with greater deployment of variable renewables.

Several barriers constrain the growth of load flexibility. First, there are limited mechanisms to compensate for load flexibility in current utility programs and rate designs. Continued work is needed to create incentives commensurate with the value of load flexibility for the grid. The CEC has undertaken several initiatives to help accelerate load flexibility for reliability and meeting the state's environmental goals. The *2019 Building Energy Efficiency Standards*[130] require load-flexibility capability for battery storage and heat pump water heaters to obtain compliance credit. The 2020 Load Management Standards proceeding[131] will create a platform to enable greater automation of load flexibility. The AB 3232 *Building Decarbonization Assessment*[132] assesses the potential and value of load flexibility as a key strategy.

On October 14, 2020, the CEC approved an order instituting rulemaking for the flexible demand appliance standards and labeling requirements included in Senate Bill 49 (Skinner, Chapter 697, Statutes of 2019). Staff will be working throughout 2021 to develop a set of initial proposed flexible demand appliance standards based on a range of considerations relating to technology readiness, load-shifting potential, and estimated GHG emissions savings.

For many applications, the enabling technologies for load flexibility are still in the early development stages. For example, in the transportation space, smart charging and

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130 CEC 2019 Building Energy Efficiency Standards Web page, https://www.energy.ca.gov/programs-and-topics/programs/building-energy-efficiency-standards/2019-building-energy-efficiency.

131 CEC 2020 Load Management Rulemaking Web page, https://www.energy.ca.gov/proceedings/energy-commission-proceedings/2020-load-management-rulemaking.

132 CEC Building Decarbonization Assessment Web page, https://www.energy.ca.gov/data-reports/reports/building-decarbonization-assessment.

bidirectional power flow technologies are largely precommercial, and continued development will improve the associated value proposition. Demand flexibility costs vary significantly by end use. Costs for a range of demand response applications and scenarios are discussed in Lawrence Berkeley National Laboratory's 2025 California Demand Response Potential Study.[133]

Through EPIC, the state is pursuing a wide array of load-flexibility research to further develop the needed technology, lower costs, and foundation for market growth. The CEC released a solicitation (GFO-19-309) in September 2020 to fund a California Flexible Load Research and Deployment hub to conduct R&D and deployment projects that increase the use and market adoption of advanced, interoperable, and flexible demand technologies.

Overall, state agencies can leverage research and development investments in technology innovation to help achieve SB 100 goals. This leveraging will require strategic and coordinated investment over the long term, with a focus on technologies, state incentives, and targeted regulations and strategies that augment or complement existing commercially available solutions.

Land-Use and Environmental Impacts

Natural and working lands are important to the state's climate change strategy because they sequester carbon and support clean air, wildlife and pollinator habitat, and rural economies. They are also critical components of the state's water infrastructure and can be a source and sink for GHG emissions. Keeping these lands and waters intact and functioning ecologically in the future is necessary to supporting the well-being and security of Californians and reducing conversion to intensified uses.

Because renewable and zero-carbon energy technologies often have large footprints and may require new supporting infrastructure to deliver power (for example, transmission), incorporating land use into planning is necessary to minimize adverse societal and environmental impacts and maximize potential environmental, health, and economic co-benefits.

It will be important to incorporate land-use planning into electric system planning to consider trade-offs between energy development and conservation of land for agricultural, natural lands, or housing. Several geospatial studies, such as NREL's GIS mapping of renewable energy resources,[134] have already screened for locations with high renewable energy resource potential in California. However, energy-planning processes have not yet been fully integrated

133 Lawrence Berkeley National Laboratory. March 2017. *2025 California Demand Response Potential Study – Charting California's Demand Response Future: Final Report on Phase 2 Results*. https://eta-publications.lbl.gov/sites/default/files/lbnl-2001113.pdf.

134 National Renewable Energy Laboratory Geospatial Data Science Web page, https://www.nrel.gov/gis/.

with land conservation values to evaluate the environmental and system cost and benefit implications of clean energy policies and siting decisions.

As California considers the more ambitious renewable energy goals of SB 100, proactive landscape-scale planning can help identify opportunities for renewable energy facility and transmission development while reducing adverse effects. Landscape-scale planning considers a wide range of potential constraints and conflicts, including environmental sensitivity, conservation and other land uses, tribal cultural resources, and more when considering future renewable energy development. The benefits of using landscape-level approaches for renewable energy and transmission planning include early identification and resolution of large issues or barriers to development, coordinated agency permitting processes, increased transparency in decision making, increased collaboration, avoidance of impacts, and more rapid development of environmentally responsible renewable energy projects.

Planning should also reflect the Garamendi Principles,[135] encouraging strategies to maximize the use of the existing transmission system and existing rights-of-way before considering the expansion or creation of new rights-of-way. Such strategies include using advanced transmission technologies as well as siting supply resources in strategic locations.

California has already worked extensively with stakeholders and other agencies through science-based collaborative landscape planning processes in multiple geographic areas of the state with renewable energy potential. Previous planning efforts include the first and second Renewable Energy Transmission Initiatives[136] (RETI) processes, the joint agency work on the

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135 California Senate Bill 2431, Chapter 1457, declared that it is in the best interest of the state to conduct transmission siting according to the following principles ("Garamendi Principles"):

1. Encourage the use of existing right-of-way (ROW) by upgrading existing transmission facilities where technically and economically justifiable.
2. When construction of new transmission line is required, encourage expansion of existing ROW, when technically and economically feasible.
3. Provide for the creation of new ROW when justified by environmental, technical, or economic reasons as determined by the appropriate licensing agency.
4. Where there is a need to construct additional transmission capacity, seek agreement among all interested utilities on the efficient use of that capacity.

136 *Renewable Energy Transmission Initiative Phase 2A Final Report*, September 2019, available at: https://web.archive.org/web/20100330223729/http://www.energy.ca.gov/2009publications/RETI-1000-2009-001/RETI-1000-2009-001-F-REV2.PDF. *Renewable Energy Transmission Initiative 2.0 Final Plenary Report*, February 23, 2017, available at https://efiling.energy.ca.gov/getdocument.aspx?tn=216198.

Desert Renewable Energy Conservation Plan (DRECP),[137] and the stakeholder-led San Joaquin Valley Identification of Least-Conflict Lands study.[138]

Through these, federal and state agencies, local governments, tribes, and stakeholders have gained experience with planning approaches to identify the most appropriate areas for renewable energy development and long-term conservation. These planning efforts have also enabled the collection of environmental data and information into a single, publicly accessible portal, the California Statewide Energy Gateway.[139] This information supports science-based conservation planning, decision-making for renewable energy expansion, and future landscape-scale planning.

The CPUC's IRP process includes environment and land-use screens as part of capacity expansion modeling. The CEC then uses the land use and environmental information assembled from these landscape planning efforts to map selected resources to substation busbars for input to the California ISO's transmission modeling for the TPP. The CPUC's inclusion of land-use screens in the upcoming IRP cycle will also inform statewide land-use planning.

California's lands are naturally capable of sequestering huge amounts of carbon to limit climate change and are, therefore, a key component of meeting the state's carbon neutrality goals. Ongoing disturbances to natural and working lands such as severe wildfire, land degradation, and land conversion cause these landscapes to emit more carbon dioxide than they store. Policy in the electricity sector must be made with a clear understanding of the need to balance increased renewable energy demand with loss of ecosystem carbon storage and loss of future sequestration associated with large footprint energy resources such as utility-scale solar. California's climate objectives for natural and working lands are to maintain them as a resilient carbon sink (that is, net-zero or negative GHG emissions) and minimize the net GHG emissions associated with management, biomass disposal, and wildfires.

Moreover, Governor Newsom's Executive Order (N-82-20) requires the state to have a target for the natural and working lands sector in achieving California's carbon neutrality goal. The order directs state agencies to use strategies to maximize the full climate benefits of natural and working lands and sets a first-in-the-nation goal to conserve 30 percent of the state's land and coastal water by 2030 to fight species loss and ecosystem destruction.

In future assessments of land-use impacts, the joint agencies can draw from these efforts and experiences. As next steps, the joint agencies plan to review methods to include land-use

137 CEC Desert Renewable Energy Conservation Plan Web page, https://www.energy.ca.gov/programs-and-topics/programs/desert-renewable-energy-conservation-plan.

138 See *A Path Forward: Identifying Least-Conflict Solar PV Development in California's San Joaquin Valley*. Available at : https://sjvp.databasin.org/pages/least-conflict.

139 Access the California Statewide Energy Gateway at: https://caenergy.databasin.org.

impacts in system modeling and assess needs to update previous land-use studies to reflect the increased resource requirements of SB 100. Future system modeling and land-use impacts must be coordinated with any recommendations from the Climate Smart Strategy called for in Executive Order N-82-20 and the AB 32 Scoping Plan.

Social Costs and Non-Energy Benefits

Another key area for further analysis is the inclusion of social costs and non-energy benefits (NEBs). For this report, community leaders and advocacy organizations[140] recommended the joint agencies consider an equity scenario that excludes combustion resources and includes social costs and NEBs.

The comment letter states that "social costs" are the negative externalities or impacts on society associated with the construction and operation of energy infrastructure and any associated activity, with a specific focus on localized public health impacts. Non-energy benefits (NEBs) represent the benefits or positive impacts on society associated with the construction and operation of energy infrastructure and any associated activity.

Stakeholders recommended the joint agencies integrate at least the following NEBs and social costs into SB 100 planning:

- Land-use impacts
- Public health and air quality
- Water supply and quality
- Economic impacts
- Resilience

As discussed in Chapter 3, the joint agencies included a study scenario that excludes all new and existing combustion resources in the modeling scope. Further refinement to localized air pollution impacts and the other NEBs listed above was not feasible in this round of modeling, partly because of the modeling tools used, unknowns about where generation resources will be located, and lack of higher resolution data on when and how specific resources will be used.

The joint agencies plan to continue engaging with the DACAG and other stakeholders to explore opportunities to better integrate these topics into future analyses. Land use is addressed in the preceding section, and further discussion on the other recommended NEBs is included below.

140 Including the UC Berkeley Environmental Law Clinic, Central California Asthma Collaborative (CCAC), the Center on Race, Poverty & the Environment (CRPE), the Greenlining Institute, GRID Alternatives, Leadership Counsel for Justice and Accountability, Sierra Club California and the California Environmental Justice Alliance.

State Efforts to Evaluate Social Costs

The joint agencies will explore the use of emerging cost analysis tools and methods that integrate social costs. Some of these new methods are being tested in active proceedings such as the CPUC's San Joaquin Valley Affordable Energy proceeding (R.15-03-010) to begin evaluating energy solutions with consideration of NEBs and social costs.

The CPUC is also performing Societal Cost Test modeling, as ordered by IDER D.19-05-019. This work includes changing RESOLVE assumptions to reflect a social discount rate, a social cost of carbon, and an air quality adder. A report that contains this analysis and select sensitivities will be released through the IRP in early 2021. The Public Health and Air Quality section below includes a preliminary social cost assessment for a subset of portfolios.

The joint agencies are monitoring the application of available tools and stakeholder input to determine if they are appropriate for SB 100-related analysis.

Preliminary Analysis on Avoided Social Costs of SB 100

For this report, CARB performed an initial assessment of the avoided social costs of carbon of the SB 100 Core Scenario relative to the 60 percent RPS Scenario (reference). Future assessments will build off this initial analysis and more thoroughly reflect state efforts to quantify social costs.

The social cost[141] of carbon (SC-CO_2) estimates the value of damages avoided by reducing GHGs. It is intended to provide a comprehensive measure of net damages — the monetized value of the net impacts — from global climate change that result from an additional ton of carbon dioxide (CO_2). These include changes in net agricultural productivity, energy use, human health, property damage from increased flood risk, as well as nonmarket damages, such as services that natural ecosystems provide to society. Many of these damages from CO_2 emissions today will affect economic outcomes throughout the next several centuries.[142]

Table 22 presents the range of SC-CO_2 values developed by the Council of Economic Advisors and the Office of Management and Budget-convened Interagency Working Group on the Social

141 "Social costs" are generally defined as the cost of an action on people, the environment, or society and are widely used to evaluate the impact of regulatory actions.

142 From The National Academies, Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide, 2017, available at https://www.nap.edu/catalog/24651/valuing-climate-damages-updating-estimation-of-the-social-cost-of.

Cost of Greenhouse Gases (IWG)[143] and used in the *2017 California Climate Change Scoping Plan.*[144]

The SC-CO_2 increases over time as systems become stressed from the cumulative impacts of climate change, and future emissions cause incrementally larger damages. The SC-CO_2 is highly sensitive to the discount rate. Higher discount rates decrease the value today of future environmental damages, reflecting the trade-off of consumption today and future damages.

Table 22: Social Cost of CO2, 2015–2050 (in 2007 Dollars per Metric Ton CO2)

Year	5% Discount Rate	3% Discount Rate	2.5% Discount Rate
2015	$11	$36	$56
2020	$12	$42	$62
2025	$14	$46	$68
2030	$16	$50	$73
2035	$18	$55	$78
2040	$21	$60	$84
2045	$23	$64	$89
2050	$26	$69	$95

Source: CARB staff analysis

Table 23 shows the estimated avoided social costs of the SB 100 core scenario (high electrification demand) relative to the 60 percent RPS scenario. (See calculation details in Appendix C.)[145]

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143 Originally titled the Interagency Working Group on the Social Cost of Carbon, the IWG was renamed in 2016.

144 U.S. EPA. The Social Cost of Carbon: Estimating the Benefits of Reducing Greenhouse Gas Emissions. Retrieved on November 19, 2020, from: https://19january2017snapshot.epa.gov/climatechange/social-cost-carbon_.html.

145 The 2045 values shown in **Table 23** were translated into 2016 dollars and multiplied by the differential between the GHG emissions associated with the two scenarios, as detailed in Chapter 3.

Table 23: Estimated Avoided Social Cost (Avoided Economic Damages) of SB 100 in 2045

Scenario	Social Cost of Carbon, $ million USD (2016 dollars) 5% Discount Rate	Social Cost of Carbon, $ million USD (2016 dollars) 3% Discount Rate	Social Cost of Carbon, $ million USD (2016 dollars) 2.5% Discount Rate
SB 100 Core Scenario relative to 60% RPS Scenario	$887	$2,470	$3,430

Source: CARB staff analysis

The SC-CO_2, while intended to be a comprehensive estimate of the damages caused by carbon globally, does not represent the cumulative cost of climate change and air pollution to society due to modeling and data limitations.[146] The joint agencies will continue engaging with experts to evaluate the comprehensive California-specific impacts of climate change and air pollution.

Public Health and Air Quality

The state's air quality and climate policies, strategies, and regulations strive to maximize public health protection through reducing respiratory, cardiovascular, and other chronic illnesses; reducing early deaths; and promoting healthier and more sustainable lifestyles in all communities. Despite decades of progress in improving air quality, California still suffers some of the worst air quality in the nation, resulting in more than 7,000 premature deaths and thousands of illnesses and emergency room visits each year.

The effects of climate change are already felt today in California. Climate change can impact human health through extreme weather events including drought, precipitation, floods, heat waves, and wildfires.[147] These climate impacts contribute to heat-related illnesses, increases in cardiovascular and respiratory illnesses, increased prevalence of asthma and allergies, increased water-borne and vector-borne diseases, adverse child and reproductive health

146 Including costs associated with changes in copollutants and the social cost of other GHGs including methane and nitrous oxide.

147 (a) U.S. Global Change Research Program. 2018. *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II* (Reidmiller, D.R., C.W. Avery, D.R. Easterling, K.E. Kunkel, K.L.M. Lewis, T.K. Maycock, and B.C. Stewart [eds.]). U.S. Global Change Research Program, Washington, D.C., United States of America. https://nca2018.globalchange.gov/. (b) World Health Organization. 2003. *Climate Change and Human Health, Risks and Responses*. Geneva, Switzerland. https://www.who.int/globalchange/publications/climchange.pdf. (c) NRDC. 2019. Climate Change and Health in California. https://www.nrdc.org/sites/default/files/climate-change-health-impacts-california-ib.pdf.

outcomes, and other effects. Climate change is already taking a toll on human health, and taking action to reduce greenhouse gas emissions is a necessity.

Power generated from fossil fuel combustion[148] also emits criteria air pollutants and related precursors, including oxides of nitrogen (NOx) and oxides of sulfur (SOx). While NOx and SOx are directly harmful, they are more impactful on health when they are converted to fine particles by chemical processes in the atmosphere. Fine particle pollution (that is, pollution from particulate matter with a diameter ≤2.5 μm, also known as $PM_{2.5}$) contributes to more fatalities than other air pollutants. Health effects from long-term exposure to fine particle pollution includes increased risk of heart attacks and heart disease, impaired lung development in children, the development and exacerbation of asthma, and premature death. U.S. EPA has determined that fine particles play a causal role in premature death from heart- and lung-related illnesses.[149]

Millions of California residents live in disadvantaged communities that experience a combination of increased vulnerability to adverse health effects from pollution and high levels of exposure to pollution sources. Research has demonstrated higher rates of illness and early death in disadvantaged communities.[150] For these residents, actions to transition from fossil fuel combustion are even more urgent.

Those individuals and communities that are at a social and financial disadvantage are also less able to deal with stresses caused by climate change such as high temperatures and wildfire damages, and they are more likely to suffer physical and psychological harm. Replacing fossil fuel-powered generation plants with clean electricity resources will reduce the burden on public health from air pollution and climate change and help address environmental justice disparities.

Quantifying Health Benefits of SB 100

To illustrate the potential quantified health benefits in 2045 from decreased $PM_{2.5}$ pollution linked to power plant emissions, CARB used a simplified version of its Incidence-Per-Ton (IPT)

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148 Power generation that uses conventional combustion technologies are typical sources of criteria air pollutant emissions; however, noncombustion thermal technologies can also emit criteria air pollutants.

149 U.S. EPA. September 2019. *Policy Assessment for the Review of the National Ambient Air Quality Standards for Particulate Matter, External Review Draft*. https://www.epa.gov/sites/production/files/2019-09/documents/draft_policy_assessment_for_pm_naaqs_09-05-2019.pdf.

150 (a) American Lung Association. 2020. *State of the Air*. https://www.stateoftheair.org/assets/SOTA-2020.pdf. (b) Union of Concerned Scientists, USA. January 28, 2019. *Inequitable Exposure to Air Pollution From Vehicles in California (2019)*. https://www.ucsusa.org/resources/inequitable-exposure-air-pollution-vehicles-california-2019#ucs-report-downloads. (c) Cushing L., Faust J., August L. M., Cendak, R., Wieland, W., and Alexeeff, G. 2015. "Racial/Ethnic Disparities in Cumulative Environmental Health Impacts in California: Evidence From a Statewide Environmental Justice Screening Tool (CalEnviroScreen 1.1)." Am J Public Health 105(11): 2341–2348. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4605180/.

method, which evaluates the health endpoints of premature mortality, cardiopulmonary hospitalizations, and asthma emergency room (ER) visits.

Health impacts were estimated using California-specific relationships between emissions and air quality. This method is assumed to have an approximately linear relationship between changes in $PM_{2.5}$ emissions and health outcomes. CARB estimated the numbers of health outcomes by multiplying emissions by an incidents-per-ton scaling factor.[151] **Table** 24 summarizes these estimated health impacts for SB 100 at the statewide level for 2045. These are rough estimates using limited emission information and should not be taken as absolute values of the health outcomes of the 100 percent clean electricity policy. Further, this analysis does not attempt to quantify the improved health outcomes from reduction in greenhouse gases nor global climate change, as climate change mitigation requires global actions.

Table 24: Summary of Ranges of Estimated Health Impacts for the SB 100 Scenario in 2045

	Fewer Premature Deaths	Fewer Cardiopulmonary Hospitalizations	Fewer Asthma ER Visits
Primary $PM_{2.5}$	174 (136-213)	61 (8-114)	80 (50-109)

Source: CARB staff analysis. Numbers in parentheses represent the 95% confidence interval.

A more comprehensive analysis can use well-established methods that translate regional emissions reductions in criteria air pollutants into health outcomes.[152] Steps to further analyze the health impacts from criteria air pollution, specifically $PM_{2.5}$, include the following:

1. Estimate $PM_{2.5}$ emissions from power plants for at least two points in time, such as the current year and at full implementation of the SB 100 target in 2045. Key milestone years (for example, achievement of 60 percent renewables by 2030) may also be evaluated, as well as impacts in disadvantaged communities.
2. Use estimates of $PM_{2.5}$ emissions and exposures, together with an effect estimate, to quantify health impacts at the statewide or air basin level. The quantitative analysis should include updated ranges of estimated premature deaths, hospitalizations, and emergency room visits on a statewide basis, as well as cancer risk estimates if sufficient data are available.

151 These factors are derived from research studies showing the associations between the number of incidents (premature deaths, hospitalizations, emergency room visits) and exposure to PM2.5.

152 CARB 2019a, Fann et al. 2009, 2012. Fann, N., C. M. Fulcher and B. J. Hubbell (2009). "The influence of location, source, and emission type in estimates of the human health benefits of reducing a ton of air pollution." Air Qual Atmos Health 2(3): 169-176.

Climate change impacts, such as extreme weather events, can also affect air quality and health. A more comprehensive analysis of health impacts and benefits may include factors related to climate impacts to yield a fuller picture of economic benefits.

Analysis of health impacts is closely connected to economic analysis: the monetized value of avoided illness and premature death provides a helpful measure of the health value of air pollution controls. According to U.S. EPA methodology, the current value of a statistical life (VSL) is nearly $10 million, so the cumulative health impacts of a regulation over decades can be substantial.[153]

As the energy sector continues to evolve and decarbonize, the behavior of facilities and the design of the grid will change, with important distributional effects. Some power plants may operate more flexibly to balance renewables, emerging technologies may become more prevalent, and aging facilities may be replaced. These trends will likely shift patterns of criteria pollutant emissions with local benefits and impacts. Because many existing power plants are in or near disadvantaged communities, it is important that this transition benefits those most burdened by pollution.[154]

Water Supply and Quality

The energy-water nexus is a critical juncture between energy production, environmental impacts, and dependence on water resources. The joint agencies' analysis of NEBs and social costs should therefore encompass energy resource impacts on water quality or quantity and impacts of water supply on the energy system.

Conserving fresh water and avoiding its wasteful use have long been state priorities, as reflected in the State Constitution[155] and state policies. A State Water Resources Control Board (Water Boards) resolution[156] protects beneficial uses of the state's water resources and keep the consumptive use of fresh water for power plant cooling to only essential levels. The policy reflects the state's concerns over discharges from power plant cooling, as well as the conservation of fresh water.

In response to concerns about power plants significantly impacting local water supplies, the CEC adopted a water policy in 2003 that calls for the use of alternative technologies and water sources. Since then, there has been a trend away from the use of fresh water for power plant

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153 National Center for Environmental Economics et al., *Appendix B: Mortality Risk Valuation Estimates, Guidelines for Preparing Economic Analyses* (EPA 240-R-10-001, Dec. 2010) available at https://www.epa.gov/sites/production/files/2017-09/documents/ee-0568-22.pdf.

154 California Health and Safety Code Section 38562(b)(2).

155 Article X, Section 2.

156 Resolution No. 75-58, Water Quality Control Policy on the Use and Disposal of Inland Waters Used for Powerplant Cooling, June 19, 1975, https://www.waterboards.ca.gov/board_decisions/adopted_orders/resolutions/1975/rs75_058.pdf.

cooling compared to previous years, as well as increased use of recycled water, more efficient cooling technologies, dry cooling, and recycling of process wastewater through zero-liquid-discharge systems.[157]

Both solar PV and wind technologies can operate with essentially no water requirements, though PV facilities typically use some water for panel washing. However, because of size, all utility-scale renewable energy facilities can require large amounts of water during construction for dust control and soil grading. With sandy, dry, and windy conditions typical of the desert, where many projects are located (and where significant buildouts may be in the future), the amount of water used for construction can be considerable, especially considering limited water supplies available in many parts of the desert.

Water efficiency in California's electric generation sector will continue to improve as the fleet modernizes and natural gas-fired plants are run less often, recycled water sources are used preferentially, and renewables are deployed. However, given that a reliable supply of water will continue to be a key contributor to a reliable generation sector, it will be imperative for water quality and quantity impacts to be considered in planning and permitting processes.[158]

Economic Development and Impacts

SB 100 presents a significant opportunity for job creation and sustainable careers because of the expected record-setting resource build. While this report does not contain an analysis of local economic impacts or benefits, nor job creation associated with SB 100 implementation, these topics will be explored quantitatively and qualitatively in future SB 100 work.

The joint agencies will continue coordinating with the California Workforce Development Board (CWDB) to maximize alignment between SB 100 implementation and the state's efforts to ensure a just transition into the clean energy future and promote equity in the clean energy workforce. The CPUC has recently entered into an agreement with CWDB to draw upon CWDB's expertise to ensure the state has the workforce and industry-based training partnerships necessary to meet its clean energy goals.

The CWDB's new report titled *Putting California on the High Road: A Jobs and Climate Action Plan for 2030*[159] provides a vision to integrate economic and workforce development into climate policies and programs to help achieve California's major climate goals. The CWDB's report, developed following Assembly Bill 398 (E. Garcia, Chapter 135, Statutes of 2017),

157 Even before adoption of the 2003 water policy, a good portion of California's steam-cycle facilities (combined-cycle, steam boiler, and geothermal) used recycled water for cooling.

158 For more detailed information on the energy-water nexus for California's electric generation system, see the CEC staff report *Final 2016 Environmental Performance Report of California's Electrical Generation System*.

159 UC Berkeley Labor Center. *Putting California on the High Road: A Jobs and Climate Action Plan for 2030*. June 2020. https://laborcenter.berkeley.edu/wp-content/uploads/2020/09/Putting-California-on-the-High-Road.pdf.

creates a framework for maximizing the positive labor market outcomes of California's climate investments by simultaneously advancing equity and economic mobility for Californians and delivering skills and competitiveness for California employers. Key takeaways from the report include the following:

- Labor should be considered an investment rather than a cost — and investments in growing, diversifying, and upskilling California's workforce can positively affect returns on climate mitigation. In other words, well-trained workers are key to delivering emissions reductions and moving California closer to its climate targets.
- California can achieve greater social equity in labor market outcomes for disadvantaged workers and communities when policy makers pay attention to job quality. Identifying high-quality careers (in other words, ones that offer family-supporting wages, employer-provided benefits, worker voice, and opportunities for advancement) first, and then building pathways up and into such careers, are critical to ensuring that investments in workforce education and training meaningfully improve workers' economic mobility.
- Deliberate policy interventions are necessary to advance job quality and social equity as California transitions to a carbon-neutral economy, just as such efforts are required to reduce pollution, protect human and environmental health, and safeguard communities from an already-changing climate.

DACAG's Equity Framework[160] serves as another guide in assessing local economic and workforce opportunities. The framework states, "Climate policies and programs should invest in a clean energy workforce by ensuring California has a trained and ready workforce prepared to improve our infrastructure and built environment as well as bring green technologies to market by:

- Promoting and funding workforce development pathways to high-quality careers in the construction and clean energy industries, including pre-apprenticeship and other training programs,
- Setting and tracking hiring targets for low-income, disadvantaged, and underrepresented populations (including women, re-entry, etc.) to enter these industries,
- Ensuring that these careers are high-road, with a career-ladder, family-sustaining wages and with benefits,
- Training the next generation of climate leaders and workers for the clean energy economy, and
- Supporting small and diverse business development and contracting."

160 CPUC. Disadvantaged Communities Advisory Group Equity Framework, available at https://www.cpuc.ca.gov/uploadedFiles/CPUCWebsite/Content/UtilitiesIndustries/Energy/EnergyPrograms/Infrastructure/DC/DAC%20AG%20Equity%20Framework%20(Revised).pdf.

The road to economic recovery is even more critical now that the COVID-19 pandemic has hit the entire country. People of color are disproportionately impacted by the economic downturn resulting from the pandemic and are overrepresented in nonessential, low-wage jobs.[161] The clean energy economy represents a unique opportunity to focus workforce development efforts in disadvantaged communities. Creating clean jobs and careers with growth potential can help accelerate the economic rebuilding for workers, families, and the greater economy.

Community Resilience

The Governor's Office of Planning and Research defines resilience as "...the capacity of any entity — an individual, a community, an organization, or a natural system — to prepare for disruptions, to recover from shocks and stresses, and adapt and grow from a disruptive experience."[162] Future investments in electric generation, storage, distribution, and transmission facilities must be designed and operated with reliability and resilience in mind to account for a changing climate. In particular, planning for and developing these facilities require an understanding of the challenges posed by increasing wildfire risk, extreme heat, and other effects of climate change. This planning is especially important as the electric grid expands to serve additional end uses, such as transportation.

Resilience to climate impacts is a priority in state policy and program design and implementation. Several state agencies, including the CEC and Strategic Growth Council, administer grant programs focused on improving local resilience to climate impacts. These grants have enabled cities to develop local adaptation plans that consider regional climate threats and identify regionally relevant adaptation strategies. Local adaptation planning may benefit from more refined results from the SB 100 and related proceedings on the resource mix and likely location and operation of resources. A more detailed discussion of electricity system resilience and planning for climate impacts is included later in this chapter.

Accelerating SB 100 Implementation

This report includes study scenarios in which the 100 percent renewable and zero-carbon target is accelerated to 2030, 2035, and 2040. While preliminary modeling results suggest accelerating the implementation timeline of the SB 100 target is technically achievable, these scenarios are exploratory and require more rigorous analysis.

Notably, the accelerated timelines resulted in additional economic gas retirements, increased selection of geothermal resources, and decreased selection of solar and battery storage. These results suggest accelerated implementation could affect the overall 2045 resource portfolio.

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161 PolicyLink. "Race, Risk, and Workforce Equity in the Coronavirus Economy." June 2020. https://www.policylink.org/our-work/economy/national-equity-atlas/COVID-workforce.

162 Governor's Office of Planning and Research. 2018. *Planning and Investing for a Resilient California: A Guidebook for State Agencies*. https://opr.ca.gov/docs/20180313-Building_a_Resilient_CA.pdf.

Each accelerated timeline scenario results in increased annual costs compared to the SB 100 Core scenario. In general, the TRC increases in the year in which the 100 percent target is accelerated but largely levels off by 2045. For example, in the 2030 accelerated scenario, the 2045 TRC is less than a 1 percent increase over the SB 100 core scenario. Total cumulative cost differences between these scenarios have not been evaluated.

The joint agencies plan to continue analysis of the 2030, 2035, and 2040 scenarios in the 2025 SB 100 report analyses. In the meantime, the CPUC, in the IRP process, will continue to evaluate requiring load-serving entities to meet reduced GHG emission targets within the range set by CARB. These processes will be done in collaboration with CEC and may support opportunities to accelerate progress toward the SB 100 goal.

Additional Considerations for Implementation

As the joint agencies produce more refined analysis of the SB 100 scenarios, additional factors must be considered in planning for SB 100 implementation and coordination with complementary proceedings and programs.

Equity

As stated by the DACAG, “The impact of climate change on low-income and disadvantaged communities can exacerbate existing inequities but can also be an opportunity to level the playing field through intentional interventions that address climate impacts on these communities directly.” In 2018, the DACAG developed an Equity Framework to guide the CEC and CPUC along with other state agencies to help ensure equity is kept “front and center” during all phases of policy design and implementation of clean energy such as SB 100.[163] The Equity Framework includes the following components:

- Health and safety
- Access and education
- Financial benefits
- Economic development
- Consumer protection

Future SB 100 work will consider this framework and other recommendations made by equity experts and community leaders throughout the process, including the AB 32 Environmental Justice Advisory Committee, to benefit communities in a meaningful and measurable way. The Equity Framework priorities will be considered as part of the continued efforts of SB 100, including program design, modeling, analysis, implementation, and evaluation. In addition, AB

163 CPUC, Disadvantaged Communities Advisory Group Equity Framework, available at https://www.cpuc.ca.gov/uploadedFiles/CPUCWebsite/Content/UtilitiesIndustries/Energy/EnergyPrograms/Infrastructure/DC/DAC%20AG%20Equity%20Framework%20(Revised).pdf.

617 Community Emissions Reduction Plans provide a resource for actions that will achieve air pollution emission and exposure reductions within disproportionately impacted communities and are tailored to address the communities' air quality priorities.

The joint agencies conducted ongoing engagement with equity stakeholders throughout the development of the 2021 Report, and plan to have continued engagement with the DACAG's SB 100 subcommittee and other stakeholders to further refine the agencies' approach to equity in SB 100 implementation.

Affordability

Meeting the SB 100 2045 target will likely require substantial new investments in the electric system, which may have impacts on electricity rates for consumers. Under some emissions reduction scenarios, modeling conducted for this report indicates that the state's installed electric generation capacity may grow from about 85,000 MW today to between 227,000 MW and 301,000 MW in 2045 — roughly a threefold increase in capacity. As the transportation, buildings, and industrial sectors deploy low-carbon technologies to meet the state's long-term climate goals, they will likely rely more on the electricity sector, which will increase load and customer sensitivity to rates. Maintaining affordable electricity rates is critical to successful achievement of the state's GHG targets across sectors.

As mentioned in Chapter 3, the 2021 Report analysis results provide rough estimates of system costs associated with the various scenarios. However, further analysis is required to better understand how these costs will be factored into rates that directly affect consumers. The modeling does not take into account important factors including costs associated with build-out to maintain local reliability and system hardening efforts for improved system resilience to wildfires and other climate threats.

Through proceeding (R.18-07-006), the CPUC aims to better understand and define affordability for residential utility customers within California. This proceeding has primarily analyzed metrics that may be used to compare affordability as rates change. However, a baseline threshold to determine when something is or is not affordable has not yet been established, and the CPUC continues to assess appropriate methods to do so.

The decision adopted in the first phase of the proceeding defines affordability as "the degree to which a representative household is able to pay for an essential utility service charge, given its socioeconomic status."[164] The decision also adopted three metrics to compare and assess affordability:

> **Household affordability ratio**: a ratio that sums the expected cost for three utility services (energy, telecommunication, and water services — together, these are deemed "essential utility services") and divides them by a household's income less total housing

164 California Public Utilities Commission. *Decision Adopting Metrics and Methodologies for Assessing the Relative Affordability of Utility Service*. July 16, 2020. https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M344/K049/344049206.PDF.

costs. This ratio provides a percentage for how much a household spends of its nonhousing budget on utilities.

Socioeconomic vulnerability index: a 100-point scale that can be used to compare one census tract area to another. The metric is a composite of five socioeconomic indicators that are components of California Office of Environmental Health Hazard Assessment's CalEnviroScreen: educational attainment, housing burden, linguistic isolation, poverty, and unemployment.[165] This metric provides an index that is independent of essential service charges. It answers the question: "What is the underlying socioeconomic vulnerability of a given geography?"

Hours at minimum wage: a statistic based on the estimated total cost for the essential utility services of energy, telecommunication, and water. This total is then compared to the minimum wage for a given locality. The number of hours of minimum wage needed to afford essential utility service is then calculated by dividing the total utility cost by the minimum wage value.

Taken together, these various metrics allow the utility to understand how rate changes may affect affordability for different regions and communities.

Implementing SB 100 with a focus on equity will require statewide focus on energy affordability with an emphasis on vulnerable populations and households in areas of the state that spend a disproportionately high share of their household income on energy. This focus underscores the importance of managing overall energy costs and engaging in thoughtful ratemaking to avoid large price spikes for vulnerable households, and integrated program implementation whereby grants and other targeted programming can be directed toward households that face affordability challenges.

Safety

In the last decade, California has experienced the challenges of safely operating the electric infrastructure that is built to serve high fire-threat areas of the state, and the consequences of underinvestment in the safety of gas storage, transmission, and distribution. California is grappling with how to prioritize the mitigation of numerous new risks associated with electric and gas infrastructure and how to pay for the mitigation. All these present-day safety challenges must be considered in long-term planning to meet the goals of SB 100.

To support the goals of SB 100, some existing energy infrastructure will need maintenance, hardening, repurposing, upgrades, or retirement. Similarly, newly constructed infrastructure under the given scenarios and patterns of the buildout must be capable of safe operation.

The areas of safety that will need to be considered in such analyses include:

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165 California Office of Environmental Health Hazard Assessment. CalEnviroScreen 3.0 (Updated June 2018) Web page. https://oehha.ca.gov/calenviroscreen/report/calenviroscreen-30.

- Safety in the planning, engineering, construction, operation, and maintenance of the electric, natural gas, biofuel, and hydrogen infrastructure and resources depending on the scenario and pattern of the buildout,
- Safety of workers, customers, and the public.

The CPUC and IOUs must engage in an ongoing assessment of risks and a prioritization of how to address those risks, including how to pay for the costs of mitigation. The risk mitigation strategies related to electric infrastructure being implemented and considered today include:

- System hardening.
- Undergrounding or covered conductors.
- Vegetation management and right-of-way (ROW) management to effectively protect the environment.
- Weather forecasting to develop situational awareness.
- Appropriate retirement schedules given changing climate conditions to ease safe transition.
- New and adaptive infrastructure proposals using California's climate change forecasts in the Fourth Climate Assessment and the forthcoming Fifth Climate Assessment.
- Upgrade transmission and distribution switching protocols to safely and reliably operate the transmission and distribution systems in an islanding mode and/or develop microgrids to minimize the impact of power shut-offs or to avoid the power shut-offs to end users at all.
- Public safety power shutoffs (PSPS) as the last resort.

The CPUC and gas utilities must similarly engage in an ongoing assessment of risks and prioritization of how to address those risks. California's natural gas infrastructure faces an additional layer of complexity under the goals of SB 100: fossil-based gas could be phased out over the long term, but the infrastructure used by the fossil-based gas energy may still be needed if the state embarks on a pathway that includes biofuels energy or hydrogen energy.

These challenges highlight the importance of assessing public safety within the context of 2045 scenario planning. While each scenario with different buildout patterns will present its own unique challenges, the state has a responsibility to ensure this transition and the services provided by new resources and infrastructure occur in a safe, reliable manner — minimizing risk as much as possible and maintaining public safety. State planners should seek to better understand the current state of energy sector public safety in California, identify approaches to decarbonization that enhance public safety, and recommend how to formally incorporate public safety into long-term planning and the road map to the goal of 100 percent clean electricity.

Electric System Resilience

Assessing Climate Impacts

The electric grid must now be designed and operated to be resilient, especially as changing climate causes more unpredictable and extreme weather events. Already, climate change-induced extreme weather events, such as wildfires and heat waves, are affecting the ability of the grid to provide continuous power to customers.

In the last few years, California's grid experienced considerable challenges from wildfires, which resulted in a greater application of public safety power shutoffs (PSPS) — in which California investor-owned utilities (IOUs) turn off power off in areas high winds and dry conditions to reduce the risk of the electric utility infrastructure starting wildfires. While PSPS events are an important tool to reduce the risk of catastrophic wildfires, the duration and frequency of the PSPS events posed challenges to communities and customers who rely on essential services. Moreover, the extreme heat events that occurred in 2020 resulted in rolling blackouts over two days in August and the threat of additional rolling blackouts later in August and again in September, which the state has not experienced since the California Electricity Crisis of 2000–2001.

Cost-effective achievement of SB 100 goals requires that investments in electricity generation and integration technologies and infrastructure consider how climate change may alter the geographic and temporal distribution of renewable energy resources and other impacts to electric infrastructure. Examples of such changes include:

- **Hydropower availability** — Summertime hydroelectric generation, which has historically provided an important renewable resource for meeting peak demand, depends upon spring and summer snowmelt, which is projected to decline substantially within this century.[166] Without additional innovation or cost reductions in zero-carbon dispatchable resources, increased variability in hydropower supplies could induce greater reliance on dispatchable fossil resources.
- **Wind and solar resources** — Climate impacts such as warmer temperatures and changes in wind patterns may alter the output of solar and wind resources.[167] The CEC is supporting research to better understand possible impacts, including one such

166 Pierce, D. W., J. F. Kalansky, and D. R. Cayan, (Scripps Institution of Oceanography). 2018. *Climate, Drought, and Sea Level Rise Scenarios for the Fourth California Climate Assessment*. California Energy Commission. Publication Number: CNRA-CEC-2018-006. https://www.energy.ca.gov/sites/default/files/2019-11/Projections_CCCA4-CEC-2018-006_ADA.pdf.

167 U.S. Department of Energy. *Climate Change and the Electricity Sector: Guide for Climate Change Resilience Planning*. September 2016. https://www.energy.gov/sites/prod/files/2016/10/f33/Climate%20Change%20and%20the%20Electricity%20Sector%20Guide%20for%20Climate%20Change%20Resilience%20Planning%20September%202016_0.pdf.

project[168] that aims to develop methods to improve projections of climate-related parameters that govern availability and distribution of solar and wind resources, with a focus on surface-level solar radiation and hub-height wind fields.

- **Water-energy nexus** — The intensity of drought conditions could impact the availability of water needed for cooling associated with certain renewable energy technologies, such as solar thermal and geothermal power plants.[169] Further, drought exacerbated by higher temperatures increases demand on groundwater supplies, which in turn requires substantial energy for pumping. For example, during California's 2011–2015 drought, farmers' increased reliance on groundwater supplies roughly doubled their energy consumption compared to predrought conditions.[170]
- **Extreme Heat** — Heat waves increase cooling loads, which in extreme cases can lead to supply shortages, such as those experienced in August 2020. Extreme heat can also compromise the performance and accelerate the degradation of generation, transmission, and distribution infrastructure. This strain can also precipitate local power outages, such as occurred in July 2018 when a Southern California heat wave led to more than 700 power outages that affected more than 80,000 customers.[171]
- **Wildfire Risk** — Wildfires can directly damage transmission and distribution systems, and associated ash can also impact performance of nearby solar generation. Further, windy and dry weather conditions raise the risk of fire ignitions from utility infrastructure and indirectly result in planned power shutoffs to protect public safety, such as the series of shutoffs in fall of 2019 and 2020 that have affected millions of Californians.

168 EPIC-funded grant EPC-16-063 titled "Advanced Statistical-Dynamical Downscaling Methods and Products for California Electricity System Climate Planning." For more information, see the February 2018 *Electric Program Investment Charge 2017 Annual Report* (California Energy Commission Publication Number CEC-500-2018-005, available at http://web.archive.org/web/20181202000310/https://www.energy.ca.gov/2018publications/CEC-500-2018-005/CEC-500-2018-005-CMF.pdf.)

169 Tarroja, Brian (et al.), University of California, Irvine. 2019. *Building a Climate Change Resilient Electricity System for Meeting California's Energy and Environmental Goals*. California Energy Commission. Publication Number: CEC-500-2019-015. https://ww2.energy.ca.gov/2019publications/CEC-500-2019-015/CEC-500-2019-015.pdf.

170 Public Policy Institute of California (PPIC). October 2016. "Energy and water use in California are interconnected." https://www.ppic.org/content/pubs/report/R_1016AER.pdf.

171 Los Angeles Department of Water and Power. July 9, 2018. Weekend of July 6, 2018 Heat Storm Related Power Outages and Response. https://s3-us-west-2.amazonaws.com/ladwp-jtti/wp-content/uploads/sites/3/2018/07/11114410/July-2018-Heat-Storm-Outage-Event-Summary-071118.pdf.

- **Sea-Level Rise** — Climate change-driven tidal inundation, flooding, and erosion increase the risk of physical damage and disruption to coastal substations, transformers, power lines, and other equipment.[172]
- **Out-of-state resources** — Furthermore, the state needs to consider the impacts of climate change on the availability of real-time imports to balance the grid. For example, westwide heat waves, such as the one experienced in August 2020, can result in short-term impacts to the availability of imports as cooling loads can drive sustained energy demand over a large geographic region.

State agencies are working to better understand these impacts and incorporate the latest research into energy planning efforts. Through EPIC, the CEC is advancing the next generation of climate projections and analytics to develop decision-relevant parameters for state agencies and energy sector stakeholders. State-funded climate research has also informed the state's Climate Change Assessments, which provide a scientific foundation for understanding climate-related vulnerabilities. California's Fifth Climate Change Assessment is anticipated for release before the 2025 SB 100 update.

Through its ongoing climate adaptation rulemaking (R.18.04-019), the CPUC has directed the IOUs to develop vulnerability assessments every four years, including anticipated climate change impacts to utility operations, services, and assets, over a 20–30-year horizon. The IOUs will also provide options to address identified vulnerabilities. A key part of the IOUs' development of the vulnerability assessment is deep engagement with disadvantaged vulnerable communities.

Microgrids to Support Resilience

In addition to taking steps to better understand worsening climate impacts to the electric system, state agencies are exploring options for backup power when there are disruptions to the grid. Clean energy microgrids have emerged an important alternative to fossil fuel backup generators, which degrade air quality and emit greenhouse gases. However, like all backup power solutions, clean energy microgrids have limitations, particularly in how long they can keep the power on and the associated relatively high cost. State efforts[173] are underway to

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172 Bruzgul, Judsen, Robert Kay, Andy Petrow, Tommy Hendrickson, Beth Rodehorst, David Revell, Maya Bruguera, Dan Moreno, Ken Collison. (ICF and Revell Coastal). 2018. *[Rising Seas and Electricity Infrastructure: Potential Impacts and Adaptation Actions for San Diego Gas & Electric]()*. California's Fourth Climate Change Assessment, California Energy Commission. Publication Number: CCCA4-CEC- 2018-004. https://www.energy.ca.gov/sites/default/files/2019-11/Energy_CCCA4-CEC-2018-004_ADA.pdf.

173 Through EPIC, the CEC has awarded more than $90 million grants to fund nearly 45 microgrid projects across a diverse range of applications. The CEC's *2020 IEPR Update* (planned for release in early 2021) will outline key findings from the state's microgrid research efforts. Through Rulemaking 19-09-009, the CPUC is

explore technological and economic improvements to microgrids and assess the strategic deployment of microgrids as a resilience asset.

Addressing Barriers to Project Development

The initial SB 100 analysis indicates that several resources that have lengthy permitting requirements or development times will be necessary to meet the SB 100 2045 target of 100 percent clean electricity. Offshore wind, long-duration storage, and resources dependent on new transmission, such as out-of-state wind, require significant time between the initial identification of need and interconnection. All these resources may require up to 10 years from permitting to completion. Furthermore, large, long lead-time projects may require multiple off-takers because of the necessary size of the project.

New transmission will also be necessary to achieve the large resource builds needed to meet the SB 100 goals. While California has historically taken a proactive approach to transmission planning for renewable energy goals, it will be necessary to continue to identify appropriate development sites years in advance of when resources will be needed. One key challenge with transmission development is aligning planning between relevant entities. SB 100 is a state energy policy, but project implementation is a local process and must address local resource values. Today, most of California's local jurisdictions are not equipped with plans achieve the state's energy goals. To reach 100 percent clean electricity by 2045, a unified planning process for developing utility-scale energy projects and the respective transmission lines must be considered.

Collaboration Across Western States

As described in Chapter 1, California is part of a larger integrated electricity system in the western United States called the Western Interconnection, which includes all or parts of 14 western states as well as Alberta, British Columbia, and Baja California. Regional coordination is a key component of California's strategy to realize its renewable energy and GHG emission reduction goals. With other states in the West also adopting higher clean energy goals or standards,[174] opportunities exist for increased coordination and market development that can take advantage of the geographic diversity of loads and resources

Coordination offers significant potential to ease importation and integration of additional renewable energy facilities in regions where resource attributes match or complement California's seasonal and daily operational needs. Much of this coordination follows naturally

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assessing microgrid-related actions to reduce the impact of outages associated with public safety power shutoffs or unplanned grid failures. In the longer term, the rulemaking will consider a wider range of microgrid and resilience issues.

174 For details on states with clean energy or renewable goals or standards, see the [Link to the Center for Climate and Energy Solutions State Climate Policy Maps Web page](https://www.c2es.org/content/state-climate-policy/) (https://www.c2es.org/content/state-climate-policy/) or the [Clean Energy States Alliance (CESA) 100% Clean Energy Collaborative Web page](https://www.cesa.org/projects/100-clean-energy-collaborative/table-of-100-clean-energy-states/) (https://www.cesa.org/projects/100-clean-energy-collaborative/table-of-100-clean-energy-states/).

from peak load diversification; the Northwest peaks in winter, and the rest of the West in summer, allowing each region to rely on the other for a share of its seasonal peak capacity needs. Regional coordination also provides for geographic diversification in renewable energy, allowing for more consistent supply.

The Western Energy Imbalance Market (EIM) serves as the primary platform for interstate coordination across the west. The EIM (described in more detail in Chapter 1) is a real-time wholesale energy trading market that enables participants anywhere in the West to buy and sell energy when needed. This market has proven successful in producing cost savings and reducing renewables curtailment for all Western participants. For instance, when one utility area has excess hydroelectric, solar or wind power, the market optimizes delivery to market participants within the EIM footprint to help meet demands that would otherwise be met by more expensive — and less clean — energy resources.

There are opportunities to build on the success of the EIM and unlock additional benefits associated with increased regional coordination. As successful and valuable as the real-time EIM has been, it is only the tip of the iceberg to unlocking the potential benefits associated with increased regional coordination. There is growing interest in extending the California ISO's day-ahead market to include Western EIM entities on a voluntary basis. To that end, the California ISO launched its Extended Day-Ahead Market (EDAM) Initiative to develop an approach to extend participation in the day-ahead market to EIM entities. The EDAM initiative, which is still in its early stages, would aim to improve renewable integration and market efficiency through day-ahead scheduling and unit commitment across a larger area.

California's continued engagement with regional entities — including the Western Electricity Coordinating Council, Western Interstate Energy Board, Western Interconnection Regional Advisory Board, and Western Governors' Association — is critical to ensuring that California's energy policies and interests are represented in efforts related to reliability, transmission planning, market development, and other issues of interest to states and provinces in the West.

CHAPTER 5: Recommendations

Following the results of the 2021 Report analysis and comments from stakeholders and the public, the joint agencies propose key recommendations for near- and medium-term actions to support the implementation of SB 100 and inform long-term planning. The recommendations highlight areas for further analysis and additional actions to support the successful implementation of the 100 percent policy. For further discussion on these topics, please refer to Chapter 4.

This report does not contain specific recommendations for guidelines and compliance related to a 100 percent clean electricity program. Instead, the joint agencies pose the following for consideration as part of the ongoing efforts that agencies undertake, both in the context of future SB 100 reports and in other existing planning processes, to plan for a 100 percent renewable and zero-carbon electricity grid. Separately and in parallel, the CPUC will also continue to analyze the 2045 goal in its ongoing IRP modeling so that decisions about near-to-medium term portfolio selection and GHG target setting can be informed by the long-term needs of SB 100.

Areas for Further Study in the 2025 SB 100 Report

1. **Perform a comprehensive reliability assessment as the next step in the modeling process.**

   The analytical portion of this report includes capacity expansion modeling, which provides possible resource portfolios that meet the requirements of SB 100. The next step in this process is to perform additional modeling to ensure the projected portfolios meet system reliability requirements. This modeling may be an iterative process to arrive at resource portfolios that meet all requirements. The CEC and CPUC recommend using deterministic production cost modeling to assess operability across all hours of a selected modeled year or years, as well as probabilistic production cost modeling to assess system reliability through metrics such as loss of load probability.

   This step could be completed as part of the 2025 SB 100 Report, or possibly through existing state efforts. The CEC and CPUC are assessing resource availability to complete this modeling ahead of the next report. The joint agencies will continue to consult with the California balancing authorities when developing the tools and metrics for this analysis to best represent their respective areas.

2. **Continue to assess the role and impacts of emerging technologies and nongeneration resources.**

   Modeling inputs and assumptions should be updated in future analyses to reflect market changes in existing and emerging technologies, including changes in price, the commercialization of new technologies, and updates to total resource potential. Furthermore, the joint agencies should continue to evaluate and consider ways to better assess the impacts of less-proven technologies that could have a significant impact to a 2045 resource mix and total cost. This work will build off the “generic” zero-carbon firm resources included in the study scenarios to explore the projected impact of technologies that can achieve specific price milestones. These technologies could include green hydrogen combustion, lower-cost geothermal resources, and gas with carbon capture and sequestration (CCS), among other emerging technologies.

Similarly, future modeling should aim to capture the value of hybrid resources and key nongeneration resources, such as long-duration energy storage, behind-the-meter energy storage, and demand flexibility, which can significantly alter the generation capacity needs in 2045.

3. **Analyze projected land-use impacts of scenarios and opportunities to address environmental impacts.**

   Work to better quantify the carbon stored in natural and working lands is continuing across state agencies, but given the long timelines to change landscapes, actions to manage, restore, and conserve these lands must be incorporated into electricity land-use planning to complement climate measures. Closer collaboration with other state agencies, tribal governments, local and regional jurisdictions, and stakeholders to plan for development will be important to balance the clean electric grid infrastructure needs of the built environment while supporting and investing in efforts to restore, conserve, and strengthen natural and working lands.

   The CEC is developing tools to assess the total land area required to implement SB 100 and the potential areas across the state where new resources could be located. This work can expand to understand how land use impacts vary across scenarios, assess the relative environmental impacts in different areas, and identify strategies to avoid or mitigate environmental impacts and maximize environmental cobenefits. The CPUC’s inclusion of land-use screens in the upcoming IRP cycle will also inform state-wide land-use planning.

4. **Define and include social costs and non-energy benefits (NEBs) in future analyses.**

   The joint agencies will continue evaluating available modeling tools and metrics to capture non-energy benefits and social costs in future SB 100 analyses. Stakeholders including the DACAG and environmental justice, equity, and health organizations representing communities throughout the state recommended the inclusion of at least the following NEBs and social costs, which will be included as appropriate:

   - Land-use impacts
   - Public health and air quality

- Water supply and quality
- Economic impacts
- Resilience

The modeling tools used for the analysis in this report do not provide information regarding where generation resources will be located nor data on when and how specific resources will be used. This higher-resolution information needed to meaningfully address the topics above, requires using additional tools and metrics to better understand localized impacts of the 100 percent policy. To this end, the joint agencies plan to continue engaging with the DACAG SB 100 subcommittee and other stakeholders to explore opportunities to better integrate these topics into future analyses. CARB has also already begun work to assess local air pollution impacts associated with climate action. The 2022 Scoping Plan Update will include quantified benefits associated with climate action, specifically less combustion of fossil fuels.

5. **Continue to study opportunities and impacts related to achieving the 100 percent clean electricity target prior to 2045.**

   The joint agencies plan to continue analysis of the 2030, 2035, and 2040 scenarios in future SB 100 report analyses.

Process and Engagement for SB 100 Reports

6. **Convene an annual joint-agency SB 100 workshop in years between reports.**

   Hosting an annual workshop will support alignment between agencies on relevant topics and proceedings and enhance continuity between SB 100 reports. These workshops will also provide an opportunity for joint agency leadership and staff to hear from stakeholders and the public on topics related to SB 100 progress.

7. **Align future SB 100 planning with findings and outcomes from relevant state efforts.**

   The joint agencies aim to incorporate findings and outcomes from other relevant efforts in future SB 100 reports. Relevant efforts include:

   - The CEC's energy demand forecasts, including electrification trends and updates for extreme climate event planning.
   - Transmission planning and development.
   - Reliability planning, including possible updates to resource adequacy requirements.
   - Electric system resilience planning.
   - Assessments from CPUC's Integrated Resource Planning, CEC's Integrated Energy Policy Report, and CARB's Scoping Plan.

8. **Consult with advisory groups to guide equitable planning and implementation.**

   For the 2021 Report, the joint agencies engaged with the DACAG, the advisory body to the CEC and CPUC on clean energy matters, through its SB 100 subcommittee, and other environmental justice, health and equity stakeholders. These groups provided valuable input on the scope of the report, key findings, and considerations for ongoing analyses.

   For the 2025 SB 100 Report, the joint agencies plan to continue collaborating with the DACAG and other equity stakeholders, as well as the Environmental Justice Advisory Committee (EJAC), CARB's advisory body on climate change efforts. DACAG and EJAC are essential liaisons that should convene and coordinate to help ensure SB 100-related efforts benefit all Californians, particularly those in disadvantaged and low-income communities.

9. **Retain and expand upon best practices for community outreach and accessibility.**

   The joint agencies worked to ensure broad access to the 2021 Report process by holding workshops across the state; conducting significant outreach by phone, email listservs, and social media; and offering remote attendance options for all workshops. For future SB 100 reports (every four years), the agencies will retain these best practices while exploring additional methods to maximize participation and access to meeting information and materials for California residents. Specific best practices and recommendations for development of future SB 100 reports include the following:

   - Continue to host workshops in different sites throughout the state to engage with more geographically diverse communities.
   - Continue to promote outreach to state legislators and their constituents, particularly around meetings held in their districts.
   - Build closer partnerships with local governments on workshop outreach and continue to find meeting sites that are trusted and accessible to communities, such as spaces frequently used by community-based organizations and residents.
   - Broaden engagement with tribal governments, particularly on efforts related to land-use planning.
   - Continue to use accessible virtual platforms for all meetings, including those with an in-person attendance option and tailor workshops to accommodate community logistical needs.

Supporting Achievement of the 100 Percent Target

10. **Continue state support for research and innovation in clean energy technologies.**

    While the SB 100 target is achievable with existing technologies, continued investments in research and innovation can accelerate technology performance and cost improvements that can make progress easier and faster and reduce costs to electricity ratepayers. The Electric Program Investment Charge (EPIC) — California's flagship electricity R&D program — invests $130 million annually to support the development of emerging clean energy technologies. In August 2020, the CPUC reauthorized EPIC for another $1.5 billion over the next decade.

    Moving forward, EPIC will continue to catalyze advancements to support the cost-effective implementation of SB 100 in areas including renewable and zero-carbon generation, long-duration energy storage, energy efficiency, and load flexibility. Further, the EPIC-funded California Energy Innovation Ecosystem connects clean energy entrepreneurs with the funding, training, resources, and expertise needed to help turn concepts into products that benefit consumers, companies, and utilities. This ongoing collaboration with cleantech incubators, research labs, and private investment firms will be critical to best leverage state funding in innovation.

11. **Continue to prioritize energy efficiency and load flexibility to minimize total implementation costs.**

    In 2003, the state established a loading order policy that directs that California's energy demands be met first by efficiency and demand response before new generation is considered. Prioritizing cost-effective energy efficiency and load flexibility measures remains critical as the state moves toward a 100 percent clean electricity future. Taking steps to reduce energy demand can offset the need for additional generation capacity, saving Californians money, while reducing land use and other environmental impacts associated with the construction of new facilities.

12. **Identify and address bottlenecks in project permitting and development.**

    Numerous stakeholders highlighted barriers that can slow planning and construction of projects, such as permitting delays and long lead times for transmission projects. Because SB 100 implementation will require sustained record-setting construction rates, these barriers need to be addressed early and comprehensively. The CEC and CPUC should engage with stakeholders — including developers, utilities, balancing authorities, local governments, and community organizations — to better understand the specific barriers to project development and advance strategies to address them.

13. **Promote workforce development programs that focus on high-quality job creation.**

    Implementation of SB 100 creates a significant opportunity to support California companies, benefit local economies, and create family-sustaining jobs while optimizing climate outcomes. The joint agencies should continue collaborating with the California Workforce Development Board (CWDB) and other stakeholders to identify strategies and best practices to support an equitable clean energy workforce and high-quality job creation. The agencies can also seek the expertise of the DACAG's workforce subcommittee. As a starting point, the joint agencies shall consider the takeaways from the CWDB's 2020 report, *Putting California on the High Road*,[175] including the following:

- Labor should be considered an investment rather than a cost, as well-trained workers are key to delivering emissions reductions and moving California closer to its climate targets.
- Identifying high-quality careers that offer family-supporting wages, employer-provided benefits, worker voice, and opportunities for advancement, along with building pathways into such careers, is critical to ensuring investments in workforce education and training meaningfully improve workers' economic mobility.
- Deliberate policy interventions are necessary to advance job quality and social equity as California transitions to a carbon-neutral economy.

175 UC Berkeley Labor Center. *Putting California on the High Road: A Jobs and Climate Action Plan for 2030*. June 2020. https://laborcenter.berkeley.edu/wp-content/uploads/2020/09/Putting-California-on-the-High-Road.pdf.

APPENDIX A: Acronyms and Abbreviations

AB – Assembly Bill

ATB – Annual Technology Baseline

BA – balancing authority

BANC – Balancing Authority of Northern California

BOEM – Bureau of Ocean Energy Management

BTM – behind-the-meter

BUILD – Building Initiative for Low-Emissions Development

CalFlexHub – California Flexible Load Research and Deployment Hub

California ISO – California Independent System Operator

CARB – California Air Resources Board

CCA – Community choice aggregation

CCGT – combined cycle gas turbine

CCS – carbon capture and sequestration

CEC – California Energy Commission

CESA – Clean Energy States Alliance

CHP – combined heat and power

CNG – compressed natural gas

CNRA – California Natural Resources Agency

CO_2 – carbon dioxide

COVID-19 – Coronavirus Disease 2019

CPUC – California Public Utilities Commission

CREPC – Committee on Regional Electric Power Cooperation

CSP – concentrating solar power

CT – combustion turbine

CWDB – California Workforce Development Board

DACAG – Disadvantaged Communities Advisory Group

DR – demand response

DRECP – Desert Renewable Energy Conservation Plan

DWR – California Department of Water Resources

E3 – Energy and Environmental Economics, Inc.

EDAM – extended day-ahead market

EE – energy efficiency

EIM – Western Energy Imbalance Market

EJAC – Environmental Justice Advisory Committee

ELCC – effective load-carrying capacity

EO – executive order

EPIC – Electric Program Investment Charge

ESP – electric service provider

EV – electric vehicle

FERC – Federal Energy Regulatory Commission

GDP – gross domestic product

GHG – greenhouse gas

GW – gigawatt

GWh – gigawatt-hours

HVAC – heating, ventilation, and air conditioning

IEPR – Integrated Energy Policy Report

IID – Imperial Irrigation District

IOU – investor-owned utility

IRP – integrated resource plan

IWG – Interagency Working Group on the Social Cost of Greenhouse Gases

kW – kilowatt

kWh – kilowatt-hour

LADWP – Los Angeles Department of Water and Power

LBNL – Lawrence Berkeley National Laboratory

LCOE – levelized cost of energy

LOLE – loss of load expectation

LOLP – loss of load probability

LSE – load-serving entity

MMT – million metric tons

MMT CO_2e – million metric tons of carbon dioxide equivalent

MW – megawatt

MWh - megawatt-hour

NEB – non-energy benefit

NERC - North American Electric Reliability Corporation

NO_X – oxides of nitrogen

NRDC – Natural Resources Defense Council

NREL - National Renewable Energy Laboratory

O&M – operations and maintenance

OOS – out-of-state

OSW – offshore wind

PAH – polycyclic aromatic hydrocarbon

PG&E – Pacific Gas and Electric

PM – particulate matter

PM2.5 – fine inhalable particles with diameters that are generally 2.5 micrometers and smaller

POU – publicly owned utility

PSPS – public safety power shutoff

PV – photovoltaic

R&D – research and development

RA – resource adequacy

RC – reliability coordinator

RETI – Renewable Energy Transmission Initiative

ROW – right-of-way

RPS – Renewables Portfolio Standard

SB – Senate bill

SC-CO_2 – social cost of carbon

SCE – Southern California Edison

SDG&E – San Diego Gas & Electric

SGIP – Self-Generation Incentive Program

SMUD – Sacramento Municipal Utility District

SoCalGas – Southern California Gas Company

SOx – oxides of sulfur

SWRCB – State Water Resources Control Board

TECH – Technology and Equipment for Clean Heating

TID – Turlock Irrigation District

TPP – Transmission Planning Process

TRC – total resource cost

UCLA – University of California, Los Angeles

USEPA – United States Environmental Protection Agency

USGCRP – United States Global Change Research Program

VGI – vehicle-grid integration

WECC – Western Electricity Coordinating Council

WGA – Western Governors Association

WHO – World Health Organization

WIEB – Western Interstate Energy Board

WIRAB – Western Interconnection Regional Advisory Board

ZEV – zero emission vehicle

APPENDIX B: Glossary

For additional information on commonly used energy terminology, see the following industry glossary links:

- California Air Resources Board Glossary, available at https://ww2.arb.ca.gov/about/glossary
- California Energy Commission Energy Glossary, available at https://www.energy.ca.gov/resources/energy-glossary
- California Energy Commission Renewables Portfolio Standard Eligibility Guidebook, Ninth Edition Revised, available at: https://efiling.energy.ca.gov/getdocument.aspx?tn=217317
- California Independent System Operator Glossary of Terms and Acronyms, available at: http://www.caiso.com/Pages/glossary.aspx
- California Public Utilities Commission Glossary of Acronyms and Other Frequently Used Terms, available at https://www.cpuc.ca.gov/glossary/
- Federal Energy Regulatory Commission Glossary, available at https://www.ferc.gov/about/what-ferc/about/glossary
- North American Electric Reliability Corporation Glossary of Terms Used in NERC Reliability Standards, available at: https://www.nerc.com/pa/Stand/Glossary%20of%20Terms/Glossary_of_Terms.pdf
- US Energy Information Administration Glossary, available at: https://www.eia.gov/tools/glossary/

Adaptation

In human systems, the process of adjustment to actual or expected climate and its effects, in order to moderate harm or exploit beneficial opportunities. In natural systems, the process of adjustment to actual climate and its effects; human intervention may facilitate adjustment to expected climate and its effects.

Ancillary services

Ancillary services include regulation, spinning reserve, non-spinning reserve, voltage support and black start, together with such other interconnected operation services as the California ISO may develop in cooperation with market participants to support the transmission of energy from generation resources to loads while maintaining reliable operation of the CAISO controlled grid in accordance with Western Electricity Coordinating Council standards and good utility practice.

Balancing authority

A balancing authority is the responsible entity that integrates resource plans ahead of time, maintains load-interchange-generation balance within a balancing authority area, and supports interconnection frequency in real time. Balancing authorities in California include the Balancing Authority of Northern California (BANC), California ISO, Imperial Irrigation District (IID), Turlock Irrigation District (TID) and Los Angeles Department of Water and Power (LADWP). The California ISO is the largest of about 38 balancing authorities in the Western Interconnection, handling an estimated 35 percent of the electric load in the West. For more information, see the WECC Overview of System Operations: Balancing Authority and Regulation Overview Web page.

Biodiversity

Biological diversity means the variability among living organisms from all sources, including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems.

Bioenergy

Energy derived from any form of biomass or its metabolic by-products.

Biogas

Biogas is a type of biofuel that is naturally produced from the decomposition of organic waste (such as food scraps) and includes methane, carbon dioxide, and other gases. Biofuels differ from fossil fuels because a biofuel is fuel from recently living biological matter, where fossil fuels come from long dead biological matter.

Biomass

Biomass energy resources are derived from organic matter. These include wood, agricultural waste and other living-cell material that can be burned to produce heat energy. They also include algae, sewage and other organic substances that may be used to make energy through chemical processes.

Capacity expansion modeling

Capacity expansion modeling analyzes different resource investment options over a planning horizon. The model identifies the least cost resource investments, given the policy and reliability constraints. Due to the large number of resources that can be selected by the model, simplifications are necessary. These simplifications can include, only modeling characteristic days for each year, simplified power plant operating characteristics, and simplified transmission networks. For more information, see the US Department of Energy Overview of Power Sector Modeling.

Cap-and-Trade Program

The Cap-and-Trade Program is a key element of California's strategy to reduce greenhouse gas (GHG) emissions. It complements other measures to ensure that California cost-effectively meets its goals for GHG emissions reductions. The Cap-and-Trade Regulation establishes a declining limit on major sources of GHG emissions throughout California, and it creates a powerful economic incentive for significant investment in cleaner, more efficient technologies. The Program applies to emissions that cover approximately 80 percent of the State's GHG emissions. CARB creates allowances equal to the total amount of permissible emissions (i.e., the "cap"). One allowance equals one metric ton of carbon dioxide equivalent emissions (using the 100-year global warming potential). Each year, fewer allowances are created and the annual cap declines. An increasing annual auction reserve (or floor) price for allowances and the reduction in annual allowances creates a steady and sustained carbon price signal to prompt action to reduce GHG emissions. All covered entities in the Cap-and-Trade Program are still subject to existing air quality permit limits for criteria and toxic air pollutants. For more information, see the CARB Cap-and-Trade Program Web page.

Carbon capture and sequestration (CCS)

A process in which a relatively pure stream of carbon dioxide (CO_2) from industrial and energy-related sources is separated (captured), conditioned, compressed and transported to a storage location for long-term isolation from the atmosphere. For more information, see the CARB Carbon Capture & Sequestration Web page.

Carbon dioxide (CO_2)

A naturally occurring gas, CO_2 is also a by-product of burning fossil fuels (such as oil, gas and coal), of burning biomass, of land-use changes, and of industrial processes (for example, cement production). It is the principal anthropogenic greenhouse gas (GHG) that affects the Earth's radiative balance. It is the reference gas against which other GHGs are measured and therefore has a global warming potential (GWP) of 1.

Carbon neutrality

Carbon dioxide and other greenhouse gas (GHG) emissions generated by sources such as transportation, power plants, and industrial processes must be less than or equal to the amount of carbon dioxide that is stored, both in natural sinks such as forests and mechanical sequestration such as carbon capture and sequestration. Executive order B-55-18 established a target for California to achieve carbon neutrality by 2045 and maintain net negative emissions thereafter. For more information, see the CARB Carbon Neutrality Web Page.

Carbon price

The price for avoided or released carbon dioxide (CO_2) or CO_2-equivalent emissions. This may refer to the rate of a carbon tax or the price of emission permits. In many models that are used to assess the economic costs of mitigation, carbon prices are used as a proxy to represent the level of effort in mitigation policies.

Carbon sink

A reservoir (natural or human, in soil, ocean, and plants) where a greenhouse gas, an aerosol or a precursor of a greenhouse gas is stored.

Climate

Climate in a narrow sense is usually defined as the average weather, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period for averaging these variables is 30 years, as defined by the World Meteorological Organization. The relevant quantities are most often surface variables such as temperature, precipitation and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.

Climate adaptation

A growing body of new policies — referred to as “climate adaptation” — is intended to grapple with what is known from climate science and incorporate planning for climate change into the routine business of governance, infrastructure management, and administration.

Climate change

Climate change refers to a change in the state of the climate that can be identified (for example, by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use. **Anthropogenic** climate change is defined by the human impact on Earth's climate while **natural** climate change are the natural climate cycles that have been and continue to occur throughout Earth's history. Anthropogenic (human-induced) climate change is directly linked to the amount of fossil fuels burned, aerosol releases, and land alteration from agriculture and deforestation. For more information, see the Energy Education Natural vs Anthropogenic Climate Change Web page.

Climate Change Scoping Plan

CARB’s 2022 Scoping plan Update will provide an actionable, cost-effective, and technologically feasible path to achieve economy-wide carbon neutrality by 2045. For more information, see the CARB AB 32 Climate Change Scoping Plan Web page.

CO_2 equivalent (CO_2-e) emissions

The amount of carbon dioxide (CO_2) emissions that would cause the same integrated radiative forcing or temperature change, over a given time horizon, as an emitted amount of a greenhouse gas (GHG) or a mixture of GHGs. There are a number of ways to compute such equivalent emissions and choose appropriate time horizons. Most typically, the CO_2-equivalent emission is obtained by multiplying the emission of a GHG by its global warming potential (GWP) for a 100-year time horizon. For a mix of GHGs it is obtained by summing the CO_2-equivalent emissions of each gas. CO_2-equivalent emission is a common scale for comparing emissions of different GHGs but does not imply equivalence of the corresponding climate change responses. There is generally no connection between CO_2-equivalent emissions and resulting CO_2-equivalent concentrations.

Community choice aggregation (CCA)

Community choice aggregation (or CCA) lets local jurisdictions aggregate, or combine, their electricity load to purchase power on behalf of their residents. In California, community choice aggregators are legally defined by state law as electric service providers and work together with the region's existing utility, which continues to provide customer services (for example, grid maintenance and power delivery). For more information see What Is CCA? or Community Choice Is Transforming the California Energy Industry.

Decarbonization

The process by which countries, individuals or other entities aim to reduce or achieve zero fossil carbon emissions. Typically refers to a reduction of the carbon emissions associated with electricity, industry and transport.

Demand response (DR)

Demand response refers to providing wholesale and retail electricity customers with the ability to choose to respond to time-based prices and other incentives by reducing or shifting electricity use ("shift DR"), particularly during peak demand periods, so that changes in customer demand become a viable option for addressing pricing, system operations and reliability, infrastructure planning, operation and deferral, and other issues. It has been used traditionally to shed load in emergencies ("shed DR"). It also has the potential to be used as a low-greenhouse gas, low-cost, price-responsive option to help integrate renewable energy and provide grid-stabilizing services, especially when multiple distributed energy resources are used in combination and opportunities to earn income make the investment worthwhile.

For more information, see the CPUC Demand Response Web page.

Disadvantaged community

Disadvantaged communities refer to the areas throughout California which most suffer from a combination of economic, health, and environmental burdens. These burdens include poverty, high unemployment, air and water pollution, presence of hazardous wastes, as well as high incidence of asthma and heart disease. One way that the state identifies these areas is by collecting and analyzing information from communities all over the state. CalEnviroScreen, an analytical tool created by the California Environmental Protection Agency, combines different types of census tract-specific information into a score to determine which communities are the most burdened or "disadvantaged." For more information, see the California Office of Environmental Health Hazard Assessment's CalEnviroScreen Web page.

Disadvantaged Communities Advisory Group (DACAG)

The Clean Energy and Pollution Reduction Act of 2015 (also known as Senate Bill 350) called upon the CPUC to help improve air quality and economic conditions in disadvantaged communities by, for example, changing the way the state plans the development and future operations of power plants, or rethinking the location of clean energy technologies to benefit burdened communities. Additionally, Senate Bill 350 required the CPUC and the CEC to create a group representing disadvantaged communities to advise the agencies about in understanding how energy programs impact these communities and could be improved to benefit these communities.

For more information, see the CPUC Disadvantaged Communities Advisory Group Web page.

Distributed energy resources (DER)

Distributed energy resources are any resource with a first point of interconnection of a utility distribution company or metered subsystem. Distributed energy resources include:

- Demand response, which has the potential to be used as a low-greenhouse gas, low-cost, price-responsive option to help integrate renewable energy and provide grid-stabilizing services, especially when multiple distributed energy resources are used in combination and opportunities to earn income make the investment worthwhile.
- Distributed renewable energy generation, primarily rooftop photovoltaic energy systems.
- Vehicle-Grid Integration, or all the ways plug-in electric vehicles can provide services to the grid, including coordinating the timing of vehicle charging with grid conditions.
- Energy storage in the electric power sector to capture electricity or heat for use later to help manage fluctuations in supply and demand.

Effective load carrying capability (ELCC)

Effective load carrying capability" (ELCC) is the increment of load that could met by the resource while maintaining the same level of reliability. The ELCC of a variable renewable energy resource is based on both the capacity coincident with peak load and the profile and quantity of existing variable renewable energy resources. For a detailed description of ELCC implementation in RESOLVE, see page 87 of the Inputs & Assumptions: CEC SB100 Joint Agency Report.

Electric Program Investment Charge Program (EPIC)

The California Energy Commission's Electric Program Investment Charge (EPIC) program invests in scientific and technological research to accelerate the transformation of the electricity sector to meet the state's energy and climate goals. The EPIC program invests more than $130 million annually in areas including renewable energy, energy storage, electric system resilience, and electric technologies for buildings, businesses, and transportation. For more information, see the CEC Electric Program Investment Charge Program Web page and the CPUC Energy Research, Development & Deployment Web page.

Electric service provider (ESP)

An electric service provider is a company that purchases wholesale electricity from electricity generators and sells it at a retail level to the general public.

Electrolyzer

A device that breaks a chemical compound down into its elements by passing a direct current through it. Electrolysis of water, for example, produces hydrogen and oxygen.

Energy efficiency

Energy efficiency means adapting technology to meet consumer needs while using less energy. The CEC adopts energy efficiency standards for appliances and buildings, which reduces air pollution and saves consumers money. The CPUC regulates ratepayer-funded energy efficiency programs and works with the investor-owned utilities, other program administrators, and vendors to develop programs and measures to transform technology markets within California using ratepayer funds. For more information, see the CEC Energy Efficiency Web page and the CPUC Energy Efficiency Web page.

Environmental justice

Environmental justice is the fair treatment of people of all races and incomes with respect to development, implementation and enforcement of environmental laws, regulations and policies.

Equity (Energy equity)

Energy equity is the principle of fairness in burden sharing and is a basis for understanding how the impacts and responses to climate change, including costs and benefits, are distributed in and by society in more or less equal ways. It is often aligned with ideas of equality, fairness and justice and applied with respect to equity in the responsibility for, and distribution of, climate impacts and policies across society, generations, and gender, and in the sense of who participates and controls the processes of decision-making.

Extreme weather event

An extreme weather event is an event that is rare at a particular place and time of year. Definitions of rare vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations. By definition, the characteristics of what is called extreme weather may vary from place to place in an absolute sense. When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g., drought or heavy rainfall over a season).

Federal Energy Regulatory Commission (FERC)

The *Federal Energy Regulatory Commission*, also known as *FERC*, is an independent agency that regulates interstate transmission of electricity, oil, and natural gas. It also regulates natural gas and hydropower projects in the United States. For more information, see the Federal Energy Regulatory Commission Web page.

Fossil fuels

Carbon-based fuels from fossil hydrocarbon deposits, including coal, oil, and natural gas.

Fuel cell

An energy conversion device that combines hydrogen with oxygen in an electrochemical reaction to produce electricity. A fuel cell powered by **green hydrogen** is an RPS-eligible resource.

Generic firm baseload resource

For modeling purposes, a generic firm baseload resource is a zero-carbon generating technology that is intended to run continuously. Examples include low-cost geothermal or imports of emerging nuclear generation technologies.

Generic firm dispatchable resource

For modeling purposes, a generic firm dispatchable resource is a zero-carbon generating technology that can be dispatched as needed. Examples include natural gas with 100 percent carbon capture and sequestration or 100 percent drop-in renewable fuels.

Geothermal

Natural heat from within the earth, captured for production of electric power.

Green hydrogen

Green hydrogen means hydrogen gas that is not produced from fossil fuel feedstock sources and does not produce incremental carbon emissions during its primary production process.

Greenhouse gas (GHG)

Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, the atmosphere itself and by clouds. This property causes the greenhouse effect. Water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary GHGs in the Earth's atmosphere. Moreover, there are a number of entirely human-made GHGs in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Beside CO_2, N_2O and CH_4, the Kyoto Protocol deals with the GHGs sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs). In response to

Assembly Bill 32 (California Global Warming Solutions Act of 2006), the definition of greenhouse gases defined in Health and Safety Code section 38505 includes nitrogen trifluoride (NF3) in addition to those defined under the Montreal and Kyoto Protocols.

Hydroelectric (Large, Small)

A technology that produces electricity by using the kinetic energy of flowing or falling nonmarine water to turn a turbine generator.

A **large hydro facility** is an electrical generation facility employing one or more hydroelectric turbine generators, the sum capacity of which exceeds 30 megawatts. A large hydro facility is not RPS-eligible, but is a zero-carbon resource.

A **small hydro facility** is an electrical generation facility employing one or more hydroelectric turbine generators, the sum capacity of which does not exceed 30 megawatts except in the case of qualifying efficiency improvements under Public Utilities Code Section 399.12.5. A small hydro facility is an RPS-eligible resource.

Integrated Energy Policy Report (IEPR)

Senate Bill 1389 (Bowen, Chapter 568, Statutes of 2002) requires the California Energy Commission to prepare a biennial integrated energy report. The report, which is crafted in collaboration with a range of stakeholders, contains an integrated assessment of major energy trends and issues facing California's electricity, natural gas, and transportation fuel sectors. The report provides policy recommendations to conserve resources, protect the environment, ensure reliable, secure, and diverse energy supplies, enhance the state's economy, and protect public health and safety. For more information, see the CEC Integrated Energy Policy Report Web page.

Integrated Resource Planning (IRP)

The CPUC's Integrated Resource Planning (IRP) process is an "umbrella" planning proceeding to consider all of its electric procurement policies and programs and ensure California has a safe, reliable, and cost-effective electricity supply. The proceeding is also the Commission's primary venue for implementation of the Senate Bill 350 requirements related to IRP (Public Utilities Code Sections 454.51 and 454.52). The process ensures that load serving entities meet targets that allow the electricity sector to contribute to California's economy-wide greenhouse gas emissions reductions goals. For more information see the CPUC Integrated Resource Plan and Long-Term Procurement Plan (IRP-LTPP) Web page.

Investor-owned utility (IOU)

Investor-owned utilities (IOUs) provide transmission and distribution services to all electric customers in their service territory. The utilities also provide generation service for "bundled" customers, while "unbundled" customers receive electric generation service from an alternate provider, such as a Community Choice Aggregator (CCA). California has three large IOUs offering electricity service: Pacific Gas and Electric, Southern California Edison, and San Diego Gas & Electric.

Landscape-scale planning

Landscape-level approaches, also known as landscape-scale planning, take into consideration a wide range of potential constraints and conflicts, including environmental sensitivity, conservation and other land uses, tribal cultural resources, and more when considering future renewable energy development. The benefits of using landscape-level approaches for renewable energy and transmission planning include early identification and resolution of large issues or barriers to development, coordinated agency permitting processes, increased transparency in decision making, increased collaboration, avoidance of impacts, and more rapid deployment of environmentally responsible renewable energy projects.

Levelized cost of energy (LCOE)

The levelized cost of energy (LCOE) is a measure of the average net present cost of electricity generation for a generating plant over its lifetime. The LCOE is calculated as the ratio between all the discounted costs over the lifetime of an electricity generating plant divided by a discounted sum of the actual energy amounts delivered. The LCOE is used to compare different methods of electricity generation on a consistent basis. Inputs to LCOE typically include cost of capital, fuel costs, fixed and variable operations and maintenance costs, financing costs, and an assumed utilization rate.

Load serving entity (LSE)

A load serving entity is defined by the California Independent System Operator as an entity that has been "granted authority by state or local law, regulation or franchise to serve [their] own load directly through wholesale energy purchases." For more information see the California Independent System Operator's Web page.

Loss of load expectation (LOLE)

The expected number of days per year for which available generating capacity is expected to be insufficient to serve the daily peak demand (load). When given in hours/year, it represents a comparison of hourly load to available generation.

Loss of load probability (LOLP)

The proportion (probability) of days per year, hours per year or events per season that available generating capacity/energy is expected to be insufficient to serve the daily peak or hourly demand.

Methane (CH_4)

One of the six greenhouse gases (GHGs) to be mitigated under the Kyoto Protocol and is the major component of natural gas and associated with all hydrocarbon fuels. Emissions also occur as a result of dairy and livestock operations and disposal of organics in landfills, and their management represents a major mitigation option. Methane is a short-lived climate pollutant. Unlike CO_2, which lasts for about 100 years in the atmosphere, reductions of methane can create a relatively quick reduction in global warming.

Metric ton

A metric ton is a unit of weight equal to 1,000 kilograms (or 2,205 pounds).

Microgrid

A microgrid is an interconnected system of loads and energy resources, including, but not limited to, distributed energy resources, energy storage, demand response tools, or other management, forecasting, and analytical tools, appropriately sized to meet customer needs, within a clearly defined electrical boundary that can act as a single, controllable entity, and can connect to, disconnect from, or run in parallel with, larger portions of the electrical grid, or can be managed and isolated to withstand larger disturbances and maintain electrical supply to connected critical infrastructure. (Source: Senate Bill 1339)

Mitigation (of climate change)

A human intervention to reduce greenhouse gas emissions and/or enhance carbon sinks.

Mitigation measures

In climate policy, mitigation measures are technologies, processes or practices that contribute to mitigation, for example, renewable energy technologies, waste minimization processes and public transport commuting practices.

Negative GHG emissions

Removal of greenhouse gases (GHGs) from the atmosphere by deliberate human activities, i.e., in addition to the removal that would occur via natural carbon cycle processes.

Net load

Net load is electricity load minus solar and wind generation.

Net negative emissions

A situation of net negative emissions is achieved when, as result of human activities, more greenhouse gases are removed from the atmosphere than are emitted into it. Where multiple greenhouse gases are involved, the quantification of negative emissions depends on the climate metric chosen to compare emissions of different gases (such as global warming potential, global temperature change potential, and others, as well as the chosen time horizon).

Non-energy benefits (NEBs)

Non-energy benefits (NEBs) represent the benefits or positive impacts on society associated with the construction and operation of energy infrastructure and any associated activity. For more information, see Chapter 4.

Non-spinning reserves

The portion of resource capacity that is capable of being synchronized and ramping to a specified load in ten minutes (or that is capable of being interrupted in ten (10) minutes) and that is capable of running (or being interrupted) for at least thirty (30) minutes from the time it reaches its award capacity.

North American Electric Reliability Corporation (NERC)

The *North American Electric Reliability Corporation*, also known as *NERC*, is an international regulatory authority whose mission is to reduce risks to the reliability and security of the grid. Its area of responsibility spans the continental United States, Canada, and the northern part of Baja California, Mexico. For more information see the NERC Web page.

Nuclear (existing)

Electricity generated by the use of the thermal energy released from the fission of nuclear fuel in a reactor. Because the State effectively has a moratorium on new in-state nuclear power plants under the Warren-Alquist Act, only existing nuclear generating facilities are modeled. A nuclear facility is not RPS-eligible, but is a zero-carbon resource.

Offshore wind

Refers to an ocean-based (or other body of water) technology that converts energy from the environmental movement of air into mechanical energy and then electricity. Offshore wind turbine technologies include both fixed foundation and floating types.

Once-through cooling (OTC)

Once-through cooling technologies intake ocean water to cool the steam that is used to spin turbines for electricity generation. The technologies allow the steam to be reused, and the ocean water that was used for cooling becomes warmer and is then discharged back into the ocean. The intake and discharge have negative impacts on marine and estuarine environments. For more information on the phase-out of power plants in California using once-through cooling, see the Statewide Advisory Committee on Cooling Water Intake Structures Web page and the CEC Once-Through Cooling Phaseout Tracking Progress Report.

Onshore wind

Refers to a land-based technology that converts energy from the environmental movement of air into mechanical energy and then electricity.

Particulate matter

Any material, except pure water, that exists in the solid or liquid state in the atmosphere. The size of particulate matter can vary from coarse, wind-blown dust particles to fine particle combustion products.

PATHWAYS Model

The PATHWAYS model, developed by Energy and Environmental Economics, Inc (E3), is an economy-wide scenario tool used to identify pathways to achieve economy-wide decarbonization. For more information, see PATHWAYS Model.

Planning reserve margin (PRM)

Planning reserve margin (PRM) is used in resource planning to estimate the generation capacity needed to maintain reliability given uncertainty in demand and unexpected capacity outages. A typical PRM is 15% above the forecasted 1-in-2 weather year peak load, although it can vary by planning area.

Power flow modeling

Power flow modeling evaluates the flow of power on the electric grid. Power flow models provide a snapshot of transmission, generation and load and used to determine if the grid is stable and within operating limits for the case study. For more information see North American Transmission Forum's Power Flow Modeling Reference Document.

Precursors

Atmospheric compounds that are not greenhouse gases (GHGs) or aerosols, but that have an effect on GHG or aerosol concentrations by taking part in physical or chemical processes regulating their production or destruction rates.

Production cost modeling

Production cost modeling simulates least-cost dispatch given a set of generating resources, load, fuel prices and transmission and dispatch constraints. Production cost models can be run deterministically or probabilistically. Typically, a deterministic production cost model models all 8,760 hours of each year modeled with specified load and weather conditions. Typically, a probabilistic production cost model simulates the same system with changing inputs, such as load, weather, and generator outages to study how these changes impact the dispatch of the system. This approach can be used to determine the loss-of-load probability of the system.

Public safety power shutoff (PSPS)

A *public safety power shutoff*, also known as *PSPS*, is a system used by utilities to prevent wildfires by proactively turning off electricity when gusty winds and dry conditions present a heightened fire risk. More information can be found at the Prepare for Power Down Web page.

Publicly owned utility (POU)

Publicly owned utilities (POUs), or Municipal Utilities, are controlled by a citizen-elected governing board and utilizes public financing. These municipal utilities own generation, transmission and distribution assets. In contrast to CCAs, all utility functions are handled by these utilities. Examples include the Los Angeles Department of Water and Power and the Sacramento Municipal Utility District. Municipal utilities serve about 27 percent of California's total electricity demand.

Pumped Hydro

An energy storage technology consisting of two water reservoirs separated vertically; during off-peak hours, water is pumped from the lower reservoir to the upper reservoir, allowing the off-peak electrical energy to be stored indefinitely as gravitational energy in the upper reservoir. During peak hours, water from the upper reservoir may be released and passed through hydraulic turbines to generate electricity as needed.

Reliability coordinator

The entity designated by the Western Electricity Coordinating Council (WECC) as responsible for reliability coordination in real time for the area defined by WECC.

Renewables Portfolio Standard (RPS)

The *Renewables Portfolio Standard*, also referred to as *RPS*, is a program that sets continuously escalating renewable energy procurement requirements for California's load-serving entities. The generation must be procured from RPS-certified facilities (which include solar, wind, geothermal, biomass, biomethane derived from landfill and/or digester, small hydroelectric, and fuel cells using renewable fuel and/or qualifying hydrogen gas). More information can be found at the CEC Renewables Portfolio Standard web page and the CPUC RPS Web page.

Resilience

The capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure while also maintaining the capacity for adaptation, learning and transformation.

RESOLVE Model

The RESOLVE mode is a capacity expansion model developed by Energy and Environmental Economics, Inc. (E3). The tool identifies least-cost resource investments given a set of reliability and policy constraints. For more information, see the Inputs & Assumptions: CEC SB100 Joint Agency Report.

Resource adequacy (RA)

The program that ensures that adequate physical generating capacity dedicated to serving all load requirements is available to meet peak demand and planning and operating reserves, at or deliverable to locations and at times as may be necessary to ensure local area reliability and system reliability. For more information, see the CPUC Resource Adequacy Web page.

Resource build

Resource build is a set of generating, transmission and integration resources identified to meet future policy and reliability goals.

Scenario

A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key driving forces (for example, rate of technological change, prices) and relationships. Note that scenarios are neither predictions nor forecasts, but are used to provide a view of the implications of developments and actions.

This report includes three types of scenarios with different zero-carbon load coverage targets:

- The **60% RPS scenario** is based on 60 percent of retail sales
- The **SB 100 Core scenario** is based on 100 percent of retail sales and state loads.
- The **Study scenario** includes the Core loads plus system losses with High Electrification demand.

For more information, see Chapter 3.

Short-lived climate pollutant (SLCP)

A short-lived climate pollutant is an agent that has a relatively short lifetime in the atmosphere, from a few days to a few decades, and a warming influence on the climate that is more potent than that of carbon dioxide. (Source: Senate Bill 605)

Solar PV

A technology that uses a semiconductor to convert sunlight directly into electricity via the photoelectric effect.

Solar Thermal

The conversion of sunlight to heat and the related concentration and use to power a generator to produce electricity.

Solar-plus-storage

A *solar-plus-storage* project is a battery system that is charged by a connected solar system.

Spinning reserves

The portion of unloaded synchronized resource capacity that is immediately responsive to system frequency and that is capable of being loaded in ten (10) minutes, and that is capable of running for at least thirty (30) minutes from the time it reaches its award capacity.

Supply-side measures

Policies and programs for influencing how a certain demand for goods and/or services is met. In the energy sector, for example, supply-side mitigation measures aim at reducing the amount of greenhouse gas emissions emitted per unit of energy produced.

Sustainability

A dynamic process that guarantees the persistence of natural and human systems in an equitable manner.

Sustainable development

Development that meets the needs of the present without compromising the ability of future generations to meet their own needs and balances social, economic and environmental concerns.

Time-dependent electricity rates

Also known as time-of-use rates, time-dependent electricity rates vary depending on the time periods in which the energy is consumed. In a time-of-use rate structure, higher prices are charged during utility peak-load times. Such rates can provide an incentive for consumers to curb power use during peak times.

Total resource cost

Total resource cost (TRC) is the total cost of the system to meet the future policy and reliability goals. The TRC in the SB 100 scenarios includes non-modeled, existing costs which are the same across all scenarios, as well as scenario-specific non-modeled costs that vary by demand sensitivities. It also includes scenario-specific fixed costs, which are levelized capital investments associated with generation, transmission, storage and shed demand response resources selected in the model, as well as operating costs.

Transmission Planning Process (TPP)

The California Independent System Operator's annual transmission plan, which serves as the formal roadmap for infrastructure requirements. This process includes stakeholder and public input and uses the best analysis possible (including the Energy Commission's annual demand forecast) to assess short- and long-term transmission infrastructure needs. For more information, see the California ISO Transmission Planning Web page.

Utility-scale solar

A utility-scale solar power plant, using either photovoltaic [PV] or concentrating solar thermal technology, that sells its electricity to wholesale utility buyers. Often, utility-scale solar projects are described as being "in front of the meter" as opposed to small distributed generation systems, which tend to be "behind the meter."

Vehicle-grid integration

The term vehicle-grid integration or VGI, encompasses the ways EVs can provide grid services, including coordinating the timing of vehicle charging with grid conditions. To that end, EVs must have capabilities to manage charging or support two-way interaction between vehicles and the grid.

Western Electricity Coordinating Council (WECC)

The *Western Electricity Coordinating Council*, also known as *WECC*, is a nonprofit organization that works to address risks to the reliability and security of the Western Interconnection's power system. For more information, see the WECC Web page.

Western Energy Imbalance Market (EIM)

The *Western Energy Imbalance Market*, or Western EIM, is a real-time bulk power trading market. The Western EIM's systems automatically find the lowest-cost energy to serve customer demand across a wide geographic area in the western United States. For more information, see the Western Energy Imbalance Market Web page.

Western Governors Association (WGA)

The Western Governors' Association (WGA) is a non-partisan organization of all 22 United States Governors (representing 19 U.S. States and 3 U.S. territories) that are considered to be part of the Western region of the nation. The WGA addresses important policy and governance issues in the West, advances the role of the Western states in the federal system, and strengthens the social and economic fabric of the region. WGA develops policy and carries out programs in the areas of natural resources, the environment, human services, economic development, international relations and state governance. For more information, see the Western Governors Association Web page.

Western Interconnection (WI)

The *Western Interconnection* is a wide area synchronous grid. It is one of the two major alternating current power grids in the continental United States (the other is the Eastern Interconnection). For more information, see the WECC's Western Interconnection Web page.

Western Interconnection Regional Advisory Body (WIRAB)

The Western Interconnection Regional Advisory Body (WIRAB) was created by Western Governors under the Federal Power Act and focuses on electric grid reliability in the Western Interconnection. WIRAB advises the Electric Reliability Organization (North American Electric Reliability Corporation ["NERC"]), the regional entity (Western Electricity Coordinating Council ["WECC"]), and the Federal Energy Regulatory Commission ("FERC") on whether proposed reliability standards within the region, as well as the governance and budgets of NERC and WECC, are just, reasonable, not unduly discriminatory or preferential and in the public interest. WIRAB's membership is composed of member representatives from all states and International provinces that have load within the Western Interconnection. For more information, see the Western Interstate Energy Board's WIRAB Web page.

Western Interstate Energy Board (WIEB)

The *Western Interstate Energy Board* is an organization of 11 western states and three Canadian provinces. The Board promotes energy policy that is developed cooperatively among member states and provinces and with the federal government. For more information, see the Western Interstate Energy Board Web page.

Zero-carbon resource (for modeling purposes)

The joint agencies' interpretation of "zero-carbon resources," as stated in the SB 100 statute, includes generation resources that meet one or both of the following criteria. (This set of criteria is referred to as "RPS+" in SB 100 workshops and documents.)

- Meets the requirements for RPS-eligibility set forth in the most recent RPS Eligibility Guidebook.[176]
- Has zero onsite greenhouse gas emissions.[177]

For more information, see the 2021 Senate Bill 100 (SB 100) Joint-Agency Report Modeling Framework and Scenarios Overview.

Zero-emission vehicles (ZEVs)

There are three types of zero-emission vehicles:

- Battery-electric vehicles (BEVs) that refuel exclusively with electricity.
- Plug-in hybrid electric vehicles (PHEVs) that can refuel with either electricity or another fuel, typically gasoline. BEVs and PHEVs are collectively known as “plug-in electric vehicles,” or PEVs.
- Fuel cell electric vehicles (FCEVs) that refuel with hydrogen.

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176 California Energy Commission. *Renewables Portfolio Standard Eligibility Guidebook, Ninth Edition (Revised)*. Publication Number: CEC-300-2016-006-ED9-CMF-REV. January 2017. https://efiling.energy.ca.gov/getdocument.aspx?tn=217317.

177 For modeling purposes, this list does not acknowledge *de minimis* emissions associated with included technologies. SB 100 compliance programs would need to establish clear requirements for qualification as a zero-carbon generation resource.

APPENDIX C: Assumptions and Calculations to Estimate the Social Cost of Carbon in SB 100 Core Scenario

This appendix describes the assumptions and calculations employed to estimate the social cost of carbon associated with the SB 100 core scenario under high electrification demand.

Greenhouse Gas Reductions

The greenhouse gas (GHG) emissions reductions associated with implementation of SB 100 were estimated by taking the emissions difference between the 60 percent RPS and SB 100 core scenarios modeled under high electrification demand. The GHG emissions associated with in-state generation and unspecified imports are summarized in Table C-1 for year 2045.

Table C-1: Avoided GHG Emissions in 2045 from Core Scenario High Electrification Demand

Scenario	In-State, MT CO_2	Unspecified Imports*, MT CO_2	Total, MT CO_2
60% RPS	42,639,193	15,207,098	57,846,291
SB 100 core	18,423,033	6,574,439	24,997,472

*Unspecified imports use the emissions intensity of 0.428 MT CO_2 per MWh.

The total GHG emissions difference between the 60% RPS and SB 100 Core scenario is 32,848,819 MT CO_2.

Social Cost of Carbon Values

As described in Chapter 4, the social cost of carbon (SC-CO_2) estimates the value of damages avoided by reducing an additional ton of carbon dioxide (CO_2). These damages include, but are not limited to, changes in net agricultural productivity, energy use, human health, property damage from increased flood risk, as well as nonmarket damages, such as the services that natural ecosystems provide to society.

In 2009, the Council of Economic Advisors and the Office of Management and Budget convened the Interagency Working Group on the Social Cost of Greenhouse Gases (IWG) to develop a methodology for estimating the SC-CO_2. This methodology relied on a standardized range of assumptions and could be used consistently when estimating the benefits of regulations across agencies and around the world. The IWG, comprised of scientific and economic experts, recommended the use of SC-CO_2 values based on three integrated assessment models developed over decades of global peer-reviewed research, which are summarized in Table C-2.[178]

Table C-2: Social Cost of CO2, 2015-2050 (in 2007 dollars per metric ton CO2)

Year	5% Discount Rate	3% Discount Rate	2.5% Discount Rate
2015	$11	$36	$56
2020	$12	$42	$62
2025	$14	$46	$68
2030	$16	$50	$73
2035	$18	$55	$78
2040	$21	$60	$84
2045	$23	$64	$89
2050	$26	$69	$95

The IWG SC-CO_2 values are in 2007 dollars. These were translated into 2016 dollars using California Department of Finance consumer price index values for California and are shown in Table C-3.[179]

178 Additional documents relating to the IWG process, including iterations of the Technical Support Document for the Social Cost of Carbon for Regulatory Impact Analysis under Executive Order 12866 are available at the President Barack Obama White House Office of Management and Budget Social Cost of Greenhouse Gases Web page. https://obamawhitehouse.archives.gov/omb/oira/social-cost-of-carbon.

179 State of California, Department of Finance. Inflation: Consumer Price Index Web page. See Calendar Year averages: from 1950 available at: http://www.dof.ca.gov/Forecasting/Economics/Indicators/Inflation/ (version last updated January 2021).

Table C-3: Social Cost of CO2, 2015-2050 (in 2016 dollars per metric ton CO2)

Year	5% Discount Rate	3% Discount Rate	2.5% Discount Rate
2015	$12.92	$42.28	$65.76
2020	$14.09	$49.32	$72.81
2025	$16.44	$54.02	$79.85
2030	$18.79	$58.72	$85.73
2035	$21.14	$64.59	$91.60
2040	$24.66	$70.46	$98.64
2045	$27.01	$75.16	$104.52
2050	$30.53	$81.03	$111.56

Avoided Social Costs

The estimated avoided social cost of the SB 100 Core scenario compared to the 60% RPS scenario is calculated by multiplying the IWG SC-CO_2 values in Table C-3 for year 2045 at the 2.5, 3, and 5 percent discount rates by the GHG emissions difference in Table C-1. The social costs using these assumptions are shown in Table C-4 at the various discount rates.

For example, 32,848,819 MT CO_2 x $27.01/MT CO_2 = $887,236,053

Table C-4: Estimated Social Cost (Avoided Economic Damages)

Scenario	Social Cost of Carbon (2016 dollars) 5% Discount Rate	Social Cost of Carbon (2016 dollars) 3% Discount Rate	Social Cost of Carbon (2016 dollars) 2.5% Discount Rate
SB 100 core, high electrification demand	$887,236,053	$2,468,830,755	$3,433,217,769

Building Permits Update: April 2021

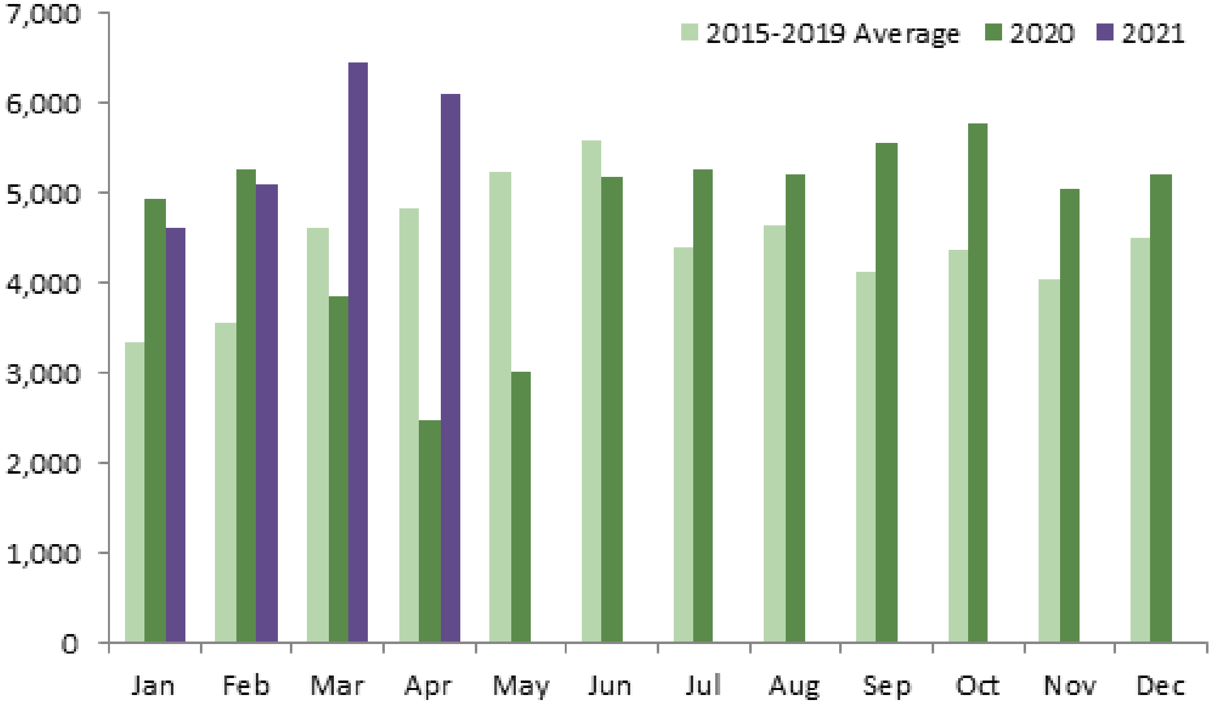
June 9, 2021

Justin Garosi Brian Uhler

California recorded 10,903 housing permits in April, up 103 percent from April 2020, the trough of the pandemic recession. Total permits in 2021 year to date are 34 percent above the same months in 2020.

April’s total of 6,083 single family permits was slightly down from March, but the biggest April total since 2007. This is also the first time since 2007 that the state has had two straight months over 6,000 units. Single family activity has rebounded strongly since last spring’s pandemic-driven slump, as prices have risen sharply in most of the state’s metropolitan areas. Permits have been at least 25 percent above the 2015-19 average every month this year. The Inland Empire, Sacramento, and Los Angeles areas had the most permits as usual, but the Oakland and Fresno areas also posted high totals.

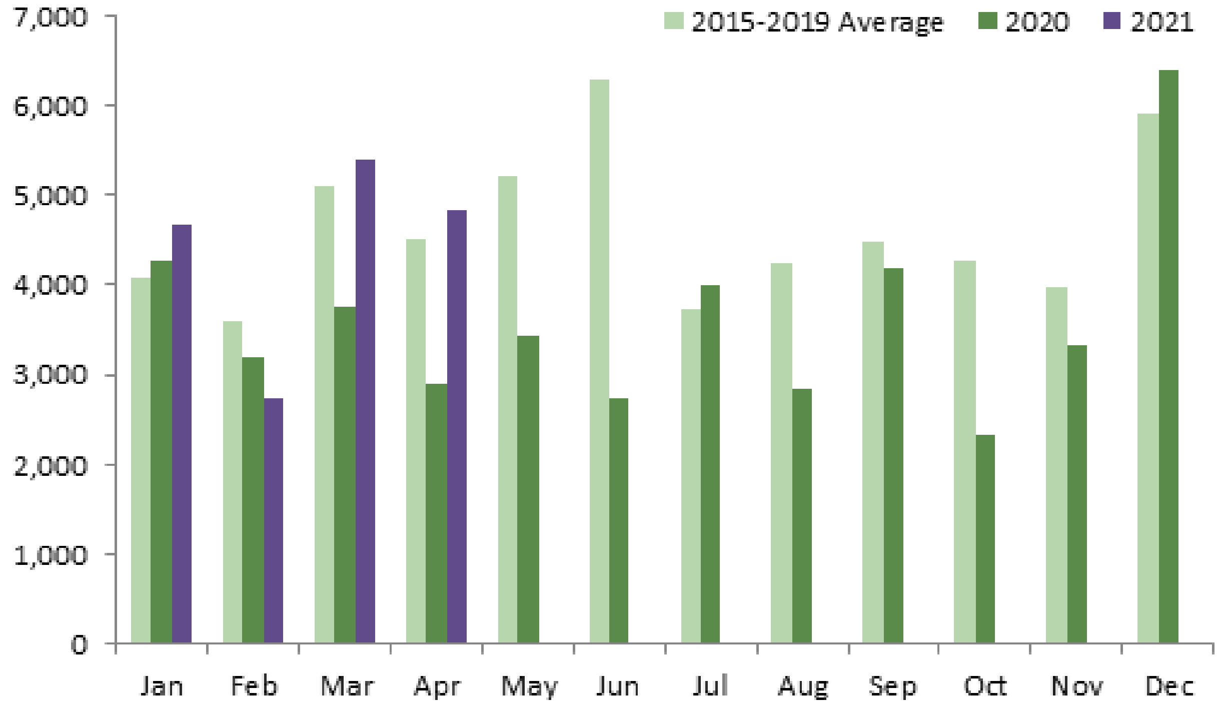
Single Family Housing Permits Issued in California



Source: Construction Industry Research Board

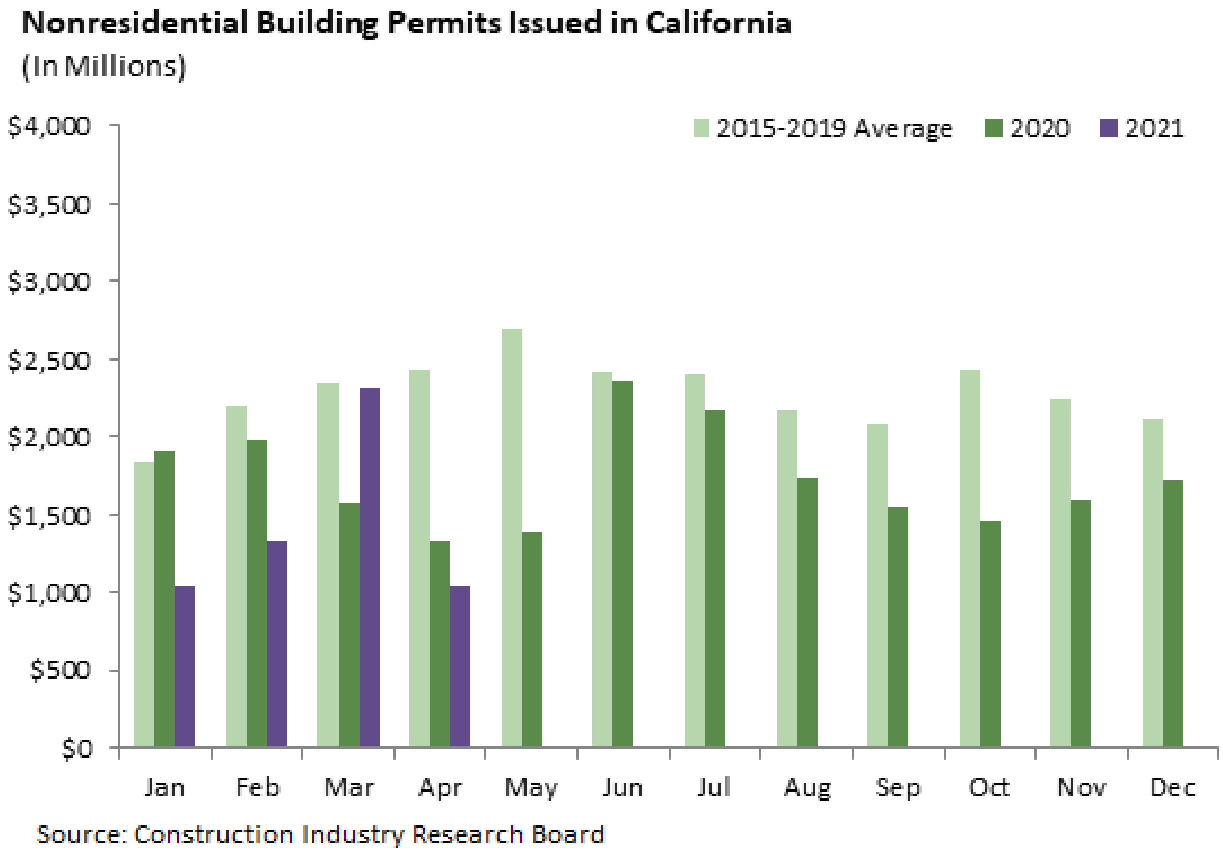
California builders recorded 4,820 multifamily permits in April. This figure is modestly above the pre-pandemic average for the month, as was the case in January and March. Los Angeles County permitted the most units as usual, followed by Santa Clara and Alameda counties. Santa Clara's total of 765 was more than it recorded in the previous seven months combined.

Multifamily Housing Permits Issued in California



Source: Construction Industry Research Board

Nonresidential construction permit activity was surprisingly strong in March but dropped sharply in April, and the total of $1.041 billion was the lowest figure for any month since at least 2012. The weakness was across the board as the commercial, industrial, and alterations categories all recorded totals well below their monthly averages even since the start of the pandemic.



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Journal of The Electrochemical Society

Review—Meta-Review of Fire Safety of Lithium-Ion Batteries: Industry Challenges and Research Contributions

To cite this article: Laura Bravo Diaz *et al* 2020 *J. Electrochem. Soc.* **167** 090559

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Review—Meta-Review of Fire Safety of Lithium-Ion Batteries: Industry Challenges and Research Contributions

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The Lithium-ion battery (LIB) is an important technology for the present and future of energy storage, transport, and consumer electronics. However, many LIB types display a tendency to ignite or release gases. Although statistically rare, LIB fires pose hazards which are significantly different to other fire hazards in terms of initiation route, rate of spread, duration, toxicity, and suppression. For the first time, this paper collects and analyses the safety challenges faced by LIB industries across sectors, and compares them to the research contributions found in all the review papers in the field. The comparison identifies knowledge gaps and opportunities going forward. Industry and research efforts agree on the importance of understanding thermal runaway at the component and cell scales, and on the importance of developing prevention technologies. But much less research attention has been given to safety at the module and pack scales, or to other fire protection layers, such as compartmentation, detection or suppression. In order to close the gaps found and accelerate the arrival of new LIB safety solutions, we recommend closer collaborations between the battery and fire safety communities, which, supported by the major industries, could drive improvements, integration and harmonization of LIB safety across sectors.
 [DOI: 10.1149/1945-7111/aba8b9]

Manuscript submitted March 15, 2020; revised manuscript received July 22, 2020. Published August 17, 2020. *This paper is part of the JES Focus Issue on Battery Safety, Reliability and Mitigation.*

Lithium-Ion Batteries and Fire Hazards

The Lithium-ion battery (LIB) is an important technology for the present and future of energy storage. Its high specific energy, high power, long cycle life and decreasing manufacturing costs make LIBs a key enabler of sustainable mobility and renewable energy supply.[1] Lithium ion is the electrochemical technology of choice for an increasing number of industries, ranging from small cells in consumer electronics to large scale packs in the electrification of road transport and smart grids. The combined LIB market is immense, for example, the global electric vehicle market alone is predicted to rise up to $93.1 billion by 2025.[2]

Although great success has been made on LIB commercialization, safety concerns have emerged because of unexpected fires. Some LIBs can display a tendency to ignite under abuse conditions and initiate fires or release toxic gases, thus creating a hazard. Moreover, as LIB technology moves to larger scales, from single cells to modules and packs, assuring their safety is an issue of growing severity and stakes. Exceeding the window of conditions in which LIBs operate safely can trigger thermal runaway (TR) and lead to fires (see Fig. 1). Thermal runaway is a state that occurs when the temperature of the LIB reaches a critical value such that the reaction rate of an exothermic reaction increases the temperature, which in turn leads to further acceleration of the reaction rate.[3] This positive feedback of temperature increase is a sign of ignition and creates the fire hazards. Once a cell fails, the large amount of heat generated could trigger the thermal runaway of adjacent cells, contributing to fire propagation. Fires on the module and pack scales can release large amounts of heat and toxic gases[4] and are difficult to suppress.

During the last two decades, fires of LIB-powered devices have captured the headlines several times, ranging from small consumer electronics to large power systems. The most notable fires are summarized in Table I. Initial concerns arouse in portable devices such as cell phones and laptops. The first major product recall due to fire safety took place in 2006, when Sony recalled more than 9.6 million LIB that powered notebooks of well-known computer manufacturers, with an estimated direct cost of $360 m.[5] Ten years later, in 2016, Samsung made one of the largest recalls in history: 2.5 million Note 7 smartphones, with an estimated direct cost of $5.3bn ($17bn including loss of profit).[6] Later concerns affected larger LIB assembled into modules and packs, for example in electric vehicles (EV), where fires of Chevy Volt and Tesla Model S hit the headlines.

Beyond media, official statistics collected by agencies in specific sectors show the impact of LIB fires. In China, the world's largest market of EVs, 31 LIB fires are recorded per year on average,[7–9] with the most common cause being sudden ignition (36.9%), followed by charging (26.2%).[7] In the USA, the National Transportation Safety Board (NTSB) has reported 17 Tesla and 3 BMWi3 LIB fires out of 350,000 and 100,000 vehicles respectively.[10] Large-scale LIBs have also led to safety problems during storage and transportation, before connection into a product. The USA Federal Aviation Administration (FAA) has recorded 252 air and airport fire incidents involving LIBs in cargo or baggage since 2006.[11] And the USA Consumer Product Safety Commission (CPSC) reported 25,000 fire incidents in more than 400 consumer products between 2012 and 2017.[12]

Although statistically rare, LIB fires are a concern because LIBs are ubiquitous in modern society, and also because LIB fires pose hazards which are significantly different to other fire hazards in terms of initiation, spread, duration, toxicity, and extinction. It has even led to the new concept of strained energy in reference to the persistent and intermittent burning behaviour observed in many EV fires. There are many technologies for increasing the level of safety of LIBs which can be organised into four main layers of fire protection (as shown in Fig. 2): prevention, compartmentation, detection and suppression. The concept of layers of protection is common in fire engineering but rarely applied before to LIB fires. It has the advantage of rational classification of different technologies according to aims. The prevention layer aims at avoiding thermal runaway; it is about the intrinsic safety of LIB design. Once prevention fails, ignition occurs and it leads to a fire. Compartmentation aims to hinder fire propagation and avoid a cascading failure. Early detection is key to allow time for the emergency response, evacuation and trigger suppression. Once activated, sprinklers or similar suppression systems could quench the

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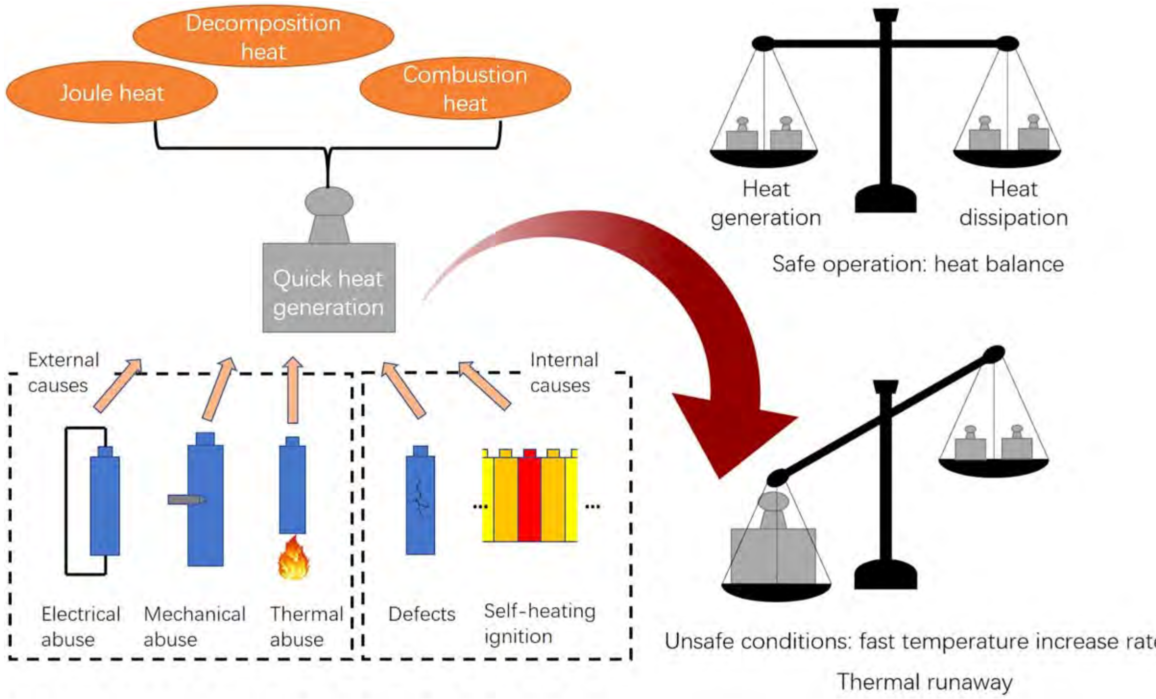

Figure 1. The 4 known abuse conditions that can lead to LIB thermal runaway and the imbalance between heat generation and heat dissipation.

Table I. Lithium-ion battery fires that received large media coverage in the last two decades. Incidents are arranged by application and then presented chronologically.

Application	Company	Year	Incident description
Cell phone	Nokia	2003–07	Sudden failure in batteries of mobile phones.
	Kyocera Wireless	2004	
	Samsung	2016	
Notebook	Sony	2006	Sudden failure of batteries powering notebooks.
Electric Vehicle	Chevrolet	2011	Chevy Volt on fire weeks after crash test.
	Tesla	2013	Model S on fire after hitting debris.
		2013	Model S on fire after crash.
		2016–19	Model S suddenly on fire while parked.
	Jaguar	2018	i-Pace suddenly on fire while parked.
Aerospace	Boeing	2013	Sudden failure in auxiliary units of Dreamliner 787.
Hoverboard	Various	2015–17	Sudden failure in many hoverboard's batteries.
Marine	Corvus Energy	2019	Hybrid-battery ferry on fire due to coolant leaking.
Stationary energy storage systems	Various	2017–19	Battery fires in large grid-connected systems

flames and cool the battery. Each layer of protection has a different role at each of the scales of LIB technology, which span from active materials to cell to pack (see Fig. 3). For example, the development of safer chemistries is typically conducted at the active materials scale, while techniques to avoid thermal runaway are studied at the cell scale, and fire propagation at the module and pack scales.

This paper collects and analyses the safety challenges faced by LIB industries across sectors, and compares them to the research contributions found in the field. We present the safety challenges faced by LIB industries and convert them into research questions then an analysis of the state of the art of LIB fire research structured into the layers of protection and scales. Finally, we compare the industry challenges with the research contributions to identify knowledge gaps and opportunities going forward.

This paper aims to bring together knowledge and experts from two different disciplines, i.e. battery and fire, to share knowledge and different approaches to LIB safety, which is an intrinsically interdisciplinary topic. Such an exchange should have a dramatic impact on the rate of finding successful solutions to the problems currently hindering a fuller uptake of LIBs. The successful integration of disciplines requires also bridging the terminologies. Battery experts and fire experts often prefer different terms to describe the same phenomena. In this paper, the term ignition includes thermal runaway initiation, and the term fire propagation includes the cascade of thermal runaway events among cells (also called thermal runaway propagation).

The Safety Challenges Faced by Industry

Many industry sectors are actively working to advance and improve the safety of LIB technology. Here we analyze the major safety challenges faced by different industries and their research needs to tackle LIB fires. We sent a survey to 12 LIB companies covering many industry sectors. We asked for their main safety concerns and research needs. 9 replied, providing their views and informing our analysis (6 companies agreed to be named in the acknowledgments). The industry sectors considered include manufacturing, consumer electronics, EVs, heavy-duty off-road vehicles, aerospace, drones, logistic,

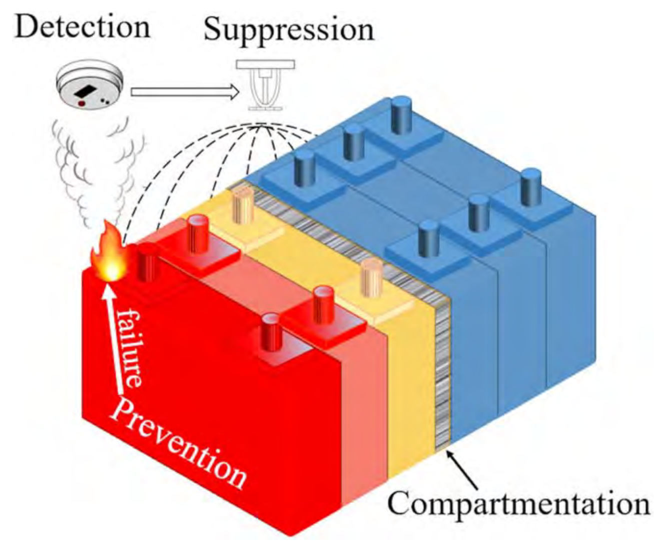

Figure 2. The four layers of fire protection present in LIB. Prevention includes safety components and safety devices. Once prevention fails, the detection layer can provide quick warning, triggering suppression and the emergency response. Compartmentation aims at delaying or stopping the propagation to other cells and modules.

grid, stationary energy storage, waste treatment and battery recycling. We have grouped all their concerns into five main challenges (see Fig. 4): Ignition and Propagation, Regulations and Standards, Detection and Reliability, Emergency Response, and Transport and End-of-life. These five challenges have been ranked by relevance, listing first the safety challenges most common to these companies.

Ignition and propagation challenges.—The major LIB safety challenge, as perceived across industries ranging from consumer electronics to stationary energy storage, is the possibility of thermal runaway initiation in one of the cells. Thermal runaway is perceived as the most safety-critical failure mode of a battery.[13] Its associated effects include cell overheating, overpressure, gas and particulate emissions, sparks, flames and even explosion.

There are several causes that can trigger thermal runaway, summarized in Fig. 1, which can be classified into external abuse (e.g. mechanical, thermal, electrical) or internal failure (e.g. defects, self-heating).[13] The abuse conditions are related to each other. The mechanical abuse, such as penetration or crushing, causes a short circuit, which is electrical abuse. The electrical abuse results in joule heating, which increases the cell temperature (thermal abuse) which can trigger thermal runaway. Internal failure can lead to spontaneous ignition. Most of the studies focus on abuse conditions, and only a small portion of the papers investigate spontaneous ignition. This is despite the statistics of EV safety showing that spontaneous ignition is the most frequent cause, accounting for 80% of the fire. Failures attributed to manufacturing defects are by far the most worrying as these are very difficult to detect, even with the extensive efforts carried out by battery manufacturers. Thus, internal cell defects and internal faults that develop inside individual cells over time, causing the initiation of thermal runaway, are a major concern for all industries which demand methods and tools to reliably identify them. Manufacturing defects can also be induced at the module and pack levels and these faults might not be detected until the unit is powered up and the battery management system (BMS) identifies a resistance issue (assuming a BMS with this capability). After a defect has been detected, re-manufacturing of modules where the bus bars have been welded onto cells is problematic, as re-working the weld can result in excessive heat build-up or internal cell damage that, in turn, can cause a short circuit. For this reason, the defected module as a whole may need to be scrapped. Pack manufacturers therefore demand research into early-detection methods of sub-standard welds (before the module assembly is completed and the BMS powered up) and into ways of safely reworking welds at both module and cell levels, thus avoiding the need to scrap them. One approach to avoid this problem is to develop new ways of attaching bus bars to cells.[14]

The link between the type of abuse and the time to ignition (also called incubation period) is another topic that has drawn significant interest, with a wide range of industries asking for further research. For example, heating the cell surface to 200 °C for 10 s does not lead to thermal runaway, but holding a cell at 110 °C for 1 h does.[13] Factors such as SOC, chemistry and SOH also influence time to ignition, in ways not sufficiently understood.[13] Furthermore, understanding crash-related fires is an issue of high importance in the

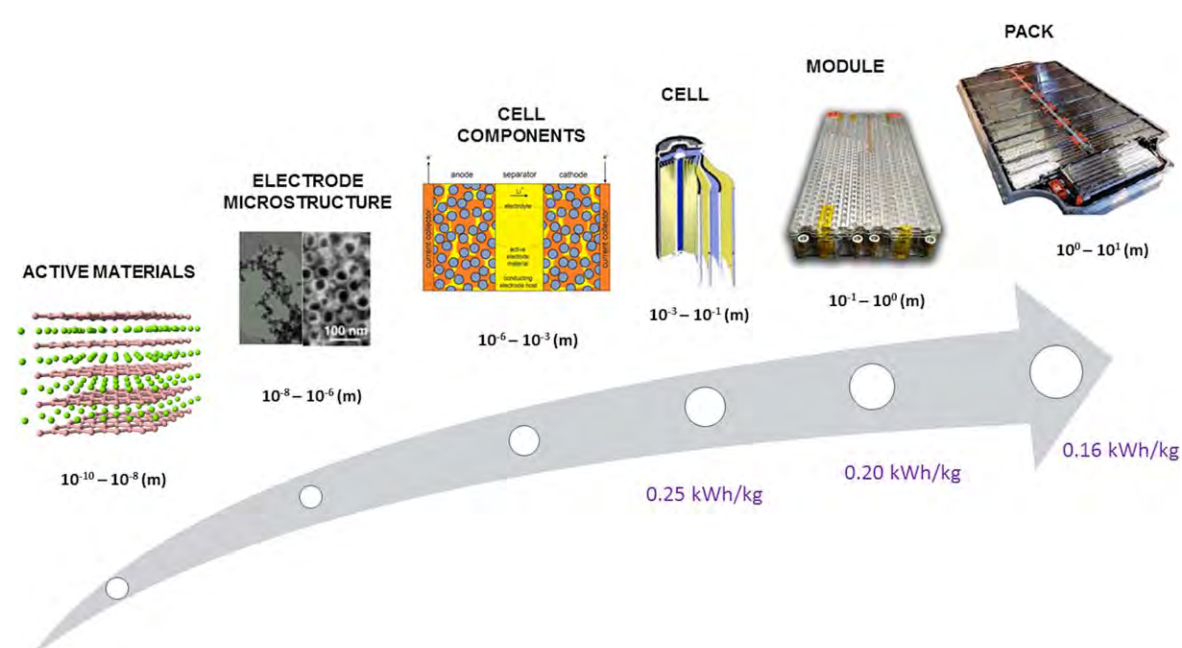

Figure 3. The different scales involved in LIB technology from active materials to cell to pack. At different scales, the fire hazard and the protection strategies are different.

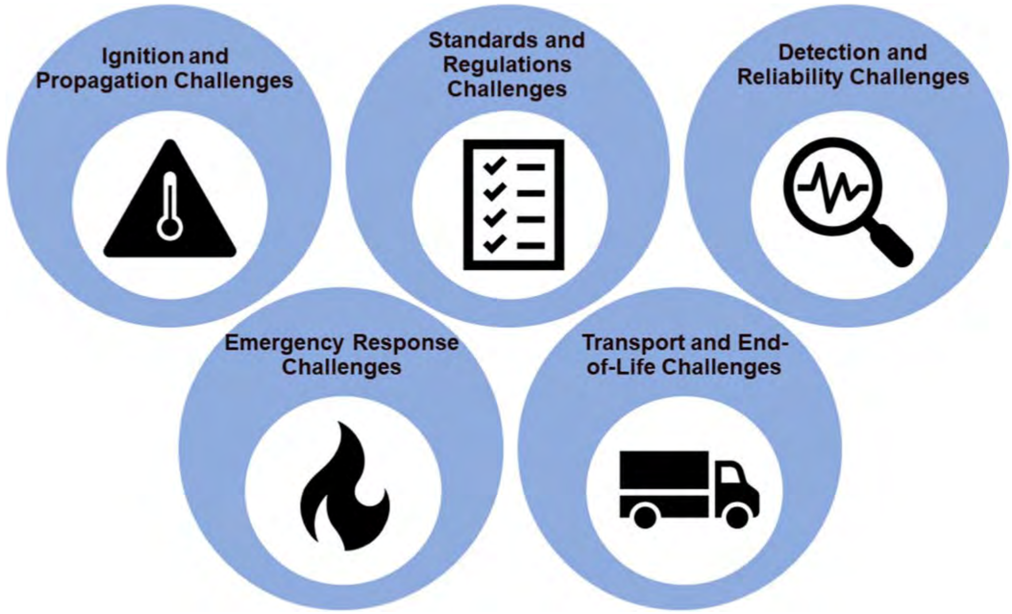

Figure 4. The top five safety challenges faced by Lithium-ion battery industries according to the data collected in this work.

automotive industry. The consequences of a battery being crushed in a vehicle, the likelihood of ignition and how to assess its safety, are major concerns for the EV and HV industries.

According to manufacturing, advanced engineering, automotive and aerospace industries, research should focus on control measures to detect battery failures through the fundamental understanding of cell limits. Three areas of research should be key to avoiding thermal runaway initiation; (i) developing methodologies to determine the maximum safe temperature (T_{safe}) for specific cells, (ii) evaluating the relationship between T_{safe} and the maximum allowed temperature by the BMS and (iii) understanding the variability of T_{safe} with SOC and ageing (SOH), and location within the module. This relates back to fundamental research on cell heat generation and its variation with SOC, ambient temperature, current and SOH understanding. Furthering understanding of the processes involved in cell heat rejection will reduce the risk of thermal runaway initiation.[15,16]

Fire propagation in LIB systems is a major issue for industries involved in large-scale batteries where the evacuation time of people can be long, such as automotive or stationary grid.[17] Cell to cell propagation depends on the thermal runaway characteristics and the balance between heat generation and heat dissipation (Fig. 1). One of the major concerns in this regard is the relationship between the mode of thermal runaway (type of abuse) and the fire severity, and therefore the propagation characteristics. This relationship has produced significant confusion, as the abuse methods included in regulations and standards are not always representative of real scenarios. The short circuit current is a fundamental parameter in the process. As of this date, no reliable method exists to create on-demand internal shorts in cells that lead to propagation and thus showing a response that is representative of the shorts originated by real failures.[13] Therefore, there is a need to develop a robust propagation test in addition to the single-cell thermal runaway test.

Fire propagation is also influenced by other contributing factors such as the initial temperature of the system, the thermal boundary conditions (e.g. heat conduction to adjacent cells, cooling strategies and cooling power of the module or pack), architecture and mechanical structure of the module, temperature inhomogeneity within the cells or among cells in a module leading to thermal gradients and accelerated localised degradation, etc. Aside from the total heat generated in a thermal runaway event, other important quantities for describing and predicting fire propagation are the heat generation rate, able with cell chemistry, SOC, current and SOH, and other external factors, such as presence of an ignition source, and availability of oxygen.

There are two specific approaches recommended by industry towards fire protection of batteries.[18] The first recommended approach is the development of safe battery chemistries or safe battery designs that do not result in thermal runaway or subsequent fire propagation. There is a consensus that some cathode chemistries are safer than others (e.g. LFP has higher thermal stability than LCO, LMO or NMC).[19,20] Other protection strategies are the use of modified separators (with ceramic coating or particles) that rise the thermal runaway trigger temperature or shutdown separators that stop the transport of Lithium ions once a set temperature has been reached. The use of modified electrolytes or non-flammable electrolytes would limit heat generation and potential further damage.[18,21] Solid state batteries are seen as the next game changers in terms of safety as they do not contain a flammable electrolyte.[21] Other candidates for future battery chemistries such as the LiS batteries present different risks related to the rapid reactions favoured at the surface of a Lithium anode. However, an overall safety assessment would be required to establish the safety effects of these choices at cell and module levels.

The second approach recommended by industry towards fire protection, most common in automotive, aerospace and advance engineering industries, assumes that thermal runaway will eventually occur and relies on the implementation of reliable, lightweight, low-volume safety features that centre on the detection, compartmentation and mitigation of cell to cell and module to module fire propagation. Having reliable detection and compartmentation measures would be advantageous, reducing battery weight, improving its performance and ultimately reducing its cost.[13] Thus, these industries demand specific research on protection strategies by battery design. Analytical studies of the impact of cell spacing distance, spacing materials, clearance above the cell burst disc, cell surface treatment, individual cell fusing, and cell holders designed to slow down fire propagation are some examples of research on design strategies needed at the cell and module levels. An example of adequate cell spacing is illustrated in Fig. 5, where a thermal runaway is induced in the cell located at the centre of the pack and no propagation occurs to the adjacent cells.

At the moment, no single approach has been identified to mitigate fire propagation and as a consequence a wide range of different safety strategies are combined to achieve a sufficient level of

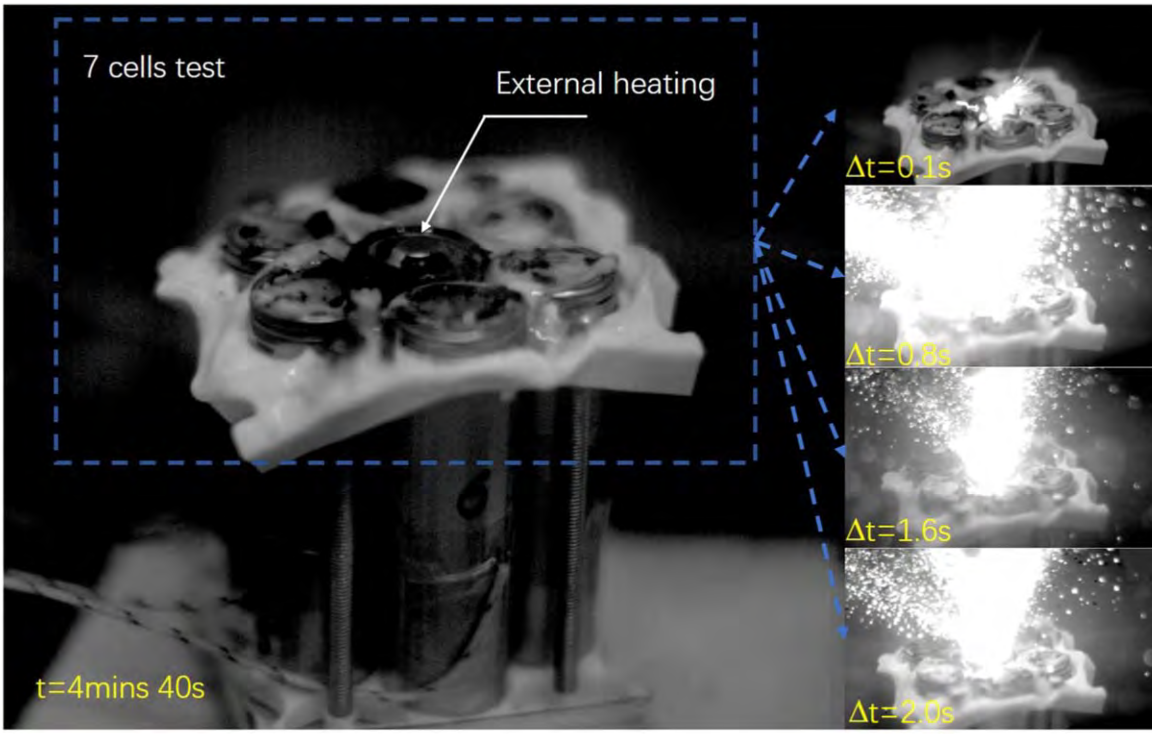

Figure 5. High-speed camera images showing ignition and evolution of the fire in the central cell of a 7-cell 18650 battery pack. External heating was applied to the central cell and ignition took place after 4 min and 40 s. Footage provided by Cognition Energy.

safety.[13] Shut-down separators, thermal fuses, temperature cut-off devices, positive temperature coefficient devices, current limiting fuses, current interrupt devices, vent disks or plugs and BMSs are incorporated into cell, module, and battery pack levels to protect against off-normal conditions.[13,19,20] However, containing any fire or explosion within the battery case during failure is still a challenge for most industries that operate with large format cells (e.g. EVs, HVs, aerospace, manufacturing or stationary grid). Specific research on what energy needs to be contained in the battery case, how to calculate it and thus what thickness of material to use for the case, is still required.

Another major challenge that it is relevant to these industries in the event of LIB failure is how to direct any vent gases safely away from passengers. Standards such as SAE J2289:2008[22] describe that material vented from the battery should not be directed towards the passenger compartment as it may pose a hazard. Research on this subject supported by modelling (e.g. accident case studies in different scenarios) is demanded by many transportation industries.

Battery developers, product designers and OEMs also demand more testing at module and pack level in order to improve the understanding of fire propagation. A holistic view of cell, module, pack and application is required to mitigate the risks of fire propagation, avoiding the subsystem optimisation trap that leads to a limited increase in safety at a higher cost.

Regulations and standards challenges.—LIBs must pass a series of safety tests to be certified for use in applications according to international and national standards and regulations. These safety tests have been developed based on research and pre-normative findings by regulatory bodies, industry and academia. While regulations are issued by governments and have legal enforcement, standards are voluntary documents defining industry consensus on minimum design and test requirements to achieve a desired level of safety or operation. As LIB technology is still evolving, there is not yet an industry consensus on system design and performance-based test methodologies.[19] However, the standards available provide a basis for sharing knowledge and experience, and allow a consistent level of safety to be established across industry.

In the case of the EV industry, a number of recognized international (SAE,[23,24] ISO,[25–27] IEC[28–30]) and national (e.g. US,[31–33] Korea,[34] India,[35] China[36]) standards are in place focusing on LIB safety testing at the system, pack, module and cell levels. LIB safety standards are also available for other industry types such as consumer electronics,[37] manufacturing and industrial applications,[38] aircraft installations[39] and stationary applications.[40,41] These standards may be referred to by battery regulations such as the UN/ECE-R100.02[42] or the GRT-EVS[17] in the case of the EV sector.

One of the major concerns across all these industries is that the standards available may not be representative of real-world scenarios. In the case of EV and HV, most standards and regulations impose test conditions derived from internal combustion engine vehicle regulations and therefore not representative of LIB field failures. Despite vehicle accidents being dynamic events, the testing described in the relevant standards is carried out at a component level using static assemblies (e.g. nail penetration test).[43] These industries demand more analysis and data evaluation specific to electrified powertrains and the addition of relevant tests such as low temperature hazards, flammability, toxicity, roll over, drop and immersion into future standards and regulations.[43]

Another concern raised by most industries is the need to further harmonization among standards in terminology, testing conditions, testing parameters and pass/fail criteria. For example, further harmonization is needed on the way batteries qualify against the risk of thermal runaway,[17,31] since various options appear in different standards.[13] Including details on temperature increase rate, occurrence of venting and fraction of energy released would be useful to establish thermal runaway sub-categories.[13]

Despite many standardisation efforts, current standards allow for very different initiation methods and test setups. There is currently no reliable method of driving cells into thermal runaway that is also representative of field failure modes.[13,44] The wide variability in testing conditions (e.g. SOC, temperature, charging/discharging rate) for abuse tests such as overcharge, short circuit or thermal shock hinders comparisons based on data obtained by using different standards.[43] Differences in test conditions might be intended to consider different scenarios but further harmonisation efforts are required in this regard. In addition, internal short circuit thermal runaway testing remains controversial as there is not a representative test that emulates a true internal short circuit characteristic of field failure in a testing environment.[13,43,45] Research is needed to gain further knowledge on the ways in which an internal short circuit develops within a battery. This would enhance the development and implementation of a representative test method. Industries also request a better understanding of the range of conditions that change the severity of the response to abuse; e.g. external short circuit testing at 60 °C is much closer to real life conditions in which thermal runaway will occur than testing at 25 °C. Additionally, they demand clear and unambiguous testing procedures as part of the test method along with a thorough description. For example, the thermal runaway event caused by nail penetration testing depends on nail size, penetration depth, tip shape, surface of the nail, and nail material composition.[46] Including detailed procedures for testing would improve the reproducibility of safety tests[47] in cases where the test set up has a significant impact on the test result.[13] Automotive, advanced engineering and manufacturing industries, among others, demand a reliable, repeatable, and practical method to create on-demand internal short circuits that produce a response that is relevant to the ones seen in field failures. This method should also account for variability in important factors such as the cell state of charge (SOC), chemistry, form factor and state of health (SOH). In response to this demand, the Electric Vehicle Safety Informal Working Group (EVS-IWG), established under the United Nations World Forum for Harmonization of Vehicle Regulations, has as one of their objectives to find such testing method demanded by industry.[47]

A significant variability in the criteria requirements in various standards has been identified.[13] For example, pass criteria for IEC 62619[38] and UL 1973[40] is "no fire outside the system," for VDE AR 2510-50[41] the criteria is "no fire, no explosion, no leakage" and for SAE J2464[23] there is no pass/fail criteria. Another example of controversy is the presence of a source of continuous sparks during thermal runaway testing as required by some standards[31,33] and not required by others.[27] This would directly affect the "no fire" pass/fail condition as it would be tested in different environments. While safety is application dependant, such that the pass/fail criteria can differ depending on the application being tested, there is a clear benefit to a consistent approach to classification of pass/fail criteria across standards.

Another important concern that most industries agree on is the importance of the scale at which the safety testing takes place (see Fig. 3). The tests performed at component level might not be comparable to the tests performed at system level. Most of the research on safety is performed on cells[46,48] or small modules, and similar data at pack and system is scarce. Because performing all tests at system level is prohibitive, studies on the comparability of testing results at cell, module and pack level are needed urgently.[43] Industries demand further pre-normative research to address this issue, and to provide guidelines to selecting the appropriate level at which each test should be performed. Such studies would have an immediate impact in providing representative results for assessing the safety of the application, and would minimise the complexity of standards and testing cost.[13]

Finally, a common concern for all industries approached is the effect of cell ageing on safety test results, a subject currently not covered by any standard. Differences have been observed in test outcomes between beginning of life (BOL) and end of life (EOL) cells.[49] However, the aging influence on safety characteristics is not yet understood in the scientific community. Further research on this topic is encouraged by all industries.

Harmonised approaches are easier to implement when international regulations apply, as, for example, in the case of transportation of hazardous goods (e.g. UN 38.3).[50] These regulations are developed and regularly updated every two years, at the United Nations level by appropriate committees of experts. In the EV sector major efforts have been put into the development of the Global Technical Regulation on the Electric Vehicle Safety previously mentioned[17] and established under the United Nations World Forum for Harmonization of Vehicle Regulations.

In the renewable energy sector, the safe introduction of battery-based energy storage is not yet internationally regulated. In the context of the revision of the 2006 battery EU Directive which will be published in October 2020.,[51,52] the EU has requested harmonised standards for performance evaluation and for sustainability assessment.

Detection and reliability challenges.—Automotive, aerospace and transport industries are concerned about failure detection since their products and applications need to ensure plenty of egress time for passengers.[17] A better understanding of the trade-off between shutting the battery pack down or continuing to provide power to mission critical systems (e.g. emergency landing/stop) is crucial in these applications.

LIB failure can occur very rapidly after a cell is damaged, or slowly over a long period of time, causing delayed failure long after the damage is initiated.[19] The time in between is usually referred to as the incubation period which can last from several hours to years, depending on the cause and failure mechanism (see Fig. 1). However, when a critical point is reached, usually governed by the balance between heat generation and heat dissipation from the cell and battery pack to the environment, the failure happens very fast.[20] Since LIB failure processes are time-dependent, early detection plus diagnostics could evaluate the cell failure mechanisms in real time. This could identify if the failure is an emergency requiring urgent action, or if action could be delayed because it is about mitigating long-term damage to the battery.

The BMS is currently the most widely used mechanism through which failure is detected in battery applications. A BMS relies on the built-in voltage and temperature sensors to monitor the state of a battery. However, many pack designers and manufacturing industries are concerned about the reliability of the BMS. For example, the internal cell temperature is the most direct measure of a cell entering thermal runaway, while not being an accessible measurement. Instead, temperature sensors must be located on the external surface of a cell. For many realistic scenarios a significant time lag can occur between temperature rising in the middle of the cell and temperature rising on the surface.[19] A surface sensor would show a statistically significant temperature rise when the rate of temperature rise is already too large, and thermal runaway is inevitable.[20] For this reason, key parameters relevant to detecting and controlling damage evolution are not currently measured but are inferred through models.[19] Pack designers and manufacturers therefore demand the implementation of additional protection strategies beyond the BMS (e.g. fuses, relays, current interrupt device, positive thermal coefficient, heat shields, ground fault detectors) to prevent failures due to external electric or thermal abuse.

Research on BMS design (e.g. adequate number of sensors, suitable sensor location, integration of model-based sensing, reduced sensor lag and synchronization error) is encouraged by EV, HV and aerospace industries to enable early failure detection and fast activation of control and mitigation measures. These industries also demand the development of novel in situ diagnostic techniques that can identify an incipient failure and take action early enough to prevent thermal runaway. Research on diagnostics, artificial intelligence (e.g. cloud-computing, big data)[53] and other data analysis techniques is encouraged by these industries, not only to prevent failure but also to provide sufficient energy and power for emergency stop or landing if the conditions for failure are detected. There is a significant body of research aiming to design improved detection methods, as discussed below.

Battery-powered transportation industries advocate the development of fault-tolerant battery systems (e.g. fail-soft and fail-safe systems).[54] This can be achieved not only through hardware (e.g. redundant design), but also through high-level (e.g. derating strategies) and low-level software (e.g. recovery blocks, N-version programming, self-checking software).[55]

The development of models for cell, module, and battery pack safety are also a priority for these industries since they will drive understanding and improvements in the safety of large battery packs. One of the major problems faced in this regard is the lack of transferability across scales. Large amount of literature has been dedicated to improved modelling, diagnosis and prognosis techniques at cell scale, using advanced lab equipment.[56,57] However, much of this knowledge is not easily transferable to commercial systems (e.g. Electrochemical Impedance Spectroscopy (EIS) based methods)[58] due to a lack in quality and quantity of measurements available in commercial systems, and a lack in processing power within the BMS or the system's control central unit. The latter issue could be solved through 5 G technology and cloud-computing,[53] although further research is required as it may be not a problem-free solution (e.g. emissions, costs, data privacy).

A more fundamental problem hindering developments in diagnostics is the difficulty of online parameter identification of complex battery models, due to the limited system observability.[59,60] The states of the battery model are cell-dependent, and can only be inferred from voltage, current, and limited surface temperature data. Adding to the problem, in most applications there is limited controllability of those variables. The integration of active balancing systems can provide more controllability, but it will increase the complexity of the system and may affect reliability.[61,62]

***Emergency response challenges.*—**Due to the complexity involved in LIB fire safety, issues are not easy and simple, and there is a demand of sharing information, knowledge and understanding in all fields of application, e.g. EVs,[63,64] stationary grid storage,[65] or aerospace.[66]

For example, stakeholders require detailed knowledge of the various key factors influencing the heat release rate from a battery fire (the fire power), and the rate and toxicity of gases released.[63] While there are many studies focusing on cell and pack level fire safety,[67–70] there is little data published on system-level fire safety (e.g. stationary grid storage or EVs).[64,65] This gap in the literature could be explained by the higher cost of system-level destructive testing, and the consideration of these matters by stakeholders as industrial secrets because of technical reasons as well as due to reputation and brand image. While it is true that reasonable predictions of key factors could be made based on cell or pack level data, and the limited database of fire incidents in the field,[63] comprehensive and methodological system-level fire testing would shed light on these important issues like: fire test repeatability, sensitivity to test conditions, scalability with mass or SOC, and fire suppression systems.

Regarding the latter, there is not a unique approach to tackle LIB fires, and different extinguishing agents and forms of application are available. Common fire extinguishing agents available include water (pure or with additive agents), foam, dry chemical powder, wet chemical or inert gases, each one having advantages and disadvantages. There is little literature in the subject for large battery applications (e.g. stationary grid storage, EV, HV, aerospace)[64,65] and further research in this area is encouraged. However, it appears that water-based extinguishing agents are among the most effective on the basis of available evidence.[63] This is due to their cooling capabilities, although they are not a problem-free solution, as discussed below.

For instance, long extinguishing time and large volumes of water may be required to avoid glowing and re-ignition problems, which may arise even hours after the fire extinction, due to persistent electrical or thermal abuse.[63–65,71,72] Hence, risk of water supply issues may exist. In addition, the application of water to a large LIB may cause an electrical hazard. Indeed, water can damage both the battery system itself and other assets, shorting undamaged cells or modules, and resulting in total loss of the system. There is also a risk of electric current leakage. When using water suppression, the personal protection equipment and precautions should be taken and a clear distance should be observed.[64,65]

Extinguishing time, water volume, harmful gasses emissions, and risk of re-ignition due to water induced shorts are concerns that arise among most industries. However, these can be drastically reduced by: 1) design, through improved enclosure fire rating,[72] internal cascading protections or heat shields,[72–75] optimum cell spacing;[76,77] 2) using a small percentage of certain encapsulating additives;[78] or 3) more direct contact of water with damaged cells, through water lances, penetration hammers, and ad hoc system designs. Submersion of damaged batteries in ad hoc portable water-proof containers has also been proposed to avoid re-ignition, and to fully discharge large damaged batteries.[79]

Water or water-based agents can be applied through water mist or sprinkler systems, which have proven to be effective in large stationary grid storage applications and battery warehouses fires.[80,81] In this way a reduced volume of water is required, limiting water induced risks or damage in the battery system and other assets. Dielectric liquid agents have also been proposed, but they can be easily contaminated in the early stages of fire suppression, becoming conductive and as problematic as regular water. Foam agents have not proven better performance than water, showing a lower cooling capability and therefore not recommended for battery fires.[64,72]

In those cases where the use of water is a concern (e.g. stationary energy storage for data centres), inert gasses or dry powder may seem a preferred solution, although their effectiveness to suppress battery fires is limited, due to their inability to cool down the battery.[72] However, when used in combination with early prediction measures, ventilation and cooling systems, a battery fire in a module with adequate cascading protection could be suppressed with a gas agent. The risk of re-ignition would still be present due to the limited battery monitoring capability.[72] For these reasons, non-water-based agents have been proposed in staged extinguishing approaches, to put out the fire in initial stages of stationary storage fires. If the problem persists or further cooling is needed water-based solutions should follow.[72]

In the case of limited access to water supply and no further risks to public health and safety, or damage to valuable property, it has been recommended to let the battery burn as a practical self-extinguishing approach, even though the fire may be active for 24 h.[64,65,82] Such passive strategies are not viable in many indoor or underground battery fires,[64,65,83] or aerospace battery fires, which require particular fire suppression and containment strategies.[66]

Large emissions of toxic gases are expected as a result of a LIB fire, and containment or ventilation will be required. EV and HV industries demand further research on the amount and toxicity of the products (gases and residues) released from LIB fires. They also require new methodologies for containing and cleaning these gases in sensitive areas where ventilation is not possible. While there is not an exhaustive knowledge of toxic emissions of battery fires,[84] it seems that they do not differ significantly from those of plastic fires in the case of stationary grid storage applications,[72] or ICEV fires in the case of EVs.[64] However, enhancing further knowledge in this area is demanded by most industries and stakeholders.

***Transport and end-of-life challenges.*—**Transportation of pristine LIBs poses a risk. In regular conditions, while the probability of a cell fire is low, the severity of the fire incident may be high if large quantities of cells are carried together.[66] This is particularly true in the case of air carriage, and explains why Lithium-ion cells or batteries have been prohibited as cargo on passenger aircrafts,[66] and are required to pass a number of tests defined in international regulations (e.g. UN 38.3)[50] and standards (e.g. IEC 62133)[37] to be shipped by cargo-aircrafts or other means.[85]

Nowadays, while IEC standards and UN regulations have been harmonized up to some extent, there are still many differences in battery transport regulations across countries and regions, which make logistics complex, time-consuming, and costly.[85] For instance, there are many differences in packaging, marking, and labelling.[85] Test requirements at cell, battery and system level should be unified too.[85] Regulations also differ depending on the mode of transportation, and tend to be easier for road, train or sea transportation, particularly for non-pristine cells.[85,86] Furthermore, logistic industries need regulations to address battery storage at transport logistic centres.[85] Pre-normative research is required on shipping and storing BOL cells, particularly on the likelihood of safety incidents as a function of SOC. Manufacturing, transportation, logistics and recycling industries demand further research on risk assessment and mitigation measures for transportation of cells that are damaged or defective, for disposal, recycling and second life purposes.

Re-using, recycling, or disposing of battery systems may create considerable electrical, thermal, chemical, and fire risks, and require significant manual labour for partial or complete disassembly. These problems can be mitigated if battery packs and systems are designed with these final product stages in mind. This is currently an uncommon practice. "Life-cycle" battery module design would enable an automated robotic disassembling and it would also increase the rate of battery re-use or material recovery. This will in turn improve battery sustainability and recyclability.[87,88]

The Safety Contributions in the Scientific Literature

Research efforts are helping to improve LIB fire safety. Here we conduct a meta-review of the 13 most relevant review papers associated with LIB fires to identify the current state of research. We highlight areas of research rather than the specific findings of any one study, and therefore we primarily refer to review papers rather than individual papers. To understand the importance of each research area, we count the numbers of papers that are included in each review for the causes of fire, scales and protection layers. These statistics are provided in Fig. 6.

We find that the number of studies focusing on the component and cell scales is much larger than the number of studies on module and pack scales. Indeed, improving component and cell safety is essential to protect from fires. However, the fire behaviour of large-scale LIB packs is different to that of an individual cell. The outcome of fire protection strategies also differs depending on the scale at which they are studied. As an example, for suppression of LIB fires, research at the cell level is not sufficient[89,90] and LIB fire experiments have to be conducted at the pack level.

As highlighted in the introduction, and shown in Fig. 2, all four layers of fire protection are important. We find that most research has focused on prevention, and only 5% of the research investigates other protection layers. Nearly all the current detection research is based on BMS, and only a few papers investigate the use of other sensors. Compartmentation studies focus on thermal barriers alone. Only a few papers investigate LIB fire suppression, with those existing putting the emphasis on sprinkler protection of storage spaces, and without agreement on what extinguishing agents are effective in avoiding re-ignition.

Therefore, more research should focus on the module and pack scales to better understand fire dynamics at large scale and to improve fire protection combining compartmentation, detection, suppression. Further findings for each layer are reported in the following.

Prevention research.—The prevention layer aims at avoiding LIB ignition. It is the first and most important layer of protection. To make effective preventions, the first step is to understand the fundamental mechanisms of LIB ignition, and then designing the corresponding strategies to avoid the triggers.

Many studies[91,92] have analysed the behaviour of LIBs and their components at elevated temperatures, and many reviews[3,68] have already presented in detail what is known about the mechanisms of LIB failure. Here, we summarize the main processes with a focus on fire safety. Based on the physics involved, we classified the processes of heat generation into three stages: Joule heating, decomposition, and combustion.

During the electrical cycles of LIBs, a part of the energy is released in the form of heat due to the cell impedance, known as Joule heating.[48] One extreme case is the creation of a short circuit, where a large portion of the energy stored could be released as heat, increasing the temperature of the battery quickly. Many studies on the development of electrochemical models to describe this phase have been published.[3]

When the temperature of LIB reaches a certain level, the reactive components of LIB start to release heat because of the chain of exothermic reactions promoted, i.e. solid electrolyte interphase (SEI) decomposition, electrode decomposition, and electrolyte decomposition, driving the temperature even higher.[68] This is the decomposition stage. The reactions in this stage occur between solid and liquid phases, generating various gaseous fuels[91] between 100 °C–200 °C. A number of experimental studies[68,93] have been conducted using adiabatic calorimetry, i.e. accelerating rate calorimetry (ARC) and differential scanning calorimetry (DSC), to investigate the thermal performance of an individual component or coupled components. It was found that the chain of exothermic reactions start from the decomposition of the SEI layer,[3] which is a thin passivating layer formed on the electrodes. The SEI layer decomposes at around 100 °C,[3] exposing the intercalated Lithium in the negative electrode to the electrolyte, promoting further reactions. The active materials of the positive electrode are also unstable and could decompose at high temperature releasing gases.[94] The electrolyte is also found to have several exothermic stages at elevated temperature.[91] A few chemical models have also been developed to analyse the decomposition stage.[95]

When the temperature rises even more, the overpressure due to gas generation can break the outer casing of the LIB thus mixing with oxygen outside and forming a flammable mixture.[96] When the mixture is ignited, it leads to the combustion stage which involves combustion reactions, flames and fire dynamics. This stage is mainly studied so far by means of experiments.[97] The fire behaviour of LIBs has been studied at both cell level and pack level.[96,98] One cell can burn with a jet flame or a buoyant flame, and its burning period is about 20 s.[98] A battery pack can have multiple jet flames[96] while the burning period is in the order of 300 s (or longer if re-ignition takes place). The SOC has significant influence on the fire behaviour;[99] cells with lower SOC burn for shorter times and with weaker flames.

There are some studies available that focus on the development of computational models to understand and predict thermal runaway. Hatchard et al.[100] and Kim et al.[95] are the pioneers developing the multi-step reaction scheme that is the center of many computational studies. Using this reaction scheme and associated kinetics parameters, the effects of cell geometry[101] and cathode material[102] on thermal runaway was investigated. Recently, Ren et al.[103] has proposed a new reaction scheme that considers the interaction between anode, cathode and electrolyte for a LIB at 100% SOC. Thermal runaway caused by mechanical abuse has been the subject of recent research using modelling approaches.[104] The effect of ageing was studied by Abada et al.,[105] who combining experiments and modelling, found that calendar ageing lowers the critical temperature for thermal runaway and delays the onset of self-heating.

To effectively prevent ignition, there are some strategies to control each of the stages described already, especially for the Joule heating and decomposition stages. These strategies can be divided into: control heat generation, or enhance heat dissipation. Controlling heat generation involves reducing Joule heat, decomposition heat and combustion heat. Joule heat can be controlled by avoiding short circuits. For example, using cushion or isolating materials for cell spacing to avoid mechanical or electrical abuse. Even if short-circuits occurred, the Joule heat could be reduced by internal safety design[106] such as PTC, redox shuttles, and shut down separators to reduce or cut off the current when temperature rises. The heat of decomposition can be controlled by using different materials. Moving towards lower voltage systems such as LMO/LTO or using more thermally stable

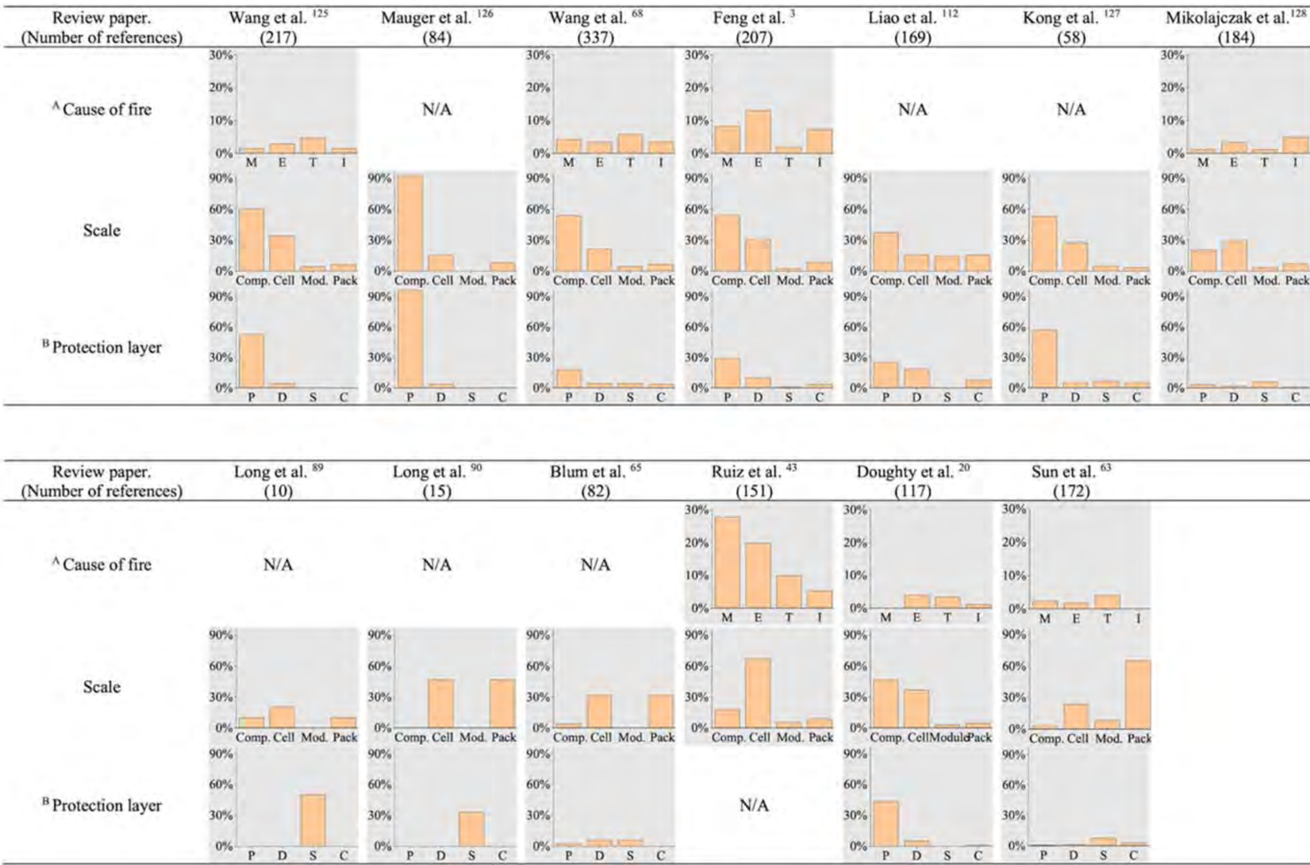

Figure 6. Meta-review of the most relevant 13 review papers found in the scientific literature. The causes of fire, scales and protection layers considered in each review paper are analysed. The value in each plot refers to the percentage of references in each review paper. [A] Causes of fire are: (M) mechanical abuse, (E) electrical abuse, (T) thermal abuse including self-heating, and (I) internal short circuit. [C] Protection layers are: (P) prevention, (D) detection, (S) suppression, and (C) compartmentation.

cathodes (e.g. LFP instead LCO) can improve safety at the expense of energy density and cost.[106] All-solid-state Lithium-ion batteries offer a wider operating temperature range in addition to improve safety and higher energy density. However, key challenges remain such as the volume change in the electrodes, interfacial charge transfer resistance, flexibility and cycling stability. Despite the advances on shape flexibility and contact with the electrodes achieved with solid polymer electrolytes,[21] these systems are limited in terms of electrochemical stability windows and ionic conductivity at room temperature.[107] If the materials for the main components cannot be changed due to the consumer's request, safety can also be improved by applying surface coating on the electrodes. Surface coating could prevent the electrodes from direct contact with electrolyte, improve structure stability and reduce side reactions.[3] Adding flame retardant additives into the electrolyte is also an effective way to improve material safety and reduce the decomposition heat.[108] This strategy also reduces the gases generated at high temperature and increases the onset temperature of the chain reactions.[68] The heat of combustion could be controlled by using safer materials with lower fire load. Safety vents can manage the internal pressure and control the direction of gas ejection during the failure, which helps to postpone combustion stage.

Another main strategy in LIB fire prevention is enhancing heat dissipation. It is mainly achieved by introducing active or passive methods that increase the heat transfer between the batteries and the environment. For EVs, the BMS is used to monitor the state of batteries and the environment.[68] BMS is usually equipped with a cooling system that ensures the temperature range for correct battery operation. One of the most commonly used methods is air cooling (forced convection). Liquids have a higher heat transfer coefficient and therefore a higher cooling efficiency. However, the weight addition from the liquid cooling system increases the load and costs. PCMs are an alternative method for thermal management. They usually have a large latent heat, allowing heat storage. For batteries with low energy density (consumer electronics), passive cooling is mainly used because of the restrict requirements on the weight of those portable devices. Natural air convection is mainly used in this case. Heat pipes could also be used for a slightly higher heat load.

Compartmentation research.—If the prevention layer fails, compartmentation is the key layer for protection against LIB fires, by containing or delaying fire propagation within a battery pack. This reduces damage, and provides more time for evacuation and for emergency response.

LIB fire propagation within a pack is dominated by heat transfer. There are three main heat transfer paths: heat conduction through cell surface, heat conduction through the pole connector (tabs), and heat radiation and convection from the flames.[68] Feng et al.[3] have found that the heat transferred through the cell surface is around 10 times larger than the heat transferred through the pole connector. Said et al.[74] have investigated the fire propagation in cell arrays in the air and the nitrogen atmosphere. The results show that the propagation rate in the air with flames is 9 times quicker than the propagation rate in the nitrogen without flames. In addition, the location of the cell that initiates the failure within a module,[109] the connections (series or parallel),[110] the cell factor[110] and the SOC[111] are important factors in fire propagation.

The strategies to restrict LIB fire propagation include hindering heat transfer paths to nearby cells and improving cell heat dissipation. To hinder the heat transfer, the simplest method is to increase the spacing between cells, which can slow down the propagation. A spacing distance of 2 mm is recommended by Lopez et al. for cylindrical cells.[112] Compartmentation can be achieved by dividing a battery pack into several compartments through the use of barriers between cells. Several strategies such as Tesla's multi-layer thermal barrier,[113] flame retardant plates,[114] metal plates,[114] heat-conducting plates[114] and PCMs[115] have been proposed. Hermann et al.[113] invented a multi-layer thermal barrier, made of a composite containing thermal insulation materials and electric materials. The barrier divides the battery pack into several compartments and reduces the heat transfer and the mechanical impact between compartments. Berdichevsky et al.[114] proposed the use of a non-combustible plate for compartmentation, such as a ceramic fibreboard, which has very low thermal conductivity. Another method to alleviate fire propagation is the use of a metal plate[114] as a heat sink between modules. The thermal mass of the plate and the thermal contact resistance between the cell and the plate are two important factors affecting the mitigation of fire propagation.[116] Lee et al.[117] studied the effect of double-layer stainless steel, intumescent material and ceramic fibreboard inserted in gaps between cells as physical barriers for fire propagation mitigation in a 9-cell compartment. The results showed that none of these physical barriers stop the fire propagation between compartments but slow down the propagation rate, with the ceramic fiberboard being the most effective. The use of phase change materials (PCM)[115] is another effective method to prevent fire propagation. A recent study[115] shows one case of fire propagation starting from a cell being stopped when the cells are surrounded by PCM. PCM, such as paraffin wax, have a high latent heat of fusion and can absorb heat when thermal runaway occurs. However, PCM can be combustible thus adding to the fire load, be costly and add significant mass to the pack.[118]

To improve heat dissipation away from cells, the basic technology is venting.[68] Feng et al.[3] and Liao et al.[108] have also proposed battery thermal management systems, such as air and liquid cooling and heat pipes, to be used to prevent fire propagation but none of these techniques have been studied for compartmentation. Compartmentation strategies during transportation are different from the compartmentation strategies used inside a battery pack to avoid fire propagation. The current compartmentation strategy during transportation is using a sealed fire compartment for LIBs. For example, a stainless steel box with walls 3 mm thick was used in the Boeing Dreamliner[119] for compartmentation. This ensures that even if there is a battery fire, it cannot spread to other compartments aboard the plane.

Detection research.—Early detection of failure, thermal runaway or fire is crucial. Batteries can quickly reach ignition, for example, in case of mechanical or electrical abuse. Detection methods can be summarised in five categories:[108] i) terminal voltage using the BMS; ii) unusual gases emitted; iii) internal battery temperature; iv) current variations as indication of short circuit; and v) mechanical deformation using strain gauge sensors.[120]

The most widely used method for detection is a mix of terminal voltage (i) and temperature (iii). The BMS of the batteries has built-in sensors which can be used to monitor the surface temperature and voltage of each cell within the battery. When any abnormal signal is detected, the BMS triggers a warning.[108] BMS can improve heat dissipation by thermal management, avoiding cell over-heating, and also locate a faulty cell within a battery pack. However, the BMS does not respond fast enough to detect the initial stages leading to thermal runaway. Internal temperatures measured via dedicated embedded sensors have a higher accuracy than the surface temperature measurements to predict thermal runaway, but they add a high cost as well as complexity to the pack.

Gas sensors can be used to detect the initialization of thermal runaway. They are faster than voltage or temperature methods as the build-up of initial gases often precedes any significant changes in the voltage or temperature signals. However, it adds complexity and cost, and faults could trigger false alarms. The use of heat, smoke or gas detectors is relevant for all battery industries. For example, gas detectors are recommended for stationary energy storage systems in enclosures so they give a warning before flammable gases build-up.[121]

Monitoring the creep of the batteries relies on the external mechanical structure of the battery to deform, and it might not reliably detect the onset of runaway.

Suppression research.—Suppression is a fundamental protection layer if the preventative measures fail. There are four suppression approaches for fires: smothering, cooling, chemical suppression, or isolating the fire.[68] Many reactions that lead fire in a battery do not require external oxygen supply as oxygen is present in its components. This makes the smothering approach not very effective. Cooling the battery with a continuous water mist is a promising approach for the suppression of LIB fires.[68] However, it can also have an impact on the integrity of the electrical circuits, as water can cause an external short circuits and further ignition or thermal runaway propagation. Conventional fire extinguishers are not suited to stop the thermal runaway reactions inside LIBs. They have only been proven effective to extinguish open flames external to the battery as the battery's surface temperature decreases. The addition of additives (i.e. C6F-ketone) has been shown to improve the fire suppression but when exposed to high temperatures these produce HF which is extremely toxic and corrosive, and therefore pose a danger to any emergency personnel.[68] Furthermore, it was also observed that the battery fire might re-ignite after initial suppression, due to the fact that the exothermic chemical processes inside the cells continue, and therefore suppressing agents would have to be reapplied even after first suppression.[68]

Research on suppression methods for battery fires is at an early stage and it is far from reaching an optimal solution to effectively and safely extinguish battery fires without the production of toxic gases, so further work is needed.[68]

Key protection technologies.—As overview, Table II shows the current key technologies used for different protection layers. Prevention technologies are comprehensive and well developed for improving cell safety. The cathode modification methods[68] to improve its thermal stability include surface coating, such as phosphate, fluoride, and solid oxide, and element substitution using Ni and Al to replace Co. Regarding anode modifications, the surface coating method[68] is also recommended, using an Al_2O_3 thin layer on the anode to serve as unstable SEI layer. Electrolyte additives have been reviewed by Feng et al.,[3] including solvent substitute additives, SEI supporting additives, flame-retardant additives, thermal shutdown additives, and overcharge protection additives. All these additives can help improve the intrinsic safety of cells.[122] Safety devices, such as the positive temperature coefficient device (PTC) and the safety vent, can protect from overcharge and overpressure, respectively.[68] The BMS is an excellent device for fire protection with roles in prevention, compartmentation and detection. The key roles of the BMS are the estimation of the state of cells, battery equalization, diagnostics, charge and discharge control, thermal management and battery safety control.[93] The thermal management system uses a cooling medium, either air, a liquid or a phase-change-material (PCM), to dissipate heat, depending on the pack design. Air cooling is the simplest cooling method but also the least efficient. While liquid cooling has a higher efficiency, its application can also create thermal gradients.[93] The thermal management system and the cell state estimation function help preventing failure. Regarding detection and compartmentation layers, the BMS can also help detecting failure at an early stage as it monitors temperature and voltage. It can also enhance heat dissipation to slow down fire propagation when the prevention measures have failed.

While prevention measures have received a lot of attention producing novel scientific breakthroughs in battery materials and components, compartmentation, detection and suppression technologies

Table II. Current key technologies used for different protection layers.[68] Prevention technologies are comprehensive and are developed for improving cell safety. Comparatively, compartmentation, detection and suppression technologies inspired by traditional fire technology are less effective for battery fires.

Protection layers	Scale	Key technologies
Prevention	Component, cell, module, pack	Cathode and anode modification, electrolyte additive, shut down or ceramic-coated separator, positive temperature coefficient device, vents, battery management system.
Compartmentation	Module, pack	Barriers, battery management system, sealed metal container.
Detection	Cell, module, pack	Battery management system (voltage, temperature, deformation), different detector (heat, smoke, off gassing).
Suppression	Cell, module, pack	Smothering, cooling, chemical suppression, isolating.

are inspired by traditional fire technologies, which are less efficient for LIB fires and need further study.

The Way Forward

Industry and research institutions share the common goal of producing safer batteries, but there are clear distinctions between their approaches. Industry embraces the top-down approach, with a focus on specific questions at larger scales, while research tends to follow the bottom-up approach, focussing on the fundamental understanding of phenomena with emphasis on the smaller scales. Bringing the two communities together sooner rather than later could prove crucial to solving LIB safety issues. Our conclusions are visually summarised in Fig. 7.

During safety testing and certification, industries perceive that there is a lack of harmonisation in the mode of abuse that leads to thermal runaway. There are no representative and repeatable methods for all relevant failure modes, and many test methods are not representative of field failures. There are multiple controversies around the best method to induce thermal runaway. While there are several recognised international standards for every industry that uses LIBs, a major concern shared by all industries is that the available standards are not always representative of real-world scenarios. Further controversy can be found in pass/fail criteria in various standards for thermal runaway. More research is needed to understand first how an internal short-circuit develops within a battery, before a method to reliably reproduce it can be defined. To prevent thermal runaway at the pack scale, the development of more fault tolerant, fail-safe or fail-soft systems is needed. Yet, there is no industry consensus on safe system designs and performance-based methodologies. Although this could be attributed to the wide range of applications that are covered by these standards, harmonisation is required. The regulations, standards and committees that do exist provide a valuable basis for sharing knowledge and experience across industries that use LIBs.

LIB fire standards and regulations have been harmonised to some extent for transport industries, but there are still significant differences between transport modes and across regions, which add costs and hinder innovation. No established regulations and standards exist for storage at logistics centres, which are especially needed for cells that are defective, possibly damaged, or aged.

Fire propagation between cells is a main concern. Two approaches are needed for fire compartmentation. Firstly, new battery chemistries or designs that do not result in thermal runaway and therefore would not require mitigation must be found. Secondly, assuming thermal runaway can occur, compartmentation technologies to prevent propagation, and adaptive control measures to detect thermal runaway must be developed. These techniques could be based upon a combination of voltage, current or temperature signals, i.e. measurements implemented in the BMS. Further research into the development of other detection methods, such as sensor for gases, heat or flames is also justified.

Another concern is the scales of most experiments. We find that the number of studies focusing on the component and cell scales is much larger than those studying the module and pack scales. Improving safety at the component and cell scales is essential but not sufficient because it is not possible to avoid completely the possibility of LIB accidental ignition. Lessons from studies performed at the component scale do not necessarily translate to the pack scale because fire dynamics are affected by scale (larger fires release more heat and propagate faster). More research is need on the pack and system scales to understand fire evolution at its highest intensities and to develop more robust protection layers. Further research into how the knowledge at each scale can be integrated is

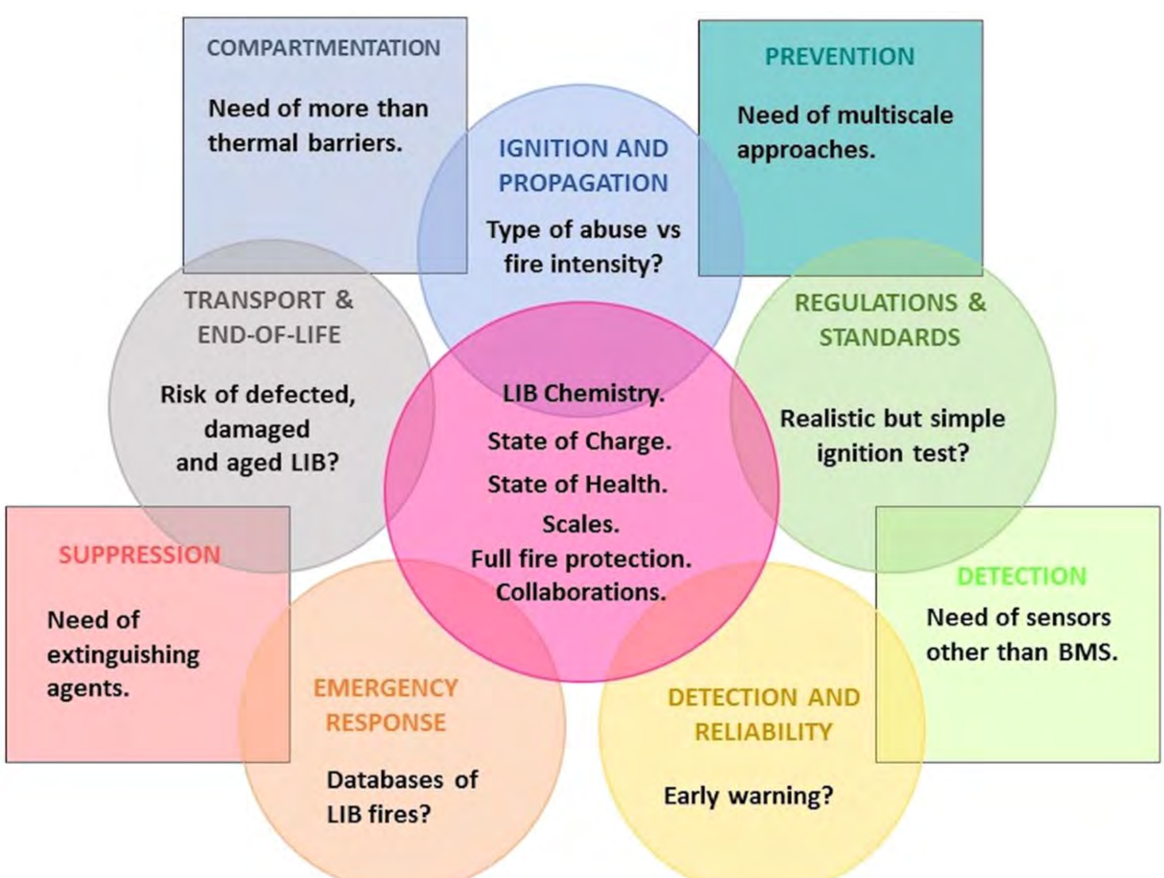

Figure 7. Summary of the conclusions of the meta-review in the form of a Venn diagram combining the five industrial challenges and research contributions to the four layers of protection.

justified. A multiscale research approach is needed as LIB fire safety involves many scales.

Further research in all four layers of fire safety is needed - prevention, detection, compartmentation and suppression. We find that most research has focused on prevention, and very little research investigates other protection layers. Nearly all the current detection research is based on BMS, and only a few papers investigate the other sensors. Compartmentation studies focus on thermal barriers alone. Just a few papers investigate LIB fire suppression, showing that there is no agreement on what extinguishing agents are effective for LIB fires. Given the current fire concerns of industry and stakeholders, early detection, robust compartmentation and effective suppression deserve more research attention. We strongly recommend that LIB industries embrace more comprehensive fire protection strategies that integrate all four layers. This way, LIB safety will surely improve.

Research studies would increase their immediate impact by using real-world data from industry as a baseline to develop new approaches to battery safety. The lack of fire statistics at the international level for LIB incidents could be mitigated by establishing a single international body, representing all the major industries that use LIBs, responsible for facilitating communication and harmonising standards and regulations across the multiple industries. International professional syndicates such as Recharge (industry association for advanced rechargeable Lithium batteries) in the EU and PRBA (Rechargeable Battery Association) in USA do exist to provide guidelines.

In order to close the gaps uncovered in this meta-review and accelerate the arrival of more LIB safety solutions, we recommend closer collaborations between the battery and fire safety communities, which, supported by the major industries, could drive improvements, integration and harmonization of fire safety across sectors.

Acknowledgments

The authors thank the following companies for contributing with their views to this work: Williams Advanced Engineering, Aston Martin, Rolls-Royce, Vantage Power, Brill Power and Avid Technology Ltd. The authors gratefully acknowledge the financial support from Innovate UK BATMAN project (grant number 104180) to LBD, and from China Scholarship Council (CSC) to XH and ZH.

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References

1. International Energy Agency, 1–82 (2017), http://iea.org/publications/freepublications/publication/tracking-clean-energy-progress-2017.html.
2. Grand View Research (2017), https://grandviewresearch.com/press-release/global-lithium-ion-battery-market.
3. X. Feng, M. Ouyang, X. Liu, L. Lu, Y. Xia, and X. He, *Energy Storage Mater.*, **10**, 246 (2018).
4. A. Pfrang, A. Kriston, V. Ruiz, N. Lebedeva, and F. di Persio, *Safety of Rechargeable Energy Storage Systems with a Focus on Li-ion Technology* (Elsevier Inc) p. 253 (2017).
5. Reuters, *Sony recalls PC batteries* (2008), https://reuters.com/article/us-sony-battery/sony-recalls-pc-batteries-idUSTRE49U1EZ20081031.
6. Reuters, *Note 7 fiasco could burn a $17 billion hole in Samsung accounts* (2016), https://reuters.com/article/us-samsung-elec-smartphones-costs-idUSKCN12B0FX.
7. United Nations Economic Commission for Europe (UNECE). Electric Vehicle Safety Informal Working Group (EVS IWG), *EVS16-H14 [CN]ACT02 & 05 Statistics and Analysis on fire accidents for EVs-China-0829* (2018), https://wiki.unece.org/display/trans/EVS+16th+session.
8. Battery Safety Laboratory of Tsinghua University, *2019 Power Battery Safety Research Report* (2019).
9. L. Wang, X. Feng, and X. He, *Safety of LIBs: Understanding and Progress* (2019).
10. United Nations Economic Commission for Europe (UNECE). Electric Vehicle Safety Informal Working Group (EVS IWG), *EVS16-E7OI-0600 [US] NTSB electric vehicle fire investigations* (2018), https://wiki.unece.org/display/trans/EVS+16th+session.
11. US Federal Aviation Administration (FAA), *Events with smoke, fire, extreme heat or explosion involving lithium ion batteries* (2019), https://faa.gov/hazmat/resources/lithium_batteries/media/Battery_incident_chart.pdf.
12. US Consumer Product Safety Commission, *Status Report on High Energy Density Batteries Project* (2017), https://www.cpsc.gov/s3fs-public/High_Energy_Density_Batteries_Status_Report_2_12_18.pdf.
13. V. Ruiz and A. Pfrang (2018), *JRC exploratory research : Safer Li-ion batteries by preventing thermal propagation*.
14. E. M. Berdichevsky, P. D. Cole, A. J. Hebert, W. A. Hermann, K. R. Kelty, S. I. Kohn, D. F. Lyons, J. B. Straubel, and N. J. Mendez, U.S. Pat. 7,433,794, issued October 7 (2008), http://large.stanford.edu/publications/coal/references/docs/tesla.pdf.
15. A. Hales, L. Bravo Diaz, M. W. Marzook, Y. Zhao, Y. Patel, and G. J. Offer, *J. Electrochem. Soc.*, **166**, A2383 (2019).
16. A. Hales, M. W. Marzook, L. Bravo Diaz, Y. Patel, and G. J. Offer, *J. Electrochem. Soc.*, **167**, 020524 (2020).
17. United Nations Economic Commission for Europe (UNECE), *Global Technical Regulation on the Electric Vehicle Safety (EVS) (Phase I)* (2018), https://unece.org/fileadmin/DAM/trans/main/wp29/wp29wgs/wp29gen/wp29registry/ECE-TRANS-180a20e.pdf.
18. J. M. Tarascon, *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, **368**, 3227 (2010).
19. National Highway Traffic Safety Administration (NHTSA), *Lithium-ion Battery Safety Issues for Electric and Plug-in Hybrid Vehicles (Report No. DOT HS 812 418)* (2017), https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/12848-lithiumion-safetyhybrids_101217-v3-tag.pdf.
20. D. H. Doughty and A. A. Pesaran, *Vehicle Battery Safety Roadmap Guidance* (2012), www.nrel.gov.
21. A. Mauger, C. M. Julien, J. B. Goodenough, and K. Zaghib, *J. Electrochem. Soc.*, **167**, 070507 (2020).
22. *SAE J2289. Electric-drive battery pack system: functional guidelines* (2008).
23. *SAE J2464. Electric and hybrid electric vehicle rechargeable energy storage system (RESS) safety and abuse testing* (2009).
24. *SAE J2929. Safety standards for electric and hybrid vehicle propulsion battery systems utilizing lithium-based rechargeable cells* (2013).
25. *ISO 12405-1. Electrically propelled road vehicles—test specification for lithiumion traction battery packs and systems Part 1: high-power applications* (2011).
26. *ISO 12405-2. Electrically propelled road vehicles—test specification for lithiumion traction battery packs and systems Part 2: high-energy applications* (2012).
27. *ISO 12405-3. Electrically propelled road vehicles—test specification for lithiumion traction battery packs and systems Part 3: Safety performance requirements* (2014).
28. *IEC 62660-2. Rechargeable cells standards publication secondary lithium-ion cells for the propulsion of electric road vehicles Part 2: reliability and abuse testing* (2011).
29. *IEC 62660-3. Rechargeable cells standards publication secondary lithiumion cells for the propulsion of electric road vehicles Part 3: safety requirements of cells and modules* (2016).
30. *IEC TR 62660-4: Rechargeable Cells Standards Publication Secondary lithium-ion cells for the propulsion of electric road vehicles. Part 4 : Candidate alternative test methods for the internal short circuit test of IEC 62660-3* (2017).
31. UL 2580: Batteries for Use in Electric Vehicles (2013).
32. T. Unkelhaeuser and D. Smallwood, *SAND99-0497-USABC: United States advanced battery consortium electrochemical storage system abuse test procedure manual* (1999).
33. D. Doughty and C. Crafts, *SAND 2005–3123: freeDomCAR electrical energy storage systems abuse test manual for electric and hybrid electric vehicle applications* SAND –3123 (2005), https://prod-ng.sandia.gov/techlib-noauth/access-control.cgi/2005/053123.pdf.
34. *KMVSS Article18-3. Traction battery* (2009).
35. AIS-048 Battery operated vehicles—safety requirements of traction batteries (2009).
36. *QC/T 743. Lithium-ion batteries for electric vehicles Chinese voluntary standards for automobiles* (2006).
37. *IEC 62133-2: Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for portable sealed secondary cells, and for batteries made from them, for use in portable applications. Part 2: Lithium systems* (2017).
38. IEC 62619: Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for large format secondary lithium cells and batteries for use in industrial applications (2017).
39. RTCA DO −311: Minimum operational performance standards for rechargeable lithium battery systems (2008).
40. UL*1973 Second edition: Standard for batteries for use in light electric rail (LER) applications and stationary applications* (2017).
41. VDE-AR-E 2510-50: Stationary battery energy storage systems with lithium batteries - Safety requirements (2017).
42. *UN/ECE Regulation No. 100.02. Uniform provisions concerning the approval of vehicles with regard to specific requirements for the electric power train* (2013).
43. V. Ruiz, A. Pfrang, A. Kriston, N. Omar, P. Van den Bossche, and L. Boon-Brett, *Renew. Sustain. Energy Rev.*, **81**, 1427 (2018).
44. K. F. Yeow and H. Teng, *SAE Int. J. Altern. Powertrains*, **2**, 179 (2013).
45. A. Pfrang, A. Podias, A. Kriston, V. Ruiz, A. Antonelli, R. Van der Aat, and L. Boon-Brett, in*Advanced Automotive Battery Conference* (2019).

46. J. Lamb and C. J. Orendorff, *J. Power Sources*, **247**, 189 (2014).
47. United Nations Economic Commission for Europe (UNECE). Electric Vehicle Safety (EVS), *Electric Vehicle Safety (EVS)* https://wiki.unece.org/pages/viewpage.action?pageId=3178628.
48. R. Spotnitz and J. Franklin, *J. Power Sources*, **113**, 81 (2003).
49. F. Larsson, S. Bertilsson, M. Furlani, I. Albinsson, and B. E. Mellander, *J. Power Sources*, **373**, 220 (2018).
50. *UN 38.3: Recommendations on the Transport of Dangerous Goods Manual of Test and Criteria* (United Nations, New York and Geneva) 6th revised ed. (2015), https://www.unece.org/fileadmin/DAM/trans/danger/publi/manual/Rev.6/1520832_E_ST_SG_AC.10_11_Rev6_WEB_-With_corrections_from_Corr.1.pdf.
51. European Commission, *Evaluation of the EU Directive 2006/66/EC on batteries and accumulators (the Batteries Directive)*Evaluation of the EU Directive /66/EC on batteries and accumulators (the Batteries Directive) (2006), https://ec.europa.eu/environment/waste/batteries/evaluation.html.
52. European Commission, *Commission publishes evaluation of the EU Batteries Directive* (2019), https://www.unece.org/fileadmin/DAM/trans/danger/publi/manual/Rev.6/1520832_E_ST_SG_AC.10_11_Rev6_WEB_-With_corrections_from_Corr.1.pdf.
53. T. Kim, D. Makwana, A. Adhikaree, J. Vagdoda, and Y. Lee, *Energies*, **11**, 125 (2018).
54. J. V. Barreras, T. Raj, and D. A. Howey, *Proceedings: IECON 2018–44th Annual Conference of the IEEE Industrial Electronics Society*(Institute of Electrical and Electronics Engineers Inc) p. 4956 (2018).
55. A. Abhijeet, S. Aditya, and L. Ramanathan, *Int. Res. J. Eng. Technol.*, **4**, 2927 (2017), https://www.irjet.net/archives/V4/i4/IRJET-V4I4712.pdf.
56. W. Waag, C. Fleischer, and D. U. Sauer, *J. Power Sources*, **258**, 321 (2014).
57. A. Fotouhi, D. J. Auger, K. Propp, S. Longo, and M. Wild, *Renew. Sustain. Energy Rev.*, **56**, 1008 (2016).
58. C. Pastor-Fernández, K. Uddin, G. H. Chouchelamane, W. D. Widanage, and J. Marco, *J. Power Sources*, **360**, 301 (2017).
59. T. Yokoshima, D. Mukoyama, F. Maeda, T. Osaka, K. Takazawa, S. Egusa, S. Naoi, S. Ishikura, and K. Yamamoto, *J. Power Sources*, **393**, 67 (2018).
60. X. Li, G. Fan, K. Pan, G. Wei, C. Zhu, G. Rizzoni, and M. Canova, *J. Power Sources*, **367**, 187 (2017).
61. J. V. Barreras, C. Pinto, R. De Castro, E. Schaltz, S. J. Andreasen, and R. E. Araújo, *2014 IEEE Vehicle Power and Propulsion Conference, VPPC 2014, Institute of Electrical and Electronics Engineers Inc.* (2014).
62. J. Varela, *Aalborg Univ. PhD Ser. Fac. Eng. Sci.* (2017).
63. P. Sun, R. Bisschop, H. Niu, and X. Huang, *Fire Technol.*, **56**, 1 (2020).
64. R. Thomas Long Jr, C. F. Andrew Blum, C. J. Thomas Bress, and C. R. Benjamin Cotts, *Best Practices for Emergency Response to Incidents Involving Electric Vehicles Battery Hazards: A Report on Full-Scale Testing Results Final Report* (2013), www.nfpa.org/Foundation.
65. A. F. Blum and C. R. Thomas Long Jr, *Hazard Assessment of Lithium Ion Battery Energy Storage Systems* (Springer, New York) (2016), https://www.unece.org/fileadmin/DAM/trans/danger/publi/manual/Rev.6/1520832_E_ST_SG_AC.10_11_Rev6_WEB_-With_corrections_from_Corr.1.pdf.
66. Iata, *Safety Risk Assessment* (International Air Transport Association, Geneva) 1st ed. (2016), https://skybrary.aero/bookshelf/books/4000.pdf.
67. D. Sturk, L. Rosell, P. Blomqvist, and A. A. Tidblad, *Batteries*, **5** (2019).
68. Q. Wang, B. Mao, S. I. Stoliarov, and J. Sun, *Prog. Energy Combust. Sci.*, **73**, 95 (2019).
69. P. Ribière, S. Grugeon, M. Morcrette, S. Boyanov, S. Laruelle, and G. Marlair, *Energy Environ. Sci.*, **5**, 5271 (2012).
70. X. Liu, Z. Wu, S. I. Stoliarov, M. Denlinger, A. Masias, and K. Snyder, *Fire Saf. J.*, **85**, 10 (2016).
71. M. Egelhaaf, D. Kress, D. Wolpert, T. Lange, R. Justen, and H. Wilstermann, *SAE Int. J. Altern. Powertrains*, **2**, 37 (2013).
72. DNV GL, *Considerations for Energy Storage Systems Fire Safety* https://dnvgl.com/publications/considerations-for-energy-storage-systems-fire-safety-89415.
73. S. Atkinson, *Seal. Technol.*, **2018**, 7 (2018).
74. A. O. Said, C. Lee, S. I. Stoliarov, and A. W. Marshall, *Appl. Energy*, **248**, 415 (2019).
75. C. Ziebert, *Using battery calorimeters for Thermal propagation research* (2020), https://openaccessgovernment.org/thermal-propagation-research-battery-calorimeters/79119/.
76. Z. Wang, N. Mao, and F. Jiang, *J. Therm. Anal. Calorim.*, **140**, 2849 (2019).
77. K. Chen, Y. Chen, Z. Li, F. Yuan, and S. Wang, *Int. J. Heat Mass Transf.*, **127**, 393 (2018).
78. W. T. Luo, S. B. Zhu, J. H. Gong, and Z. Zhou, *Procedia Engineering*, **211**, 531 (2018).
79. *Dieser Lösch-Container für brennende Elektroautos macht es der Feuerwehr einfacher - ecomento.de* (2017), https://ecomento.de/2017/02/10/dieser-loesch-container-fuer-brennende-elektroautos-macht-es-der-feuerwehr-einfacher/.
80. FM Global, *Loss Prevention Technical Research Reports* https://fmglobal.com/research-and-resources/research-and-testing/research-technical-reports.
81. R. T. Long, P. E. Cfei, and A. M. Misera, *Sprinkler Protection Guidance for Lithium-Ion Based Energy Storag e Systems FINAL REPORT BY* (2019), https://fmglobal.com/research-and-resources/research-and-testing/research-technical-.
82. Tesla, *Model S - Emergency reponse guide* (2016), https://www.tesla.com/sites/default/files/pdfs/first_responders/2016_Models_S_Emergency_Responders_Guide_en.pdf.
83. T. Välisalo, *Firefighting in Case of Li-Ion Battery Fire in Underground Conditions: Literature Study* (VTT Technical Research Centre of Finland) (2019), https://cris.vtt.fi.
84. F. Larsson, P. Andersson, P. Blomqvist, and B. E. Mellander, *Sci. Rep.*, **7**, 1 (2017).
85. H. Huo, Y. Xing, M. Pecht, B. J. Züger, N. Khare, and A. Vezzini, *Energies*, **10**, 793 (2017).
86. Shipping Guidelines for Lithium Ion Batteries (2019), https://www.rrc-ps.com/fileadmin/Dokumente/Shipment/Shipping_Guidelines_Lithium_Ion_Batteries_EN.pdf.
87. E. Gies, *Nature*, **526**, S100 (2015).
88. T. Liu et al., *Nat. Commun.*, **10**, 1 (2019).
89. R. Thomas, L. Jason, A. Sutula, and M. J. Kahn, *Lithium Ion Batteries Hazard and Use Assessment Phase IIB Flammability Characterization of Li-ion Batteries for Storage Protection* (2013), http://nfpa.org/foundation.
90. R. Thomas Long Jr and C. Andrew Blum, *Lithium Ion Batteries Hazard and Use Assessment-Phase III* (Fire Protection Research Foundation, Quincy) (2016), https://nfpa.org/-/media/Files/News-and-Research/Fire-statistics-and-reports/Hazardous-materials/RFLithiumIonBatteriesPhaseIII.ashx.
91. J. S. Gnanaraj, E. Zinigrad, L. Asraf, H. E. Gottlieb, M. Sprecher, D. Aurbach, and M. Schmidt, *J. Power Sources*, **119–121**, 794 (2003).
92. R. Spotnitz, *J. Power Sources*, **113**, 72 (2003).
93. L. Lu, X. Han, J. Li, J. Hua, and M. Ouyang, *J. Power Sources*, **226**, 272 (2013).
94. D. D. Macneil, L. Christensen, J. Landucci, J. M. Paulsen, and J. R. Dahn, *An Autocatalytic Mechanism for the Reaction of Li x CoO 2 in Electrolyte at Elevated Temperature*, **147**, 970 (2000).
95. G. H. Kim, A. Pesaran, and R. Spotnitz, *J. Power Sources*, **170**, 476 (2007).
96. P. Ping, Q. Wang, P. Huang, K. Li, J. Sun, D. Kong, and C. Chen, *J. Power Sources*, **285**, 80 (2015).
97. E. P. Roth, *SAE Int. J. Passenger Cars Mech. Syst.*, **1**, 326 (2008).
98. Y. Fu, S. Lu, K. Li, C. Liu, X. Cheng, and H. Zhang, *J. Power Sources*, **273**, 216 (2015).
99. Z. Wang, N. Mao, and F. Jiang, *J. Therm. Anal. Calorim.*, **136**, 2239 (2019).
100. T. D. Hatchard, D. D. MacNeil, A. Basu, and J. R. Dahn, *J. Electrochem. Soc.*, **148**, A755 (2001).
101. C. F. Lopez, J. A. Jeevarajan, and P. P. Mukherjee, *J. Electrochem. Soc.*, **162**, A2163 (2015).
102. P. Peng and F. Jiang, *Int. J. Heat Mass Transf.*, **103**, 1008 (2016).
103. D. Ren, X. Liu, X. Feng, L. Lu, M. Ouyang, J. Li, and X. He, *Appl. Energy*, **228**, 633 (2018).
104. J. Zhu, T. Wierzbicki, and W. Li, *J. Power Sources*, **378**, 153 (2018).
105. S. Abada, M. Petit, A. Lecocq, G. Marlair, V. Sauvant-Moynot, and F. Huet, *J. Power Sources*, **399**, 264 (2018).
106. D. Lisbona and T. Snee, *Process Saf. Environ. Prot.*, **89**, 434 (2011).
107. A. Manthiram, X. Yu, and S. Wang, *Nat. Rev. Mater.*, **2** (2017).
108. Z. Liao, S. Zhang, K. Li, G. Zhang, and T. G. Habetler, *J. Power Sources*, **436** (2019).
109. D. Ouyang, J. Liu, M. Chen, J. Weng, and J. Wang, *J. Electrochem. Soc.*, **165**, A2184 (2018).
110. J. Lamb, C. J. Orendorff, L. A. M. Steele, and S. W. Spangler, *J. Power Sources*, **283**, 517 (2015).
111. G. Zhong, H. Li, C. Wang, K. Xu, and Q. Wang, *J. Electrochem. Soc.*, **165**, A1925 (2018).
112. C. F. Lopez, J. A. Jeevarajan, and P. P. Mukherjee, *J. Electrochem. Soc.*, **162**, A1905 (2015).
113. D. G. Hermann, W. A. Kohn, S. I. Mehta, and V. H. Beck, "Thermal barrier structure for containing thermal runaway propagation within a battery pack." U.S. Pat. 8,541,126 B2 (2013), https://patentimages.storage.googleapis.com/2a/c3/c0/7e635bf38449af/US8541126.pdf.
114. E. Berdichevsky, P. Cole, A. Herbert, W. Hermann, K. Kelty, S. Kohn, D. Lyons, J. Straubel, and N. Mendez, "Mitigation of propagation of thermal runaway in a multi-cell battery pack." U.S. Pat. 7,433,794 (2008), http://large.stanford.edu/publications/coal/references/docs/tesla.pdf.
115. S. Wilke, B. Schweitzer, S. Khateeb, and S. Al-Hallaj, *J. Power Sources*, **340**, 51 (2017).
116. Q. Li, C. Yang, S. Santhanagopalan, K. Smith, J. Lamb, L. Steele, and L. Torres-Castro, *J. Power Sources*, **429**, 80 (2019).
117. C. Lee, A. O. Said, and S. I. Stoliarov, *J. Electrochem. Soc.*, **167**, 090524 (2020).
118. J. Chen, S. Kang, E. Jiaqiang, Z. Huang, K. Wei, B. Zhang, H. Zhu, Y. Deng, F. Zhang, and G. Liao, *J. Power Sources*, **442**, 227228 (2019).
119. J. Paur, (2013), https://wired.com/2013/03/boeing-787-battery-redesign/.
120. Z. Chen, R. Xiong, J. Tian, X. Shang, and J. Lu, *Appl. Energy*, **184**, 365 (2016).
121. A. R. Baird, E. J. Archibald, K. C. Marr, and O. A. Ezekoye, *J. Power Sources*, **446**, 227257 (2020).
122. D. H. Doughty, E. P. Roth, C. C. Crafts, G. Nagasubramanian, G. Henriksen, and K. Amine, *J. Power Sources*, **146**, 116 (2005).
123. Q. Wang, P. Ping, X. Zhao, G. Chu, J. Sun, and C. Chen, *J. Power Sources*, **208**, 210 (2012).
124. A. Mauger and C. M. Julien, *Ionics (Kiel).*, **23**, 1933 (2017).
125. L. Kong, C. Li, J. Jiang, and M. G. Pecht, *Energies*, **11**, 2191 (2018).
126. C. Mikolajczak, M. Kahn, K. White, and R. T. Long, *Lithium-Ion Batteries Hazard and Use Assessment Final Report* (2011), https://www.prba.org/wp-content/uploads/Exponent_Report_for_NFPA_-_20111.pdf.

https://www.wsj.com/articles/pg-e-warns-of-more-blackouts-during-californias-wildfire-season-11623414658

U.S.

PG&E Warns of More Blackouts During California's Wildfire Season

Severe drought expected to heighten fire risk throughout the summer and fall

PG&E workers attaching conductors to an automatic circuit recloser in Yountville, Calif., last year.

PHOTO: DAVID PAUL MORRIS/BLOOMBERG NEWS

By Katherine Blunt
June 11, 2021 8:30 am ET

PG&E Corp. said it is likely to proactively cut power to customers in Northern California more frequently this fall in anticipation of extreme wildfire risk.

The company said it has been rushing to trim trees away from power lines and inspect poles and towers ahead of wildfire season, which starts in the summer and peaks in the fall. But it is behind on some of that work and recently agreed to implement more stringent safety recommendations.

Sumeet Singh, PG&E's chief risk officer, said in an interview that the new shut-off criteria, coupled with California's dry weather conditions, could result in the need for more shut-offs than last year, especially if seasonal winds are as strong as they have been in recent years.

California is in the middle of a crippling drought that is expected to heighten fire risk throughout the summer and fall. About 85% of the state faces extreme drought conditions, according to the U.S. Drought Monitor, up from less than 3% this time last year. California Gov. Gavin Newsom has authorized emergency-mitigation efforts in many areas.

PG&E, which serves 16 million people in Northern and Central California, has relied heavily on what are known as public safety power shut-offs in recent years, after its power lines sparked a series of wildfires in 2017 and 2018 that killed more than 100 people. The company resorts to cutting electricity when strong winds pick up, which heightens the risk of its power lines failing under stress or sparking on contact with trees.

A reservoir in Santa Clara County, Calif., this week. About 85% of the state faces extreme drought conditions, according to the U.S. Drought Monitor.
PHOTO: DAVID PAUL MORRIS/BLOOMBERG NEWS

The company recently agreed to new shut-off criteria in response to recommendations by U.S. District Judge William Alsup, who is overseeing the company's criminal probation stemming from a 2010 natural-gas pipeline explosion south of San Francisco. PG&E will now consider whether its lines are at risk of getting hit by trees when deciding if they can safely run during windstorms. The company had historically focused on whether the equipment itself might fail.

Judge Alsup made the recommendation in response to the Zogg Fire, which ignited last fall in Shasta County, near Oregon, after a tree fell on a power line that PG&E had decided to keep running as winds picked up. Four people died.

PG&E cut power at a record scale in 2019, with nine outages that affected a total of two million people. Many were in the dark for days.

Mr. Singh said the company has made substantial progress on reducing the need for large outages by installing devices that allow for more targeted shut-offs and building out a network of weather stations and cameras to monitor conditions in greater detail. He said that while outages this fall may be more frequent, they will likely be smaller in size.

"The big, big variable that's unpredictable here is the wind," Mr. Singh said. "But in all the forecasts that we've done, we do not see ourselves getting back to the same kind of [power shut-off] events like we saw in 2019."

A sign calling for PG&E to turn the power back in Calistoga, Calif., in 2019.
PHOTO: JOSH EDELSON/AGENCE FRANCE-PRESSE/GETTY IMAGES

The company has also installed backup generation at certain substations and other means of keeping some communities online during outages. It successfully reduced outage scope last year, with six shut-offs that affected a total of about 653,000 customers.

Still, PG&E faces substantial challenges in completing risk mitigation work outlined in plans required by state regulators. It disclosed in regulatory filings last month that it failed to reach its first-quarter targets for inspecting transmission towers and distribution poles, as well as clearing its lines of trees.

Mr. Singh said the company is on track to have that work back on schedule before the fall.

Southern California Edison, a unit of Edison International, also faces extreme fire risk throughout its service territory and relies on proactive shut-offs to mitigate it. The company, which serves about 15 million people throughout the southern part of the state, anticipates fewer of them this fall as a result of its efforts to make its power lines less prone to sparking.

Utilities in Southern California have been grappling with wildfire risk for longer than those in Northern California and have for years been working to strengthen their infrastructure.

Erik Takayesu, the company's vice president of asset strategy and planning, said Southern California Edison is on track this year to have installed insulated wires throughout about a quarter of its service territory at highest risk of fire. Insulated wires don't spark on contact, making them safer to run during windstorms. The company also has been installing technology to limit outage scope.

Mr. Takayesu said the work would substantially limit the need to cut power in communities that have been affected multiple times by shut-offs in recent years.

"The system is simply more resilient to higher wind conditions," he said.

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Appeared in the June 12, 2021, print edition as 'California Blackout Warning Anticipates Big Wildfire Risk.'

Emission Impact: Additional Generator Usage Associated with Power Outage

January 30, 2020

This report has been reviewed by the staff of the California Air Resources Board. The contents do not necessarily reflect the views and policies of the California Air Resources Board, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

Summary

For public safety, it may be necessary for utilities to turn off electricity when gusty winds and dry conditions, combined with a heightened fire risk, are forecasted. This is called a "Public Safety Power Shutoff" or "PSPS". According to CPUC de-energization report[1], in October 2019, there have been almost 806 PSPS events that have impacted almost 973,000 customers (~7.5% of households in California) of which ~854,000 of them were residential customers, and the rest were commercial/industrial/medical baseline/other customers. Data also indicates that on average each of these customers had about 43 hours of power outage in October 2019.

Following the PSPS events, many households and businesses in California started operating their back-up generators to provide power for their day-to-day operations. Generators used during power outage will increase emissions as compared to an average day. Staff assessment indicated that with 973,000 customers impacted by PSPS events in October 2019, approximately 125,000 back-up generators were used by customers to provide electricity during power outage. Assuming 50 hours of operation per generator during month of October 2019, staff estimated excess emissions from the use of generators which are summarized in Table 1.

Table 1: Population and excess emissions from the use of electricity power generators during October 2019 PSPS events.

Generator Type		NOx (tons)	PM (tons)	Diesel PM (tons)	Additional Generators Running in PSPS
Portable	Gasoline Less than 25 hp	24.3	10.6		122,000
	Diesel above 25 hp *Non-Rental Generator*	7.3	0.30	0.30	381
	Diesel above 25 hp *Rental Generator*	9.1	0.30	0.30	582
Permitted Stationary Back-Up Generators (Assuming 30% Load Factor)		125.7	8.3	8.3	1,810
Non-permitted generators[2]		N/A	N/A	N/A	N/A
Total		***166.4***	***19.4***	***8.9***	***124,774***

[1] https://www.cpuc.ca.gov/deenergization/

[2] This analysis does not include emissions estimates from non-permitted generators such as the residential standby natural gas powered generators with power rating of less than 50 hp (e.g, a 22 kW Guardian Series home standby generator by Generac). At this point there is no information available on their population and sales. According to discussion with industry, it is assumed that most of these generator are powered by natural gas.

To put these numbers into context, 9 tons of diesel PM is equivalent to emissions from almost 29,000 heavy duty diesel trucks (above 14,000 lbs.) driving on California roadways for the period of one month (on average each truck drives around 3,000 miles per month).

The calculations described in the rest of the document outlines the assumptions used to estimate potential emissions impact from the use of gasoline and diesel generators during PSPS events.

<u>Small Gasoline Powered Generators (less than 25 hp)</u>

Population

Based on 2018 California State University Fullerton (CSUF) Survey[3] for small off-road (SORE) equipment, about one out of 8 households own a generator in California. For a population of 973,000 households, about 122,000 generators will likely to be used to provide additional power during the power shut-off period.

Emission Factors

According to data provided by manufacturers as part of the SORE Evaporative Reporting Requirement[4], generators have an average horsepower of 3.5 hp of which when combined with a load factor of 0.68, derived from OFFROAD2007[5], results in an effective power of 2.4 hp. To determine emission factors, we used emissions data from SORE exhaust certification database. Table 2 shows the derived emission factors along with weighted average emission factors across all horsepower bins.

Table 2: Exhaust emission factors (g/bhp-hr) for gasoline powered generator less than 25 hp

Equipment	Tech Type	Horsepower	Percent Population	HC (g/bhp-hr)	NOX (g/bhp-hr)	PM (g/bhp-hr)
Generator Sets	G2-CARB	0 – 2	5%	27.860	0.900	0.600
	G4-CARB	2 – 5	82%	5.634	1.484	0.740
		5 – 15	9%	2.885	1.975	0.140
		15 – 25	3%	3.390	1.422	0.140
	G4-FI	15 – 25	1%	1.074	2.125	0.140
	Population Weighted Average			**6.296**	**1.505**	**0.655**

Using the effective power and emission factors described earlier, staff estimated excess emissions as well emissions during 50 hours of generators operation (5 days with 10 hours a day operation). For example, with 122,000 generators operating for 50 hours during power shutoff, staff estimated excess emissions of 24.3 tons of NOx, 101.5 tons of THC, and 10.6 tons of PM. The calculation below outlines the assumptions used for this emissions impact assessment. Obviously, a more refined estimate can be made with additional information.

[3] Survey of Small Off-Road Engines (SORE) Operating within California: Results from Surveys with Four Statewide Populations, Submitted May 15, 2019, Prepared by the Social Science Research Center (SSRC) at CSU, Fullerton.
[4] https://ww3.arb.ca.gov/msprog/mailouts/ecars1805/ecars1805.pdf?_ga=2.15158582.1846785299.1570743950-1632999103.1458687259
[5] https://ww2.arb.ca.gov/our-work/programs/mobile-source-emissions-inventory/msei-road-archives

Portable Diesel Generators (above 25 hp)

Portable diesel generators are generally much larger and supply more power than gasoline generators, and could be used during PSPS events to supply power to larger facilities (such as schools, industrial facilities, or buildings). Table 3 provides CARB's latest population, activity, and emissions associated diesel portable generators registered under CARB's PERP program[6].

Table 3: Emissions and Population of Diesel portable generators registered under CARB's PERP program

	Population (statewide)	Annual Activity (hours)	NOx (tons/yr)	PM (tons/yr)	PM25 (tons/yr)
Portable Equipment - Non-Rental Generator	5,081	1,299	2,537	99	91
Portable Equipment - Rental Generator	7,764	1,392	3,363	123	113

For assessing the emissions impact associated with this event, this analysis will assume that the percent of businesses that use generators and backup generators that are impacted by the PSPS is roughly proportional to the percent of households impacted (about 973,000 households out of 13,000,000 in California, or about 7.5 percent of the population of generators in the state). Table 4 shows the excess emissions from the use of portable diesel power generators during PSPS events assuming 50 hours of operations.

Table 4: Population and excess emissions from the use of portable diesel powered generators during October 2019 PSPS events

	Additional Generators Running in PSPS	NOx (tons)	PM (tons)	PM2.5 (tons)
Portable Equipment - Non-Rental Generator	381	7.3	0.30	0.30
Portable Equipment - Rental Generator	582	9.1	0.30	0.30
Total	**964**	**16.45**	**0.61**	**0.61**

Permitted Stationary Back-Up Generators (BUG)

Population

Data on permitted stationary back-up generators were provided to CARB by several air districts. Staff used the facility ID from the districts permit data to find the address of the facility that the stationary BUGs are operating and determined whether those BUGs were impacted by the PSPS events or not. Using this process, staff determined that almost 1,810 stationary BUGs across California were impacted by the October 2019 PSPS events.

Emission Factors

Additionally, using actual emission factors for each diesel BUG engines provided in the districts' stationary BUGs database (i.e., stationary BUGs permit database), staff assumed a work based emission factors of 0.44 g/bhp-hr for PM and 6.7 g/bhp-hr for NOx, based on averaging of a

[6] https://ww2.arb.ca.gov/our-work/programs/portable-equipment-registration-program-perp

sample of permitted diesel powered backup generators in the state. The analysis also indicated that an average permitted back-up generator has a power rating of ~ 627 hp and they can go up as high as 4,400 hp which when combined with a load factor assumption of 30% resulted in an effective power of 188 hp. Table 5 provides a summary of excess emissions associated with the stationary BUGs impacted by the PSPS events.

Table 5: Population and excess emissions from the use of diesel powered stationary back-up generators (BUG) during October 2019 PSPS events

	Additional Generators Running in PSPS	NOx (tons)	PM (tons)	Diesel PM (tons)
Permitted Stationary Back-Up Generators	1,810	126	8.3	8.3

Overview: Diesel Exhaust & Health

CATEGORIES

Topics Health, Air Pollution, Transportation Electrification, Construction & Earthmoving Equipment, Environmental Justice, Oceangoing Vessels & Harbor Craft, Freight & Goods Movement, Trains & Railyards, Transit, VW Diesel Vehicles

Programs Exposure, Community Air Protection Program , Community Health, Zero-Emission Powertrain Certification, Alternative Diesel Fuels, In-Use Off-Road Diesel-Fueled Fleets Regulation, Study of Neighborhood Air near Petroleum Sources, School Buses

Type Information

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Background

Diesel engines emit a complex mixture of air pollutants, including both gaseous and solid material.The solid material in diesel exhaust is known as diesel particulate matter (DPM). More than 90% of DPM is less than 1 µm in diameter (about 1/70th the diameter of a human hair), and thus is a subset of particulate matter less than 2.5 microns in diameter (PM2.5). Most PM2.5 derives from combustion, such as use of gasoline and diesel fuels by motor vehicles, burning of natural gas to generate electricity, and wood burning. PM2.5 is the size of ambient particulate matter air pollution most associated with adverse health effects of the air pollutants that have ambient air quality standards. These health effects include cardiovascular and respiratory hospitalizations, and premature death. As a California statewide average, DPM comprises about 8% of PM2.5 in outdoor air, although DPM levels vary regionally due to the non-uniform distribution of sources throughout the state.

DPM is typically composed of carbon particles (“soot”, also called black carbon, or BC) and numerous organic compounds, including over 40 known cancer-causing organic substances. Examples of these chemicals include polycyclic aromatic hydrocarbons, benzene, formaldehyde, acetaldehyde, acrolein, and 1,3-butadiene. Diesel exhaust also contains gaseous pollutants, including volatile organic compounds and oxides of nitrogen (NO_x). NO_x emissions from diesel engines are important because they can undergo chemical reactions in the atmosphere leading to formation of PM2.5 and ozone.

Most major sources of diesel emissions, such as ships, trains, and trucks operate in and around ports, rail yards, and heavily traveled roadways. These areas are often located near highly populated areas. Because of this, elevated DPM levels are mainly an urban problem, with large numbers of people exposed to higher DPM concentrations, resulting in greater health consequences compared to rural areas. A large fraction of personal exposure to DPM occurs during travel on roadways. Although Californians spend a relatively small proportion of their time in enclosed vehicles (about 7% for adults and teenagers, and 4% for children under 12), 30 to 55% of total daily DPM exposure typically occurs during the time people spend in motor vehicles.

Diesel Particulate Matter and Health

The majority of DPM is small enough to be inhaled into the lungs. Most inhaled particles are subsequently exhaled, but some deposit on the lung surface. Although particles the size of DPM can deposit throughout the lung, the largest fraction deposits in the deepest regions of the lungs where the lung is most susceptible to injury.

In 1998, CARB identified DPM as a toxic air contaminant based on published evidence of a relationship between diesel exhaust exposure and lung cancer and other adverse health effects. In 2012, additional studies on the cancer-causing potential of diesel exhaust published since CARB's determination led the International Agency for Research on Cancer (IARC, a division of the World Health Organization) to list diesel engine exhaust as "carcinogenic to humans". This determination is based primarily on evidence from occupational studies that show a link between exposure to DPM and lung cancer induction, as well as death from lung cancer. Download the IARC report (external site).

Because it is part of PM2.5, DPM also contributes to the same non-cancer health effects as PM2.5 exposure. These effects include premature death, hospitalizations and emergency department visits for exacerbated chronic heart and lung disease, including asthma, increased respiratory symptoms, and decreased lung function in children. Several studies suggest that exposure to DPM may also facilitate development of new allergies. Those most vulnerable to non-cancer health effects are children whose lungs are still developing and the elderly who often have chronic health problems.

Estimated Health Effects of DPM in California

DPM has a significant impact on California's population. It is estimated that about 70% of total known cancer risk related to air toxics in California is attributable to DPM. Based on 2012 estimates of statewide exposure, DPM is estimated to increase statewide cancer risk by 520 cancers per million residents exposed over a lifetime. Non-cancer health effects associated with exposure to DPM (based on 2014 - 2016 air quality data) are shown in the table below.

Health Effect	Estimated Annual Number of Cases*
Cardiopulmonary Death	730 (570 – 890)
Hospitalizations (Cardiovascular and Respiratory)	160 (20 – 290)
Emergency Room Visits for Asthma	370 (240 – 510)

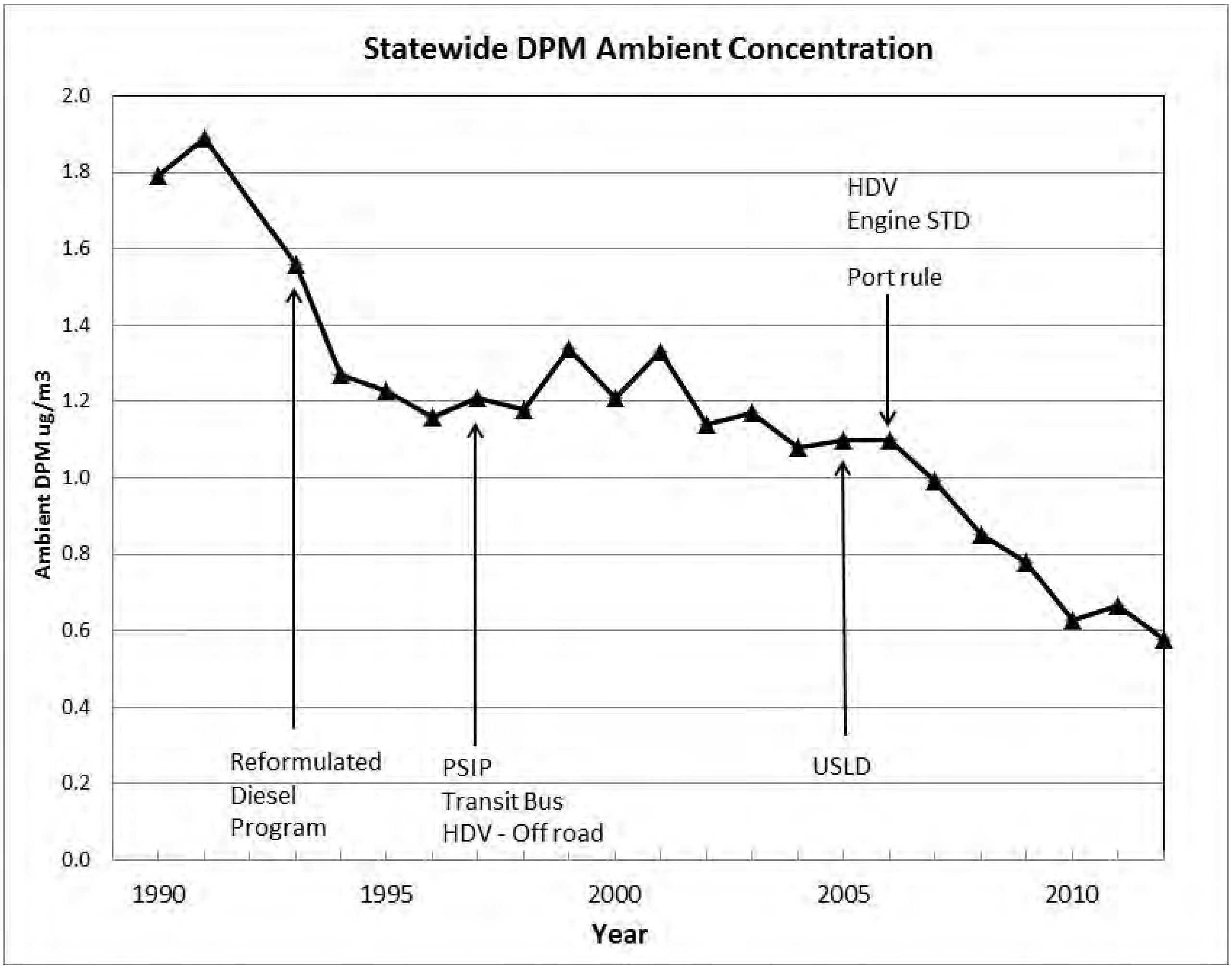
*Values in parenthesis indicate 95% confidence interval.

More Information

Trends in Outdoor Levels of DPM

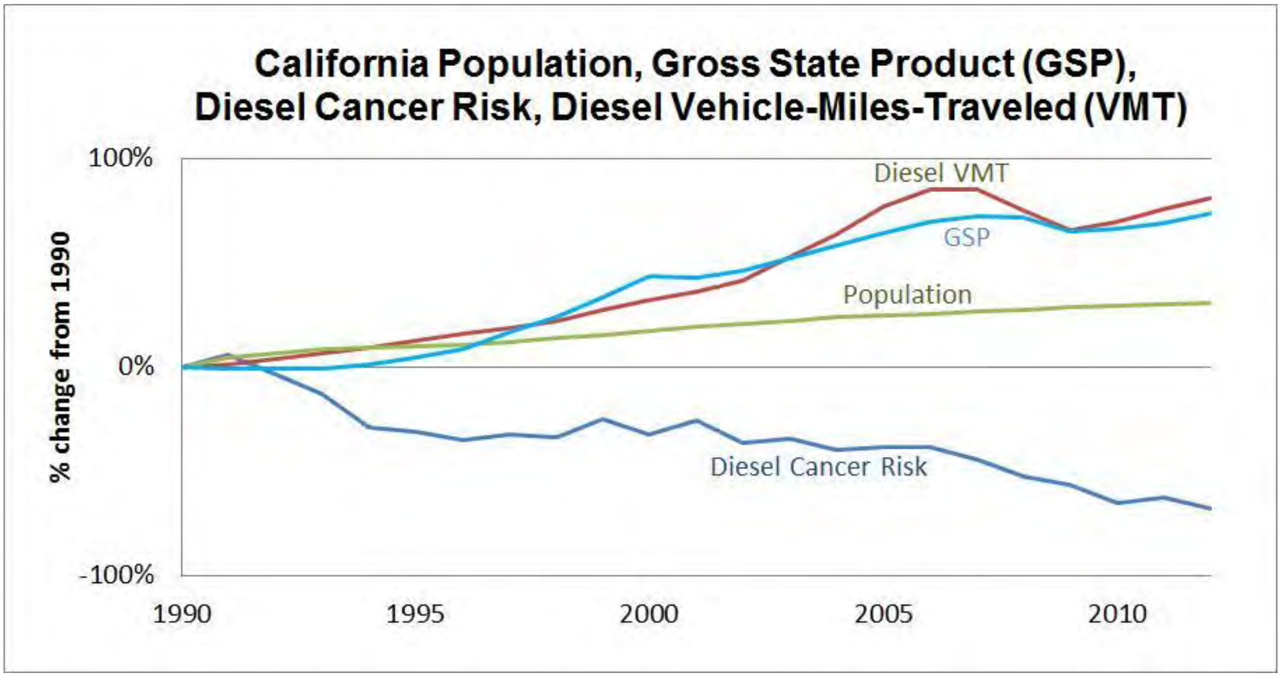
The figure below shows the trend in ambient DPM. CARB regulations** of diesel engines and fuels have had a dramatic effect on DPM concentrations. Since 1990, DPM levels have decreased by 68%. The figure also shows which regulations have had the greatest impact on DPM.

DPM levels are expected to continue declining as additional controls are adopted, and the number of new technology diesel vehicles increases.



**Abbreviations of CARB regulations used in table: HDV Engine STD = Heavy-duty diesel truck engine standard; HDV - Off road = Heavy-duty off-road diesel engines; Port rule = Port (drayage) trucks; PSIP = Periodic self-inspection program; Transit bus = Urban transit buses; ULSD = Clean diesel fuel

The figure below shows that despite the increased number of vehicle miles traveled by diesel vehicles (VMT, red line), and despite increases in statewide population (green line) and gross state product (GSP, a measure of growth in the state's economy, light blue line), CARB's regulatory programs still led to a decline in statewide cancer risk (dark blue line).



Additional Information

- CARB's diesel programs
- CARB's diesel mobile vehicles and equipment activities
- CARB's freight transport, ports and rail programs
- California's diesel fuel program
- Other diesel-related programs
- Selected references on diesel-related health effects

Environmental Effects of Diesel Exhaust

In addition to its health effects, diesel exhaust significantly contributes to haze that reduces visibility by obscuring outdoor views and decreasing the distance over which one can distinguish features across the landscape. Researchers have reported that in the San

Joaquin Valley and in southern California, diesel engines contribute to a reduction in visibility. This decrease in visibility is caused by scattering and absorption of sunlight by particles and gases present in diesel emissions.

DPM also plays an important role in climate change. A large proportion of DPM is composed of BC. Recent studies cited in the Intergovernmental Panel on Climate Change report estimate that emissions of BC are the second largest contributor to global warming, after carbon dioxide emissions. Warming occurs when BC particles absorb sunlight, convert it into infrared (heat) radiation, and emit that radiation to the surrounding air. A recent California-specific study showed that the darkening of snow and ice by BC deposition is a major factor in the rapid disappearance of the Sierra Nevada snow packs. Melting of the snow pack of the Sierra Nevada earlier in the spring is one of the contributing factors to the serious decline in California's water supply. As additional DPM controls are adopted, and the number of new technology diesel vehicles increases, BC emissions will continue to decline.

Conclusions

Although progress has been made over the past decade in reducing exposure to diesel exhaust, diesel exhaust still poses substantial risks to public health and the environment. Efforts to reduce DPM exposure through use of cleaner-burning diesel fuel, retrofitting engines with particle-trapping filters, introduction of new, advanced technologies that reduce particle emissions, and use of alternative fuels are approaches that are being explored and implemented. CARB anticipates that newly adopted diesel exhaust control measures will reduce population exposure even further, and that as the sustainable freight program expands, population exposure to diesel exhaust pollution will decrease even further. It is estimated that emissions of DPM in 2035 will be less than half those in 2010, further reducing statewide cancer risk and non-cancer health effects.

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CALIFORNIA WILDFIRES

During PG&E outages, generators caused fires, carbon monoxide poisoning

Mallory Moench

Updated: Nov. 17, 2019 8:09 p.m.

Art Bern Jr. at the home of his parents where an emergency generator sparked a fire which damaged the home�s garage and attic during a PG&E power shut off in late September, in Grass Valley, Ca. as seen on Friday Nov. 8, 2019.

Michael Macor / Special to The Chronicle

When PG&E cut power in rural Nevada County in late September, 90-year-old Art Bern went to turn on a generator outside his garage. It took him a few tries to get the machine, bought along with the house in 1989, going. But after he finally did and returned inside, the lights, which had just gone on, flickered out with a *pop*.

That's when Bern looked out his window and saw the garage on fire.

Nevada County Consolidated Fire District Fire Marshal Terry McMahan confirmed the Sept. 25 blaze was started by the generator because it was not properly maintained and too close to the building.

It destroyed the garage. But Bern's son, Art Jr., said his dad told him he was just grateful it wasn't worse.

"Thank God it didn't start anything else on fire," he said.

As Californians rushed to get backup power when PG&E cut electricity to millions this fall, some generators sparked fires or sickened people with carbon monoxide poisoning. Such risks increase when the machines aren't properly installed, placed or maintained by an electrician. And with PG&E warning that outages could keep happening for 10 years, the problems could continue.

"The longer we do this, shutting power off, the more we're going to roll the dice on the additional risks that exist because of alternative forms of power and lighting," said El Dorado County Fire Chief Lloyd Ogan. "We have traded one risk for a whole new set of risks."

Ogan said he responded to a generator fire near a garage that burned down a house in Pollock Pines on Oct. 29. The same afternoon, another generator lit a garage on fire.

Candles also ignited blazes, he said, and residents took barbecues inside to cook, triggering carbon monoxide alarms.

“People are going to do what they think they have to do even when it’s not safe,” Ogan said. “Every time they do, the risk to the community goes up.”

How to stay safe with a gas generator

Have a professional electrician install a generator.

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In Nevada County, McMahan counted at least four generator or wiring-related fires and a case of carbon monoxide poisoning during PG&E outages. On an Indian Springs horse ranch, an improperly wired generator sent electricity back into the power line when it was re-energized, consuming the machine in flames. In other outage-related problems, in Penn Valley, a community of 1,600 north of Sacramento, two trailers caught fire — one right after PG&E cut power and the other when it was restored — hinting at internal wiring problems, McMahan said.

Also in Penn Valley, a couple was treated for carbon monoxide poisoning after a generator was placed too close to the window of their mobile home, according to Penn Valley Fire District spokesman Clayton Thomas.

Their skin turned red, and they started to feel nauseous and weak and called 911 just before 11 p.m. on Oct. 9, Thomas said. Carbon monoxide in the air measured several times above safe levels.

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BY MALLORY MOENCH

"If they had gone to sleep without calling 911, they could very well have died," Thomas said. "Carbon monoxide is a colorless and odorless gas. Even if you don't smell the gas, you won't know you're being exposed until symptoms (appear). If exposure is high enough, you can be rendered unconscious." Carbon monoxide poisoning is treated simply by exposure to oxygen, he added.

In nearby Grass Valley, a customer called 911 to report a generator running in a convenience store basement, but no one was reported poisoned, said Fire Department spokesman Sam Goodspeed.

Firefighters said rural Sierra Nevada residents are used to using generators once or twice a year during winter storms, but not during hot, dry wildfire conditions — the very reason PG&E shut off power. Although the largest fire districts in the nine Bay Area counties and Cal Fire didn't report any generator incidents during outages, Cal Fire spokesman Scott McLean said, "I'm not naive to the potential by any means." On top of safety concerns, climate change regulators warn that fossil fuel-powered generators contribute to carbon emissions. In California, the California Air Resources Board, which regulates emissions, needs to approve models. On Oct. 31, the air board began allowing companies to apply for a waiver through the end of the year to sell non-certified models to meet demand during outages.

Air board spokeswoman Melanie Turner said a relatively new, average-size gas-powered generator running for an hour produces emissions on par with a car driving for about 150 miles. An older, larger industrial diesel generator spews as much in an hour as driving a truck from Sacramento to Salt Lake City, she said.

"The use of residential and industrial generators that generate substantial toxic and smog-forming emissions and are powered by fossil fuels is necessary in this crisis, but is in no way aligned with California's air quality, public health, or climate goals," Turner wrote in an email Thursday. "We need to find better solutions."

Fire Tracker

Follow wildfires across the state

Latest updates on wildfires burning across Northern and Southern California

Some generator companies are offering alternative fuels. Generac, a Wisconsin company, saw a huge increase in interest for its propane-fueled generators in Central and Northern California last month, said Jake Thomas, director of global service. Propane burns cleaner than gasoline.

Generac organizes professional installation for propane units, and sells portable gasoline generators, containing safety shut-off sensors for unsafe levels of gas, at some 300 California retailers.

Generac also started selling solar battery systems this year.

Other companies use hydrogen to fuel generators. Altergy, in Folsom (Sacramento County), saw high demand during the shut-offs for its zero-emission hydrogen fuel cell products — said to last up to a week to power traffic lights, cell towers or homes — and methanol fuel cells that create half as much carbon emissions as diesel generators.

“We’re getting interest and expect to be shipping some systems to go into areas that are most afflicted by outages,” said Eric Strayer, Altergy vice president of sales.

In Grass Valley, the Bern family struggled. A week after their garage went up in flames, Art Bern Sr. had a stroke.Now he’s in a skilled nursing facility, paralyzed on one side of his body. His wife stayed in a hotel for a while because the fire damaged wiring to the house, and moved back Friday.

Art Bern Jr. at the home of his parents where an emergency generator sparked a fire which damaged the home�s garage and attic during a PG&E power shut off in late September, in Grass Valley, Ca. as seen on Friday Nov. 8, 2019.
Michael Macor / Special to the Chronicle

Now the couple's insurance company promises them a propane generator, and in the meantime provided a portable generator, which their son used at his home nearby during a later round of PG&E outages.

But he wants a longer-term solution: "I'm considering going totally off the grid."

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Reach Mallory on

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She previously covered immigration and local news for the Albany Times Union and the Alabama state legislature for the Associated Press. Before that, she freelanced with a focus on the Yemeni diaspora while studying at the City University of New York Graduate School of Journalism.

VIEW COMMENTS

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TOP

Power of Place

Land Conservation and Clean Energy Pathways for California

The Nature Conservancy | Technical Report

Power of Place
Land Conservation and Clean Energy Pathways for California

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June 2019

Suggested Citation
Wu, G.C.; Leslie, E.; Allen, D.; Sawyerr, O.; Cameron, D.; Brand, E.; Cohen, B.; Ochoa, M.; Olson, A. *Power of Place: Land Conservation and Clean Energy Pathways for California*, 2019.

Acknowledgments
The authors would specifically like to thank the following staff and chapters of The Nature Conservancy for their important contributions to this work: Laura Crane (California), Stephanie Dashiell (California), Nels Johnson (North America), Joe Fargione (North America), Tomer Hasson (Western U.S.), Chris Hise and Sara Mascola (Great Plains Renewable Energy Strategy), and many staff at The Nature Conservancy chapters in Washington, Oregon, Nevada, Wyoming, New Mexico, Arizona, Idaho, Montana, Colorado, Utah. We are also grateful for the valuable support and contributions from Argonne National Laboratory staff (Jim Kuiper), several non-governmental organization staff (Kim Delfino from Defenders of Wildlife; Garry George from Audubon Society; Julia Prochnik, Helen O'Shea, and Mohit Chhabra from Natural Resources Defense Council; Alex Daue from The Wilderness Society, Laura Wisland and Mark Specht from Union of Concerned Scientists), National Renewable Energy Laboratory staff (Caleb Phillips, Michael Rossol, David Hurlbutt, Donna Heimiller), Western Electricity Coordinating Council staff (Fred Heutte), ICF staff (Jon Walker), Nathaniel Clark (OPDEnergy), Geoff Bedrosian (U.S. Fish and Wildlife Service), and Ranjit Deshmukh (UC Santa Barbara).

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This report has been prepared by E3 for The Nature Conservancy. This report is separate from and unrelated to any work E3 is doing for the California Public Utilities Commission. While E3 provided technical support to The Nature Conservancy in preparation of this report, E3 does not endorse any specific policy or regulatory measures as a result of this analysis. The California Public Utilities Commission did not participate in this project and does not endorse the conclusions presented in this report.

This study uses E3's California-wide RESOLVE model developed under California Energy Commission contract number EPC-14-069. Versions of this model have previously been used by E3 for projects completed on behalf of the California Energy Commission and the California Air Resources Board. These California state agencies did not participate in the project and do not endorse the conclusions presented in this report.

The RESOLVE model used for this project is distinct from the RESOLVE model developed for the CPUC's 2017-2018 Integrated Resource Planning proceeding (R.16-02-007). The following table summarizes the major differences in the RESOLVE model version used for this study and the version used in the CPUC's IRP proceeding.

Table 1: Key Differences in RESOLVE Input Assumptions as Compared to CPUC IRP Proceeding

Category	Assumption for This Study	CPUC IRP 2017-2018 Cycle Assumption
Geography	California Independent System Operator (CAISO) + Sacramento Municipal Utilities District (SMUD) + Los Angeles Department of Water and Power (LADWP)	California Independent System Operator (CAISO)
Demand forecast	Based on CEC EPIC PATHWAYS study forecast for a high electrification scenario, optimized for 2050.	Based on IEPR 2016/2017 forecast, optimized for 2030.
Carbon emissions trajectory	Developed to meet a 2050 target of 80% reduction relative to 1990 levels by 2050. An emissions target of about 8.8 MMT.	Developed to meet CARB's Scoping Plan Alternative 1 scenario for 2030.
Solar resource potential limitations	Reference case resource potential discounted to 267,076 MW in-state to accommodate the higher demand and deeper decarbonizations levels by 2050	Reference case resource potential discounted to 117,515 MW in-state.
Solar and Battery Storage Costs	Costs updated to be consistent with the 2017 National Renewable Energy Lab (NREL) Annual Technology Baseline (ATB), and Lazard Levelized Cost of Storage v3.0.	Renewable costs developed by Black & Veatch for RPS Calculator V6.3 Data Updates; Battery storage cost assumptions are derived from Lazard Levelized Cost of Storage v2.0 and DNV GL's Battery Energy Storage Study for the 2017 IRP.

Abstract

Despite the growing number of jurisdictions passing ambitious clean energy policies, including California's 100% zero-carbon electricity policy (Senate Bill 100), few studies have accounted for natural and working land impacts and how land constraints on energy availability affect infrastructure planning and the choices between technologies. To address this gap, we examine the environmental constraints and impacts of the new renewable energy development required to achieve California's goal of reducing greenhouse gas (GHG) emissions by 80% below 1990 levels by 2050. The scenarios in the study deliver 102-110% retail sales of renewable or zero-carbon electricity in 2050, which is consistent with Senate Bill 100 in 2050. Using detailed spatial datasets representing ecological, cultural, and agricultural siting criteria in 11 western states, we modeled onshore wind, solar, and geothermal energy availability under four levels of environmental land protections. We used these wind, solar, and geothermal energy estimates in a capacity expansion energy planning model, RESOLVE, to build several environmentally-constrained future electricity generation portfolios assuming both no access and access to out-of-state renewable resources. To assess each portfolio's environmental impact, we spatially modeled the locations of generation and transmission infrastructure using a site selection process and least cost path analysis, respectively. We find that California can decarbonize the electricity sector, but the balance between wind, solar PV, and storage capacity and resultant costs are sensitive to land protections and whether California has access to west-wide renewable energy. Land protections are highly effective in avoiding environmental impacts while achieving GHG targets, but can increase costs, primarily by reducing wind availability. However, higher costs can be more than offset by allowing access to out-of-state wind and solar resources, such that California can achieve both better cost and conservation outcomes by pursuing regional renewable resource development and trade. However, this path requires significantly more transmission infrastructure and can have greater land use impacts under scenarios with lower levels of environmental protections. Given the wide range of possible cost and technology mix outcomes due to renewable resource availability assumptions, energy planning studies aiming to capture drivers of model uncertainty should incorporate conservation data and siting constraints.

Keywords: land use, renewable energy, low-carbon, deep decarbonization, California, climate targets, 2050

Abbreviations and Acronyms

BLM	Bureau of Land Management
BTM	Behind-the-meter
CAISO	California Independent System Operator
Cat	Category (specifically in reference to Environmental Exclusion Categories)
CEC	California Energy Commission
CF	Capacity factor
CPA(s)	Candidate project area(s)
CPUC	California Public Utilities Commission
DER	Distributed Energy Resources
E3	Energy and Environmental Economics
GHG	Greenhouse gas
GW	Gigawatt
GWh	Gigawatt-hour
HVDC	High-voltage direct current
IRP	Integrated Resource Planning
MW	Megawatt
MWh	Megawatt-hour
NGO	Non-governmental organization
NREL	National Renewable Energy Laboratory
ORB	Optimal Renewable Energy Build-out
PAD-US	Protected Areas Database of the U.S. (U.S. Geological Survey and Conservation Biology Institute)
PV	Photovoltaic
QRA(s)	Qualifying Resource Areas
RPS	Renewable Portfolio Standard
SI	Supporting Information
SL	Siting Level
SPA(s)	Selected project area(s)
TNC	The Nature Conservancy
USDA	U.S. Department of Agriculture
USWTD	U.S. Wind Turbine Database
WECC	Western Electricity Coordinating Council
WWWMP	West-wide Wind Mapping Program

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