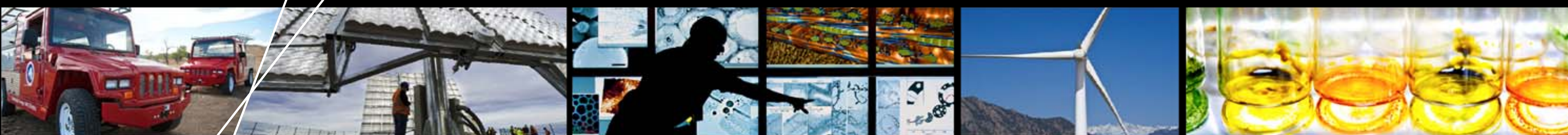
California 2030 Low Carbon Grid Study (LCGS)



Ali Ehlen

Greg Brinkman and Jennie Jorgenson, NREL

Jim Caldwell, CEERT

LCGS sponsors/steering committee

Abengoa	Energy Innovation
Alton Energy	EnerNOC
California Energy Storage Alliance	CPower
Electric Power Research Institute	General Electric
American Wind Energy Association	Iberdrola
BrightSource	Invenergy
CalEnergy	Large-scale Solar Association
Geothermal Energy Association	LS Power
Geothermal Resources Council	NRG
California Wind Energy Association	Pathfinder / Zephyr
California Biomass Energy Alliance	Recurrent
California Energy Efficiency Industry Council	Rockland Capital
Clean Line Energy	Solar Energy Industries Association
CleanPath	SolarReserve
EDF Renewable Energy	SunPower
EDP Renewables	Terra-Gen
Energy Foundation	Wellhead Electric

The steering committee sponsored the study and assembled the study team. As EE/RE experts in CA, they also helped developed the portfolios used in the study. The Energy Information Administration also helped support the study.

LCGS Technical Review Committee (TRC)

California Energy Commission	Mike Jaske, Melissa Jones
California Independent System Operator	Shucheng Liu
California Public Utilities Commission	Keith White
NV Energy	Stacey Kusters
Pacific Gas & Electric	Tom Miller, Antonio Alvarez
Sacramento Municipal Utility District	Tim Tutt
San Diego Gas & Electric	Jan Strack
Southern California Edison	Gary Stern, Carl Silsbee
Western Interstate Energy Board	Tom Carr
Western Grid Group	Brian Parsons
Woodruff Expert Services	Kevin Woodruff

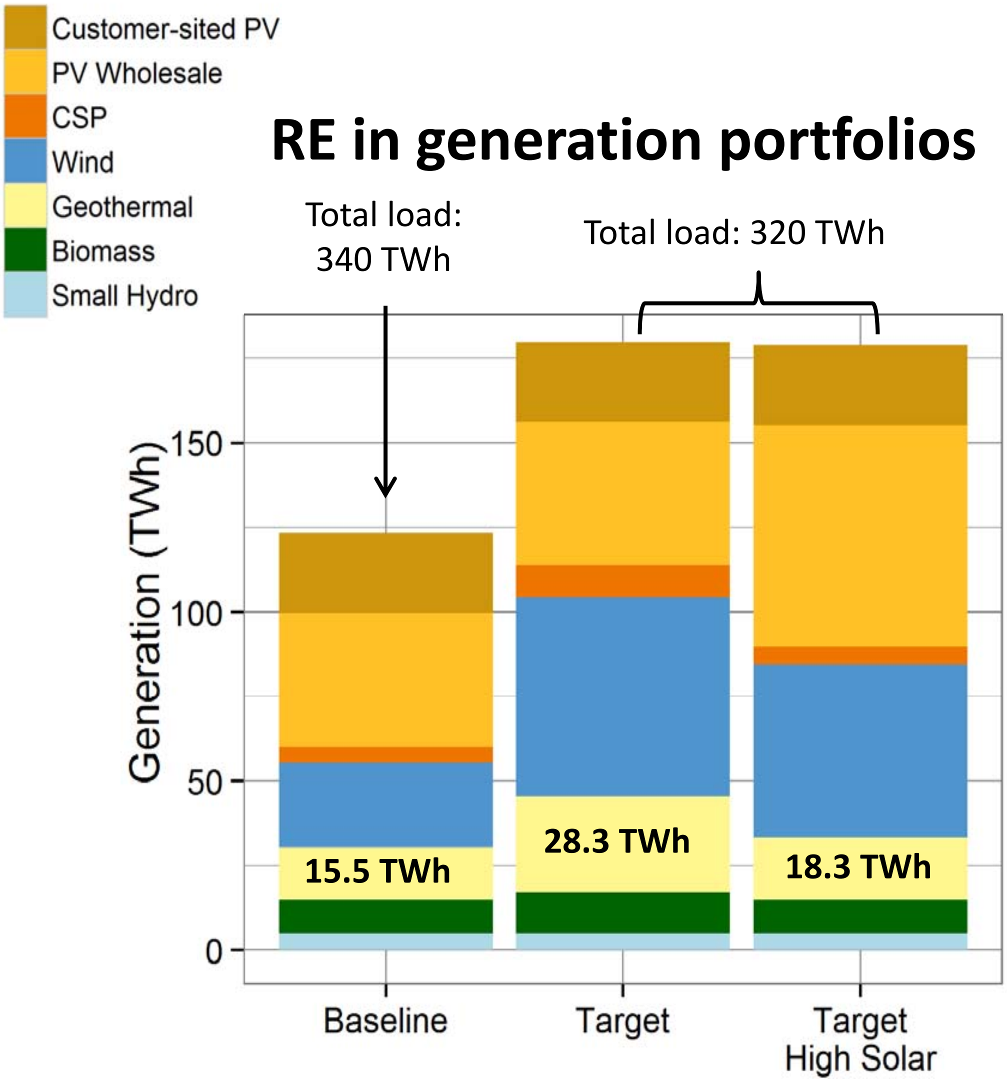
The TRC met throughout the study to review assumptions, methodology, results, and conclusions. Although the TRC helped review and prepare the report, the final report and conclusions are from the study team and may not represent specific interpretations of any committee member.

Study objectives

- Analyze the feasibility of 50% emissions reductions from California's electric sector (2012 levels) by the year 2030.
  - Puts California on track to meet longer term emissions goals
  - Three parts (NREL, JBS Energy, GE)

- **NREL analysis:** WECC-wide production cost modeling to understand operational impacts of emissions reductions scenarios

Renewable portfolios in each case



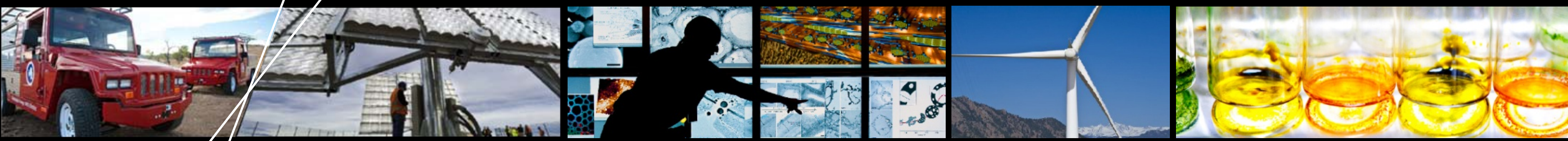
- Baseline Case: 33% RPS, similar to LTPP 2014 Trajectory case
- Target Case: 55 TWh more utility-scale RE than Baseline (diverse)
- Target High Solar: 55 TWh more utility-scale RE than Baseline (mostly CA PV)

- All cases have same rooftop PV penetration (24 TWh)
- Higher overall load to represent 2030 and higher PV penetration to continue meeting RPS

Grid flexibility assumptions

Conventional flexibility	Enhanced flexibility
70% of out-of-state (CA-entitled) renewable, nuclear, and hydro generation must be imported	Only physical limitation on imports and exports
25% of generation in California balancing authorities must come from local fossil-fueled and hydro sources	No minimum local generation requirements
1.5 GW battery storage to meet CPUC requirement	1.5 GW battery storage, 1 GW new pumped hydro, and 1.2 GW new out-of-state compressed air energy storage
Limits on ability of hydro and pumped storage for providing ancillary services (AS provision from hydro tuned to CAISO 2013)	Less strict limits on hydro and pumped storage for providing ancillary services

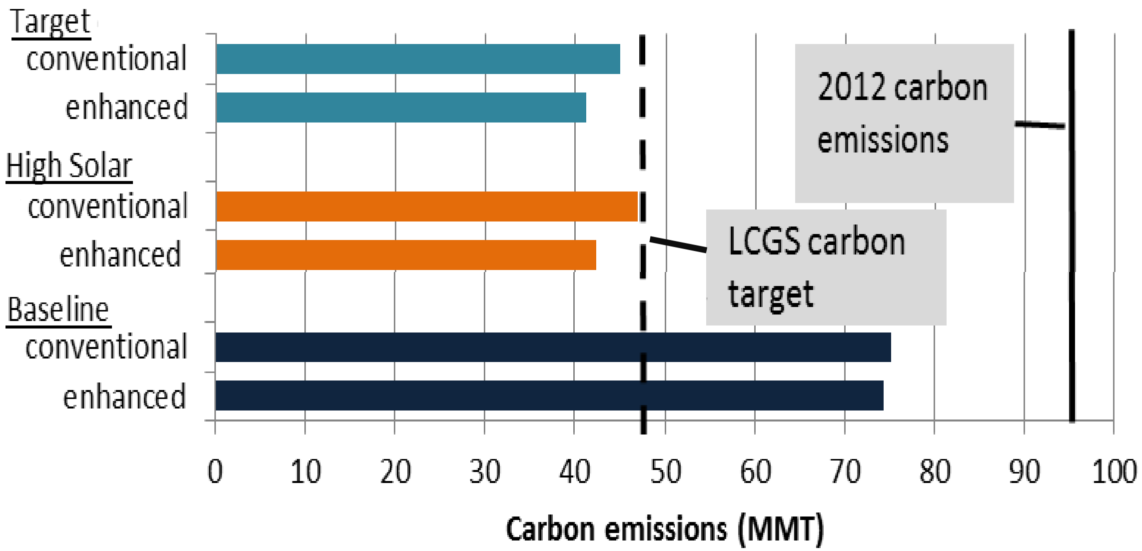
- It was interesting to test this "suite" of assumptions because the impact of two flexibility constraints can be much larger than the sum of individual impacts



Key Results

- Target conventional
- Target enhanced
- Target High Solar conventional
- Target High Solar enhanced

Achieving CO_2 target is possible with limited curtailment if institutional frameworks are flexible

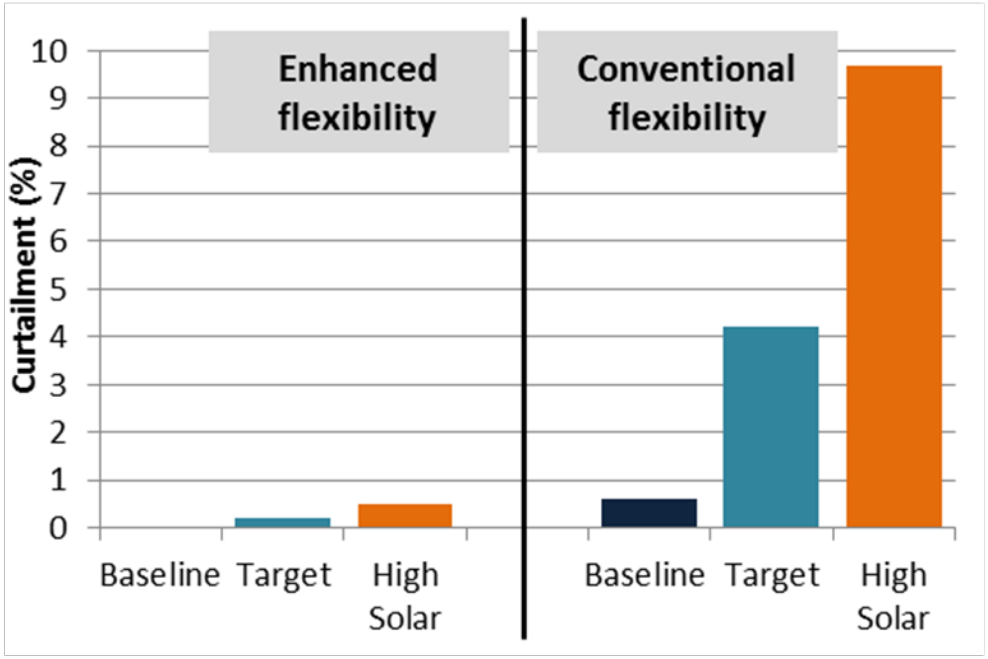


Curtailment is reduced by portfolio diversity and grid flexibility.

Emissions

Emissions reduction target achieved in all four scenarios.

Curtailment



Comparing production cost results can give estimate of value of diversity and flexibility on this system

Production cost ($million)

	Enhanced	Conventional	*Flexibility:*
Target	7,866	8,409	*543*
Target High Solar	8,078	8,642	*564*
Diversity:	*212*	*233*	

- **JBS Energy: overall rate impact in 2030 for these four cases ranges from 0.8% to 3%**

Overall conclusion

- **The modeling results indicate that achieving a low-carbon grid (50% below 2012 levels) is possible by 2030 with relatively limited curtailment (less than 1%) if institutional frameworks are flexible.**

- **Less flexible institutional frameworks and a less diverse generation portfolio could cause higher curtailment (up to 10%), operational costs (up to $800 million higher), and carbon emissions (up to 14% higher).**

Companion studies

- **JBS Energy (Marcus 2015) found that annualized capital costs of incremental renewables, transmission, and storage was $5.1b, approximately $230m more than the production cost reduction (Target Enhanced). Represents 0.6% of annual revenue requirement, ranging from -3% to 6% depending on assumptions.**

- **GE Energy (Miller 2015) found that California should be able to procure frequency response from renewables, demand, and storage in LCGS scenarios. Transient stability could present risks, although mitigation options (transmission, synchronous condensers) exist today that could provide reliability for lower costs and emissions. More study is needed.**

All materials are available at:
http://lowcarbongrid2030.org/materials/

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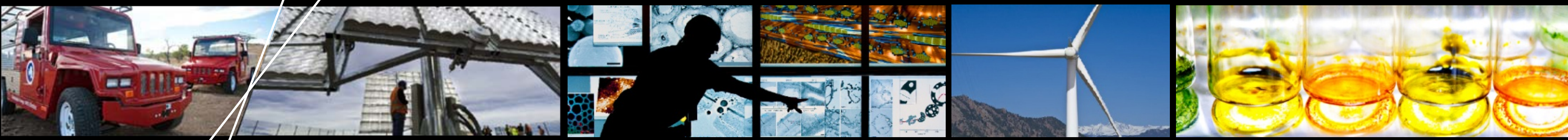
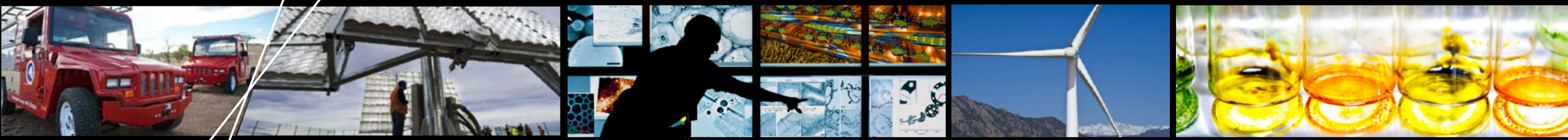


Grid modeling: Brinkman, G., J. Jorgenson, J. Caldwell, A. Ehlen. Low Carbon Grid Study: Analysis of a 50% Emission Reduction in California. National Renewable Energy Laboratory, 2016.
Full report: http://www.nrel.gov/docs/fy16osti/64884.pdf
Appendix: http://www.nrel.gov/docs/fy16osti/64884-02.pdf

Capital cost analysis: Marcus, B. Low Carbon Grid Study: Comparison of 2030 Fixed Cost of Renewables and Efficiency, Integration with Production Cost Savings, JBS Energy, 2015.

Dynamic reliability analysis: Miller, N. Low Carbon Grid Study: Discussion of Dynamic Performance limitations in WECC, GE Energy Consulting, 2015

http://lowcarbongrid2030.org



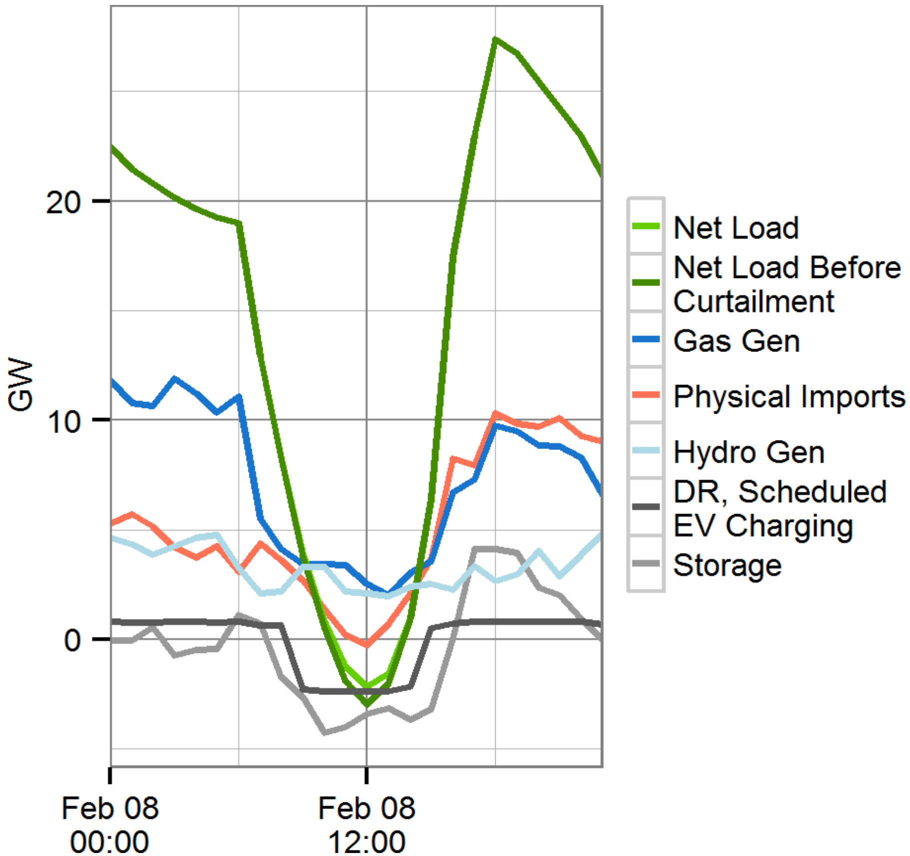
Detailed results

Key differences between today and "conventional" flexibility assumptions

Difference	Impact
Model assumes optimal west-wide dispatch subject to constraints and hurdle rates	In reality bilateral contracts and other market inefficiencies can lead to out-of-market dispatch and possibly more significant integration impacts of renewables.
Diablo Canyon nuclear generating station is assumed to retire	Diablo Canyon is a zero-carbon resource that would make hitting a carbon target easier, but could increase integration challenges.
3 million electric vehicles adding 13 TWh of load	Half of the vehicles are assumed to be optimally charged, creating the potential for up to 3000 MW of load during times of curtailment.
Non-renewable generation fleet changes include coal retirements outside California	Coal retirements and gas fleet changes are taken from WECC and CAISO projections. Combined heat and power facilities are assumed to have some operational flexibility, per CPUC policy.
Transmission is added in the Target portfolio to bring renewable resources to load.	This includes a north-south line from Idaho to southern Nevada that helps relieve north-south congestion and improves ability to use resource diversity throughout the west. Scenarios produce larger intertie flow changes than seen historically in some cases.
Rooftop PV generates 24 TWh in all scenarios (7-8% of total annual generation)	The Baseline and Target portfolios both include 24 TWh of rooftop PV generation which reduces emissions compared to today in both portfolios.

A variety of technologies provide flexibility during difficult operating periods

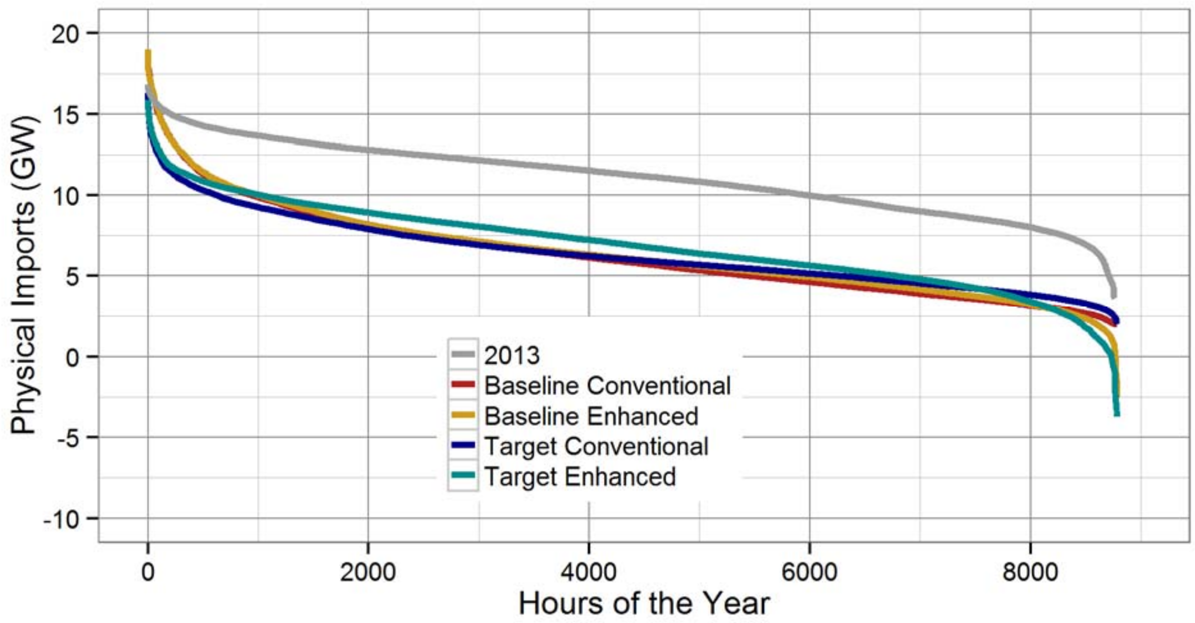
Dispatch of key categories during steepest net load ramp of the year



Technology	MW ramp between 3 and 4 pm
Physical imports	4550 MW
Storage	3230 MW
Gas fleet dispatch	3150 MW
Demand response (mostly schedulable electric vehicle charging)	240 MW
Hydro generation dispatch	-250 MW

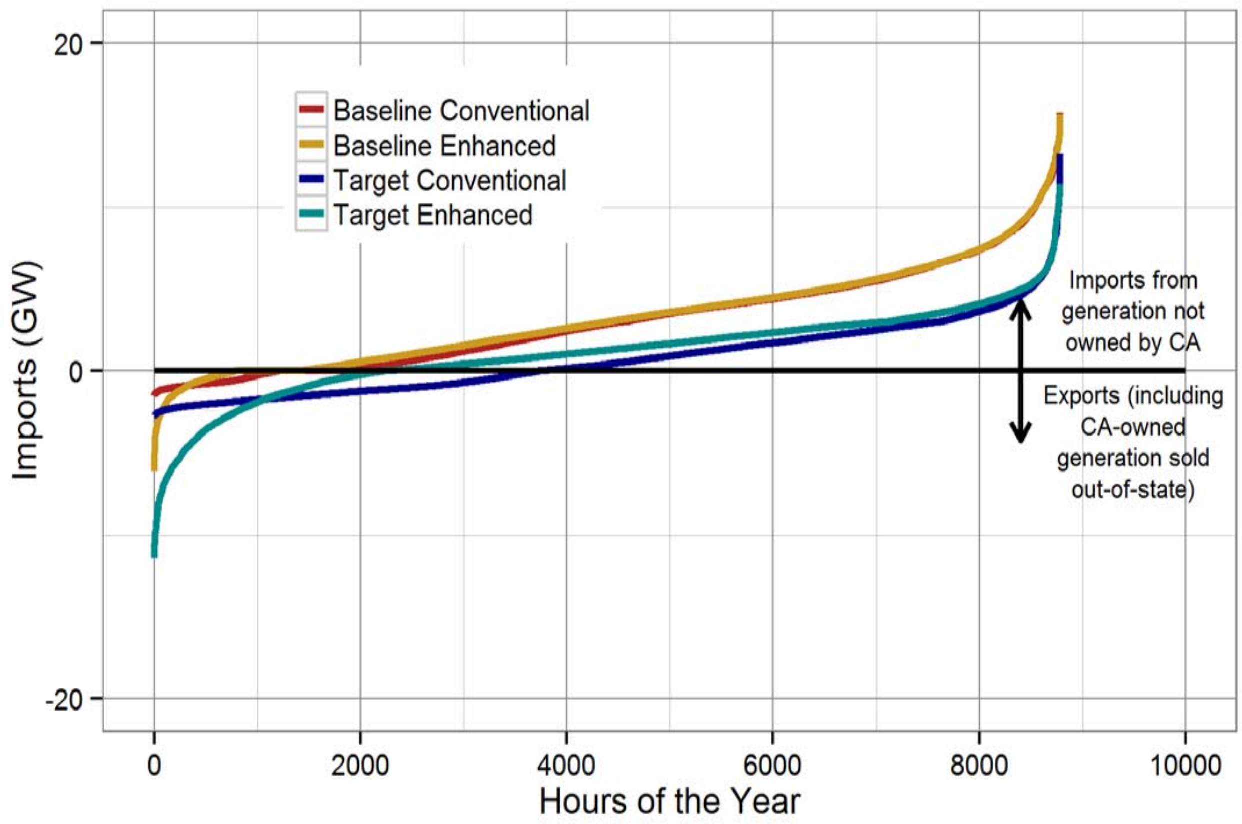
Distribution of ramping resources is different during other steep ramps, but the same 5 resources are key

Physical imports into California are reduced compared to today



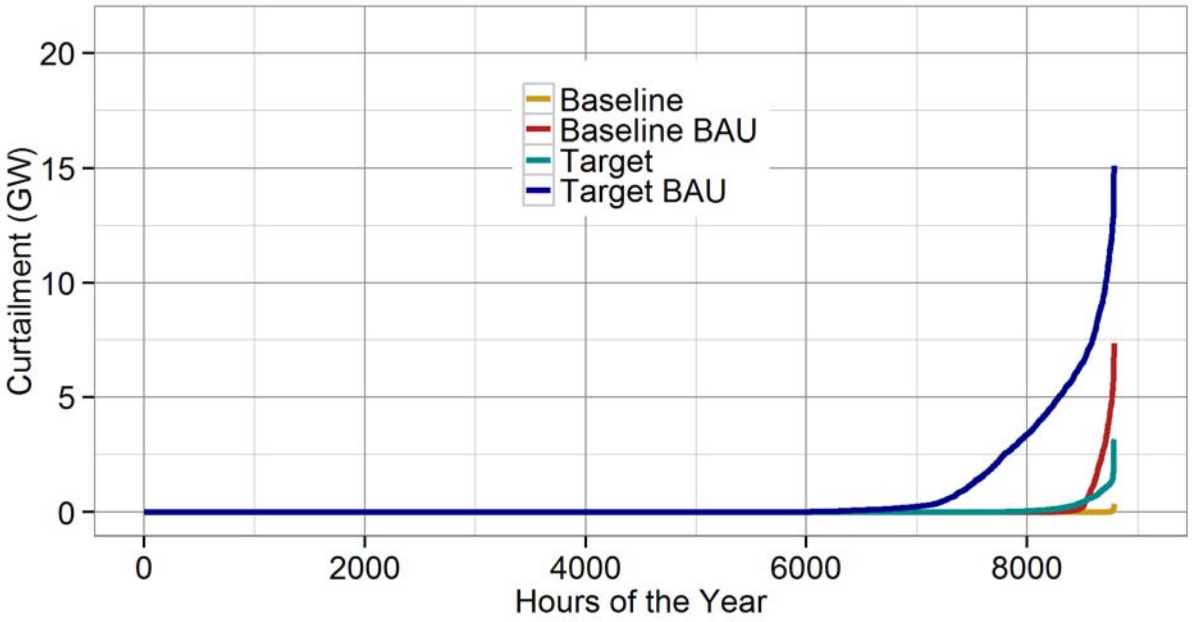
- **Between 2013 (actual) and 2030 Baseline (modeled), imports go down due to retiring coal generation outside California and increased solar generation inside California**
- **Between Target and Baseline, the imports from fossil-fuel generation is replaced by renewable generation imports**

Imports from fossil fuels in the Baseline are replaced with imports from renewable generation in the low carbon grid scenarios



- **Some power from out-of-state generation would be sold out-of-state in optimal dispatch**

Curtailment in a low carbon grid could be less than 1% or nearly 10%, depending on the institutional framework and portfolio



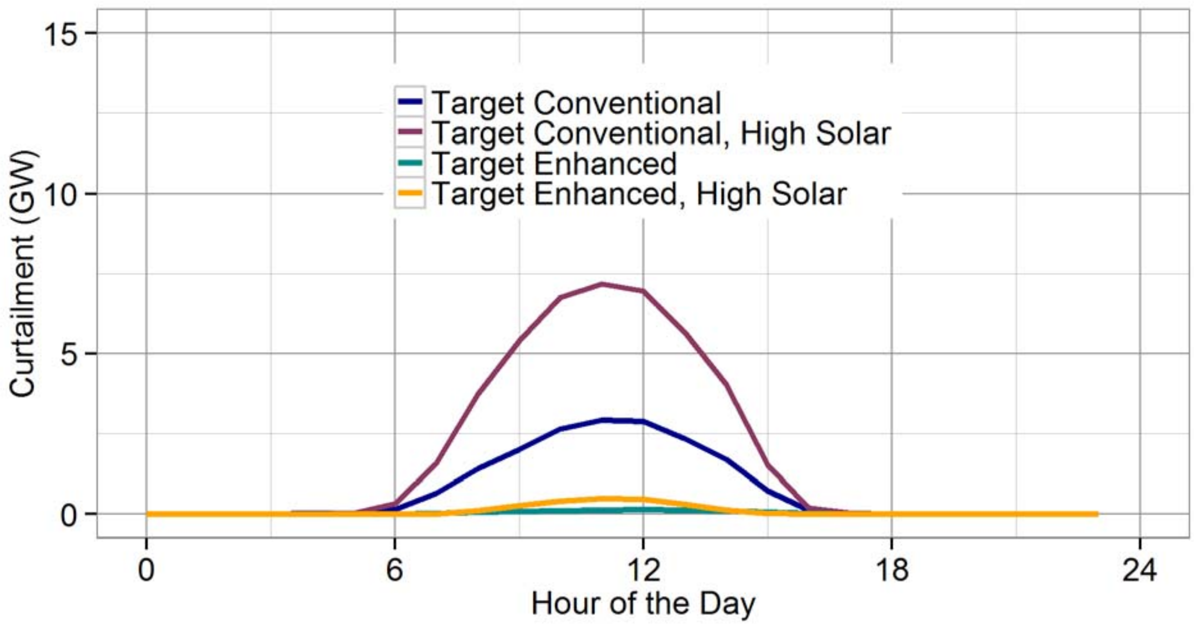
Scenario	Curtailment
Baseline Enhanced	0.0%
Baseline Conventional	0.6%
Target Enhanced	0.2%
Target Conventional	4.2%

- **Flexibility of system can be as important as the portfolio**
- **70% import requirement and portfolio are primary drivers**
- **A single flexibility challenge in a flexible system has little impact**

Higher solar penetrations could lead to 10% curtailment if institutional framework remains inflexible

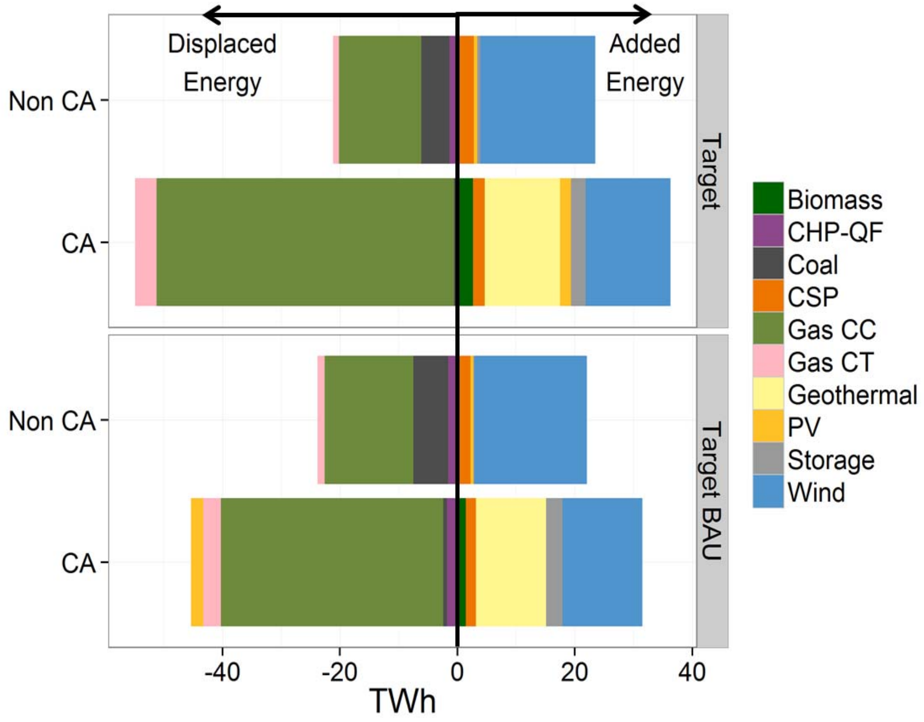
Scenario	Curtailment
Target Enhanced	0.2%
Target Enhanced, High Solar	0.5%
Target Conventional	4.2%
Target Conventional, High Solar	9.7%

- **Curtailment occurs almost exclusively during mid-day hours**
- **A flexible system can handle high solar penetrations with little curtailment; a less flexible system cannot**



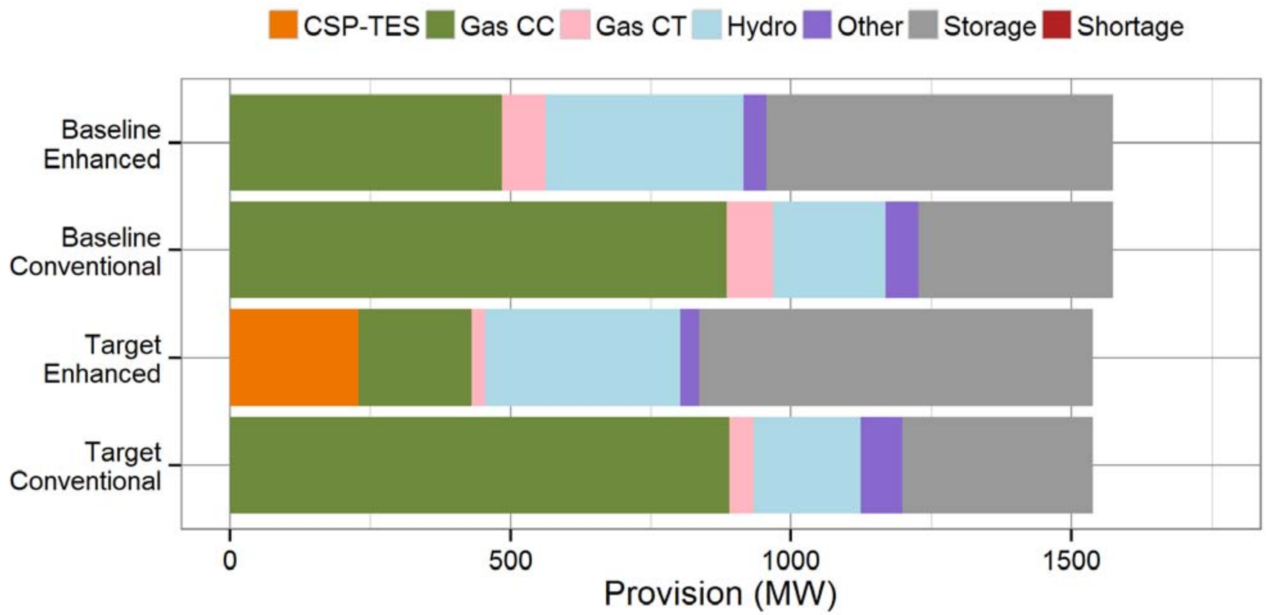
Carbon emissions could achieve a 50% reduction; emission reductions depend on calculation method and assumptions regarding institutional framework and portfolio

Scenario	Carbon (MMT)
Baseline Enhanced	74.4
Baseline Conventional	75.2
Target Enhanced	41.1
Target Conventional	45.0



- **Less flexible system has higher curtailment, leading to more carbon emissions**

Ancillary services are provided by a variety of sources



- **Conventional cases “tuned” to be similar to 2011-2013 in CAISO, based on state of market report**
- **allowed CSP, and doubled the hydro and storage capacity allowed to provide AS**
- **Reg, spin, very similar to CAISO 2014 LTPP cases**
- **Flex uses different methodology vs CAISO LF, and averages 1170 MW vs 1650 MW for LF in CAISO**

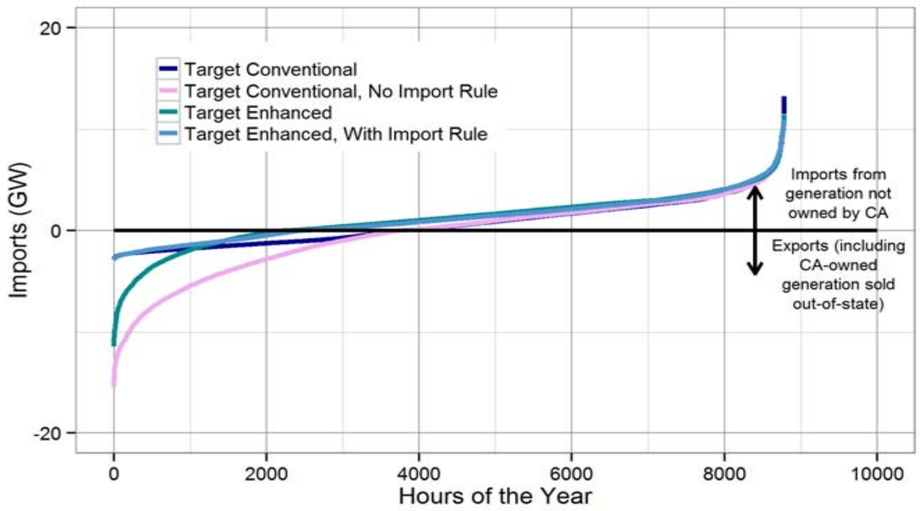
Achieving higher penetrations in the rest of the western U.S. does not impact main conclusions of this study

Scenario	Production cost savings from Baseline	Curtail-ment	Annual net imports (TWh)	CO2 assigned to CA load (MMT)	CA gas CC capacity factor (%)
Baseline Enhanced	-	0.0%	56.8	74.4	46.1
Baseline Enhanced, High West Penetration	$0.24 b	0.0%	80.3	72.9	37.7
Target Enhanced	$4.85 b	0.2%	60.5	41.1	30.0
Target Enhanced, High West Penetration	$ 4.96 b	0.7%	64.7	43.2	20.5
Target Conventional	$4.30 b	4.2%	56.1	45.0	31.9
Target Conventional, High West Penetration	$4.47 b	4.9%	66.6	45.1	26.9

- **Assumes ~35% penetration outside California**
- **Largest impact on California is the increase in imports**

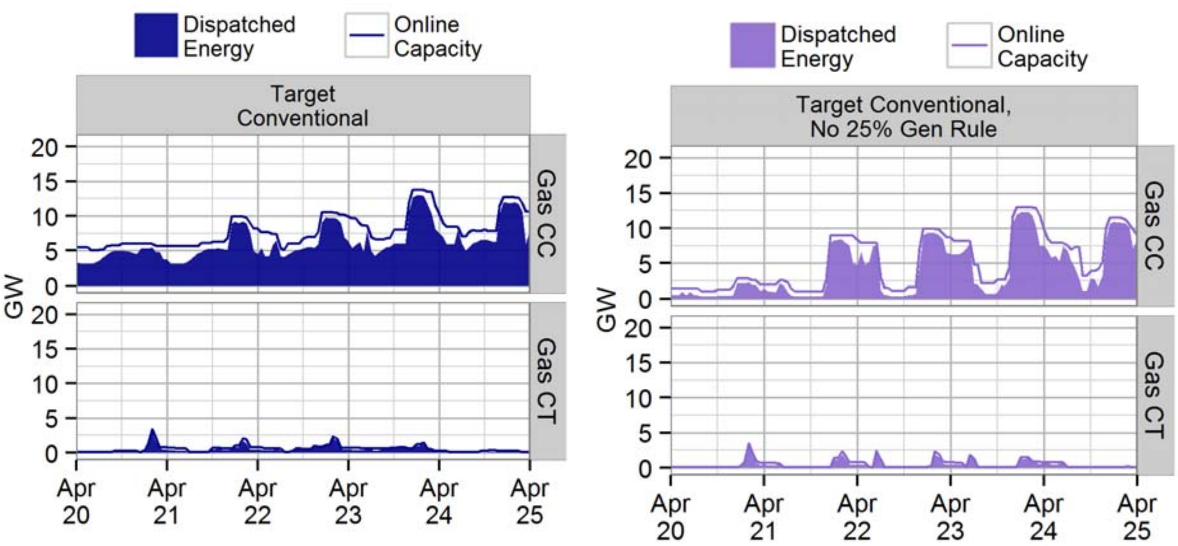
Requirements on importing out-of-state zero-carbon energy could increase curtailment, costs, and carbon

Scenario	Production cost savings from Baseline	Curtail-ment	Annual net imports (TWh)	CO_2 assigned to CA load (MMT)	CA gas CC capacity factor (%)
Target Enhanced	$4.85 b	0.2%	60.5	41.1	30.0
Target Enhanced with Import Rule	$4.71 b	0.9%	61.7	41.8	29.8
Target Conventional	$4.30 b	4.2%	56.1	45.0	31.9
Target Conventional with no Import Rule	$4.81 b	0.6%	47.6	42.3	31.9



Local generation requirements could increase curtailment and costs

Scenario	Production cost savings from Baseline	Curtail-ment	Annual net imports (TWh)	CO2 assigned to CA load (MMT)	CA gas CC capacity factor (%)
Target Enhanced	$4.85 b	0.2%	60.5	41.1	30.0
Target Enhanced, No 25% Gen Rule	$4.68 b	0.5%	49.0	42.2	32.8
Target Conventional	$4.30 b	4.2%	56.1	45.0	31.9
Target Conventional, No 25% Gen Rule	$4.71 b	1.2%	61.3	42.2	27.0



Combination of import and local generation rule is the most challenging

Efficient day-ahead scheduling is important; exports and displaced imports can be locked in the day-ahead market

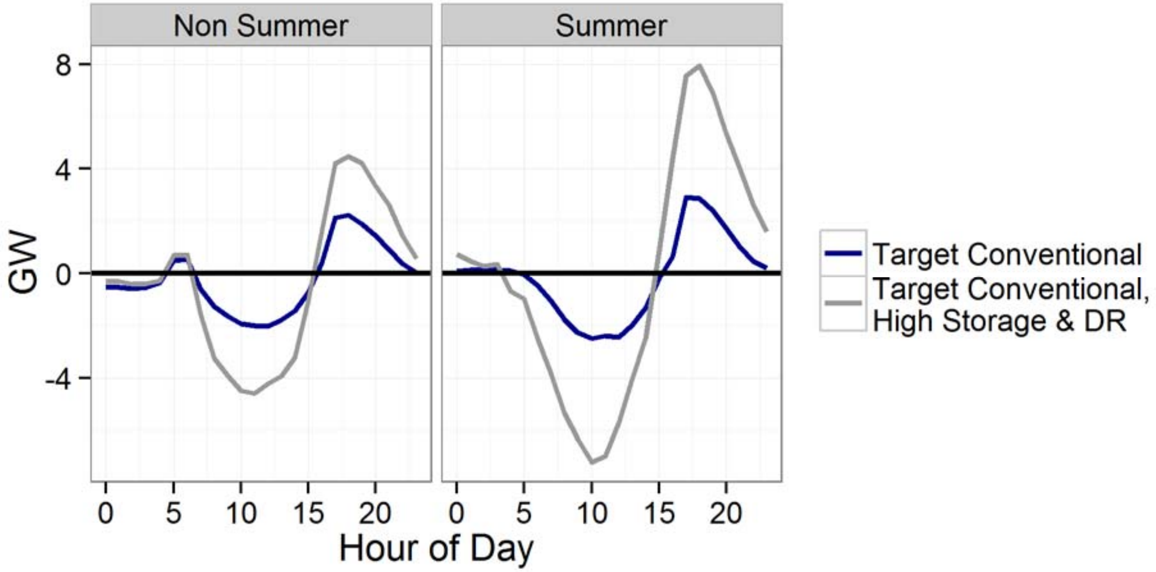
Scenario	Production cost savings from Baseline	Curtail-ment	Annual net imports (TWh)	CO2 assigned to CA load (MMT)	CA gas CC capacity factor (%)
Target Conventional	$4.30 b	4.2%	56.1	45.0	31.9
Target Conventional with locked DA import schedules	$4.20 b	5.4%	47.5	46.8	32.2

- **Curtailment goes from 4.2% to 5.4% if DA import schedules are locked between California and its neighbors during RT dispatch**

Storage and demand response could help reduce operational costs and curtailment in a scenarios where institutional flexibility is constrained

Scenario	Production cost savings from Baseline	Curtail-ment	Annual net imports (TWh)	CO2 assigned to CA load (MMT)	CA gas CC capacity factor (%)
Target Conventional	$4.30 b	4.2%	56.1	45.0	31.9
Target Conventional, High Storage & DR	$4.98 b	3.1%	54.3	41.7	30.8

Storage and DR "dispatch"



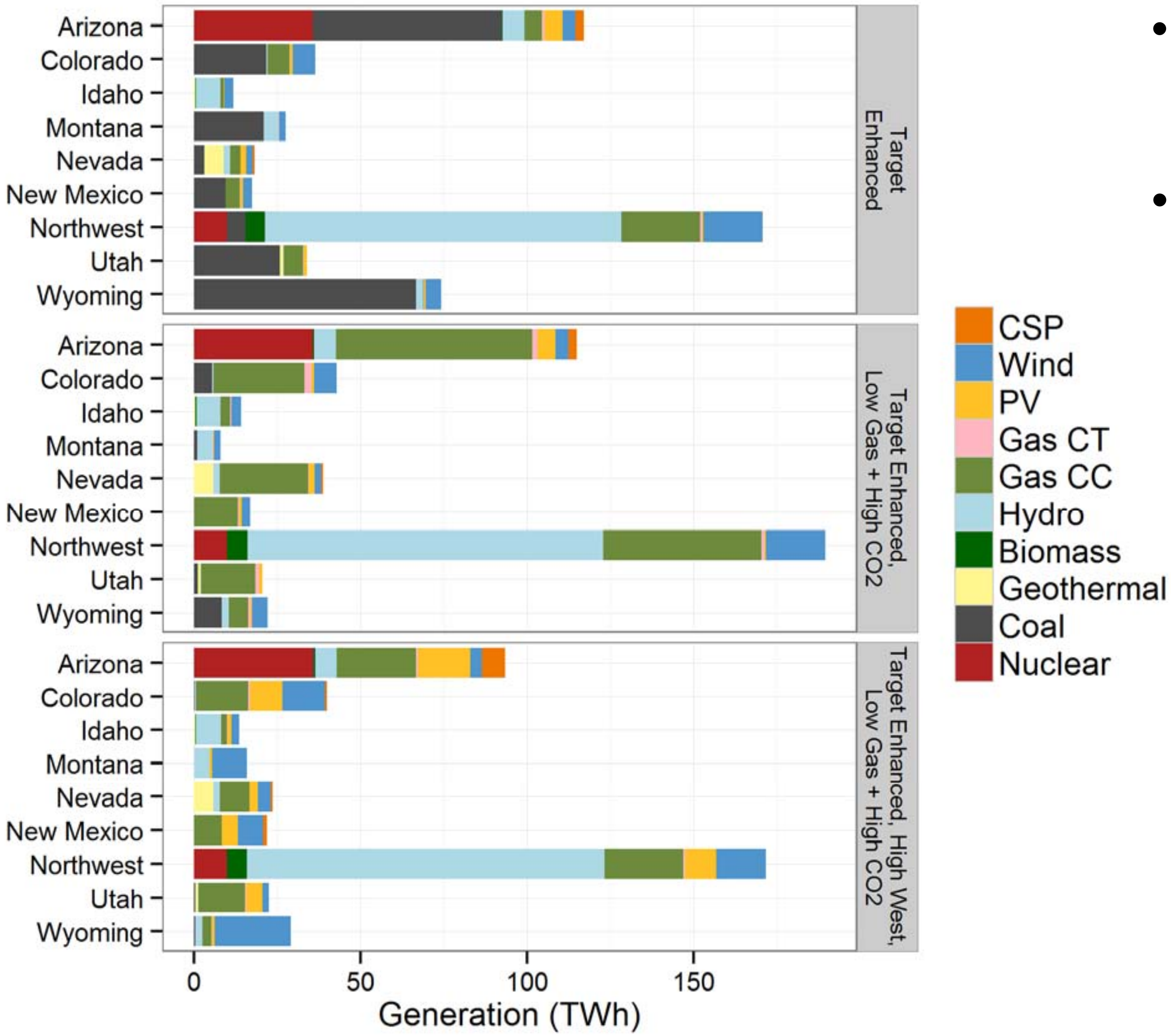
- High Storage & DR includes:
  - 2 GW additional PHS
  - "Theoretical" vs "projected" availability of DR (LBNL)
- Storage and DR reduce cycling at CA gas generators, while enhanced flexibility increases cycling

Hydropower availability doesn't have a large impact on total renewable curtailment, but it does impact total carbon emissions

Scenario	Production cost savings from Baseline	Curtail-ment	Annual net imports (TWh)	CO2 assigned to CA load (MMT)	CA gas CC capacity factor (%)
Target Enhanced	n/a	0.2%	60.5	41.1	30.0
Target Enhanced with wet hydro	n/a	0.3%	65.2	39.5	27.6
Target Enhanced with dry hydro	n/a	0.2%	56.3	47.0	30.6
Target Conventional	n/a	4.2%	56.1	45.0	31.9
Target Conventional with wet hydro	n/a	4.4%	58.5	43.7	26.8
Target Conventional with dry hydro	n/a	4.2%	53.9	50.3	31.9

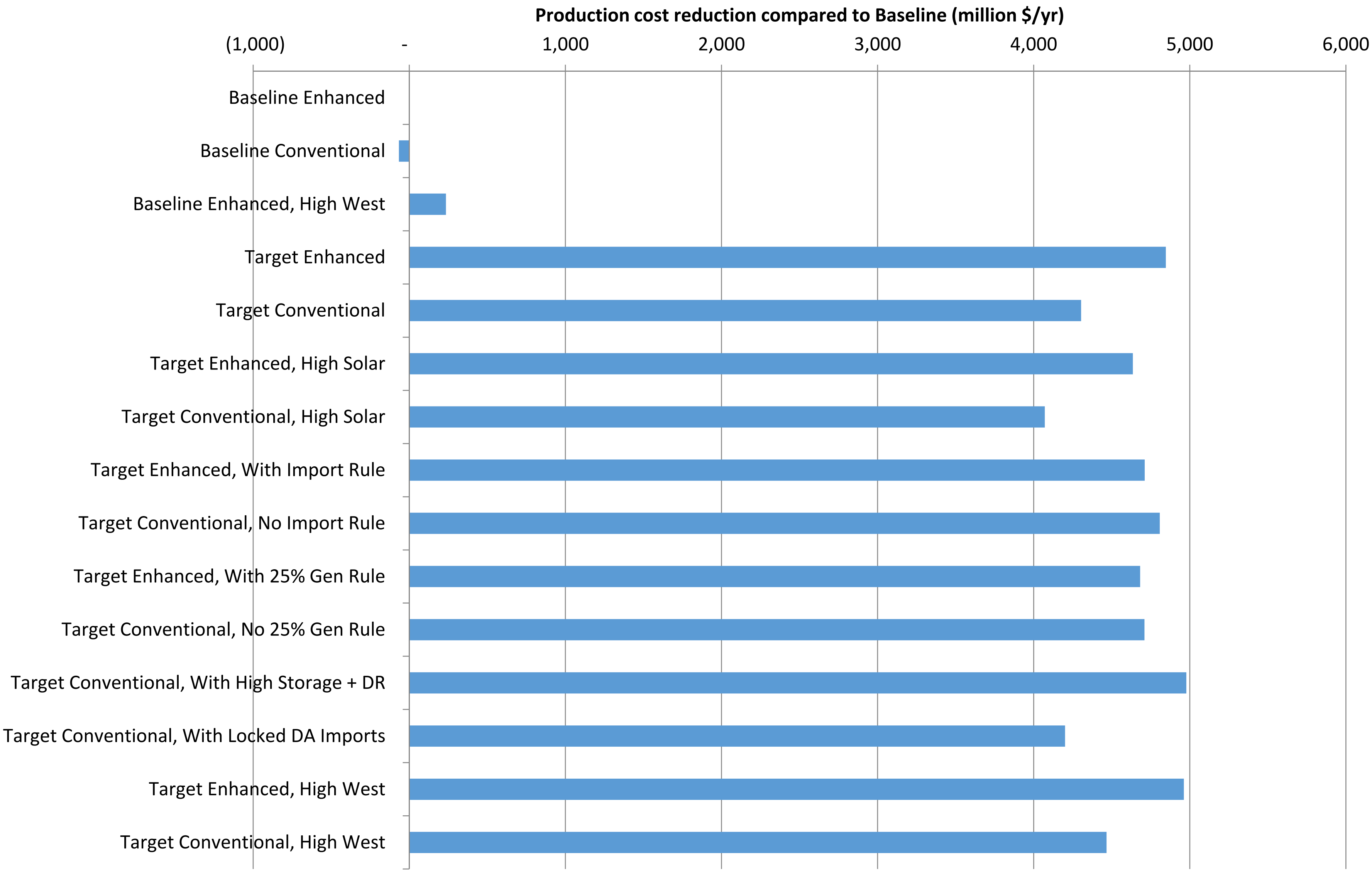
- **Imports, CO2, and capacity factors are impacted by hydro energy**
- **Curtailment is not significantly impacted**
- **More study is needed on this issue**

Increasing carbon costs and reducing gas costs doesn't have much of an effect on curtailment in California, but greatly reduces emissions outside California

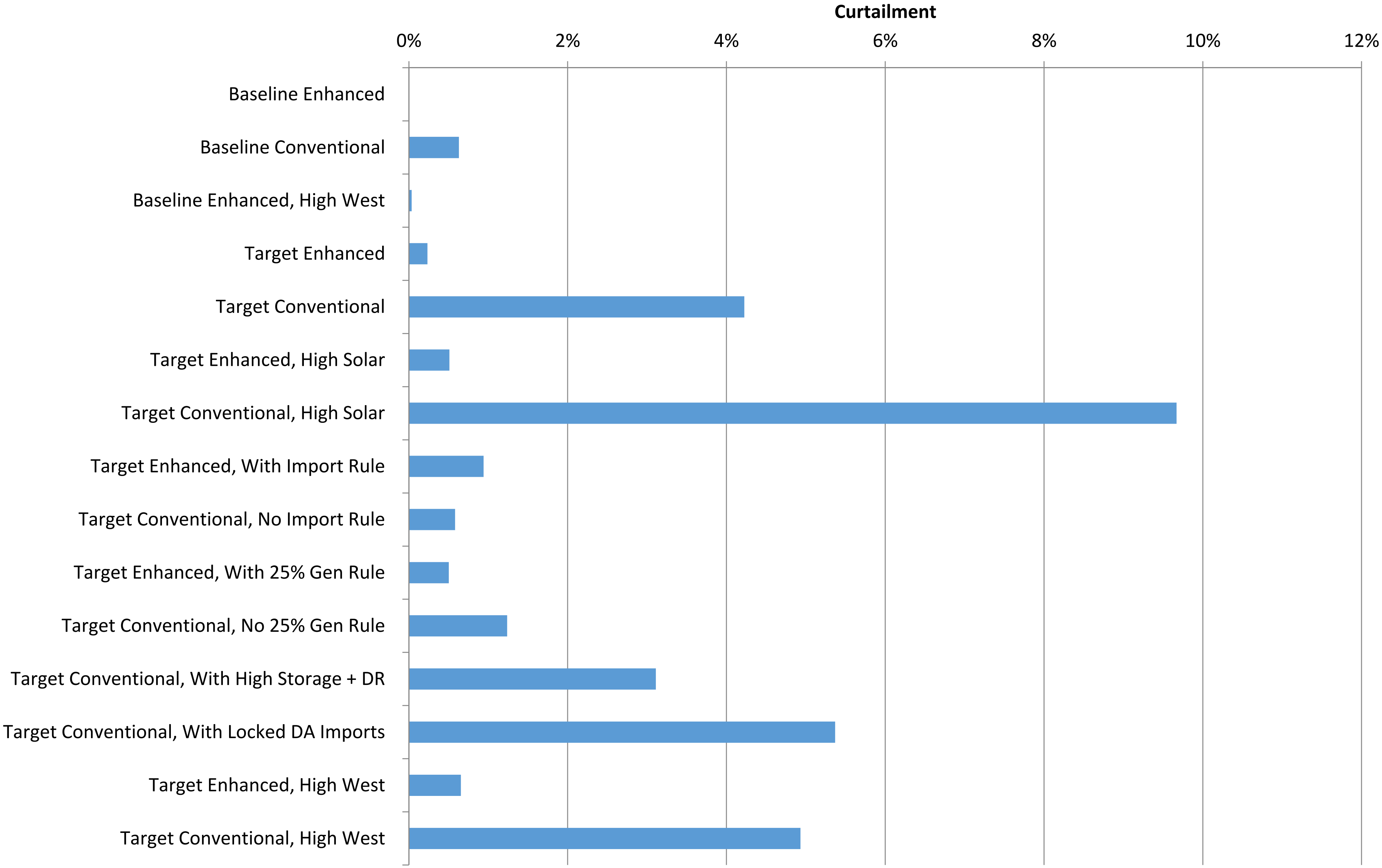


- Gas price $5.10/mmbtu (vs almost $7 in other scenarios)
- Carbon price $58 / MT (vs $32 in other scenarios)

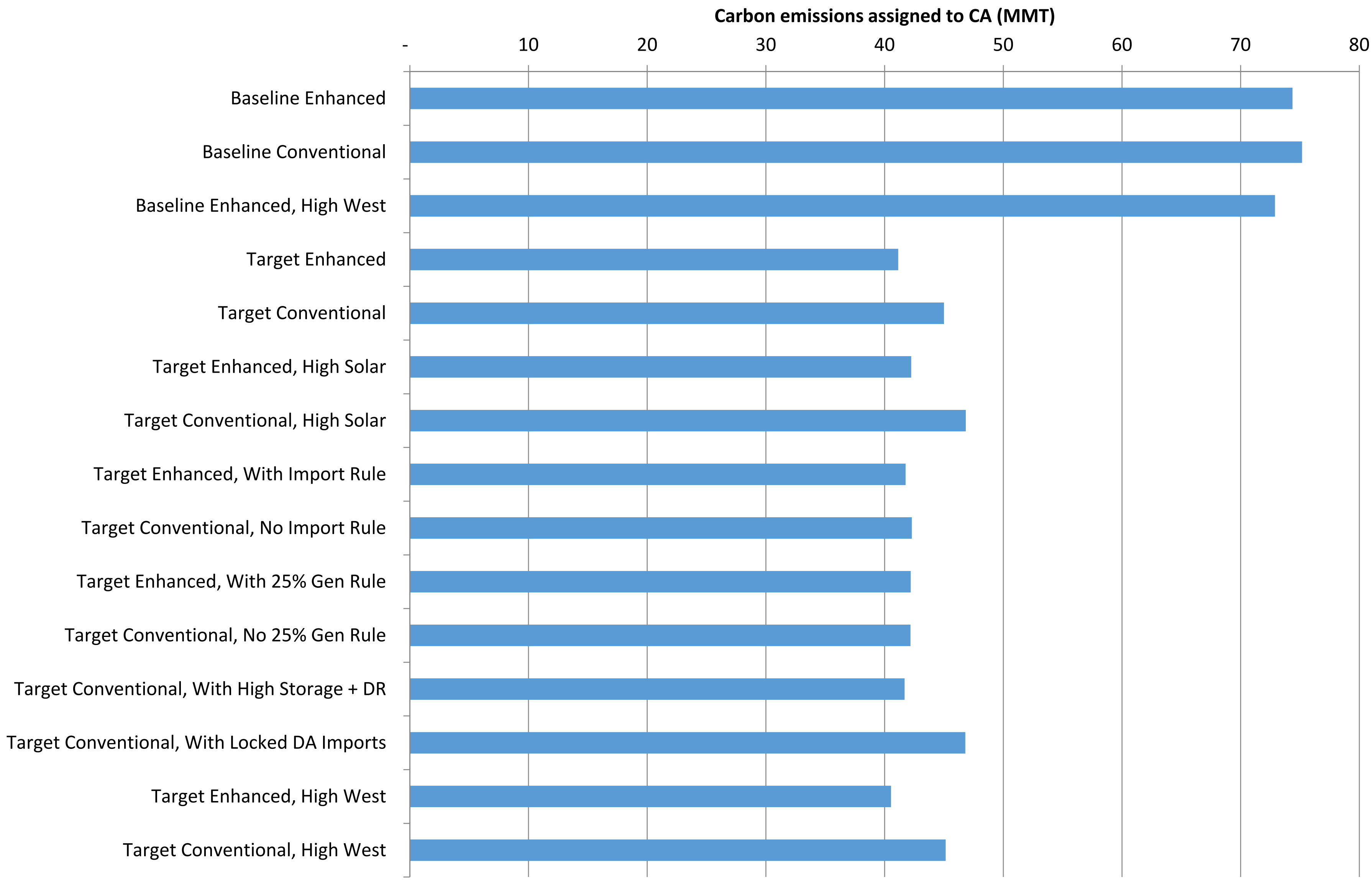
Production cost by scenario



Curtailment by scenario



Carbon emissions by scenario



Renewable energy in portfolios

Appendix: http://www.nrel.gov/docs/fy16osti/64884-02.pdf

Table 1. Renewable Portfolios

Type	Region (WECC Common Case naming convention)	Baseline generation (TWh)	Target generation (TWh)	Target High Solar generation (TWh)
Biomass	CIPB	0.6	0.6	0.6
Biomass	CIPV	6.9	8.2	6.0
Biomass	CISC	1.5	2.2	2.2
Biomass	CISD	0.4	0.4	0.4
Biomass	IID	0.0	0.1	0.1
Biomass	LDWP	0.0	0.1	0.1
Biomass	PACW	0.3	0.3	0.3
Biomass	SPPC	0.4	0.4	0.4
CSP	CISC	4.7	4.7	4.7
CSP	IID	0.1	0.1	0.1
CSP-TES	AZPS	0.0	1.0	0.0
CSP-TES	CISC	0.0	1.5	0.0
CSP-TES	IID	0.0	0.5	0.5
CSP-TES	NEVP	0.0	1.8	0.0
Geothermal	CIPV	7.5	7.5	7.5
Geothermal	CISC	2.3	2.3	2.2
Geothermal	IID	4.3	17.1	7.2
Geothermal	SPPC	1.4	1.4	1.4
Utility PV	AZPS	0.0	0.3	0.4
Utility PV	BANC	0.3	0.2	0.3
Utility PV	CIPB	0.5	1.6	2.5
Utility PV	CIPV	10.1	7.5	11.8
Utility PV	CISC	17.2	19.7	31.0
Utility PV	CISD	3.9	2.7	4.2
Utility PV	IID	2.8	4.2	6.5
Utility PV	LDWP	0.1	0.9	1.4
Utility PV	NEVP	1.6	2.6	4.1
Utility PV	PAUT	0.0	0.1	0.1
Utility PV	SPPC	3.0	1.9	3.0
Utility PV	VEA	0.4	0.5	0.7
Rooftop PV	BANC	1.5	1.5	1.6
Rooftop PV	CIPB	5.4	5.4	5.4
Rooftop PV	CIPV	3.6	3.6	3.6
Rooftop PV	CISC	8.3	8.3	8.3
Rooftop PV	CISD	1.9	1.9	1.9
Rooftop PV	IID	0.3	0.3	0.3
Rooftop PV	LDWP	2.4	2.4	2.4
Rooftop PV	PACW	0.1	0.1	0.1
Rooftop PV	TIDC	0.2	0.2	0.2
Wind	AESO	0.9	0.9	0.9
Wind	BANC	0.7	0.7	0.7
Wind	BPAT	8.1	8.1	8.1
Wind	CIPB	3.0	3.0	3.0
Wind	CIPV	2.9	3.3	3.3
Wind	CISC	9.2	18.0	18.0
Wind	CISD	0.2	0.2	0.2
Wind	IID	0.0	5.3	5.3
Wind	NEVP	0.0	0.1	0.1
Wind	PNM	0.0	7.5	0.0
Wind	WACM	0.0	11.9	11.9

CIPB - Pacific Gas & Electric Bay Area; CIPV - Pacific Gas & Electric Valley Area; CISC - Southern California Edison; CISD - San Diego Gas & Electric; IID - Imperial Irrigation District; LDWP - Los Angeles Department of Water & Power; BANC – Balancing Area of Northern California; TIDC – Turlock Irrigation District; PACW - PacifiCorp West; SPPC - Sierra Pacific Power; AZPS – Arizona Public Service; NEVP – Nevada Power; PAUT – PacifiCorp East Utah; VEA – Valley Electric Association; AESO – Alberta Electric System Operator; BPAT – Bonneville Power Administration; PNM – Public Service New Mexico; WACM – WAPA Colorado/Missouri