Roadmaps for Transitioning California and the Other 49 States to Wind, Water and Solar Power for All Purposes

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San Francisco, California
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Wind farm near Middelgrunden, Denmark

What's the Problem? Why act Quickly?

Air pollution kills 2.5-4 million people worldwide each year.

Arctic sea ice may disappear in 10-30 years. Global temperatures are rising at a faster rate than any time in recorded history.

Increasing energy demand is increasing pollution, global warming, and energy prices.

Higher energy prices lead to economic, social, political instability

→ Drastic problems require immediate and definite solutions

Beijing, China, Jan 11-14, 2013

Sukinda, India

http://www.worldinterestingfacts.com/infrastructure/top-10-most-polluted-cities-in-the-world.html

Brown and Black Carbon Particles in Los Angeles Smog (Dec. 2000)

Lung of LA Teenage Nonsmoker in 1970s;

SCAQMD/CARB

Hurricane Sandy

http://blog.wegowise.com/blog2/bid/137837/The-Environmental-Impacts-of-Hurricane-Sandy

Cleanest Solutions to Global Warming, Air Pollution, Energy Security

ELECTRIC POWER		VEHICLES
Recommended – Wind, Water, Sun (WWS)		
1. Wind	2. CSP	WWS-Battery-Electric
3. Geothermal	4. Tidal	WWS-Hydrogen Fuel Cell
5. PV	6. Wave	
7. Hydroelectricity		
Not Recommended		
Nuclear		Corn, cellulosic, sugarcane ethanol
Coal-CCS		Soy, algae biodiesel
Natural gas, biomass		Compressed natural gas

Energy & Env. Sci, 2, 148 (2009)

Why Not Natural Gas?

50-70 times more CO_2 and air pollution per kWh than wind

Methane from natural gas a main contributor to Arctic ice loss.

Natural gas causes more global warming but less air pollution mortality than coal over 150 years due to less sulfate (a cooling agent) and more methane (a warming agent) from natural gas than coal. Coal causes higher mortality.

Hydrofracking causes land and water supply degradation and enhanced methane leaks.

Why Not Clean Coal (With Carbon Capture)?

50 times more CO_2 emissions per kWh than wind

150 times more air pollutant emissions per kWh than wind

Requires 25% more energy, thus 25% more coal mining and transport and traditional pollution than normal coal.

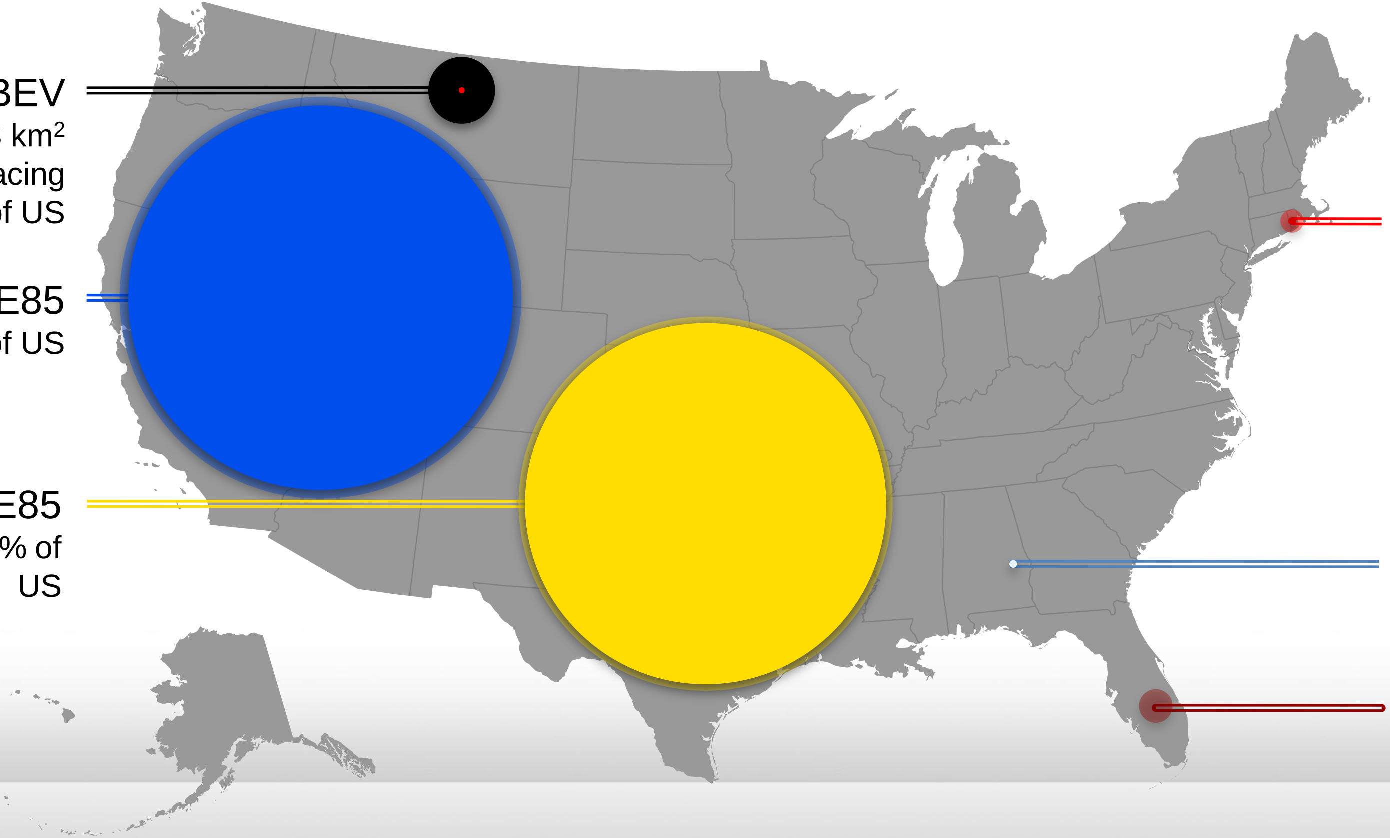
Why Not Nuclear?

9-25 times more pollution per kWh than wind from mining & refining uranium and using fossil fuels for electricity during the 10-19 years to permit (6-10 y) and construct (4-9 y) nuclear plant compared with 2-5 years for a wind or solar farm

Risk of meltdown (1.5% of all nuclear reactors to date have melted)
Risk of nuclear weapons proliferation

Unresolved waste issues

Area to Power 100% of U.S. Onroad Vehicles



Wind-BEV
Footprint 1-2.8 km^2
Turbine spacing
0.35-0.7% of US

Cellulosic E85
4.7-35.4% of US

Corn E85
9.8-17.6% of
US

Nuclear-BEV
0.05-0.062%
Footprint 33%
of total; the rest is
buffer

Geoth BEV
0.006-0.008%

Solar PV-BEV
0.077-0.18%

End-Use Power Demand For All Purposes

Year and Fuel Type	World	U.S.	CA	NY
2010 (TW)	12.5	2.5	.21	.09
2030 with current fuels (TW)	16.9	2.83	.25	.10
2030 WWS (TW)	11.5	1.78	.14	.06
2030 Reduction w/ WWS (%)	32	37	44	37

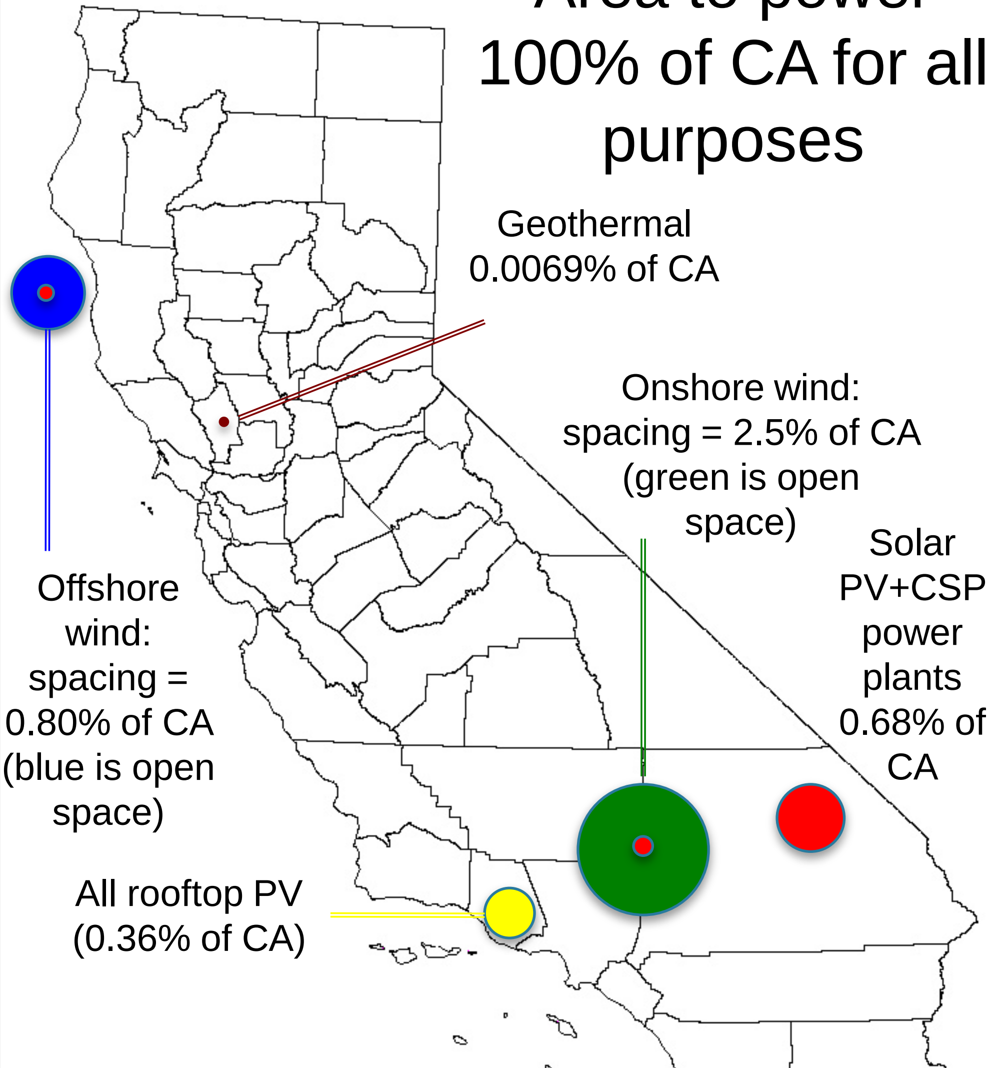
Number of Plants or Devices to Power World

TECHNOLOGY	PCT SUPPLY 2030	NUMBER
5-MW wind turbines	50%	3.8 mill. (0.8% in place)
0.75-MW wave devices	1	720,000
100-MW geothermal plants	4	5350 (1.7% in place)
1300-MW hydro plants	4	900 (70% in place)
1-MW tidal turbines	1	490,000
3-kW Roof PV systems	6	1.7 billion
300-MW Solar PV plants	14	40,000
300-MW CSP plants	20	49,000
	100%	

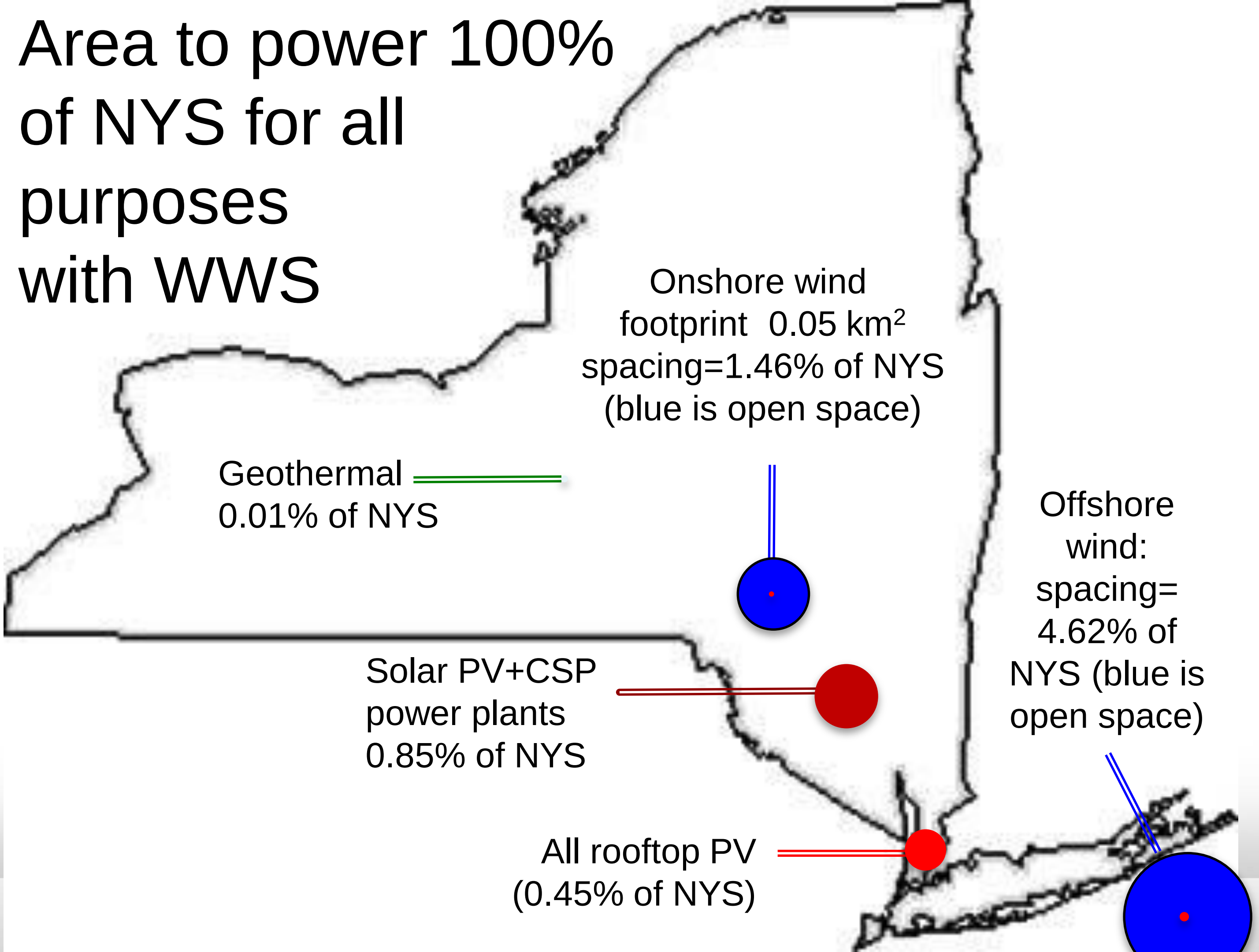
Number New Plants or Devices to Power CA 2050

TECHNOLOGY	PCT SUPPLY 2050	NUMBER
5-MW onshore wind turbines	25%	24,700
5-MW offshore wind turbines	10	7,800
5-kW Res. roof PV systems	10	19.1 million
100-kW com/gov roof PV systems	15	1.29 million
50-MW Solar PV plants	15	2140
100-MW CSP plants	15	1230
100-MW geothermal plants	5	72
1300-MW hydro plants	4	0
1-MW tidal turbines	0.5	3370
0.75-MW wave devices	0.5	4960
	100%	

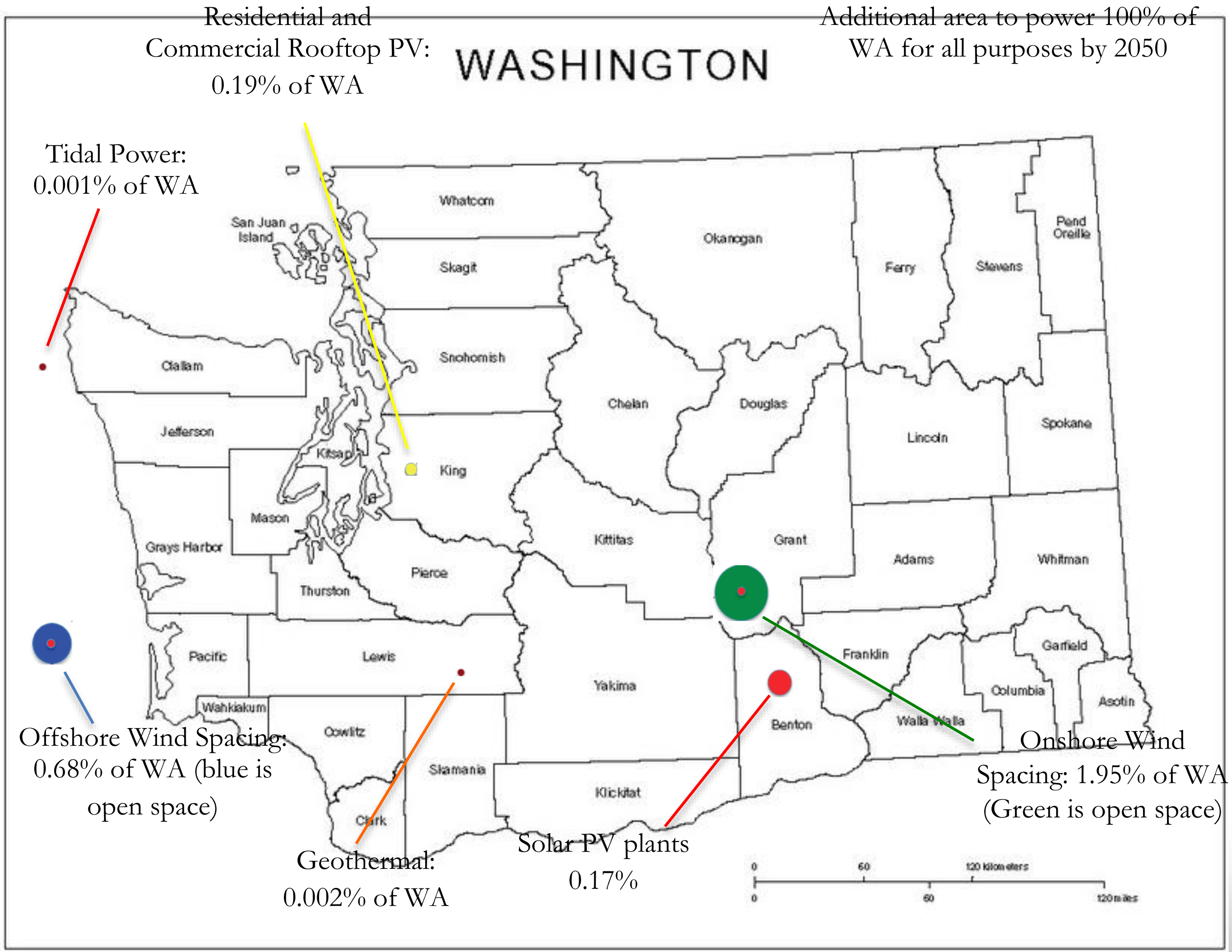
Area to power 100% of CA for all purposes



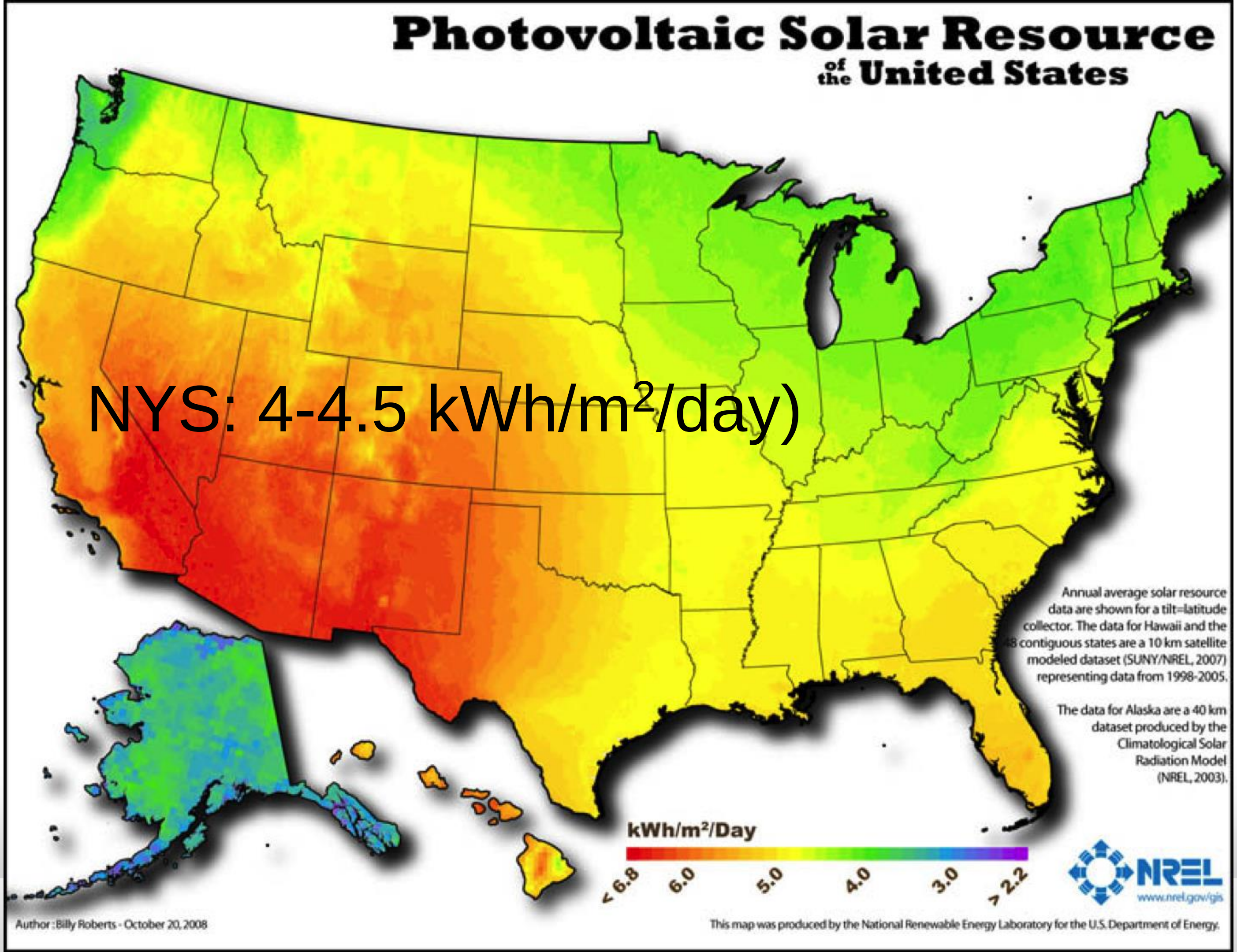
Area to power 100% of NYS for all purposes with WWS



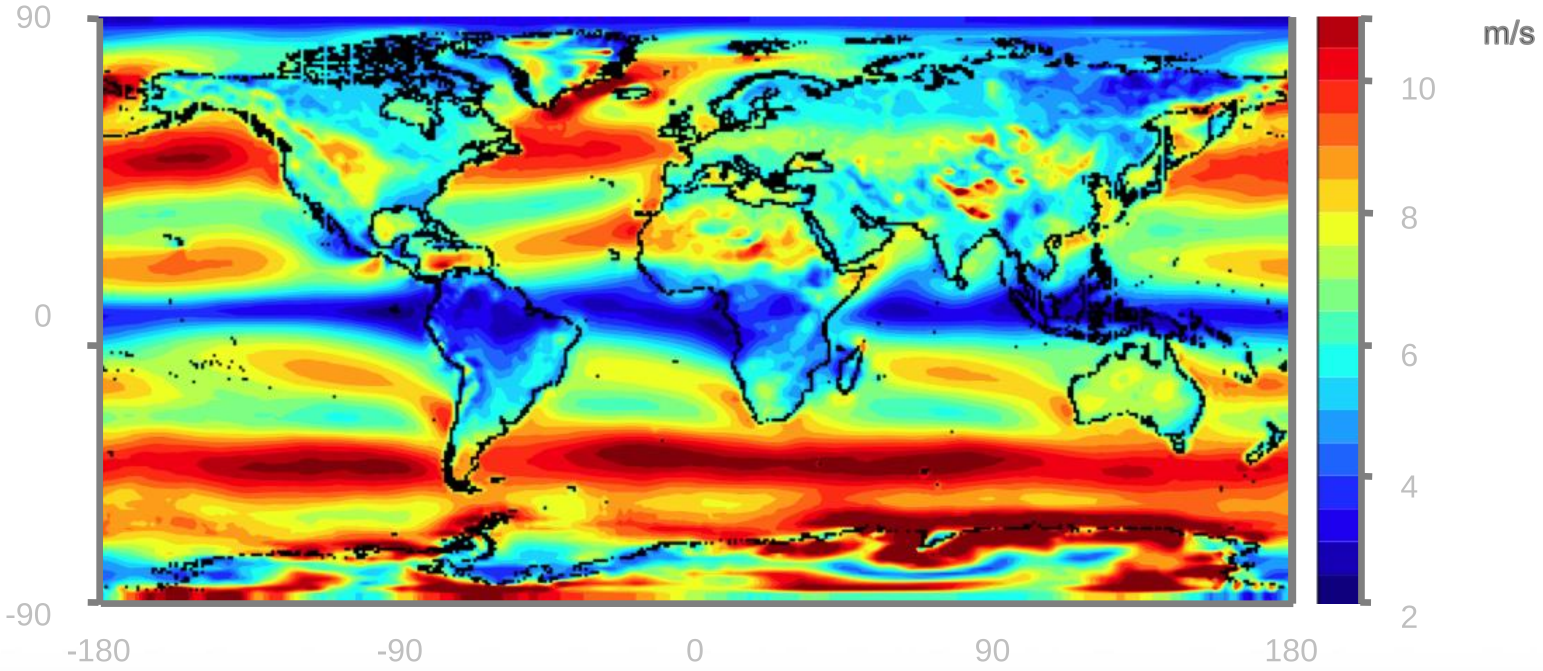
New area to power 100% of Washington State for all purposes



NYS: 4-4.5 kWh/m^2/day)



World Wind Speeds at 100m

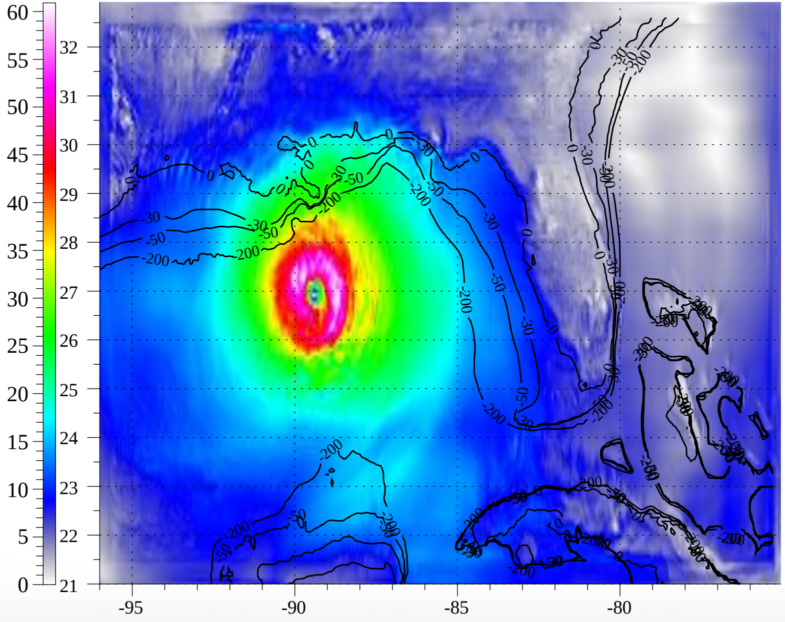


All wind over land in high-wind areas outside Antarctica ~ 70-80 TW
= 6-7 times world end-use WWS power demand 2030 of 11.5 TW

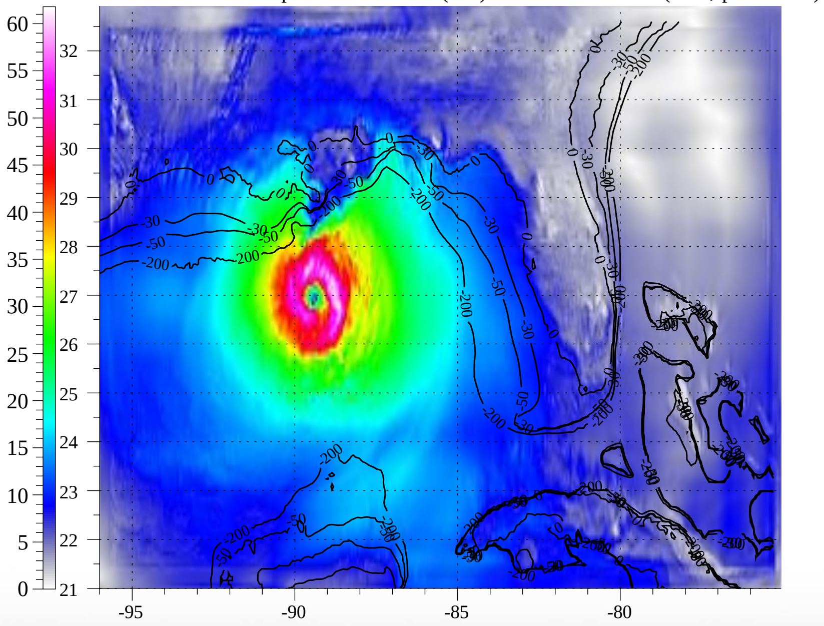
Hurricane Katrina

August 28, 22:00 GMT

2200 GMT 8/28/05 Wind speed 100 m AGL (m/s) no turbines (10.3; peak: 60.9)



2200 GMT 8/28/05 Wind speed 100 m AGL (m/s) New Orleans turbs (10.1; peak: 61.8)

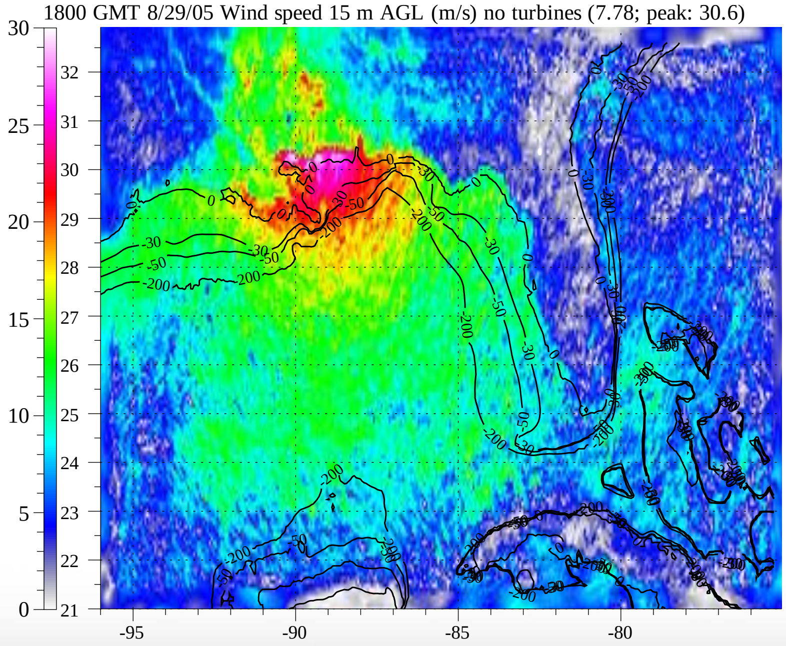


No turbines

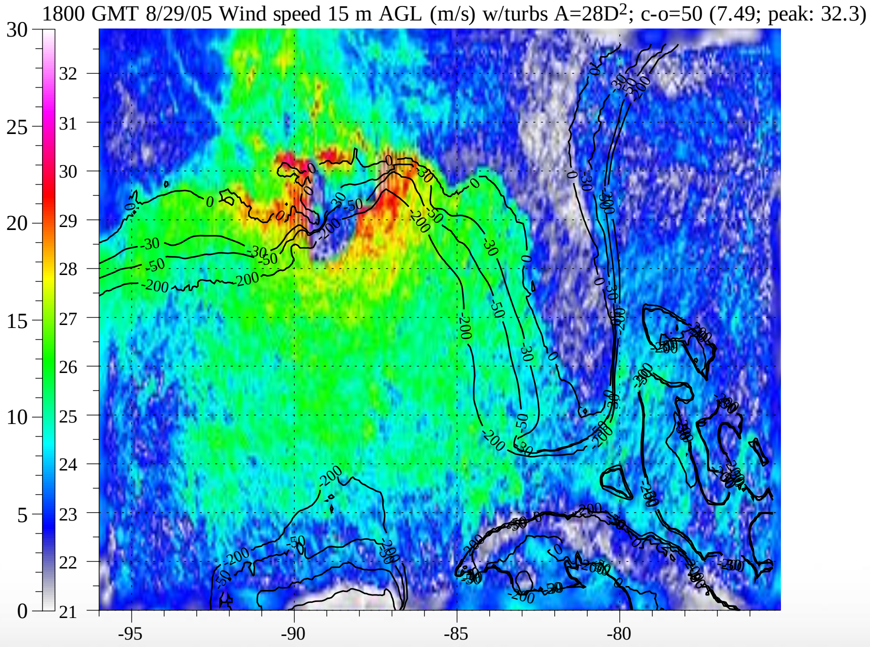
With turbines

Hurricane Katrina

August 29, 18:00 GMT



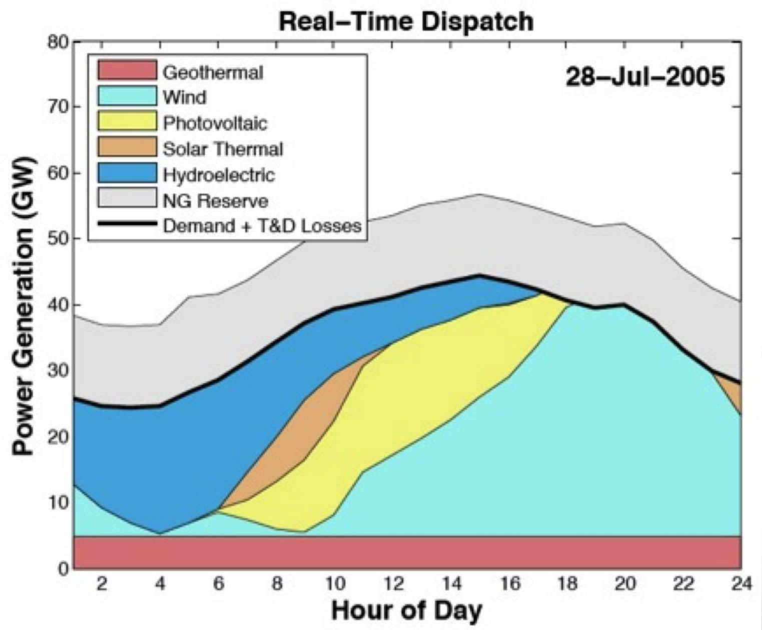
No turbines

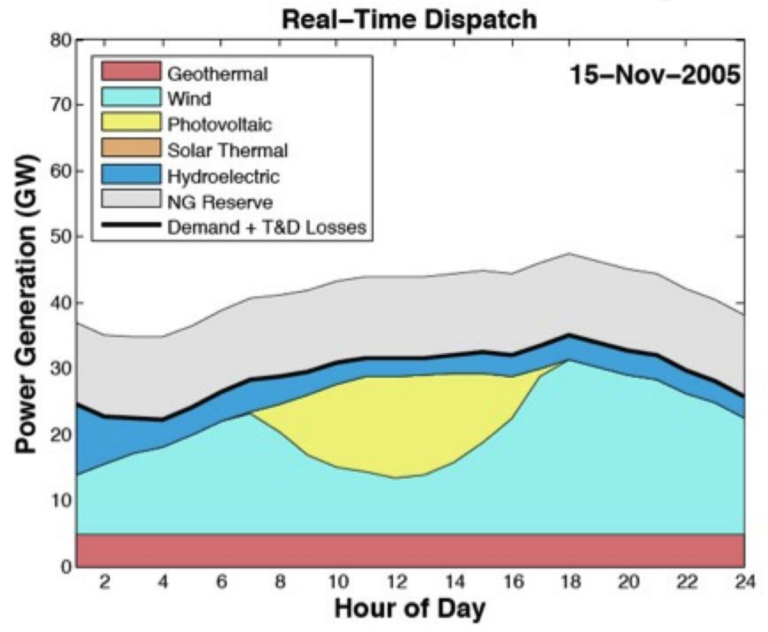


With turbines

Matching Power Demand With Solar, Wind, Geothermal, Hydro

California electricity was found to be obtainable from WWS for 99.8% of all hours in 2005, 2006 without over-sizing WWS capacity, using demand-response, or using much CSP storage.





Hart and Jacobson (2011); www.stanford.edu/~ehart/

Costs of Energy, Including Transmission (¢/kWh)

ENERGY TECHNOLOGY	2010-2013	2020-2030
Wind onshore	4-10.5	≤4
Wind offshore	11.3-16.5	7-10.9
Wave	>11	4-11
Geothermal	9.9-15.2	5.5-8.8
Hydroelectric	4-6	4
CSP	14.1-22.6	7-8
Solar PV (utility scale)	11.1-15.9	5.5
Tidal	>>11	5-7
Conventional (+Externalities)	9.2 (+5.3)=14.5	14-19 (+5.7)=20-25

Jacobson et al. (2013)

Costs Increase of Residential Electric Power 2003-13

10 states with highest % electric power from wind	+3 ¢/kWh
Remaining 40 states	+4 ¢/kWh

→States with greatest increases in percent of electricity from wind experienced lowest electric power price increases.

http://www.eia.gov/electricity/sales_revenue_price/)

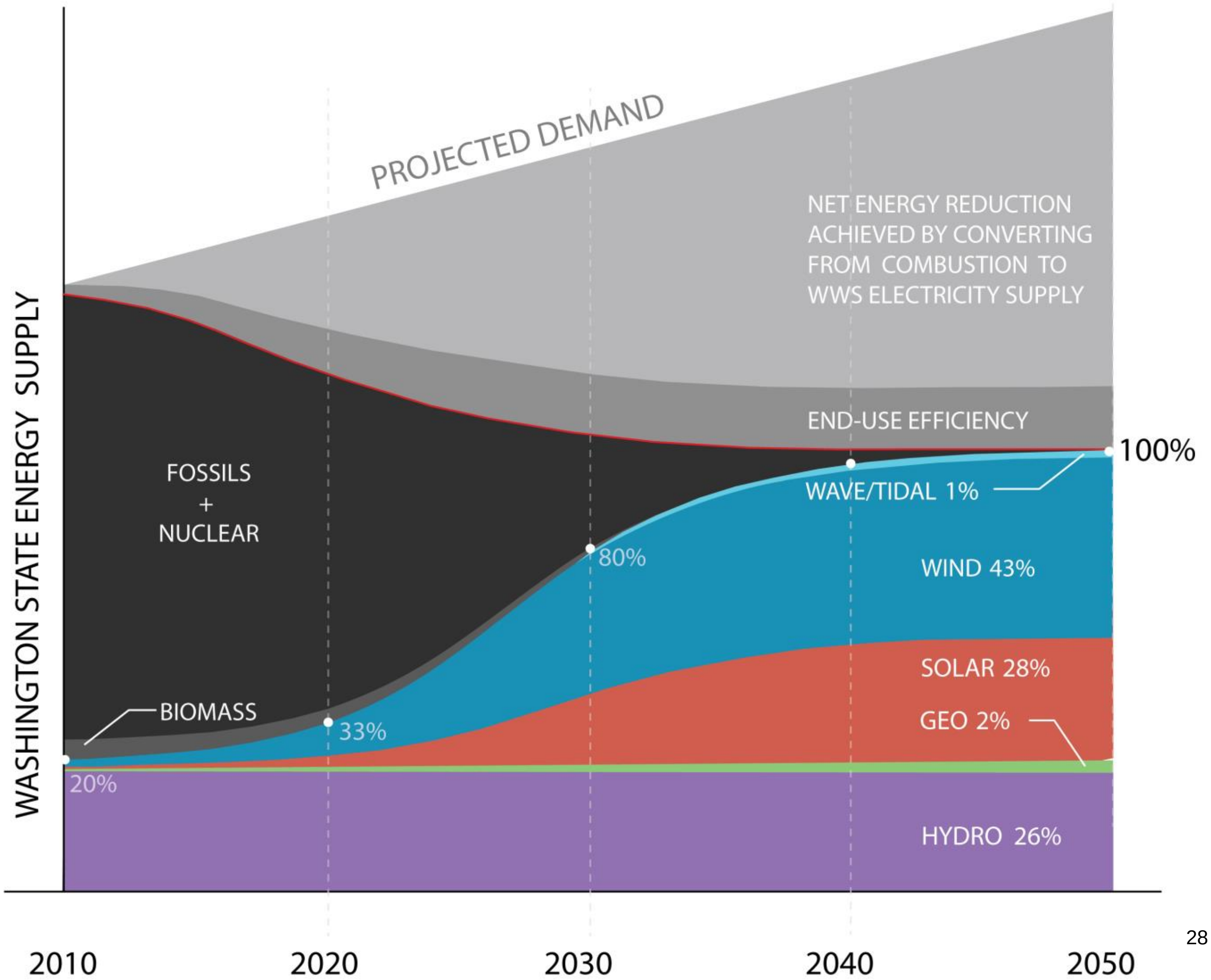
Health Cost Savings due to WWS in the U.S.

Air pollution kills 60,000 (18,000-109,000) people per year in the U.S. prematurely, costing $534 (166-980) billion/year, or 3.3 (1-6.1) % of U.S. GDP.

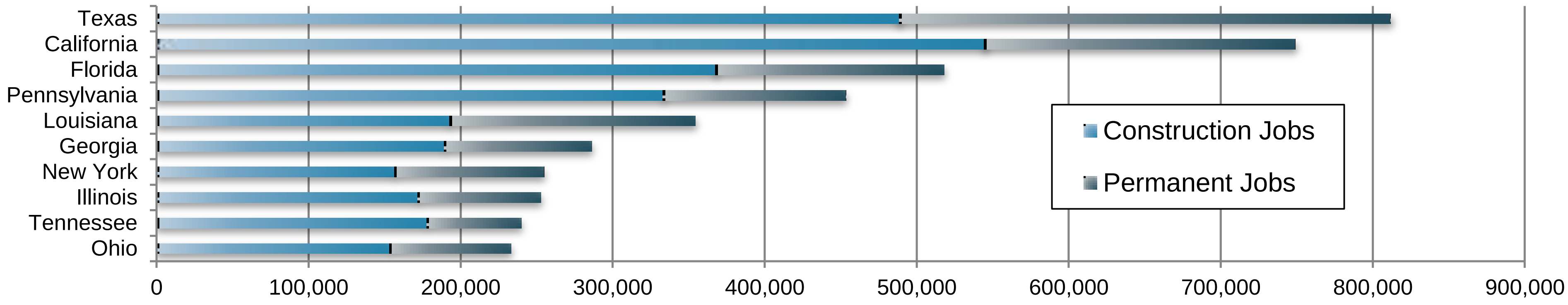
Jobs From WWS in the United States

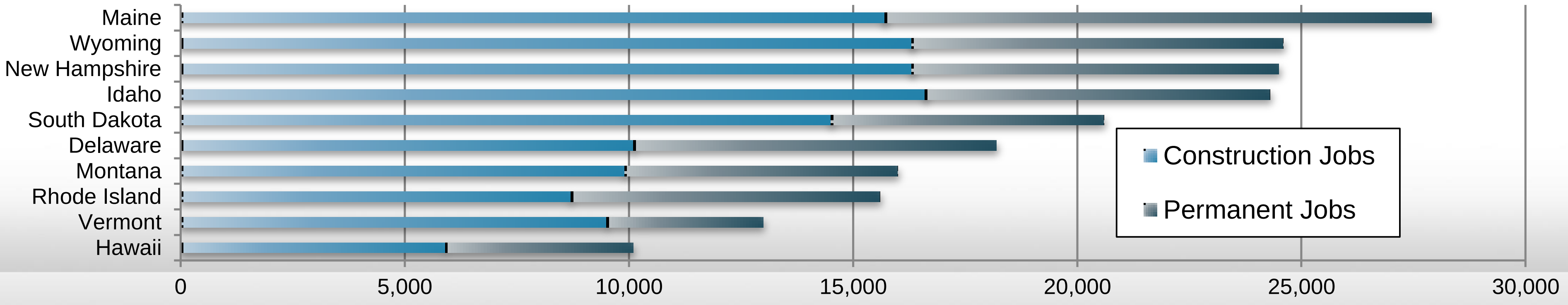
WWS will generate 5.1 million 40-yr construction jobs and 2.6 million 40-yr operation jobs in the U.S. (these are gross, not net numbers).

Transition to WWS (Washington State Example)

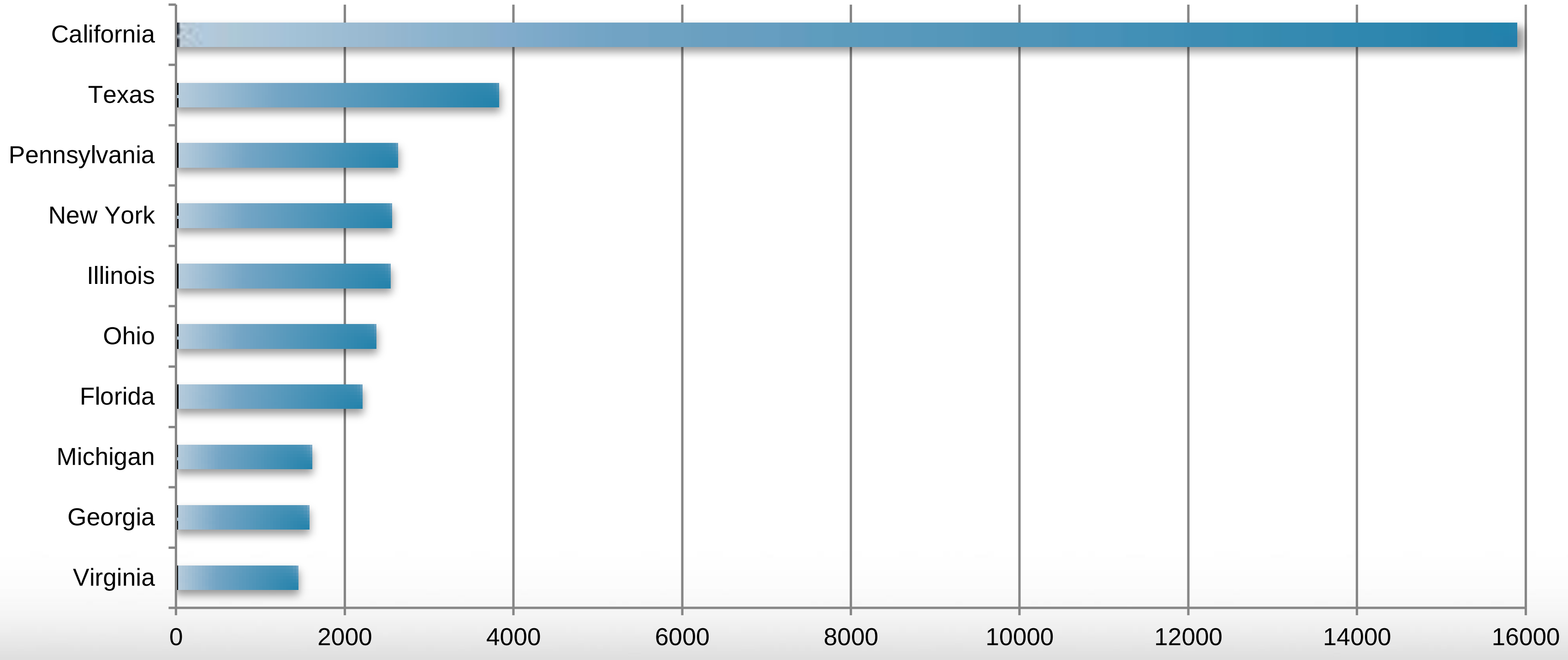


Gross 40-yr Job Production

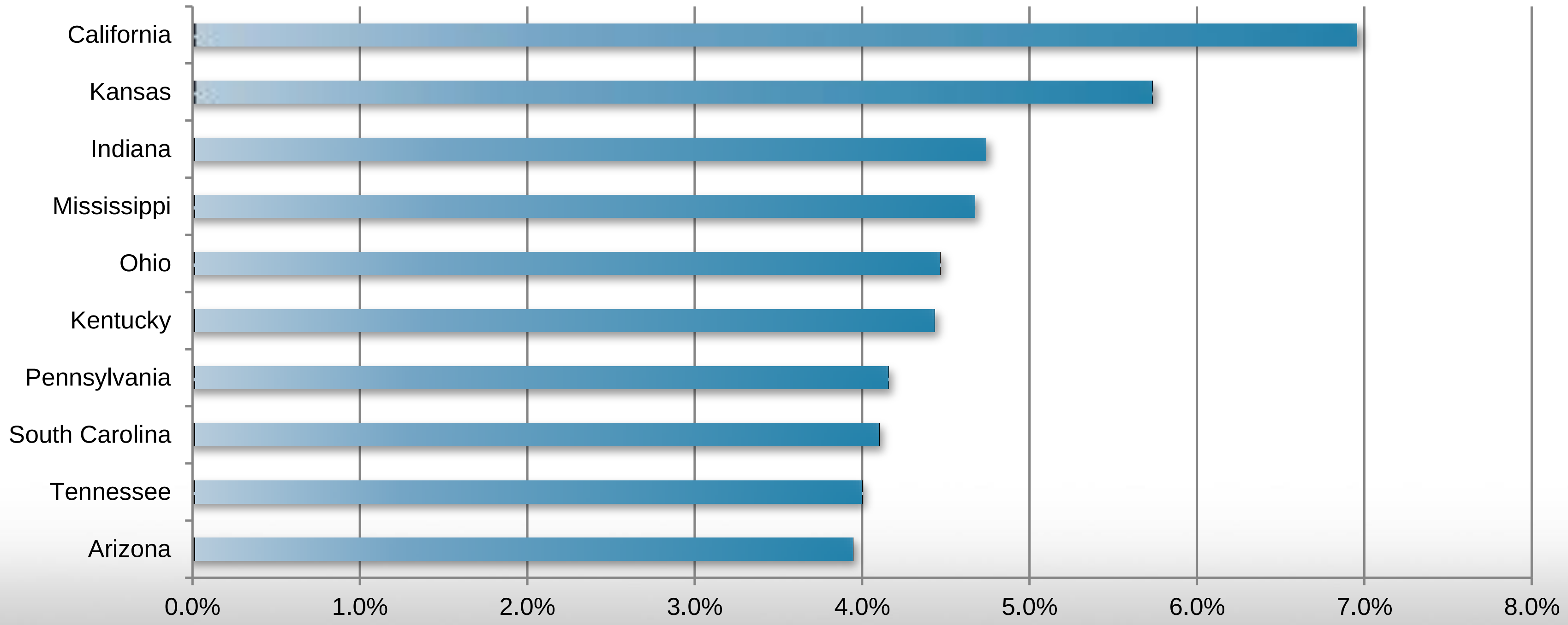




Air Pollution Mortality/Year



Avoided Air Pollution Mortality and Morbidity Cost as % of State GDP



Summary – California Plan

Converting to WWS + electricity/H_2 reduces California power demand ~44%

- →Eliminates ~16,000 air pollution deaths/yr in state (~7% of GDP)
- →Eliminates $48 billion/year in global climate costs
- →504,000 40-y construction jobs; 205,000 40-y operation jobs
- →Generates ~137,000 more operation jobs than destroys
- →Electricity cost savings: $1800/yr/person in 2050
- →Health +climate cost savings: $3700/yr/person in 2050
- →Mean footprint area of state: 0.78%; spacing area: 2.7%

Summary - 50-State Plans

Converting to WWS + electricity/H_2 reduces U.S. power demand ~37.3%

→Eliminates ~59,000 U.S. air pollution deaths/yr ($534 bil ~3.3% of GDP)
→Eliminates another $730 billion/year in global climate costs
→5.1 million 40-y construction jobs; 2.6 million 40-y operation jobs
→Energy cost savings: $3400/yr/person in 2050
→Health+climate cost savings: $3100/yr/person in 2050
→Mean footprint area of states: 0.65%; spacing area: 1.8%

Multiple methods of addressing WWS variability.
Materials are not limits although recycling may be needed.
Barriers : up-front costs, transmission needs, lobbying, politics.

More Info and The Solutions Project

www.stanford.edu/group/efmh/jacobson/Articles/I/susenergy2030.html

www.thesolutionsproject.org

@SolutionsProj (Twitter)
@mzjacobson

Energy+Environmental Economics

California's Transition to a Low Carbon Economy

Bay Area Air Quality Management District
San Francisco, CA
February 13, 2014

Dr. Jim Williams
Chief Scientist, E3

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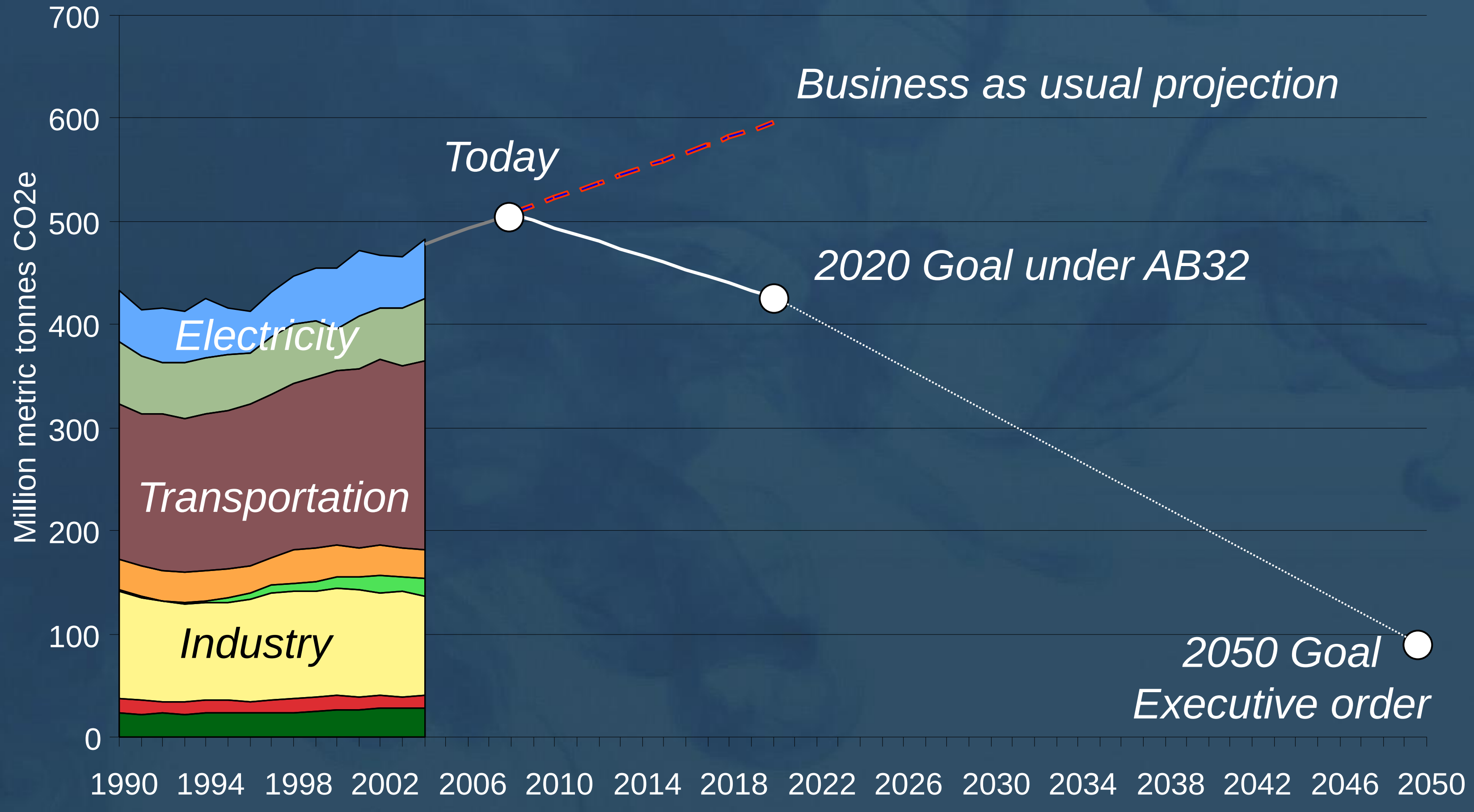
- Advisory Board
  - Dr. John Weyant, Stanford
  - Dr. Jae Edmonds, PNNL
  - Dr. John Reilly, MIT

California Climate Policy Goals

- 2020 requirement set by Assembly Bill 32 (AB 32)
  - Reduce statewide GHGs to 1990 levels by 2020

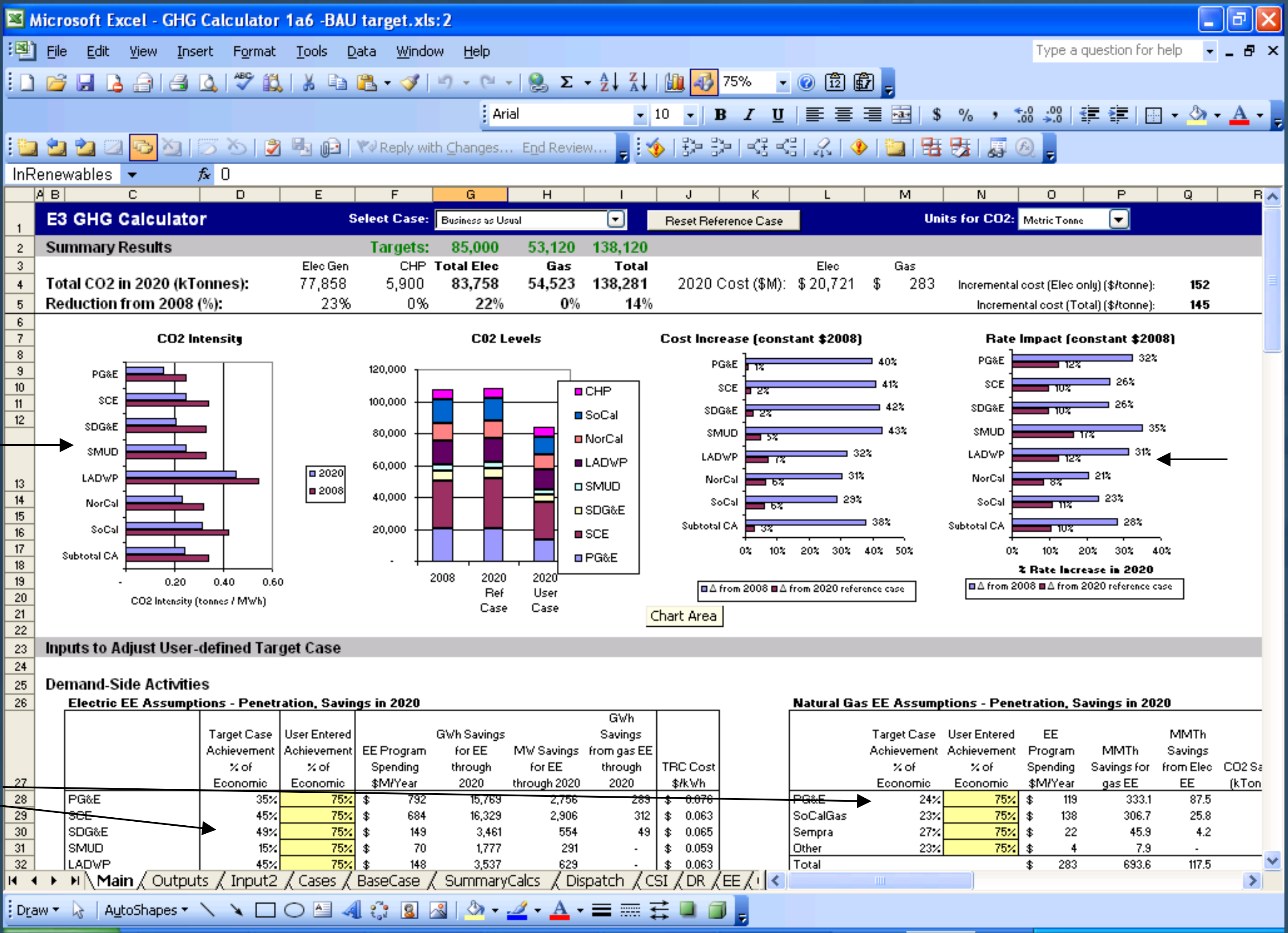
- 2050 target set by Executive Order S-3-05
  - Reduce statewide GHGs 80% below 1990 levels by 2050

AB32 and Beyond



2007 analysis of AB32 options and costs in electricity and natural gas sectors

CO2 BY UTILITY

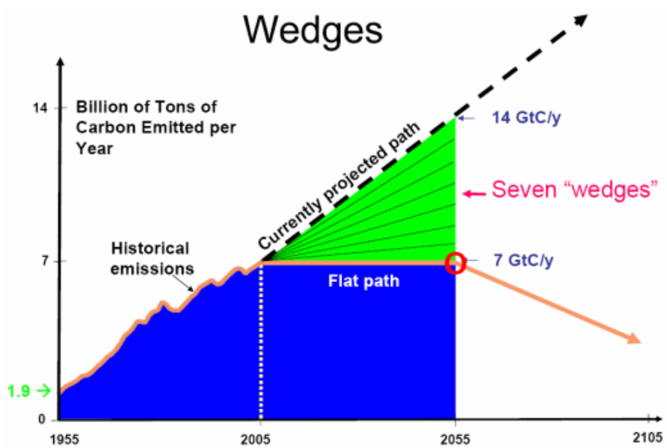


COST & RATE IMPACT BY UTILITY

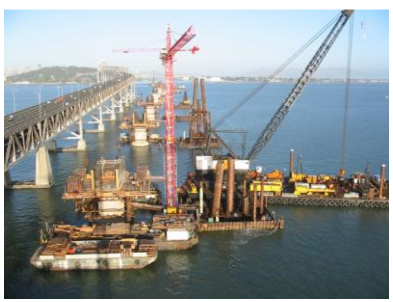
USER INPUTS

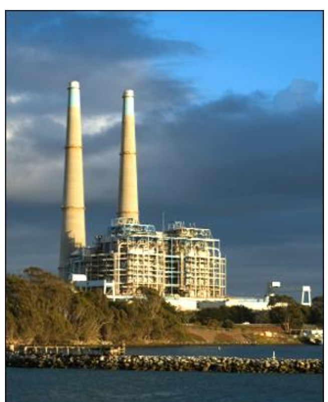
Tool and documentation at http://www.ethree.com/CPUC_GHG_Model.html

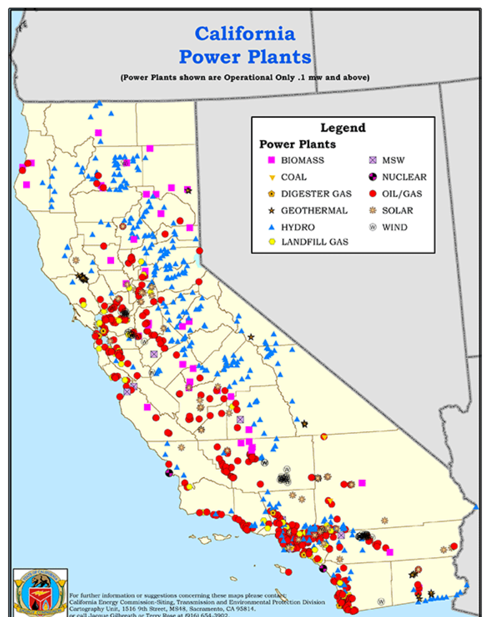
From global scale “wedges” to physically realistic, location-specific strategies



Pacala and Socolow, 2004

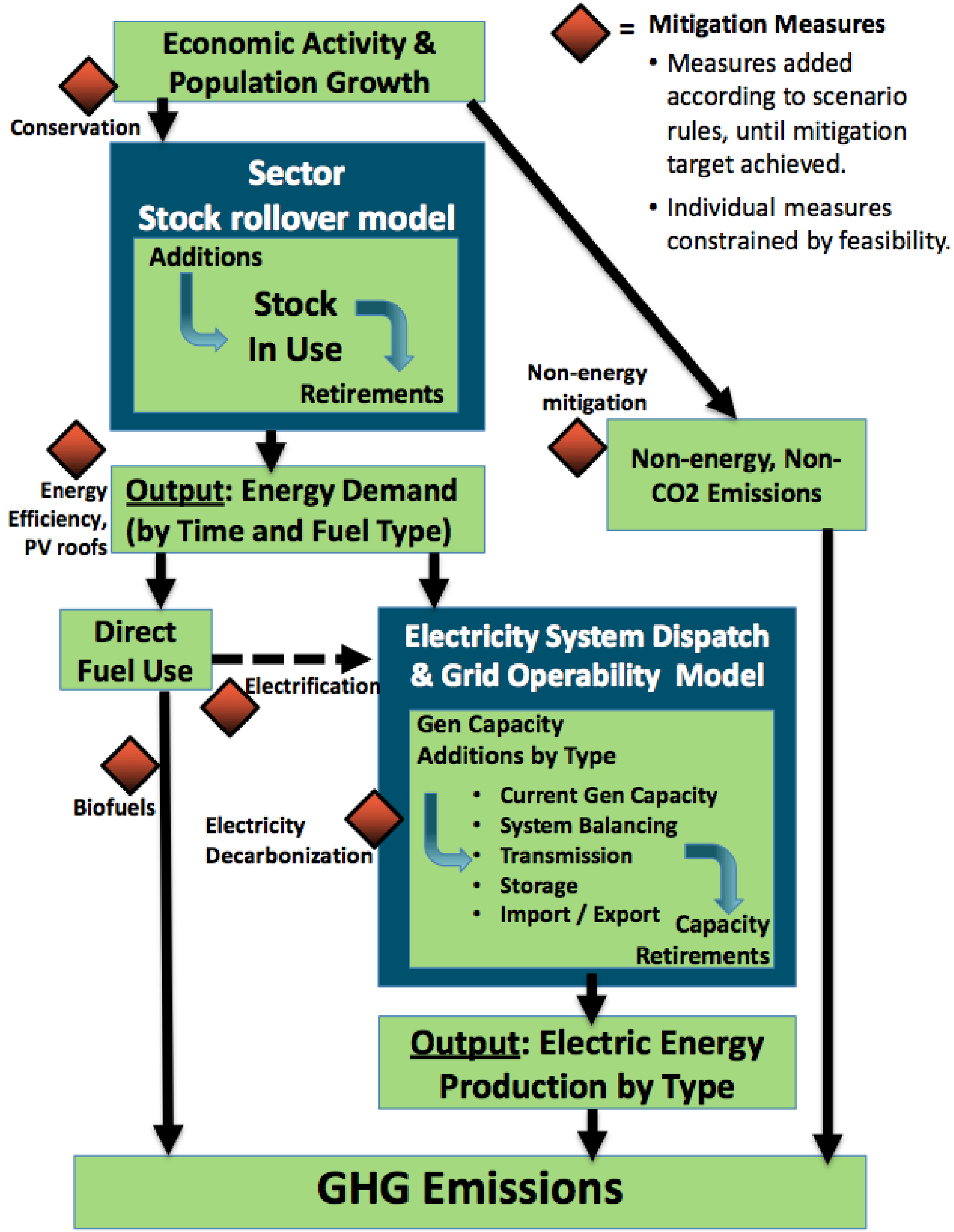




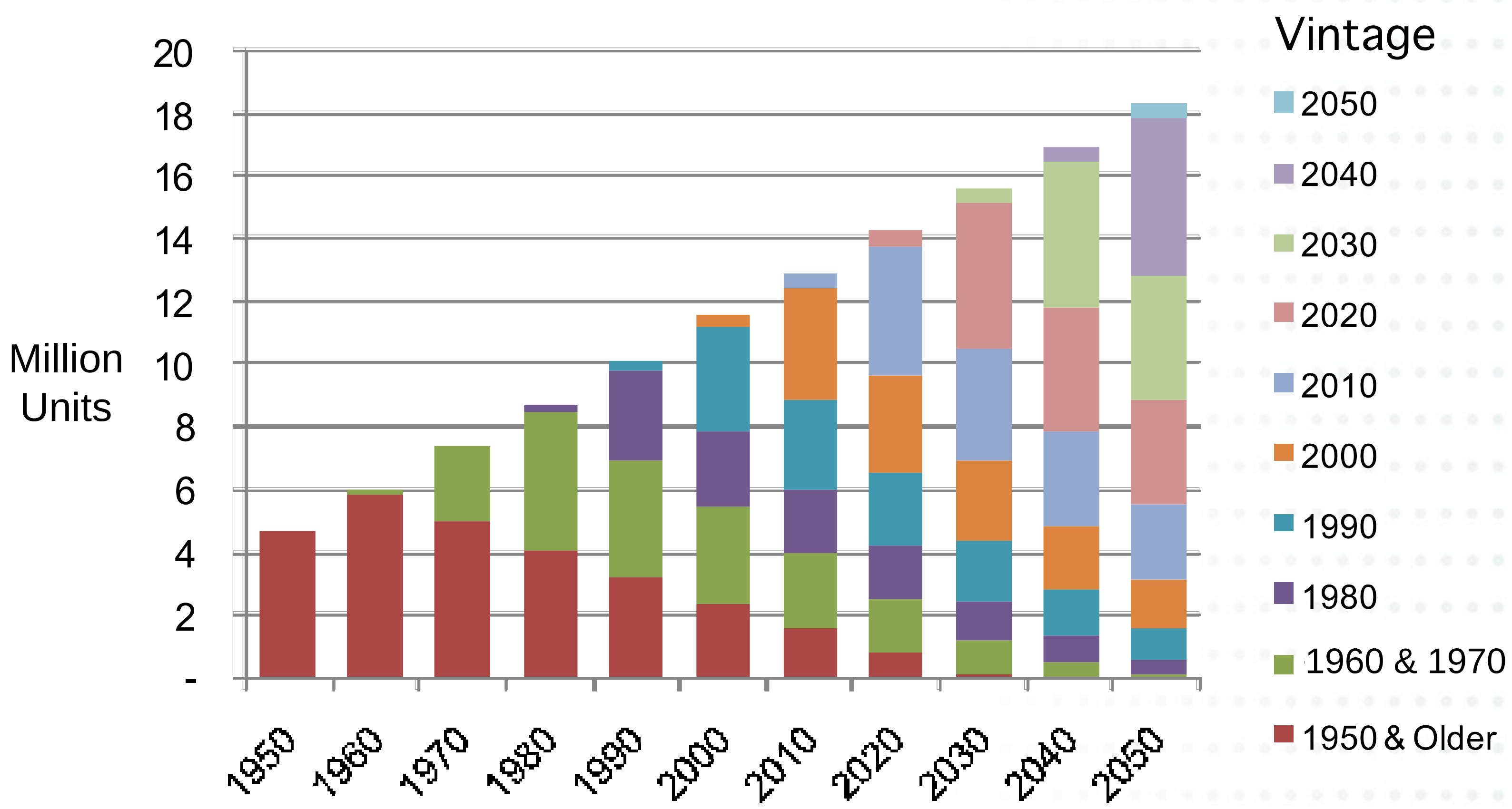


2050 Model Block Diagram

- Macroeconomic drivers
- Infrastructure stock rollover model
- Electricity system model
- Outputs
  - GHGs
  - Costs
- Scenarios
  - Baseline (BAU)
  - Mitigation



Stock Rollover Example: Housing Vintages



Williams et al, 2012, SOM

Science AAAS

The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity
James H. Williams, *et al.*
Science **335**, 53 (2012);
DOI: 10.1126/science.1208365

RESEARCH ARTICLE

The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity

James H. Williams,[1,2] Andrew DeBenedictis,[1] Rebecca Ghanadan,[1,3] Amber Mahone,[1] Jack Moore,[1] William R. Morrow III,[4] Snuller Price,[1] Margaret S. Torn[3]*

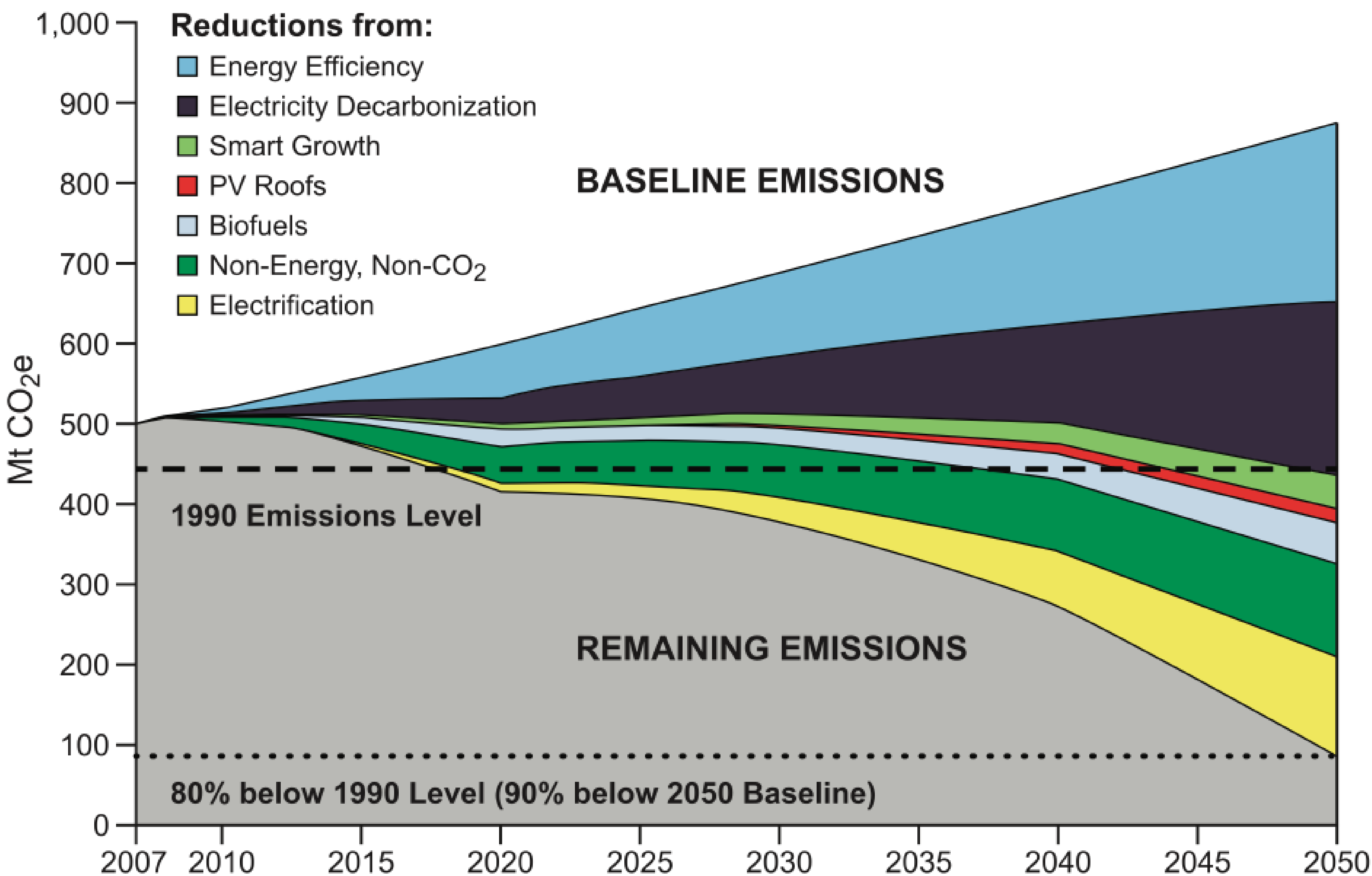
Several states and countries have adopted targets for deep reductions in greenhouse gas emissions by 2050, but there has been little physically realistic modeling of the energy and economic transformations required. We analyzed the infrastructure and technology path required to meet California's goal of an 80% reduction below 1990 levels, using detailed modeling of infrastructure stocks, resource constraints, and electricity system operability. We found that technically feasible levels of energy efficiency and decarbonized energy supply alone are not sufficient; widespread electrification of transportation and other sectors is required. Decarbonized electricity would become the dominant form of energy supply, posing challenges and opportunities for economic growth and climate policy. This transformation demands technologies that are not yet commercialized, as well as coordination of investment, technology development, and infrastructure deployment.

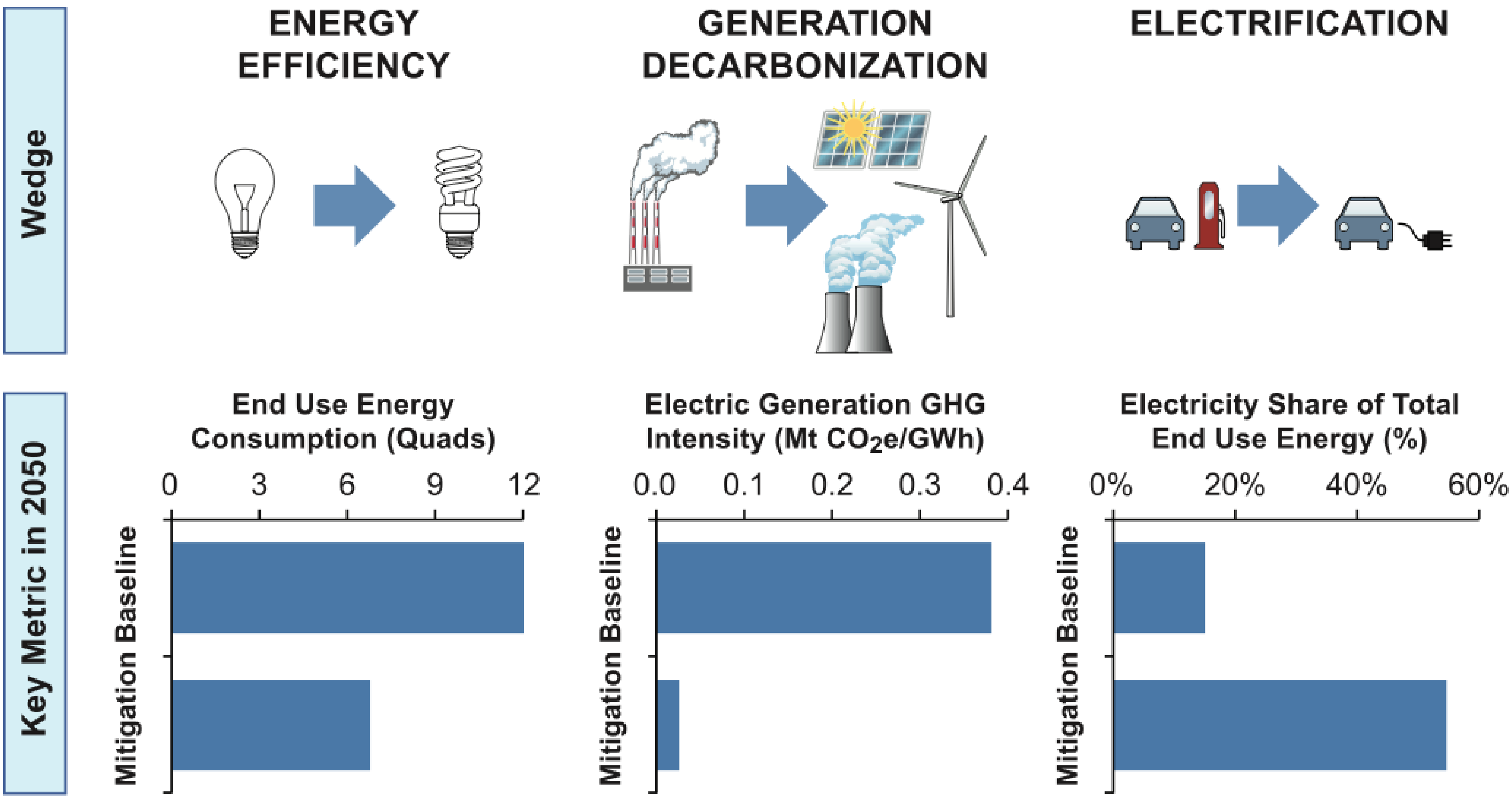
In 2004, Pacala and Socolow (*1*) proposed a way to stabilize climate using existing greenhouse gas (GHG) mitigation technologies, visistent with an Intergovernmental Panel on Climate Change (IPCC) emissions trajectory that would stabilize atmospheric GHG concentrations

bility, resource availability, and historical uptake rates rather than relative prices of technology, energy, or carbon as in general equilibrium models (*14*). Technology penetration levels in our model are within the range of technological feasibility for the United States suggested by recent assessments (table S20) (*15*, *16*). We did not include technologies expected to be far from commercialization in the next few decades, such as fusion-based electricity. Mitigation cost was calculated as the difference between total fuel and measure costs in the mitigation and baseline scenarios. Our fuel and technology cost assumptions, including learning curves (tables S4, S5, S11, and S12, and fig. S29), are comparable to those in other recent studies (*17*). Clearly, future costs are very uncertain over such a long time horizon, especially for technologies that are not yet commercialized. We did not assume explicit life-style changes (e.g., vegetarianism, bicycle transportation), which could have a substantial effect on mitigation requirements and costs (*18*); behavior change in our model is subsumed within conservation measures and energy efficiency (EE).

To ensure that electricity supply scenarios met the technical requirements for maintaining reli-

2050 Mitigation Scenario Results





Constraints

- Max feasible rate of improvement: 1.3% y^{-1}
- Fundamental changes in the built environment
- Limitations on changes in human behavior

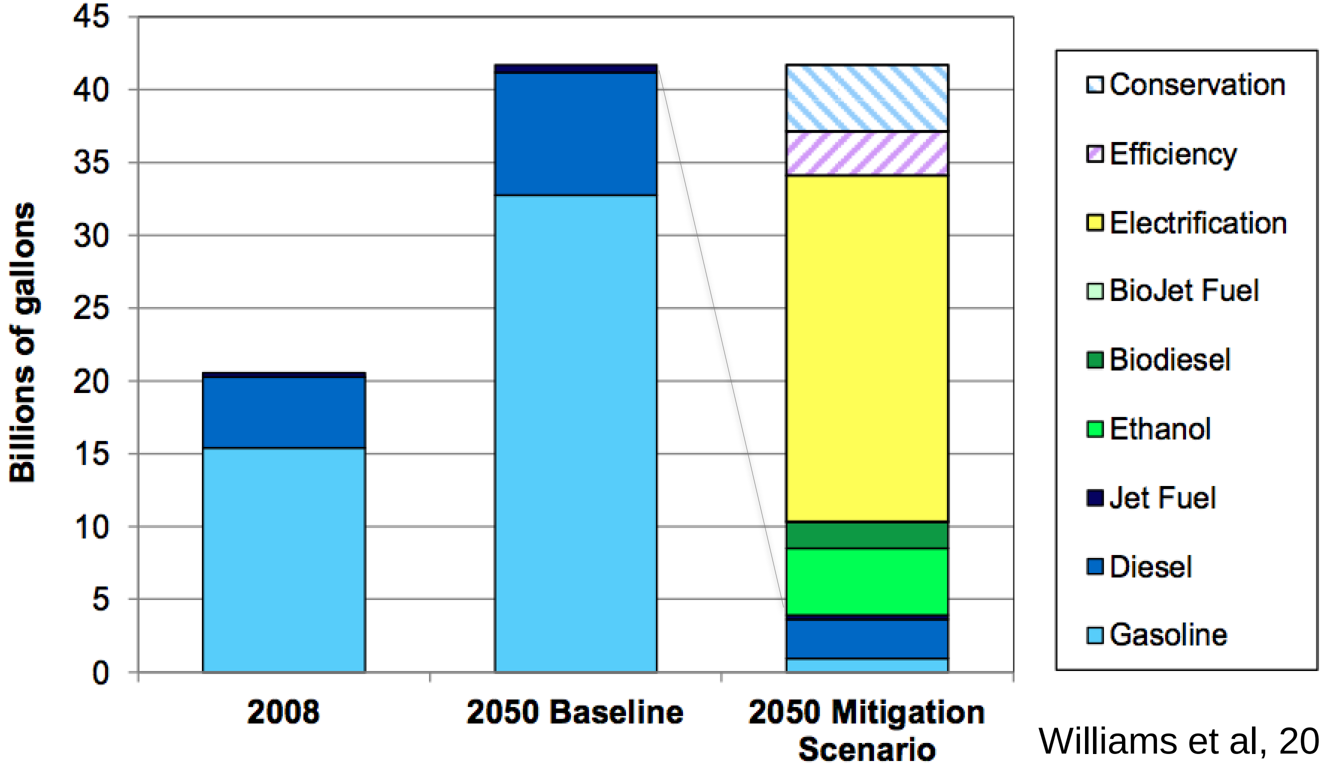
- Grid operability requires some natural gas usage
- Large infrastructure investment required
- Facility and transmission siting challenges

- Smart charging
- Battery technology and cost
- Low-carbon source of electricity

Williams et al, 2012

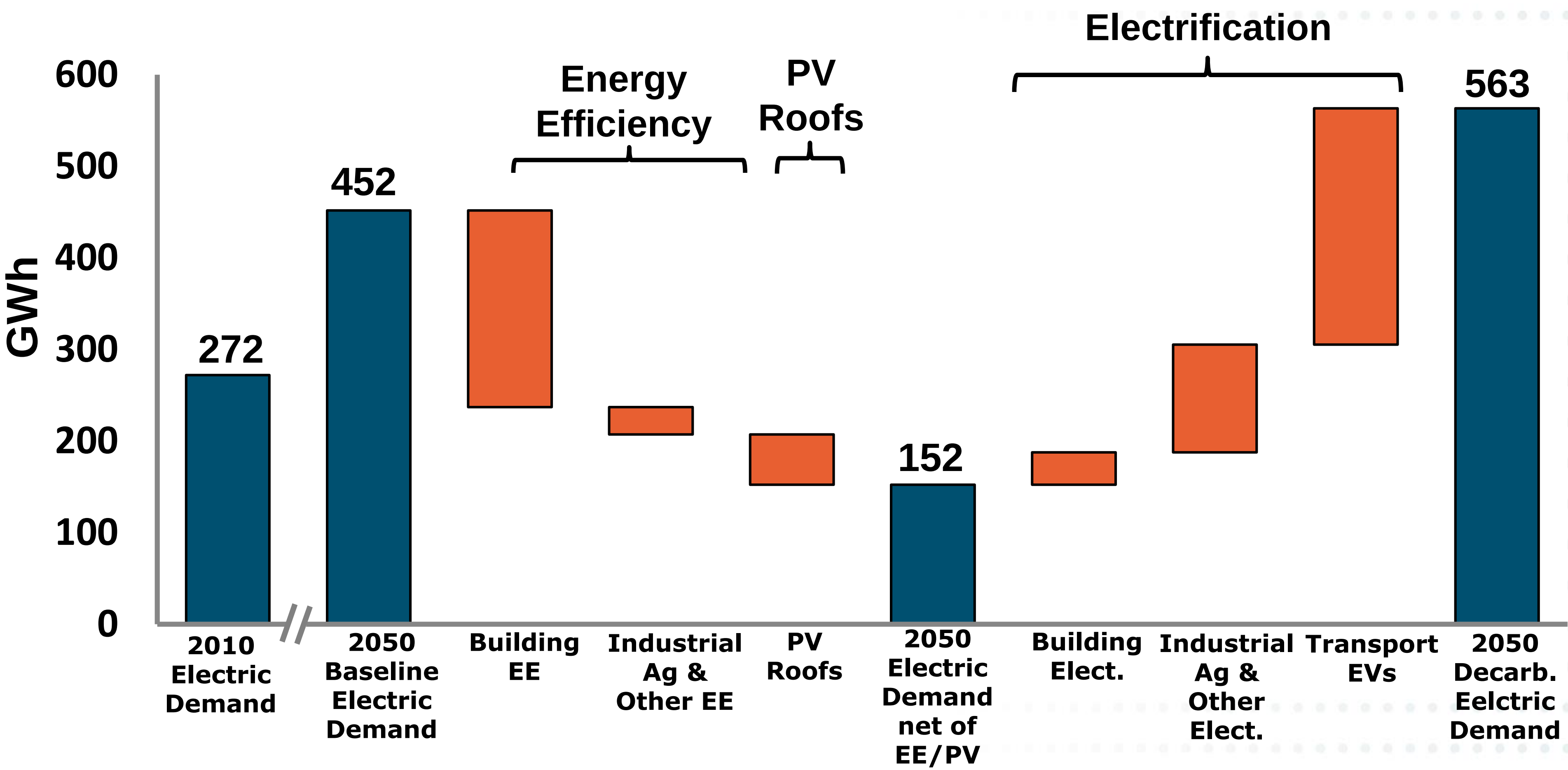
Transportation Fuel Requirement and Low-Carbon Biofuels

- California receives proportional share of US low carbon biofuel feedstock (no biofuel imports)
- Biofuels become resource-limited premium transportation fuel
- 2050: 4.6 Bgge cellulosic ethanol, 1.8 Bgge algal biodiesel



Williams et al, 2012, SOM

Electrification & Energy Efficiency



Williams et al, 2012, SOM

Low Carbon Generation

Renewable

Carbon capture and storage

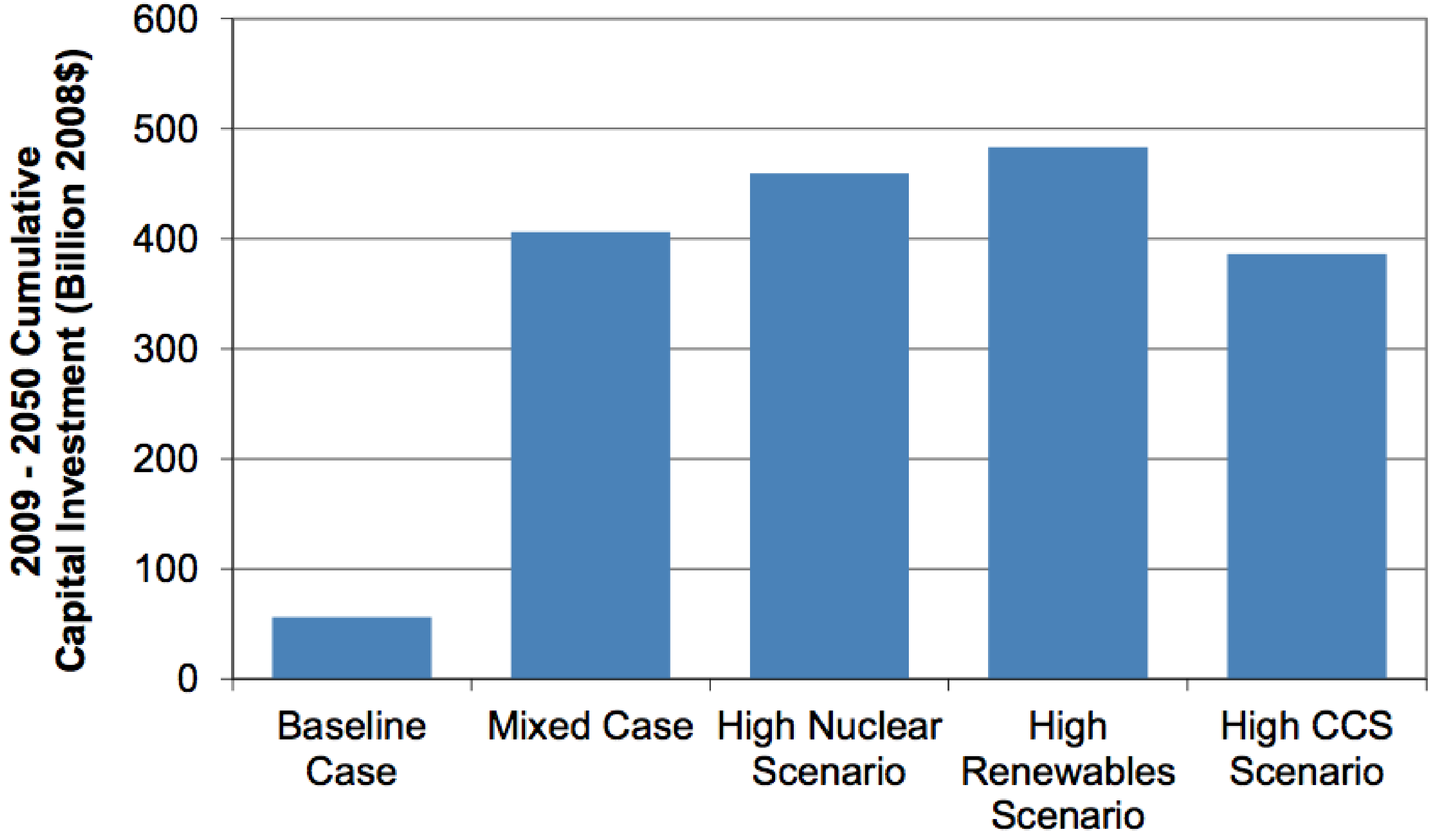
Nuclear

Table S13. 2050 Electricity Generation Mix By Scenario

Scenario	Renewable Energy	Nuclear Energy	Generation w/ CCS	Other	Energy Storage
Baseline	6%	8%	-	86%	--
High Renewables	74%	6%	-	20%	12,000 MW
High Nuclear	35%	55%	-	10%	4,000 MW
High CCS	36%	7%	47%	10%	8,000 MW
Mixed	34%	19%	39%	8%	6,000 MW

All Low-C Electricity Scenarios have high investment costs: but options similar

Cumulative Capital Investment, 2009-2050 (Billion, 2008 US$)



Williams et al, 2012, SOM

Non-Cost Factors Likely to Affect Low Carbon Generation Choice

+ Non-GHG Environmental Impact

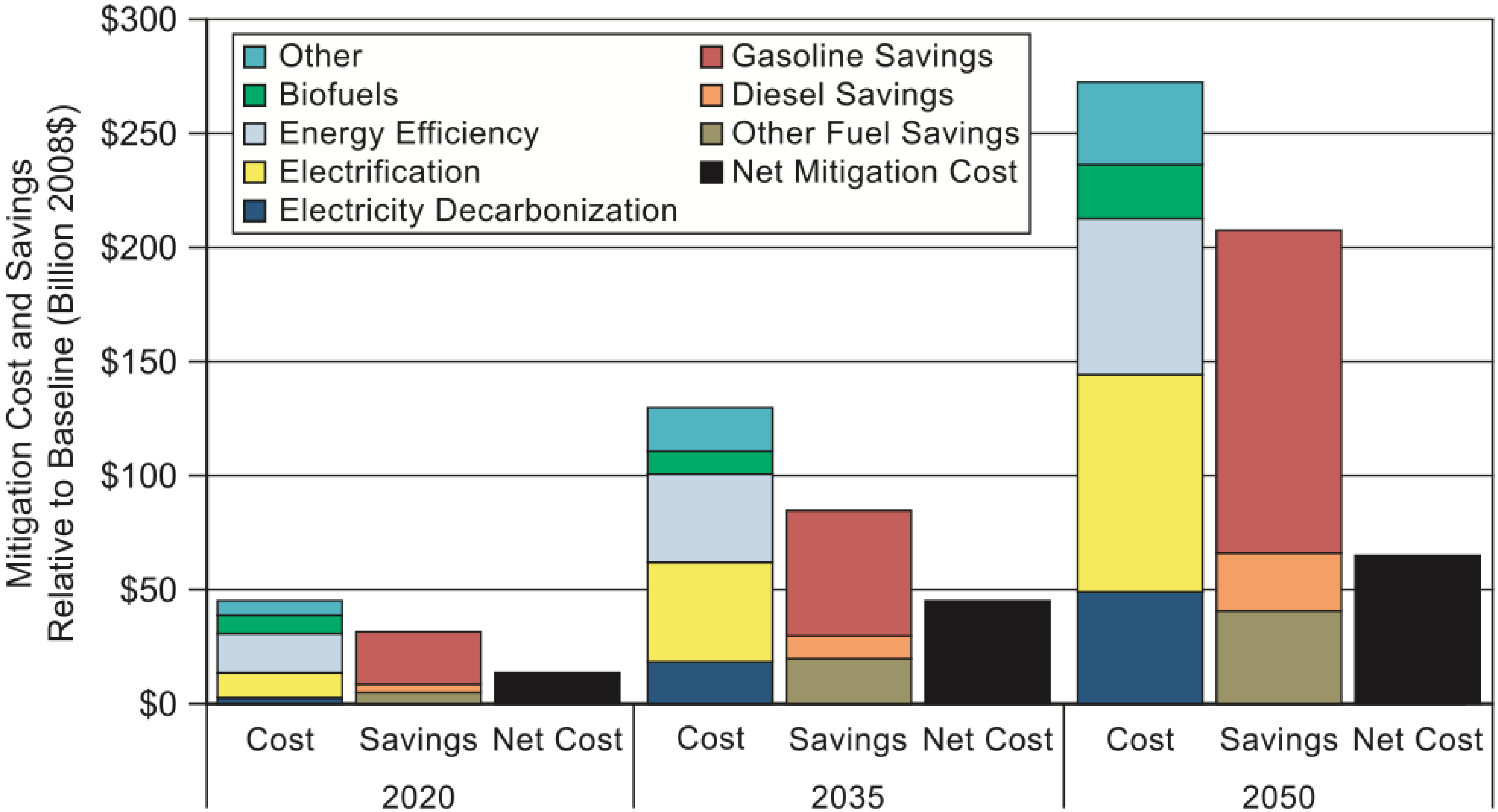
- Nuclear fuel cycle
- Land use
- Water use
- Fossil fuel extraction for CCS
- CO_2 storage

+ System Operability and Reliability

Need low carbon balancing resources

- Regional integration
- Resource diversity
- Energy storage
- Flexible load/enhanced demand response
- Curtailment

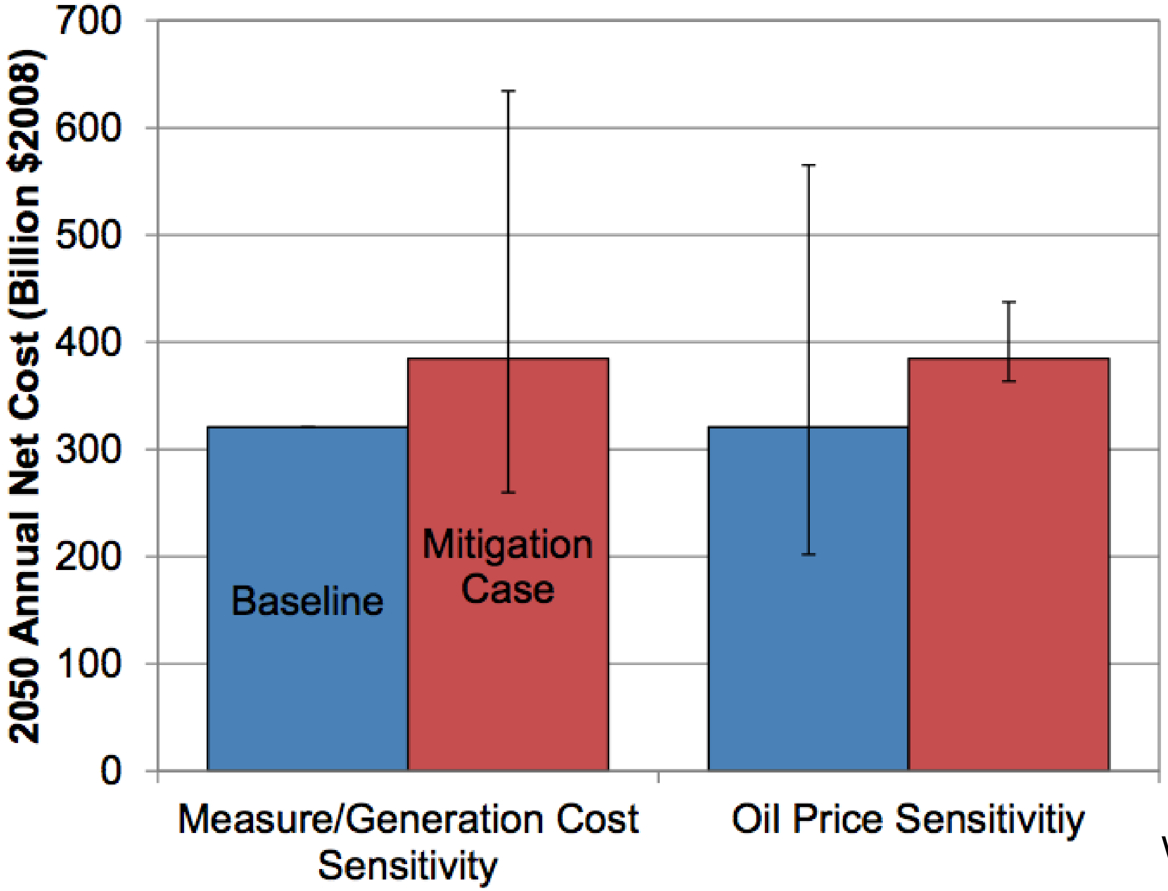
Net Cost of Mitigation



Williams et al, 2012

Current System Vulnerable to Uncertainty in Oil Prices

- Our current energy system is about as sensitive to oil price volatility as our mitigation case is to uncertainty about new technology costs



Williams et al, 2012, SOM

What's so pivotal about the role of electricity?

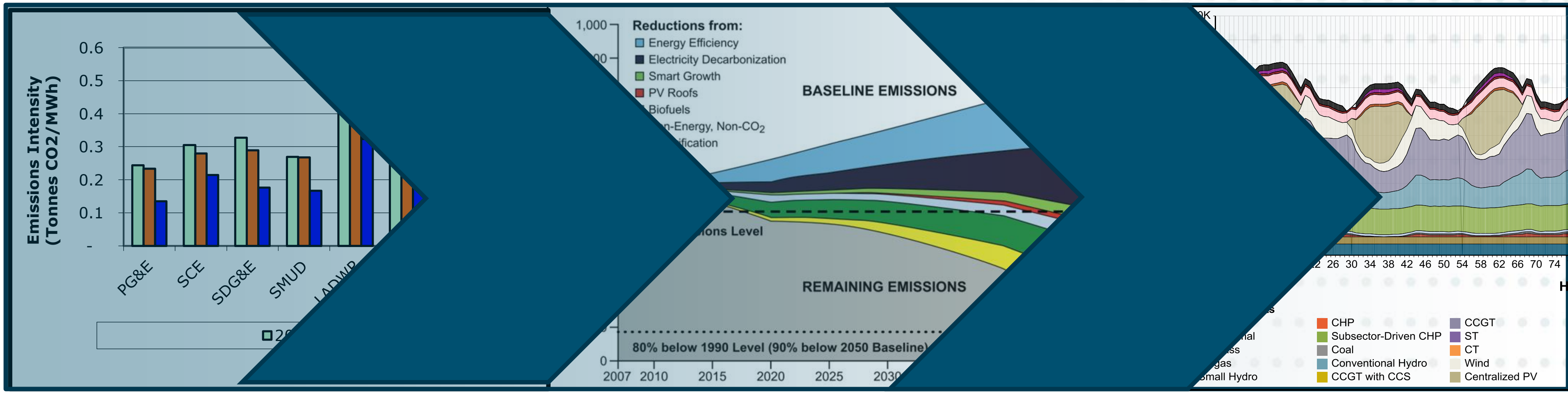
- Electricity in 2050 goes from 15% to 55% of end-use energy, changing places with oil
- Energy economy changes from one dominated by variable (fuel) costs to fixed (capital) costs
- Pegs economy to price-stable, domestically sourced energy – green kWh – instead of price-unstable, global commodity – barrel of oil
- Scale of up-front investment in low carbon generation very large – same order of magnitude for renewable, nuclear, CCS scenarios
- Puts premium on lowering the capital cost of low-carbon generation and electrified transportation before we have to buy in bulk

Key Findings

- Net cost estimate comparable to those in other 2050 studies ~ 1.3% of GDP, with large uncertainty in both technology cost and fuel cost
- Requires energy transformation: very low carbon electricity, very high EE, very high electrification
- Technical challenges: EE retrofits, HDVs, electricity balancing, biofuels, industry, non-energy/non-CO_2 GHGs
- Planning challenges: technology R&D, infrastructure deployment, land use, transportation
- Coordination challenges: across sectors; between levels of government; public-private
- Policy challenges: getting neighbors to join; adaptability; planning under uncertainty; cost containment; equity

Next Steps in Pathway Modeling

- **California 2030 GHG target**
- **US 80% decarbonization pathways for UN DDPP**
- **California-China climate cooperation**
- **Pathways v2 – new, improved tool**
  - electricity sector, uncertainty analysis, co-benefits analysis



2008 2011 2014

Energy+Environmental Economics

Deep Decarbonization Pathways Project for 12 Major Emitting Nations

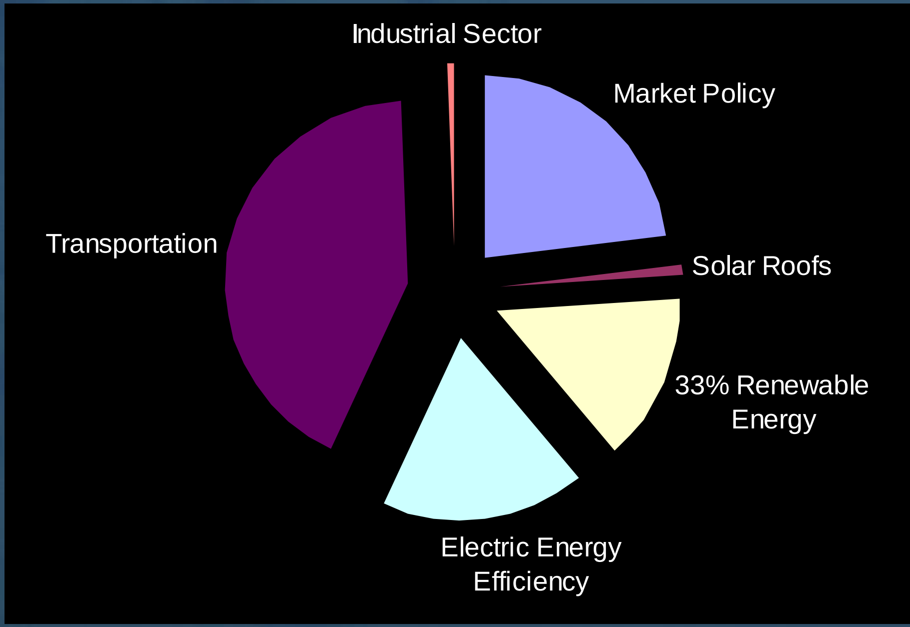
- Sponsored by UN SDSN, led by Columbia Univ. Earth Institute
- Goal is to encourage nations to make deep commitments at COP-21
- Preliminary results report at UN General Assembly Fall 2014

+ **E3/LBNL Team is Developing US Model for DDPP consistent with <2° C warming**
+ **Using two modeling platforms: Pathways v2 and GCAM**
+ **Pathways will model US at regional level based on electricity system (NERC regions)**

Regulation and Local Action

AB32 is *Not* Primarily Cap and Trade

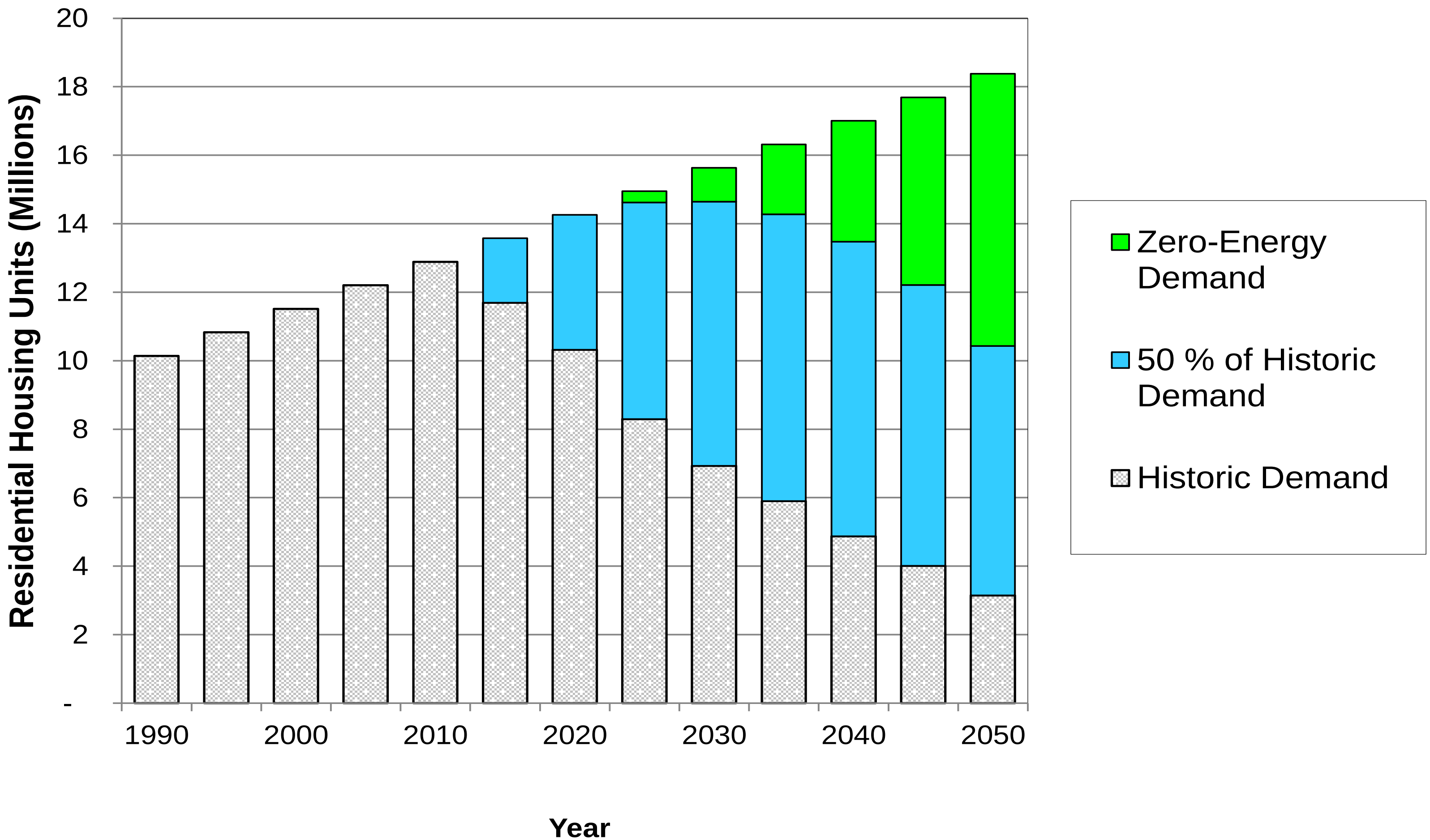
- Scoping Plan for 2020 has >80% of GHG reductions from “complementary” measures
- 33% renewable portfolio standard
- California solar initiative
- Vehicle fuel efficiency standards
- SB375 VMT reductions
- Building and appliance efficiency standards
- Water efficiency



Will post-2020 GHG policy continue similar approach?

What does low C transition look like?

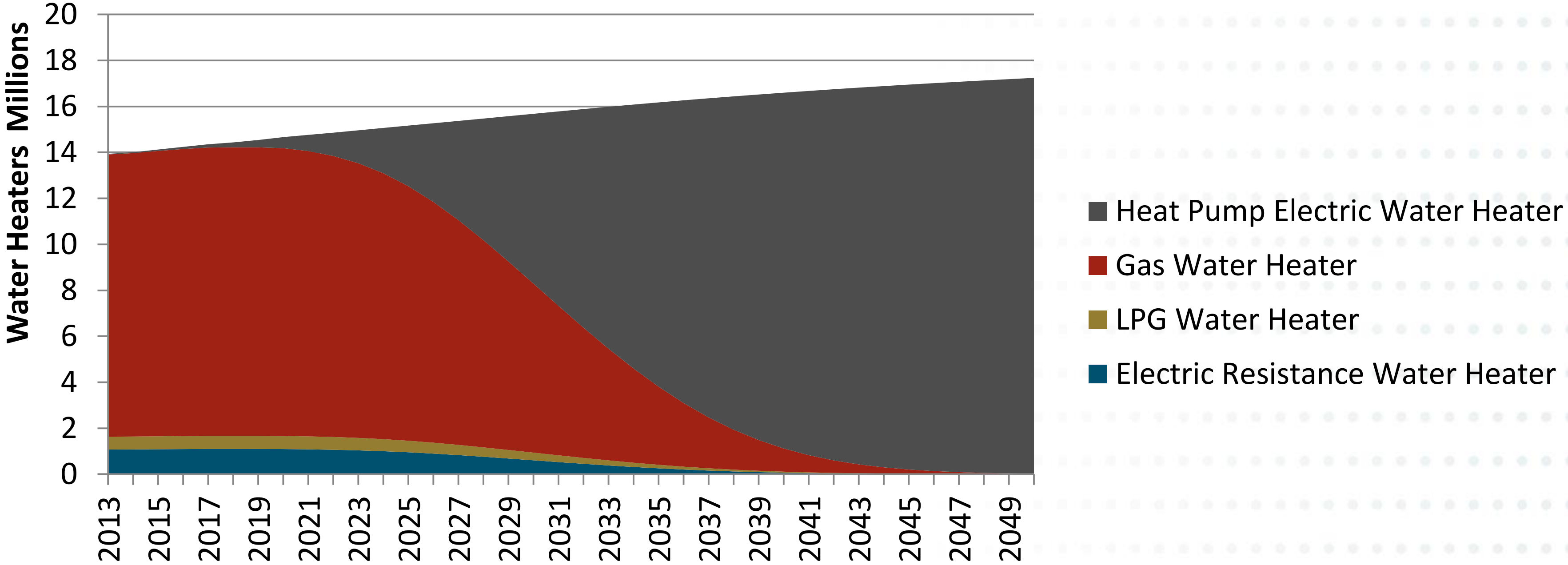
- 10 years: all new homes "zero net energy"
- 20 years: 60% of existing homes deep retrofits



What does low C transition look like?

+ Example: water heaters

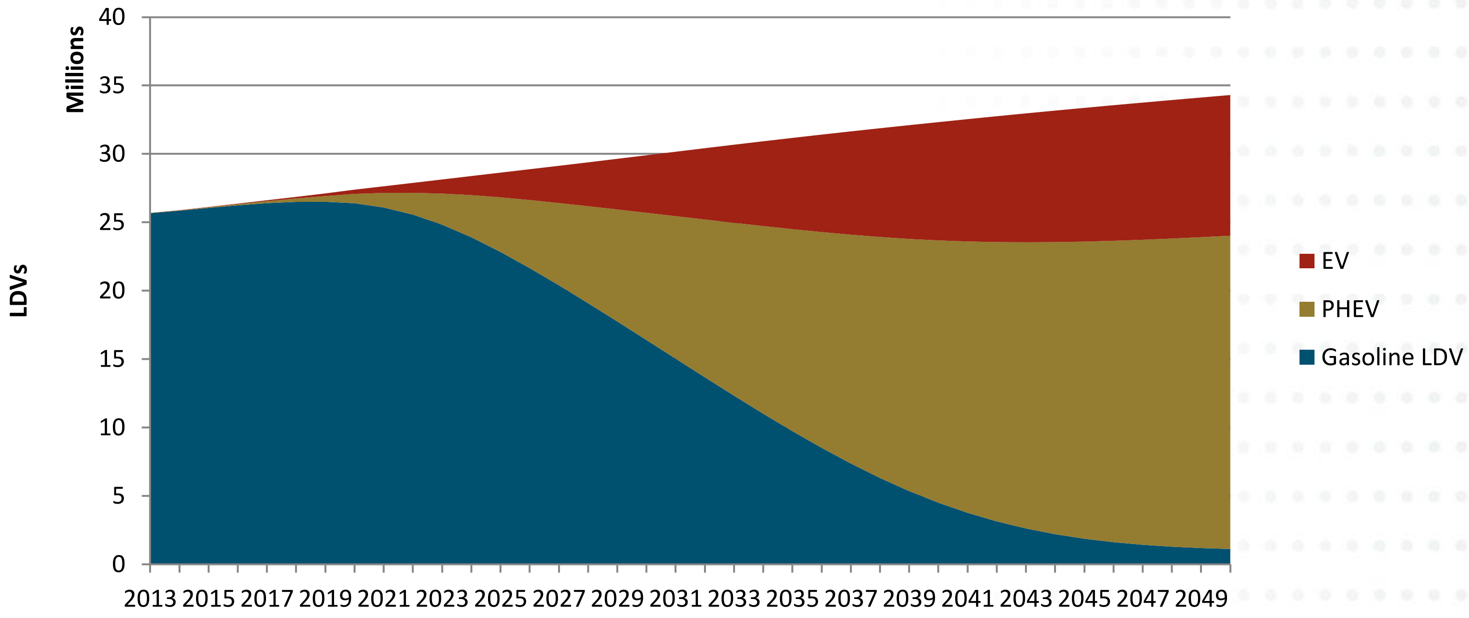
- Over next 20 years, 75% of gas water heaters need to be replaced with heat pump electric



What does low C transition look like?

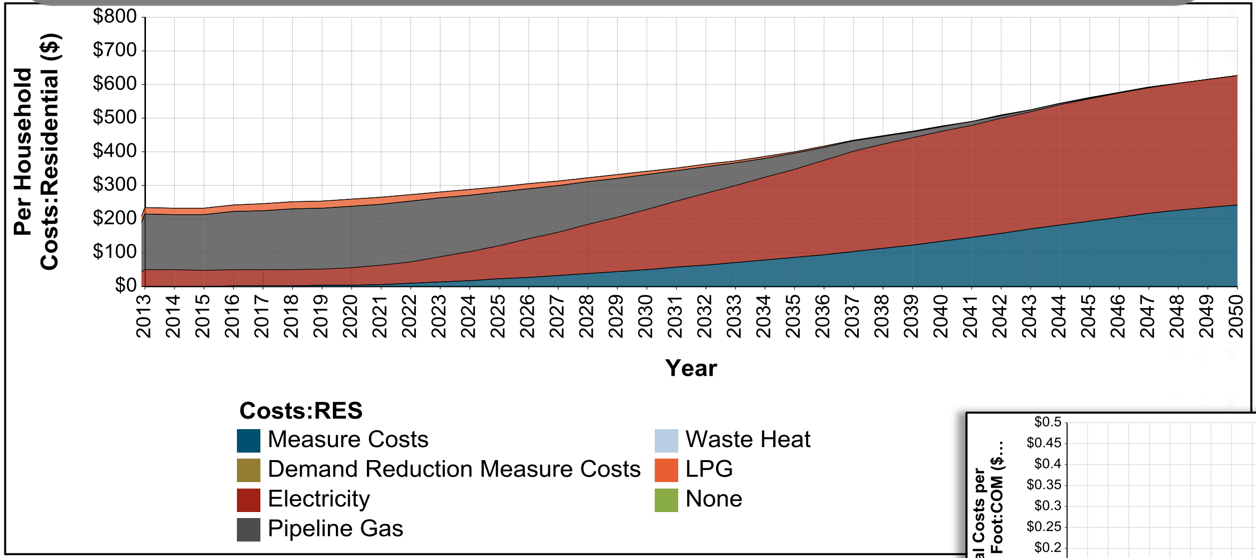
+ Example: light-duty vehicles

- Over next 20 years, 70% of gasoline and diesel LDVs need to be replaced with EVs or PHEVs



Relevant Cost Metrics

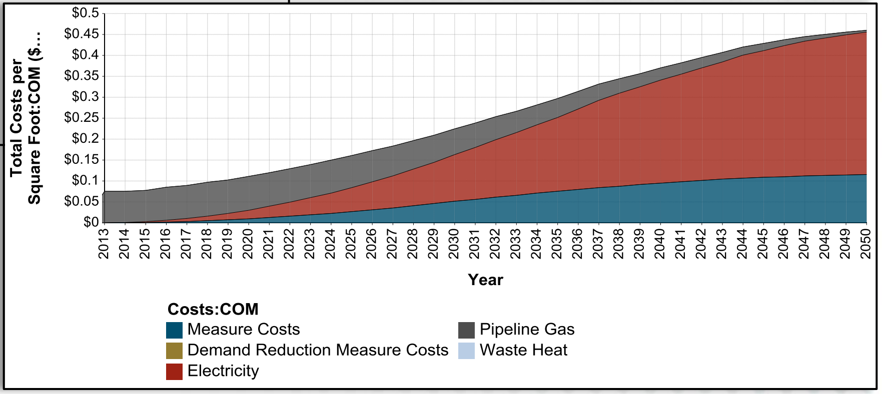
+ **$/Household for water heating**
  - Includes efficiency measure costs as well as energy costs
  - Can be reported by subsector and service area *(water heating shown below under an electrification scenario for PG&E)*



Many possible metrics

+ **cost per person or hh**
+ **changes in electric rates**
+ **improvement in air quality**
+ **changes in cost of driving & transport**

+ **$/Commercial sq. foot for space heating**
  - Space heating commercial subsector shown at right for PG&E under a high electrification scenario



Some areas where local regulators & government can play leading role

Challenge	Regulation & Local Action
Energy efficiency	- Improve codes and standards - Innovative finance for EE retrofits - Targeting of poorly performing buildings
Low carbon electricity	- Community solar - Flexible customer loads - Low impact renewables/transmission siting
Transportation	- Zoning, density, urban infill - Transit, mode shift, bike friendly - Electric charging infrastructure
Industry	- Fuel switching and efficiency options - Refinery emissions, heavy crude - On site renewable generation or CCS
Non-energy/non-CO2 GHGs	- Waste management, landfill gases - Animal feedlots, agricultural tillage - Reduce HFCs, SF6, other high GWP

A few thoughts on regulation & the low carbon transition

- **Transformation of energy system required**
  - Goes beyond incremental tailpipe/smokestack regulation
  - Active, broad-based, enduring public support essential
- **All state agencies need a carbon mandate**
  - Example: CPUC has separate electricity programs, lacks GHG organizing principle
- **Regulatory and sectoral boundaries will get blurred**
  - Example: Electrified transportation
  - New cooperation across silos will be required
- **AQMDs play special role**
  - Understanding of multi-pollutant control & tradeoffs
  - Electrification moves all emissions toward stationary sources

Energy+Environmental Economics

Thank You

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