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Deep carbon reductions in California require electrification and integration across economic sectors

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Abstract
Meeting a greenhouse gas (GHG) reduction target of 80% below 1990 levels in the year 2050 requires detailed long-term planning due to complexity, inertia, and path dependency in the energy system. A detailed investigation of supply and demand alternatives is conducted to assess requirements for future California energy systems that can meet the 2050 GHG target. Two components are developed here that build novel analytic capacity and extend previous studies: (1) detailed bottom-up projections of energy demand across the building, industry and transportation sectors; and (2) a high-resolution variable renewable resource capacity planning model (SWITCH) that minimizes the cost of electricity while meeting GHG policy goals in the 2050 timeframe. Multiple pathways exist to a low-GHG future, all involving increased efficiency, electrification, and a dramatic shift from fossil fuels to low-GHG energy. The electricity system is found to have a diverse, cost-effective set of options that meet aggressive GHG reduction targets. This conclusion holds even with increased demand from transportation and heating, but the optimal levels of wind and solar deployment depend on the temporal characteristics of the resulting load profile. Long-term policy support is found to be a key missing element for the successful attainment of the 2050 GHG target in California.

Keywords: energy system modeling, renewable energy, long term energy scenarios, electricity system optimization, deep carbon reduction

S Online supplementary data available from stacks.iop.org/ERL/8/014038/mmedia

1. Achieving the 2050 GHG target

California has become an internationally important test-bed for low-cost, low-GHG energy planning. California's landmark AB32 law mandates a return of State GHG emissions to the 1990 level by 2020, and Executive Order S-3-05 sets a goal for the State to reduce emissions to 80% below this level by 2050 [1, 2][6].

In this work, we take an integrated approach and evaluate GHG emissions across the electricity, building, transportation, and industrial sectors—90% of the current total—and do not treat agriculture or non-energy based emissions [3]. Taking the 1990 baseline of energy and industry emissions as 405 million metric tons CO_2-equivalent ($MtCO_2$-eq), an 80% reduction gives a 81 $MtCO_2$-eq target for California in 2050 [4]. We take a conservative approach by predominantly using technologies that exist in the marketplace or are beyond the demonstration stage.

Integrated long-term planning and a portfolio of public policies are being developed to meet GHG targets in California. Previous work [5–10] has highlighted the electricity sector as key to deep GHG reduction in California. This study complements and expands on previous work by providing a detailed, bottom-up assessment of electricity demand and supply. Load profiles for increased efficiency, vehicle electrification, and heating electrification are developed as inputs to a state-of-the-art variable renewable resource capacity planning model of the electric power sector. The SWITCH model [11–13] is used to explore generation, transmission, and storage deployment through 2050 in the synchronous western North American electricity grid, of which California represents roughly one-third of total demand.

We find that meeting the 2050 GHG target is achievable, but requires dramatic changes in the way California produces, delivers, and uses energy. Figure 1 shows the cumulative impact of measures that can reach the 2050 target ('Compliant Case'). Figure 2 shows the radical shift in overall primary energy resulting from these measures. Increased efficiency, low-GHG electricity, electrification of heating and vehicles, and deployment of sustainable biofuels reduce emissions to just under 100 $MtCO_2$-eq in 2050 (figure 1). Thus additional elements are required to meet the 81 $MtCO_2$-eq target, such as higher imports of low-GHG biofuels, higher penetration of electrification in industry and transportation, or savings from energy conservation (see online supplementary material available at stacks.iop.org/ERL/8/014038/mmedia). Conservation is highlighted in sections 2 and 3 as an additional element to attain the 80% target. The electricity sector modeling in sections 4 and 5 does not include demand reduction from conservation since there are other pathways to meet the 80% target (e.g., the 100 $MtCO_2$-eq case above coupled with higher biofuel imports). Table 1 provides a summary of energy demands and emission intensities for buildings, industry, and transportation sectors for 2011 and four 2050 cases.

2. Transportation electrification and biofuels are critical

Managing transportation sector emissions is vital to achieving the long-term GHG target as it makes up approximately 40% of California emissions [9]. As dictated by the current status of technology, two primary pathways are proposed to achieve low-GHG transportation and displace petroleum-based fuels: low-GHG biofuels and electrification[7]. This work does not consider hydrogen vehicles due to the multiple challenges posed by hydrogen distribution, storage, fuel cell technology, and cost, though under certain circumstances this pathway could become another viable, low-GHG option for the transportation sector.

In our analysis, all biomass is directed towards biofuel production and none is made available for electricity, owing to the difficulty in electrifying some transportation modes and the relative abundance of low-GHG sources of electricity. In keeping with the technical potential framework used in the building and industry sectors, we adopt 94 million dry tons of biomass for an overall supply of 7.5 billion gallons gasoline-equivalent in 2050 [6]. This biomass scenario results from high growth in herbaceous and forest residues, improved technical yield recovery, substantial investment in additional energy crops, and utilization of abandoned agricultural and non-productive forest lands. Consistent with State Executive Order S-06-06,[8] we limit imported biofuels to 25% of total supply. Still, total biofuels fall short of projected liquid fuel demand by 32%, necessitating a shift to electric transportation.

A stock turnover model is used to project light-duty electric vehicle deployment, with 45% of passenger vehicle miles from electricity in 2050. Passenger vehicle electrification assumes that plug-in hybrid and battery electric vehicles quickly enter the market, and by 2050 become the majority of the fleet. Vehicle sales adoption curves by drive train technology are shown in figure S6 (supplementary material available at stacks.iop.org/ERL/8/014038/mmedia), and recent State policy targets call for similarly aggressive market penetration through 2025 [14]. Fixed, nighttime load profiles for electric vehicles are developed as inputs for the electric sector model below. 81 000 GWh of demand are added to the electric power system in 2050 from vehicle electrification (figure 1(b)). Aviation, marine transport, and most heavy-duty transport are not electrified due to range and weight requirements, but other modes, including some short-distance trucks, intra-city buses, and rail transport are completely electrified.

3. Bottom-up building efficiency and electrification modeling

Natural gas currently provides most energy for building and industry heat, so a major shift in State energy policies and end-use technologies would be required to enable a transition away from fossil fuel in these sectors [15–18]. For industry, low and medium temperature processes—39% of industry fuel demand—are electrified by 2050, totaling

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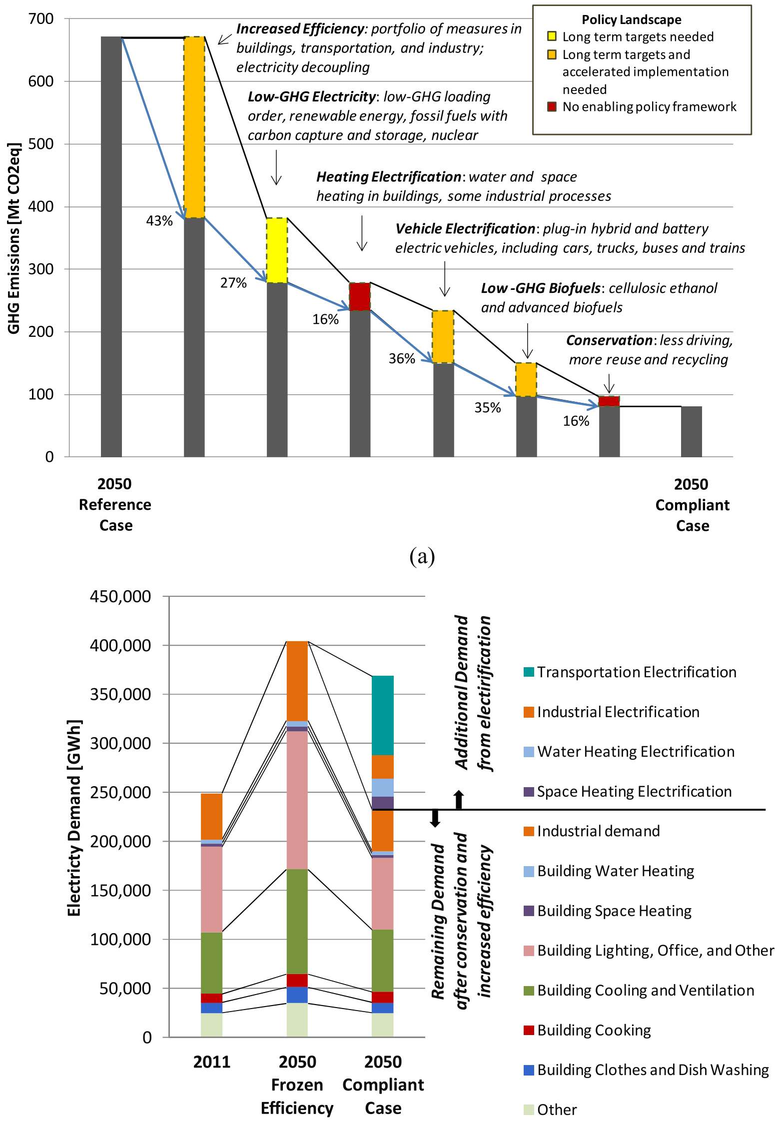
[6] Detailed information describing California climate programs can be found at www.arb.ca.gov/cc/cc.htm (Climate Change Programs, California Environmental Protection Agency, Air Resources Board).

[7] See for example http://gov.ca.gov/news.php?id=17472 (Office of Governor Edmund G Brown, State of California, Executive Order B-16-2012).

[8] Climate Change Programs, California Environmental Protection Agency, California Air Resources Board, www.arb.ca.gov/fuels/altfuels/incentives/eos0606.pdf. Accessed 1 June 2012.



(a)

(b)

Figure 1. (a) The California 2050 GHG target of 81 MtCO$_2$-eq can be met with a combination of GHG reduction pathways, each of which is insufficient on its own. Shown here is a compliant case combining increased efficiency across sectors [28], clean electricity, electrification of heating and vehicles, biofuel deployment and savings from energy conservation. The GHG savings percentages associated with each pathway relative to the previous level of emissions are shown and are representative of the savings potential for each measure. Note that the magnitude of GHG savings for each pathway depends on the presentation order. An assessment of the policy landscape is shown for each pathway. All pathways lack long-term policy targets, and no enabling policy for heat electrification or conservation currently exists.
(b) Electricity system demand. Increased efficiency in the building and industry sector can reduce California's 2050 demand from the frozen efficiency case by 35%, and conservation can provide a further 16% electricity demand reduction. Increases in electricity demand stem from electrification of building heat, industry process heating, and vehicles.

24 000 GWh of additional demand based on analysis of end-use applications by industry sector and the availability of multiple electric-based process heating technologies. Residential and commercial space and water heating are fully electrified by 2050 (figure 1(b)) through a transition to high-efficiency heat pump technology.

Hourly load profiles for electricity demand from space and water heating in buildings are developed based on historical heating load profiles, disaggregated by California climate zone, and scaled up to displace all remaining GHG-intensive heating demands within buildings (figure 3). Electricity demand from water and space heating is greatly increased (figure 1(b)), adding 32 000 GWh to the electricity load in 2050.

In addition to minimizing fossil fuel demand from the State's non-electricity energy supply, increased efficiency of electrical devices in all buildings is also assumed [19, 20]. Without increased efficiency, much higher electricity demand and greater capacity of generation supply would be required. For reference, we consider a 'frozen efficiency' case where efficiency levels are held at present day levels.

A bottom-up stock model is used to simulate efficiency improvements in residential and commercial buildings [21, 22], achieving 38% electricity savings in 2050 relative to

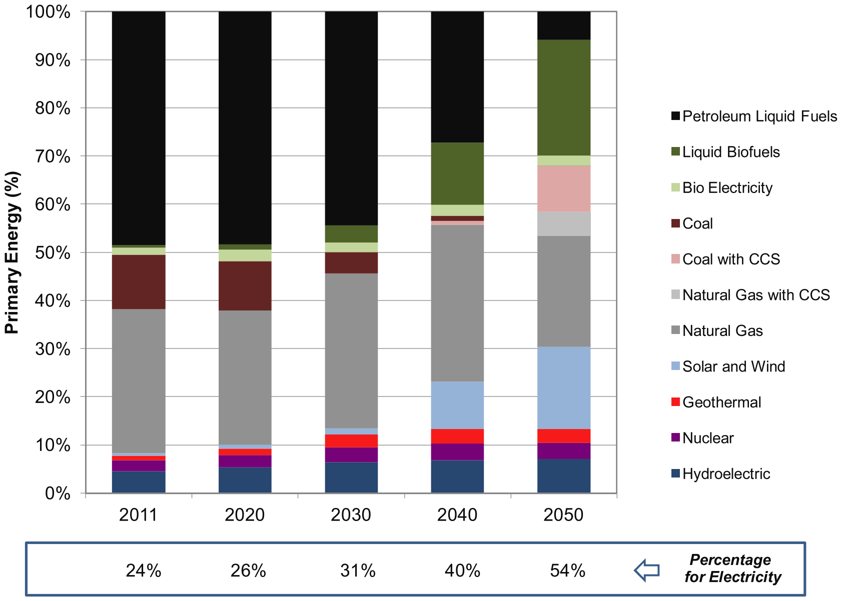


Figure 2. Primary energy evolution in California from 2011 and 2050 for the compliant case depicted in figure 1. Note the dramatic shift in energy sources over time, with the percentage of primary energy for electricity doubling present levels by 2050. Petroleum-based liquid fuel is sharply reduced and the fossil fuel fraction of primary energy drops from 90% in 2011 to 44% in 2050. Primary energy for combustible fuels (petroleum, natural gas, coal, biomass, biogas) is defined as the higher heating value of the fuel prior to combustion, whereas primary energy for non-combustible fuels (hydroelectric, nuclear, geothermal, solar, wind) is defined as the heat content of net electricity generated. Net energy from imports and exports of electricity to and from California are calculated hourly using the SWITCH model as the fraction imported multiplied by the out-of-State electricity generation minus the fraction exported multiplied by the in-State electricity generation.

the frozen efficiency case. For existing buildings, 100% of technically feasible opportunities to improve efficiency on a retrofit or 'replace on burnout' basis are applied to eligible buildings by 2050 (supplementary material available at stacks.iop.org/ERL/8/014038/mmedia). Energy savings from new construction is similar to California Public Utilities Commission initiatives for Zero Net Energy New Construction buildings [23]: 100% of new residential (commercial) buildings achieve at least 35% (30%) electricity savings by 2025 (2030) compared to 2005 efficiency standards.

Load profiles are synthesized from the mix of end-use demands and technologies using a load profile database for both efficiency and building electrification [24]. Efficiency load profiles for 8760 h yr^{-1} in 14 California climate zones and 20 end-uses are synthesized and provided as inputs to the electric sector model.

Efficiency savings in 2050 are dominated by a small number of end-uses. For residential buildings, 63% of cumulative efficiency savings come from lighting, refrigeration, and central air-conditioning. For commercial buildings, just three uses contribute 81% of the savings: interior lighting, cooling, and refrigeration.

4. High-resolution electricity sector modeling

GHG reduction from electrification is predicated on a shift to low-GHG electricity. Despite aggressive efficiency measures, overall electricity demand in the compliant case is only 10% lower than the frozen case due to increases from transportation and heating. As a result, drastic but technically feasible shifts in the electric power system appear necessary to decarbonize California's energy system.

New plants will replace a large fraction of electricity generation in today's power system by 2050, representing an opportunity to transform the State's current mix of power plants and increase the reliance on low-GHG power sources. Large-scale integrated planning using suitable policies and investments is needed to minimize the cost of this transition.

In order to leverage the spatial and temporal synergies among two of the most promising low-GHG generation technologies (solar and wind), careful combinations of investments are needed to ensure low-GHG, low-cost, and reliable electric power. High-quality renewable resources are unevenly distributed both spatially and temporally throughout western North America [25]. It is therefore essential to include the entire western North American synchronous interconnect—the geographic area of the Western Electricity Coordinating Council (WECC)—in an analysis of future California low-GHG electricity supply.

The SWITCH electric power system planning model is used to explore future electricity scenarios with a WECC-wide cap on power sector GHG emissions, reaching 80% below the 1990 level in 2050. Power sector GHG allowances are implicitly assumed to be tradable across WECC. The version of SWITCH used in this study minimizes the cost of producing and delivering electricity from present day until 2050 using a combination of existing grid assets and new generation, transmission, and storage capacity.

Shifting vehicle and heating demand toward electricity would drastically change seasonal and diurnal load profiles (figure 3). By 2050, the load profile exhibits a strong morning peak in winter due to added demand from water heating, as well as a new evening peak throughout the year due to electric vehicle charging. In addition, air conditioning

Table 1. Summary table of energy demands and emission intensities for buildings, industry, and transportation sectors for 2011 and four 2050 cases. State population is assumed to increase 60% to 59.5 million residents in 2050 from 37.7 million residents currently.

		Energy					Relative emissions intensity relative to current (2011 = 1)			
Energy supply	Units	2011	2050 frozen efficiency	2050 increased efficiency	2050 increased efficiency, low-GHG electricity, electrification, biofuels	2050 compliant (increased efficiency, low-GHG electricity, electrification, biofuels, conservation)	2050 frozen efficiency	2050 increased efficiency	2050 increased efficiency, low-GHG electricity, electrification, biofuels	2050 compliant (increased efficiency, low-GHG electricity, electrification, biofuels, conservation)
					Buildings					
Liquid, solid fuels	Tbtu	52	77	54	17	15	1	1	1	1
Gaseous fuel	Tbtu	710	1 052	735	227	209	1	1	1	1
Sum	Tbtu	762	1 129	789	244	224				
Change			48%	−30%	−69%	−8%				
Electricity	GWh	176 500	288 200	178 800	213 400	196 500	1	1	0.12	0.12
Change			63%	−38%	19%	−8%				
					Industry					
Liquid, solid fuels	Tbtu	496	611	276	130	94	1	1	0.86	0.86
Gaseous fuel	Tbtu	1 039	1 255	604	322	232	1	1	0.94	0.94
Sum	Tbtu	1 535	1 866	880	452	325				
Change			22%	−53%	−49%	−28%				
Electricity	GWh	47 200	81 100	58 400	91 900	66 200	1	1	0.12	0.12
Change			72%	−28%	57%	−28%				
					Transportation					
Liquid, solid fuels	Bgge	21.4	38.5	20.2	10.6	8.8	1	1	0.50	0.50
Change			80%	−48%	−48%	−17%				
Electricity	GWh	0	0	0	97 000	80 900	1	1	0.12	0.12
Change						−17%				

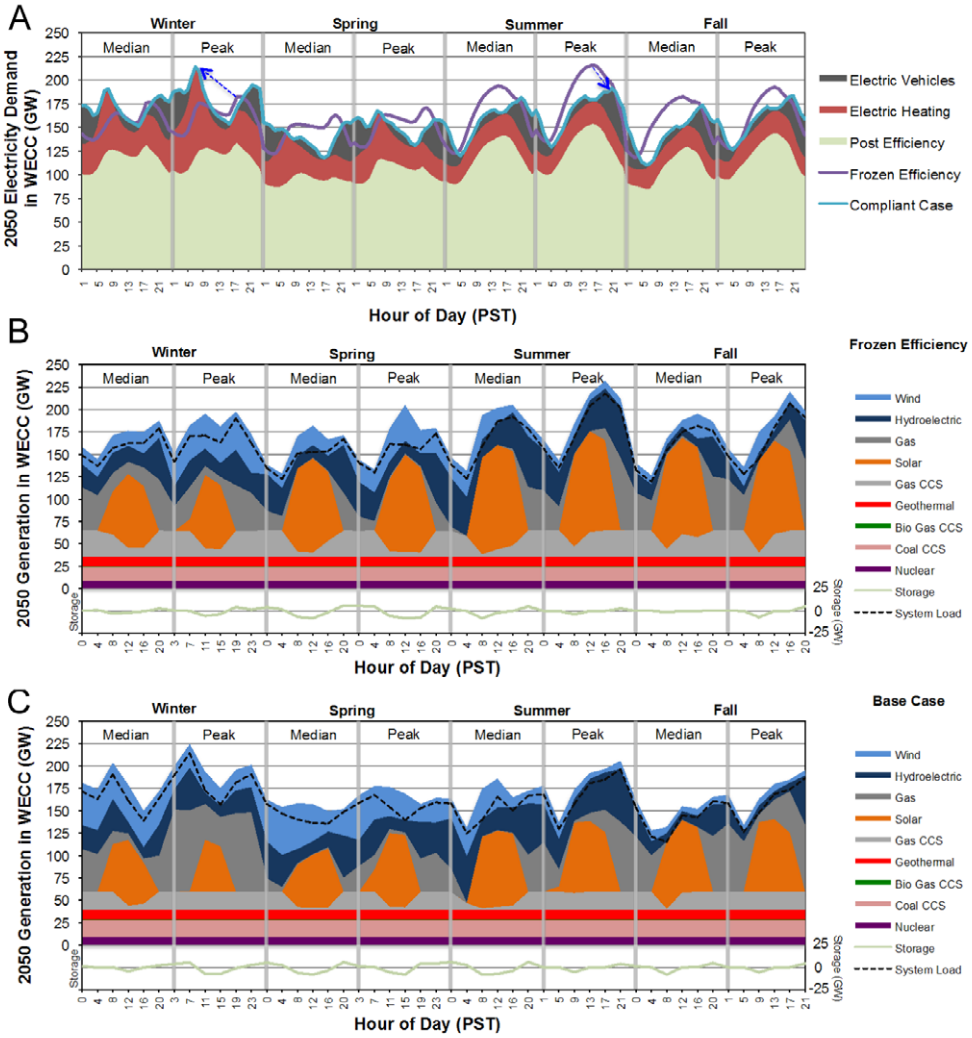


Figure 3. (a) Drastic shifts in load profile are seen from the implementation of efficiency ('post efficiency' scenario) and subsequent addition of loads from electric vehicles and heating. The compliant case ('Base Case') represents the load profile used as an input to the SWITCH model. One peak and one median demand day per season are shown in the figure for clarity, though the SWITCH model uses six days per season for each decadal time step. (b) WECC-wide electricity generation in 2050 as dispatched by SWITCH for the frozen efficiency load profile (c) WECC-wide electricity generation in 2050 as dispatched by SWITCH for the compliant case from figures 1(b) and 3(a). Note the shift from solar to wind power as the amount of efficiency and vehicle and heating electrification is increased from the frozen efficiency load profile.

loads in summer afternoons remain prominent even after new efficiency measures are introduced, producing an electricity system with high demand periods in both summer and winter. We model this load profile separately for each of 50 areas within WECC for six hours of each of 24 representative days in the decades 2020–2050. Both peak and median load days from each month are represented to ensure that SWITCH plans for average and peak conditions across an entire year. In each modeled hour, demand must be met by the optimization, as well as capacity and operational reserve margin constraints to ensure system reliability. Results from investment optimizations are validated using a full year of hourly load and variable renewable resource data.

5. Many cost-effective electricity generation options

Using the SWITCH model, we find that the WECC electricity system in 2050 has a diverse set of generation options that can cost-effectively meet aggressive GHG reduction targets, even with drastic changes in load profile shape due to efficiency and large vehicle and heating loads (supplementary material available at stacks.iop.org/ERL/8/014038/mmedia). The scenarios explored in this study show that variable renewable resources (wind and solar) could economically contribute as little as one-third or as much as three-fifths of generated power within WECC by 2050. Despite their variability, both wind and solar technologies appear poised to supply large amounts of inexpensive, low-GHG electricity to the WECC power system of the future.

The optimal fractions of wind and solar deployment are a function of the temporal characteristics of the load profile, with increasing vehicle and heating electrification favoring wind over solar power (figure 3). As nighttime heating and electric vehicle loads increase, the energy and capacity value of wind power increases relative to that of solar. Increasing

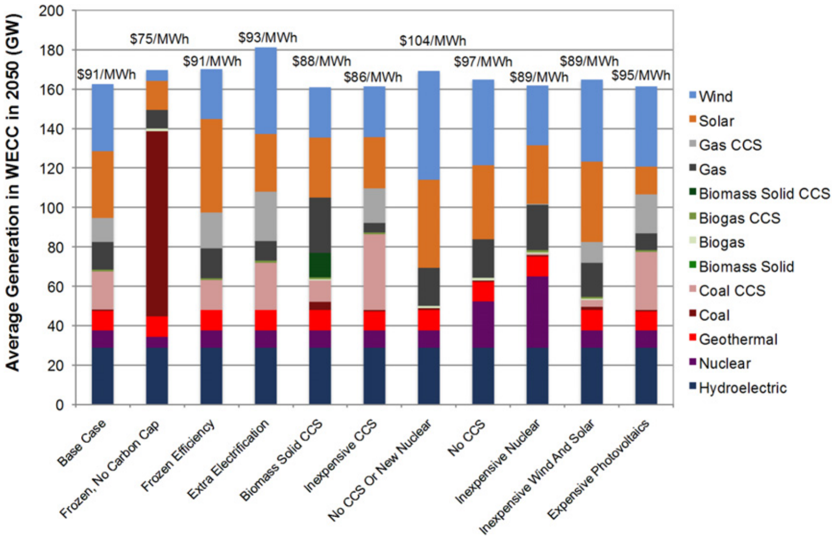


Figure 4. Average 2050 electricity generation by fuel category, and average 2050 power cost (in $2007 per MWh) for ten electricity scenarios in which WECC-wide power sector emissions are capped at 80% below 1990 levels. The biomass solid CCS scenario includes further GHG reductions. The frozen, no carbon cap scenario does not include a cap on GHG emissions. The compliant case ('Base Case') is the starting point on which other sensitivity scenarios are based. Information on specific scenarios can be found in the supplementary material (available at stacks.iop.org/ERL/8/014038/mmedia). The average power cost varies by less than $20 per MWh across GHG-capped scenarios, indicating that many low-cost, low-GHG options exist for the power sector.

demand flexibility could incentivize either wind or solar power, depending on their relative delivered costs.

Using operating reserve requirements and large balancing areas similar to those evaluated in the Western Wind and Solar Integration Study [26], we find that the majority of spinning reserves in WECC can be provided by hydroelectric power and storage technologies, with the balance provided by gas-fired technologies. Sub-hourly load balancing does not appear to be a major limitation for achieving deep emissions reduction in a future electricity grid with up to 60% of energy from variable renewable generation.

Nuclear power and fossil fuel generation with CO_2 capture and sequestration (fossil/CCS) may be attractive low-GHG baseload technologies, but neither is essential to meeting GHG targets (figure 4). With the costs assumed in this study, generating electricity from fossil/CCS can lower the cost of power while meeting emissions targets. Installation of new nuclear power is found to be a backstop against rising power costs, but is not cost-effective given our base cost assumptions.

Greater fractions of energy from variable renewable resources are found to increase the magnitude of transmission and storage deployment (figures S69 and S71 available at stacks.iop.org/ERL/8/014038/mmedia). Power systems in this study that generate less than half of their electricity from variable renewable resources are not found to need drastic expansion of the transmission system nor large-scale deployment of electric energy storage. However, as the fraction of electricity from variable renewable resources exceeds fifty per cent, increasing amounts of transmission and storage are installed in order to spatially and temporally move electricity from the point of generation to the point of consumption.

The average cost per MWh of electricity stays relatively constant between present day and 2050 across a range of cost and generator availability scenarios. While this result is in part dependent on technological improvement driving declining capital costs, sensitivity analyses show that three future supply options with the most uncertain costs—solar photovoltaics, nuclear, and fossil/CCS—are not individually essential to keep the cost of electricity low. In all scenarios, total power system cost increases roughly in proportion to load, so while increasing demand adds to total expenditures, the average cost per MWh is stable through 2050. Relative to a scenario in which no cap on GHG emissions is enforced, achieving 80% GHG reductions in the power sector raises the cost of power by 18%–42%. The tight range of power system costs found amongst a variety of scenarios (figure 4) indicates that GHG reduction via electrification is a robust strategy, as the risk of power cost overruns is reduced by the availability of a portfolio of technologies.

6. Discussion—the need for integrated planning and policy

Long-range planning can ensure that current policies and pathways are consistent with long-term goals. Policies that focus on improving natural gas heating or conventional internal combustion engine efficiency without transitioning away from fossil fuel may be appropriate for the short term, but are not sufficient for meeting long-term GHG targets. Similarly, the electrification of heating will only be an effective measure for meeting an 80% reduction goal if the electricity supply has a near zero-GHG intensity. The interaction among different sectors and various GHG-reduction pathways should continue to be an active area of research and optimization.

Technology does not appear to be the limiting factor for the State to meet its economy-wide 2050 GHG emissions target, though this conclusion is predicated upon ample low-GHG biomass supplies (with little or no associated indirect land use impacts), steady technological development and cost reduction of existing technologies, and more modest economic growth than assumed in other studies [5, 6]. Much of the technology already exists for increased electrification and building efficiency, but may need policy support to achieve cost-effective production at scale and more importantly, to induce widespread adoption (tables S1 and S2 available at stacks.iop.org/ERL/8/014038/mmedia). Plug-in electric vehicles are being rapidly developed by the automotive sector, but there is less activity in other transportation sectors. Availability of biomass and low-GHG process development are pivotal for reducing fuel-use GHG emissions.

In addition to technological solutions, substantial reductions are also possible from conservation measures [27]. Preliminary modeling of these GHG-saving measures was conducted based on historical trends in non-energy behaviors including public health, safety, and diet. By 2050, as much as 16% of GHG emissions could be conserved by measures such as reductions in vehicle-miles traveled, eco-driving, increased energy conservation, improved diets, waste reduction, and increased recycling (section 9, supplementary material available at stacks.iop.org/ERL/8/014038/mmedia). Human and social factors should be a topic for further research, as they are directly coupled with public policy, technology deployment, and market development.

Expansion of California's policy framework is needed to enable energy system changes suggested herein. Aggressive codes and standards will be required to meet building, vehicle, and industry efficiency targets. While efficiency is already a focus for the State, implementation and adoption of additional efficiency measures is critical, especially for building retrofits. Policies are currently in place for both vehicle electrification and low-GHG biofuels, but will need extension and expansion to meet the 2050 climate goal. Multiple barriers exist for building electrification, and policy development is urgently needed to ensure the transition to electrified heating. An 80% reduction in electricity sector emissions can be ensured with a continuation and expansion of aggressive renewable energy and/or GHG targets in the future.

Meeting the State's 2050 GHG target is found to be feasible but requires a portfolio of measures and a commitment to integrating and coordinating policies in the electricity, buildings, transportation, and industrial sectors. The GHG reduction measures put forward here include an increase in the efficiency of energy use for all sectors, a drastic decrease in the GHG intensity of electricity and liquid fuels, and a substitution of end-use fuel consumption for electricity. Behavioral factors may also be able to play an important role in GHG emission reduction. Long-term policy support is found to be a key missing element for the successful attainment of the 2050 GHG target in California.

7. Materials and methods

Future electricity and fuel demands were projected for three economic sectors (buildings, transportation, and industry) with piecewise additive scenarios for energy demand and energy supply. First, energy efficiency is applied across sectors, then clean electricity is added, followed by electrification, low carbon biofuels, and then energy conservation. Electricity and fuel supply mixes were developed to meet overall demand subject to biofuel availability and GHG constraints for electricity. GHG emissions were calculated for each scenario based on overall energy demands and carbon intensity of energy supplies. Assumptions for the boundaries and scope of GHG emission treatment are discussed in the supplementary material (available at stacks.iop.org/ERL/8/014038/mmedia).

Energy demand for a frozen efficiency case was first estimated as a reference case with growth rates informed by historical trends and other studies. An energy efficiency case was then developed assuming that technical potential levels of efficiency are achieved across all three sectors. A low-GHG electricity supply was added to this scenario (energy supply modeling is described below). Fuel-switching was introduced by assuming wide spread electrification from gasoline-based internal combustion engines to electrified or partially electrified passenger vehicles and from largely natural gas based heating processes to electrified heating in buildings and industry. Further carbon reduction was achieved by assuming technical potential availability of liquid biofuels and finally by assuming conservation measures are aggressively adopted.

Energy demand was disaggregated into building, transportation, and industry sectors for California. Estimates utilized a median population and economic growth forecast based on State and California Energy Commission (CEC) estimates, respectively. Building demands for electricity and fuel (e.g., natural gas for heating) were developed for residential and commercial buildings as described in the supplementary material (available at stacks.iop.org/ERL/8/014038/mmedia) and further disaggregated into single/multi-family units and new/existing buildings. Stock turnover analysis was done for a comprehensive set of end-use demands. Commercial buildings demand estimates utilized historical trends of energy demand per square foot of space by building type. Electricity demand for the rest of the Western Electricity Coordination Council geographic region was estimated from a synthesis of US Energy Information Administration data and regional utility forecasts.

Transportation demand estimates utilized vehicle stock modeling for passenger vehicles and aviation with projections for other transportation modes consistent with State or federal models. Stock modeling assumptions of vehicles per capita, vehicle-miles travelled (VMT) per vehicle, and market penetrations by vehicle drivetrain (internal combustion engines, hybrid electric vehicles, plug-in hybrid vehicles, and battery electric vehicles) are described in the supplementary material (available at stacks.iop.org/ERL/8/014038/mmedia). Industry demand estimates employed sector-based (oil and gas, food and beverage, etc) economic growth projections from the CEC.

The energy efficiency scenario utilized technical potential estimates for each sector. The building sector employed a list of over 200 unique efficiency measures while the transportation sector adopted fuel efficiency potential from existing national and State studies. Industry technical potential estimates were based on CEC reports disaggregated by industry sector and end-use (process heating, boiler-based systems, motor systems, heating, ventilation, air-conditioning, etc).

Electrification projections are based on stock modeling for building water and space heating and for passenger vehicles assuming aggressive transition to electricity-based heating systems in buildings starting in 2015 and to alternative passenger vehicles in transportation, respectively, with market penetration assumptions described in the supplementary material (available at stacks.iop.org/ERL/8/014038/mmedia).

The carbon savings potential for energy conservation was estimated using a simple adoption rate model of energy saving actions. From a database of historical non-energy actions, long-term adoption rates were estimated for a set of conservation actions in home energy usage and passenger vehicle mile reduction, as well as a number of other measures in diet, recycling, and consumption. Carbon savings as a function of time were estimated by calculating carbon intensities for electricity (CO_2/kWh) and transportation (CO_2/VMT).

Low-GHG electricity modeling utilized a high-resolution variable renewable resource capacity planning model (SWITCH) of the interconnected Western North American grid. SWITCH used spatially resolved, time-synchronized hourly solar, wind, and demand data to explore future low carbon electricity scenarios. Optimizations minimized the cost of power between present day and 2050 while subject to reliability and policy constraints. Carbon emissions were constrained to reach 80% below 1990 levels in the year 2050.

Biofuel supply estimates were made with all biomass directed to liquid biofuels and resultant biofuel assumed to replace oil-based liquid fuel. Biomass and biofuel availability projections utilized technical potential assumptions for in-State biomass supply, biomass supply mix, biofuel yield, and life-cycle carbon emission associated with biofuel production. Biofuel production was assumed to replace gasoline in the transportation sector. Sources for biomass materials availability include earlier reports from Oak Ridge National Laboratory, the University of California, Berkeley, and the University of California, Davis.

All methods and key assumptions are described more fully in the supplementary material available online at (stacks.iop.org/ERL/8/014038/mmedia) .

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