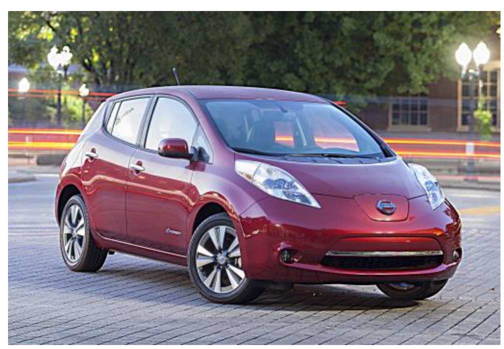
Clean Energy Transition Report

Analysis of Selective 2010-2018 Economy-Wide Decarbonization Studies

by Eileen V. Quigley



April 4, 2018

Clean Energy Transition

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Executive Summary

The Stolte Family Foundation commissioned Clean Energy Transition to analyze and summarize all relevant decarbonization pathways studies to inform Northwest policymakers, funders, legislators, local government officials, and climate advocates about how to advance a low-carbon/decarbonization pathways study for the region, particularly for Washington and Oregon. The Foundation's charge was to examine the robustness of relevant domestic and global deep decarbonization pathways models from 2010 to the present to offer insights to guide efforts to achieve a low-carbon economy in the Northwest in the next three decades.

Economy-wide pathways studies focus on decarbonizing an energy system—the network of all energy producing, converting, delivering, and consuming infrastructure—results of which can provide guidance for specific electricity-sector modeling. A decarbonized electricity sector will play a critical role in carbon emission reduction in the coming decades and therefore its modeling is critically important, and results from an economy-wide pathways study can inform electricity sector modeling.

To prepare this report, Clean Energy Transition reviewed 58 deep decarbonization pathways studies from 2010 to the present and selected 11 that offer the most guidance to Northwest policymakers interested in understanding how the region might embrace a deep decarbonization course. A Lessons Learned section with graphical illustrations can be found on page 26, the summary of which is:

1. There are three pillars for deep decarbonization of energy systems: (1) energy efficiency; (2) electricity generation decarbonization; and (3) fuel-switching.
2. Sustainable bioenergy is a key strategy for a low-carbon energy system, particularly for currently challenging to electrify sectors such as aviation, freight transportation, and industrial process heat. But supplies of sustainable (net-zero carbon) bioenergy are limited.
3. A deeply decarbonized energy economy results in more spending on technology, such as capital investments in low-carbon equipment and infrastructure, and less spending on fossil fuel, with a relatively small net cost impact.
4. Electricity supply will grow significantly to meet higher demand for heating water and buildings, passenger transportation, and/or producing synthetic electric fuels (hydrogen and synthetic natural gas) despite an overall decrease in energy demand.
5. There are increased challenges in balancing electricity supply and demand to successfully integrate variable renewable generation.

Overall, the principal findings of the pathways studies to date are that: it is technically feasible to achieve an 80% greenhouse gas (GHG) reduction below 1990 levels by 2050; multiple alternative pathways exist using current commercial or near-commercial technologies for high levels of energy efficiency; decarbonization of electric generation and electrification of most end uses is mandatory; and switching the remaining end uses to lower carbon fuels will be required. Pathways studies to date have not found the cost to achieve these reductions prohibitive.

The studies all indicate that deeply decarbonizing the economy over 35 years is an ambitious undertaking, but not necessarily one that entails massive changes in lifestyle. The critical point is to start as soon as possible to permit infrastructure replacement to follow natural replacement rates to reduce costs, ease demand on manufacturing, and allow gradual consumer adoption.

Two pathways studies have been conducted for portions of the Northwest to date: *Deep Decarbonization Pathway (DDP) Analysis for Washington State* study in December of 2016 and *Portland General Electric Decarbonization Draft Study* released in February 2018. The results of the Washington DDP study show all three non-refences cases attaining the 80 percent reduction in GHG emissions below 1990 levels by 2050 emission reduction target. An electrification pathway focuses on electrifying transport and heating; a renewable pipeline pathway substitutes fossil natural gas for decarbonized pipeline gas fuels; and an innovation pathway explores how emerging technologies might enable decarbonization.

The study found the cost of reduction "likely to be quite reasonable, ranging from $6 billion of costs to $6 billion of savings in 2050. When compared against the state's projected gross state product, these incremental costs are small (-0.6 percent to 0.6 percent)."[1] The study's conclusion offers evidence of the value of conducting a pathways study for the region that would test additional scenarios: "These three DDP scenarios are neither prescriptive nor exhaustive. There are many additional pathways that were not evaluated in our study."[2]

Portland General Electric (PGE) contracted with Evolved Energy Research to use the firm's EnergyPATHWAYS model to help the utility understand what achieving economy-wide decarbonization might mean for its service territory in Northwest Oregon, which covers approximately 45-47% of Oregon's state population.

The PGE study found that average renewable capacity additions would need to be approximately 600 MW per year between 2030 and 2050,[3] that average renewable capacity additions would need to be approximately 600 MW per year between 2030 and 2050,[4] a hugely significant increase to satisfy demand within PGE's territory. It is possible that a regional approach might reduce the cost relative to a utility-by-utility approach, yet another reason to conduct a regional pathways study.

There is significant value in developing an economy-wide pathways study that includes the energy systems for Washington, Oregon, Montana, and Idaho, drafts off the work already done modeling pathways for Washington State and PGE, and is focused on the actions that Washington and Oregon can take to get on a path to deep decarbonization. Furthermore, the Northwest creating a blueprint that could tie into the pathways work that California has conducted to date is also highly leveraged.

A study commissioned by a nonpartisan entity that does not have assets that stand to gain or lose but is focused solely on answering the question of what is needed for the Northwest to attain ambitious carbon reduction goals could provide valuable information to policymakers, legislators, city and county officials and staff, advocates, and funders dedicated to understanding how the Northwest can decarbonize on the timeline that the climate crisis requires.

[1] B. Haley, G. Kwok, R. Jones, J. Williams. Evolved Energy Research and Deep Decarbonization Pathways Project. December 16, 2016. *Deep Decarbonization Pathways Analysis for Washington State*. p. 5.
[2] *Deep Decarbonization Pathways Analysis for Washington State: Executive Summary*, footnote p. 3
[3] Gabe Kwok and Ben Haley. March 23, 2018. *Portland General Electric Decarbonization Study: Summary of Draft Findings*. p. 33
[4] Ibid, p. 33

Introduction

The Stolte Family Foundation commissioned Clean Energy Transition to research, analyze, and summarize all relevant decarbonization pathways studies to inform Northwest policymakers, funders, legislators, and climate advocates about how to advance a low-carbon/decarbonization pathways study for the region, particularly for Washington and Oregon. The Foundation's charge was to examine the robustness of relevant domestic and global deep decarbonization pathways models from 2010 to the present to offer insights to guide efforts to achieve a low-carbon economy in the Northwest in the next three decades.

Economy-wide pathways studies focus on decarbonizing an energy system—the network of all energy producing, converting, delivering and consuming infrastructure -results of which can provide guidance for specific electricity-sector modeling. A decarbonized electricity sector will play a critical role in carbon emission reduction in the coming decades and therefore its modeling is critically important, and results from an economy-wide pathways study can inform electricity sector modeling. To complete this report, 58 relevant domestic and global deep decarbonization pathways studies from 2010 to the present were reviewed and 11 were selected for analysis.

History of Economy-Wide Pathways Studies

2050 Pathways Calculator (2010)

In 2010, Sir David John Cameron MacKay, a British physicist and mathematician and professor of engineering at the University of Cambridge,[5] developed the 2050 Pathways Calculator[6] for the UK Department of Energy and Climate Change (DECC),[7] where he served as Chief Scientific Adviser from 2009-2014. The calculator is an online interactive tool based on Microsoft Excel that allows users to choose a combination of levels of changes to reduce the United Kingdom's carbon emissions by 80% by 2050, relative to 1990 levels.

In July 2010, DECC published *2050 Pathways Analysis*,[8] which described six substantially different, illustrative pathways of different approaches to reducing 80% of GHG emissions by 2050. The basic conclusions[9] from this first 2050 pathways study remain true today:

1. The greater the constraints on low-carbon energy supply, the greater the reduction in demand will need to be.
2. A substantial level of electrification of heating, transport, and industry is required.
3. Electricity supply may need to double and will need to be decarbonized.
4. A growing level of variable renewable generation increases the challenge of balancing the electricity grid.
5. Sustainable bioenergy is a vital part of the low-carbon energy system in sectors where electrification is unlikely to be practical, such as long-haul freight transport, aviation, and some industrial high-grade heating processes.

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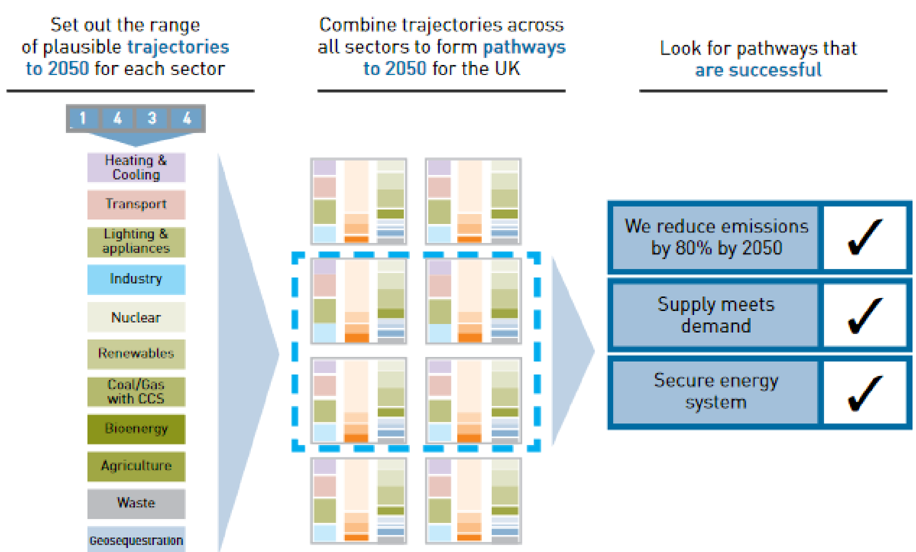
[5] University of Cambridge/Department of Engineering/News/Professor Sir David Mackay 1967-2016. http://www.eng.cam.ac.uk/news/professor-sir-david-mackay-1967-2016
[6] UK Department of Energy and Climate Change 2050 Energy Calculator. http://2050-calculator-tool.decc.gov.uk/
[7] UK Department of Energy and Climate Change (DECC). https://www.gov.uk/government/organisations/department-of-energy-climate-change
[8] HM Government. July 2100. 2050 Pathways Analysis https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/42562/216-2050-pathways-analysis-report.pdf
[9] Ibid, p. 3-4

6. The pathways also show an ongoing need for fossil fuels in our energy mix, although their precise long-term role will depend on a range of issues, such as the development of carbon capture and storage.
7. Emissions from agriculture, waste, industrial processes, and international transport make up a small proportion of emissions today, but by 2050, if no action is taken, emissions from these sectors alone would exceed the maximum level of emissions for the whole economy.

DECC used a sector-by-sector and scenario approach. For each sector, four different trajectories were set out that span the range of potential futures for each sector as follows: Level 1-little to no decarbonization; Level 2-an ambitious but reasonable effort; Level 3-very ambitious level unlikely to happen without either significant changes to the status quo or technical breakthroughs; and Level 4-pushing the physical and technical limits of what can be achieved.

The Pathways Calculator combines the sectoral trajectories in different combinations to produce possible pathways to 2050. The process looks at not just 2050 as the end point goal, but also the sequence of changes needed to occur over the 40 years from 2010 to 2050. The following graphic[10] depicts the process:

Figure 1. Pathways to 2050 Process Schematic



The energy supply sectors considered include: bioenergy; nuclear; fossil fuels with carbon capture and storage; onshore wind; offshore wind; tidal range; wave and tidal stream' micro-generation; geothermal; and hydroelectric power.

The energy demand sectors include: lighting and appliances; transport; industry; and heating and cooling. The non-energy sectors include: waste; agriculture; industrial processes; land use and forestry; and negative emissions (which remove carbon dioxide directly from the atmosphere).

[10] Ibid, p. 8

To select the trajectories, DECC consulted with several hundred stakeholders and experts and considered behavioral and lifestyle changes (i.e., reducing energy use; wasting less food; lowering thermostats; shifting from private to public transit); technological changes yielding lower carbon intensity or energy efficiency (i.e., LED lighting; ground source heat pumps); fuel-switching (i.e., natural gas to district heating or gasoline-powered cars to fuel cell or battery cars); and structural changes the economy (decline or resurgence in manufacturing).

A key point to make is that DECC's Pathways Calculator is based on physical limitations not cost optimization and therefore does not identify the least cost way of meeting the 2050 target. The model is also specific to the United Kingdom.

California Pathways (2012)

On January 6, 2012, James H. Williams, et al., published *The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity* in *Science* magazine,[11] the first time that work was done to determine what it would take for California (and, in fact, any state in the United States) to achieve both a 30% reduction in GHG emissions relative to 1990 levels by 2020 as well as 80% below 1990 levels by 2050.

Williams' colleagues at Energy + Environmental Economics (E3) in San Francisco, along with analysts and academics from the Energy and Resources Group at the University of California and the Earth Sciences Division at Lawrence Berkeley National Laboratory (LBNL), analyzed "specific changes in infrastructure, technology, cost, and governance required to decarbonize a major economy, at the state level, that has primary jurisdiction over electricity supply, transportation planning, building standards, and other key components of an energy transition."[12]

The group used a "stock-rollover methodology that simulated physical infrastructure at an aggregate level and built scenarios to explore mitigation options," adjusting infrastructure such as vehicle fleets, buildings, power plants, and industrial equipment in each sector as new infrastructure was added and old was retired each year from 2008 to 2050.

The model used back-casting from a 2050 emissions level of 85 Mt CO_2e and changed the emissions intensities of new infrastructure over time to meet the goal, using 72 different mitigation measures based on existing statewide climate policies and technologies constrained by "physical feasibility, resource availability, and historical uptake rates, not the prices of technology, energy or carbon as in general equilibrium models."[13] No technologies that were far from commercialization were assumed.

The modelers used an electricity system dispatch algorithm that tested grid operability to make sure reliable electricity service was maintained. The team created an electricity demand curve bottom up

[11] James H. Williams, Andrew DeBenedictis, Rebecca Ghanadan, Amber Mahone, Jack Moore, William R. Morrow III, Snuller Price, Margaret S. Torn. January 6, 2012. *Science.* Vol. 335, Issue 6064. pp. 53-59. *The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity* http://science.sciencemag.org/content/335/6064/53.full

[12] Ibid, p. 1

[13] Ibid, p. 1

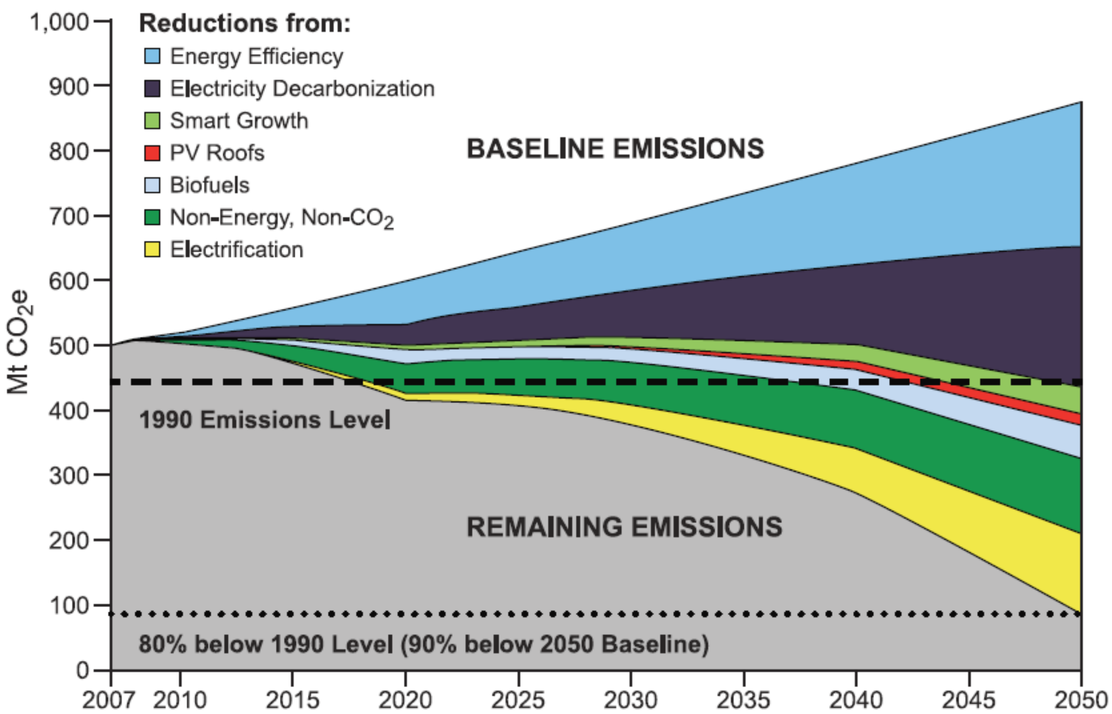
from sectoral demand by season and time of day, which “constrained generation scenarios to satisfy in succession the energy, capacity, and system-balancing requirements for reliable operation.”[14]

The following are the percentages contributing to the emissions reductions relative to 2050 baseline:

- 28% energy efficiency
- 27% electricity generation decarbonization
- 14% combination of energy conservation and other measure (smart growth, urban planning, biofuels, rooftop solar, etc.)
- 15% from non-CO_2 GHGs
- 16% from electrifying transportation, buildings, and industrial processes

The figure below depicts these reductions in a wedge analysis.[15]

Figure 2. California Pathways to 2050



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The most important finding of the California Pathways study was the requirement of widespread replacement of gasoline in cars largely with electricity. Without this fuel-switching, the target could not be reached. The model projected 70% of vehicle miles traveled powered by electricity in 2050; 20% powered by biofuels; and 10% by fossil fuels.

[14] Ibid, p. 1
[15] Ibid, p. 2

In the electricity sector, the modelers built separate high renewable energy, high nuclear, and high CCS scenarios. They assume all conventional coal plants on the Western grid were retired by the end of their 30-year lifespans. Another important finding is that the modelers found it infeasible for California to be powered by 100% renewable energy: A maximum of 74% renewable penetration was feasible, with 26% coming from nuclear, natural gas, and hydroelectricity along with high storage capacity to maintain operations.

The rate of energy efficiency required (1.3% a year) was less than what the state achieved during its 2000-2001 energy crisis, but still unprecedented over a sustained period of time. Biofuels make up only 6% when feedstocks were constrained to be carbon-neutral, produced in the United States, and only for California's consumption-weighted proportional share of the country's biofuels production.

The study found that major improvements in the functionality and cost of multiple technologies and infrastructure systems were required. These include but are not limited to: cellulosic and algal biofuels; carbon capture and storage/sequestration; on-grid energy storage; electric vehicle batteries; smart charging; building shells and appliances; cement manufacturing; electric industrial boilers; agriculture and forestry practices; and reductions/capture from high global warming potential industrial emissions.

Electricity use increases from 15% to 55%, basically swapping places with petroleum products, which fall from 45% to 15%.

Deep Decarbonization Pathways Project (DDPP) (2014-2015)

Pathways to Deep Decarbonization in the United States

In November 2014 with a technical supplement published in November 2015, E3 in collaboration with Lawrence Berkeley National Laboratory (LBNL) and Pacific Northwest National Laboratory (PNNL) published *Pathways to Deep Decarbonization in the United States*.[16]

The Sustainable Development Solutions Network (SDSN) and the Institute for Sustainable Development and International Relations (IDDRI) led the Deep Decarbonization Pathways Project (DDPP), a collaborative global initiative to explore how individual countries could reduce GHG emissions to levels consistent with limiting the anthropogenic increase in global mean surface temperature to less than 2 degrees Celsius.

This limit on global warming requires that global net GHG emissions approach zero by the second half of the 21st century, which mandates a thorough transformation of energy systems that results in steep emission reduction related to energy, a transition called deep decarbonization.

The DDPP PATHWAYS Model Architecture[17] is depicted in Figure 3 as follows:

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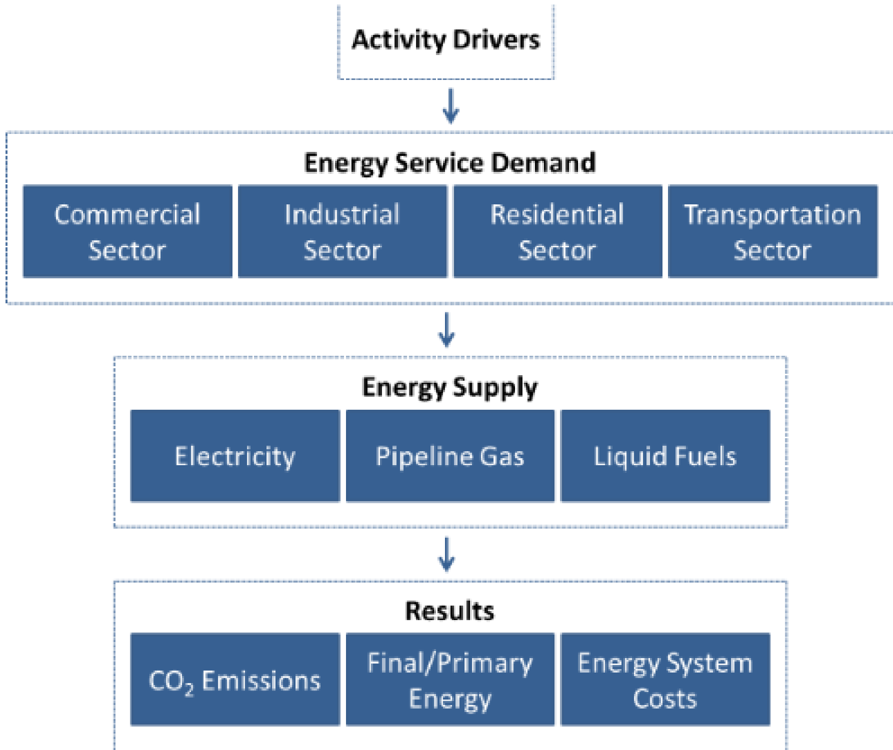
[16] Williams, J. H., B. Haley, F. Kahrl, J. Moore, A.D. Jones, M.S. Torn, H. McJeon (2014) Pathways to deep decarbonization in the United States. The U.S. report of the Deep Decarbonization Pathways Project of the Sustainable Development Solutions Network and the Institute for Sustainable Development and International Relations. Revision with technical supplement. Nov 16, 2015. http://deepdecarbonization.org/wp-content/uploads/2015/11/US_Deep_Decarbonization_Technical_Report.pdf

[17] Ibid, p. 6

Figure 3. DDP PATHWAYS Model Architecture

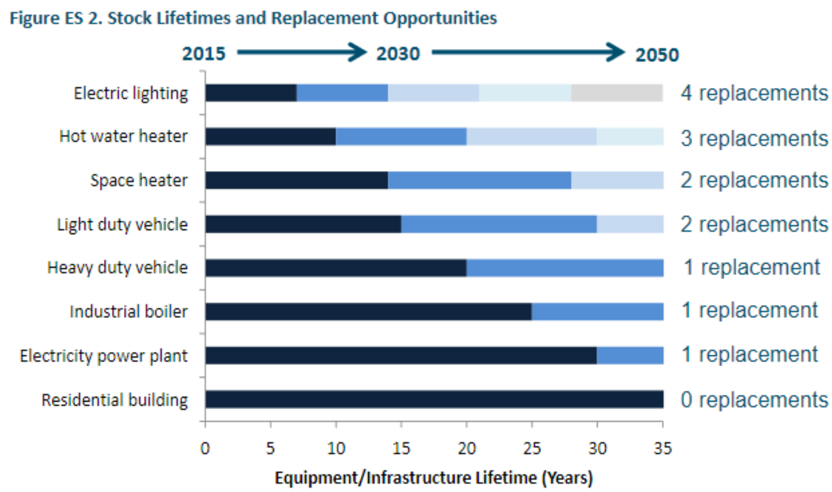


The study used E3's PATHWAYS model, a detailed, bottom-up energy model that drew upon the architecture and inputs from the U.S. National Energy Modeling System (NEMS). As with the California Pathways model described in the above section, the DDPP model evaluates annuals changes in infrastructure stocks by sector, in this case by region in each of the nine U.S. census divisions, and simulates hourly electricity in each of the three major electric grid interconnections.

The U.S. DDPP study included the following useful graphic[18] depicting the challenge of working within the replacement lifespans for various end uses. Note how limited the replacement opportunities are for key infrastructure and how important it is not to wait for new technologies or broad global consensus but instead to take advantage of replacement cycles between now and 2050.

[18] Ibid, p. 71

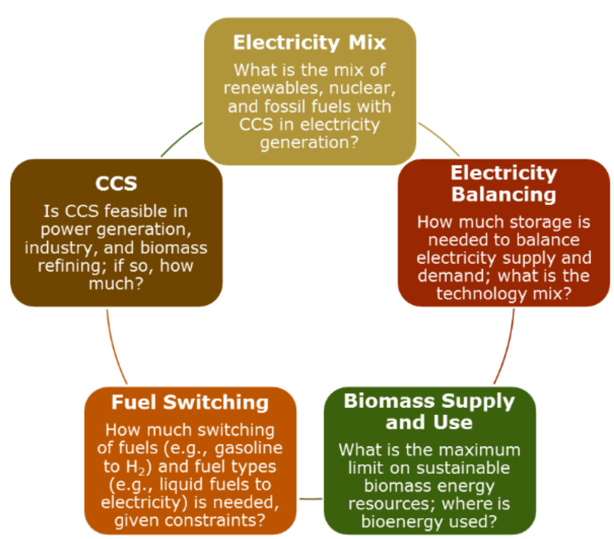
Figure 4. Stock Lifetimes and Replacement Opportunities



Different portfolios of measure were developed in scenarios with a range of decarbonization strategies across energy supply and demand sectors for electricity; fuels; residential and commercial buildings; passenger and freight transportation; and industry. Sensitivity analyses addressed uncertainty and the modelers used the Global Change Assessment Model (GCAM), a global integrated assessment to examine land-use emissions of bioenergy production and the mitigation potential of non-$C0_2$ GHGs.

The following figure from the DDPP study[19] depicts the different elements that determine the features of a low-carbon energy system:

Figure 5. Critical Elements that Determine the Features of a Low-Carbon Energy System



[19] Ibid, p. 16

The principal findings of the study were: it is technically feasible to achieve an 80% GHG reduction below 1990 levels by 2050 in the United States; multiple alternative pathways exist using existing commercial or near-commercial technologies for high levels of energy efficiency; decarbonization of electric generation electrification of most end uses is mandatory; and switching the remaining end uses to lower carbon fuels will be required.

The cost to achieve these reductions is not prohibitive (an incremental cost to the energy system of less than 1% of gross domestic product in the base case), excluding potential non-energy benefits.

The study indicates that deeply decarbonizing the economy over 35 years would be an ambitious undertaking, but not necessarily entail massive changes in lifestyle. The key is to start as soon as possible to permit infrastructure replacement to follow natural replacement rates to reduce costs, ease demand on manufacturing, and allow gradual consumer adoption.[20]

The study's conclusions mirror those of the prior California Pathways 2050 findings, namely: It is technically feasible for the U.S. to reduce GHG emissions 80% below 1990 levels by 2050 with either a High Renewable, High Nuclear, High CCS, or Mixed Case pathway; these are achievable for a reasonable cost; decarbonization relies on the same three pillars; and there is time to rely on natural infrastructure turnover, but (a more explicit finding in the DDPP study than in the California 2050 study) accounting for economic and operating lifetimes in investment decisions is required.

The DDPP study explicitly states that "[a]dding new high carbon generation (e.g., coal plants) creates infrastructure inertia that either makes the 2050 target more difficult to reach, requires expensive retrofits, or puts investments at risk."[21]

Petroleum consumption is predicted to decline from 76-91% by 2050 in all scenarios in absolute terms and as a share of final energy. The cost of decarbonizing the energy system is in the incremental capital cost of low-carbon technologies in power generation; light and heavy-duty vehicles; building energy systems; and industrial equipment.

All four deep decarbonization cases attain emissions reductions below 750 MtCO2, an 85% reduction in total emissions and an 89% reduction in emissions per capita relative to 2014 levels as Figure 6 below demonstrates:[22]

[20] Ibid, p. ix.
[21] Ibid, p. xv.
[22] Ibid, p. 22

Figure 6. Carbon Dioxide Emissions by Case 2014 and 2050

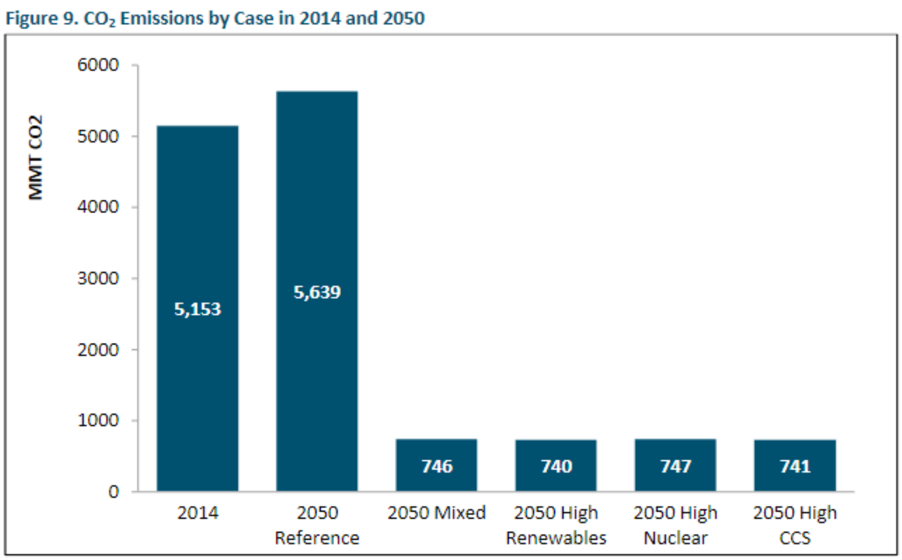
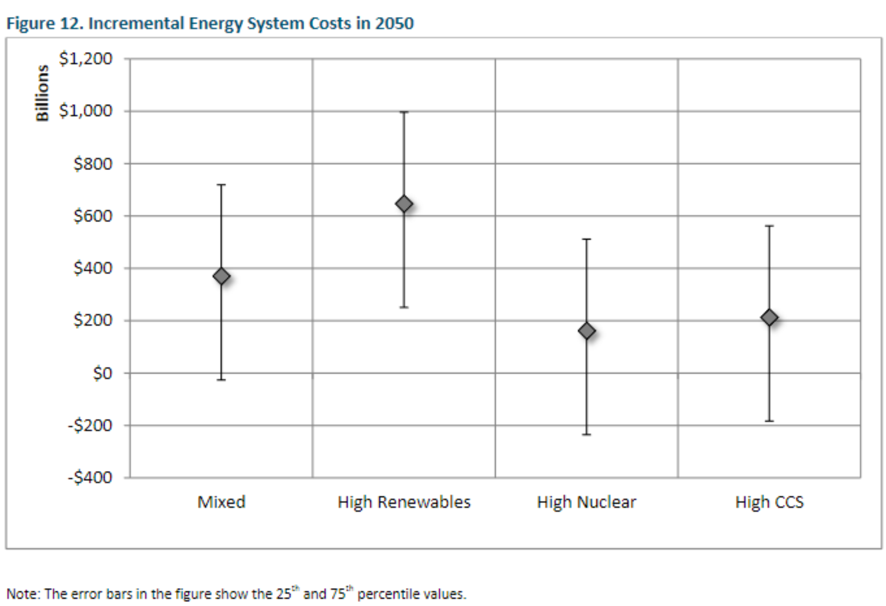


Figure 7 shows the broad range in incremental energy system costs (incremental capital costs plus net energy costs), which reflects the significant challenges of estimating technology costs and fossil fuel prices: [23]

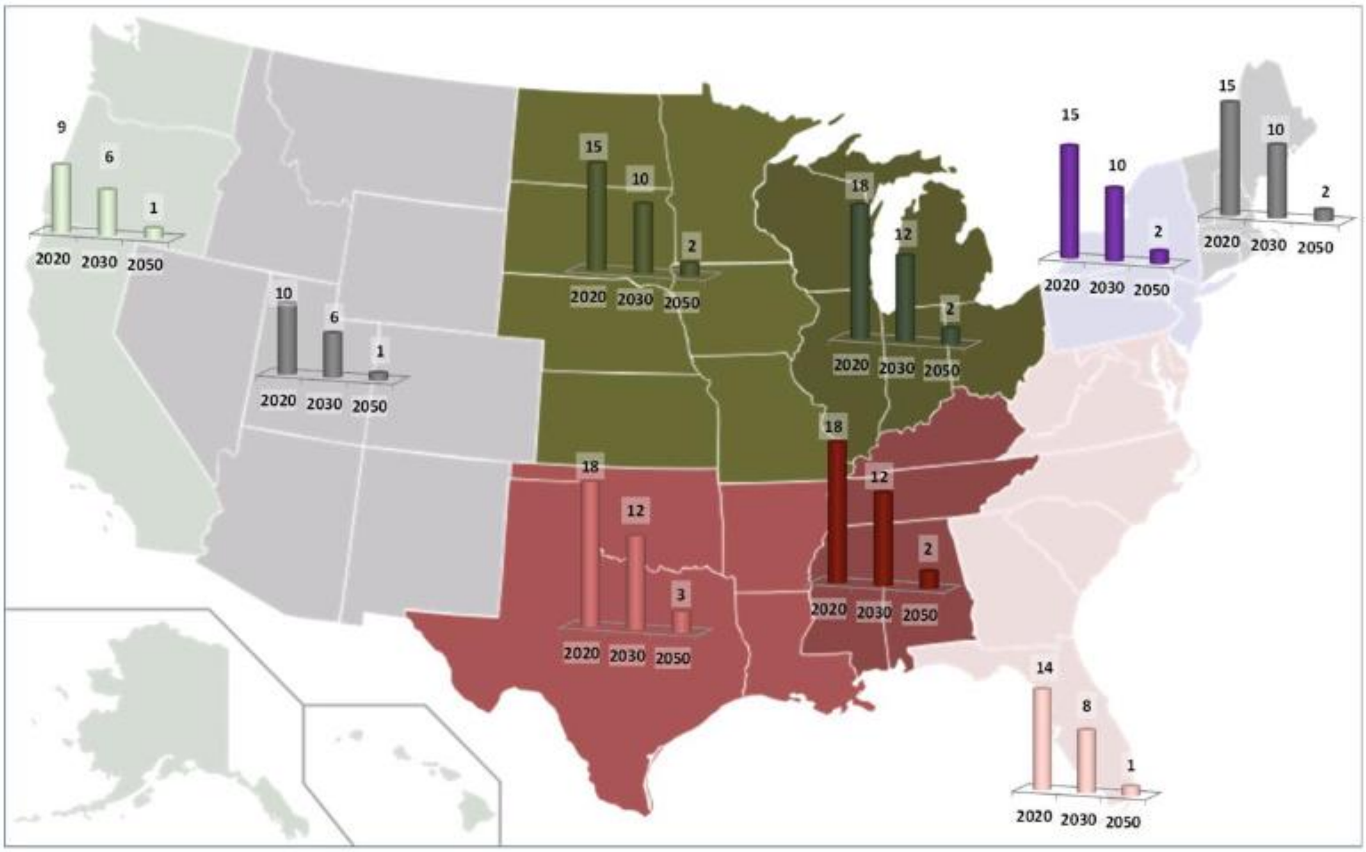
Figure 7. incremental Energy System Costs in 2050



[23] Ibid, p. 24

Figure 8 demonstrates the change in regional emissions intensity for 2020, 2030, and 2050 for the nine U.S. census division and nicely depicts the significant head start the Northwest's relatively clean energy systems have over other parts of the country:[24]

Figure 8. Mixed Case Regional Per Capita CO2 Emissions Intensity



Pathways to Deep Decarbonization

A second DDPP report, *Pathways to Deep Decarbonization,* was also released in 2015,[25] which analyzed 16 countries that comprise 74% of global GHG emissions at the time: Australia; Brazil; Canada; China; France; Germany; India; Indonesia; Italy; Japan; Mexico; Russia; South Africa; South Korea; Unites Kingdom; and United States.

This study looked at whether limiting global warming to 2 degrees Celsius was achievable; whether deep decarbonization was compatible with development and economic growth and affordable; and why the DDPs are essential for climate policy.

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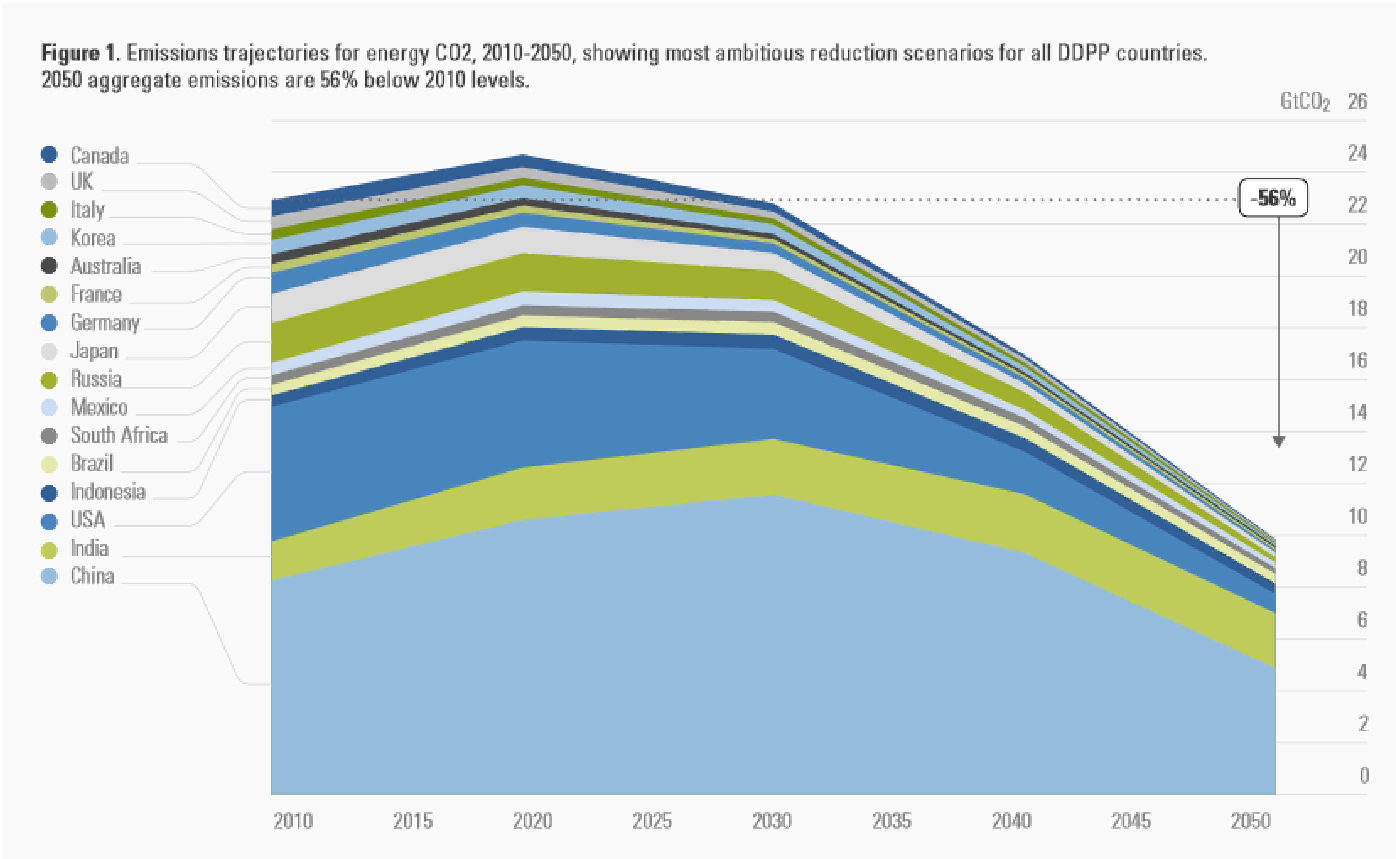
[24] Ibid, p. 44

[25] Deep Decarbonization Pathways Project (2015). *Pathways to Deep Decarbonization 2015 report*, SDSN – IDDRI. http://deepdecarbonization.org/wp-content/uploads/2016/03/DDPP_2015_REPORT.pdf

The emissions trajectories from 2010-2050 for the 16 countries with the most ambitious scenarios are depicted below,[26] achieving a 56% reduction below 2010 levels:

Figure 9. 2010-2050 CO_2 Emissions Trajectories for All DDPP Countries



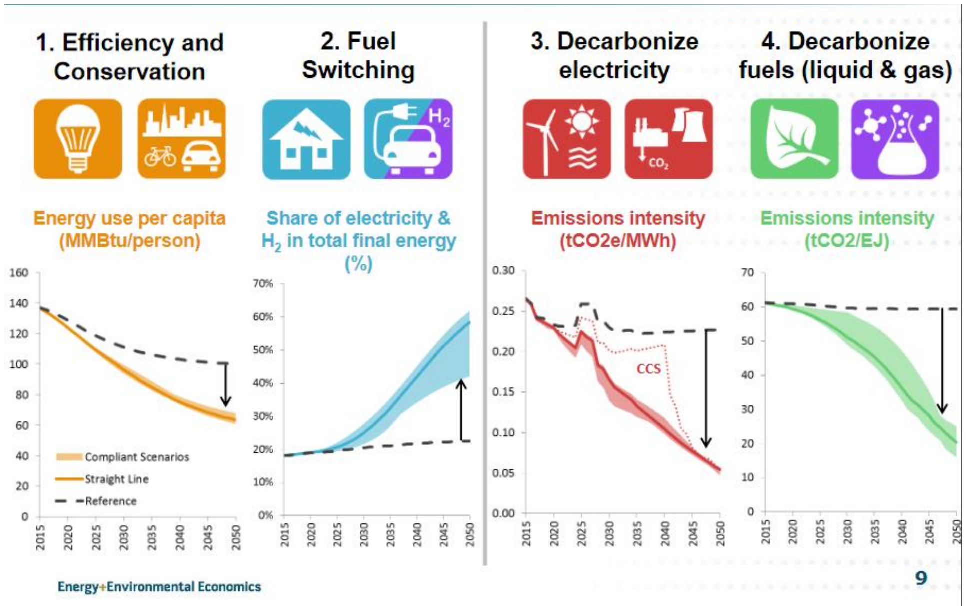
California PATHWAYS (2015)

On April 6, 2015, E3 released a PATHWAYS study for California's Air Resources Board, *California Pathways: GHG Scenario Results*, that focused on achieving a 2030 target and found that GHG reductions of 26-38% below 1990 levels appeared achievable by 2030 with a major increase in reduction efforts and mitigating key risks. The modeled efforts would result in net savings that ranged from $4 billion to $11 billion in 2012 dollars. Decarbonizing California's economy depends on four energy transitions:[27]

[26] Ibid, p. 9

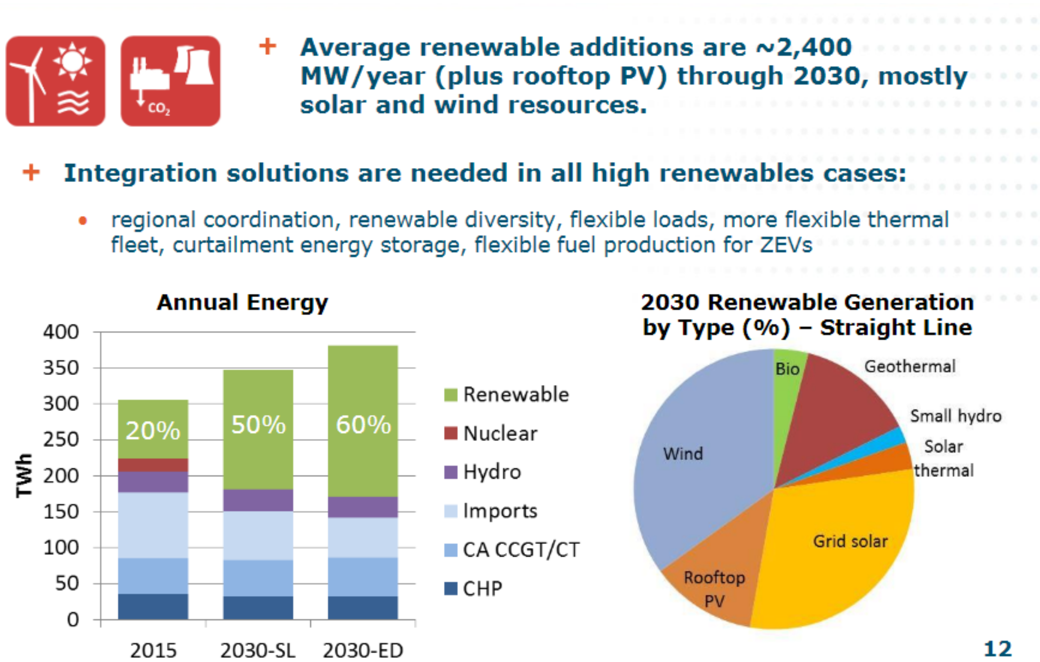
[27] A. Mahone, E. Hart, B. Haley. J. Williams., S. Borgenson, N. Ryan. S. Price. *California Pathways: GHG Scenario Results*. April 6, 2015. Slide 9. http://www.ethree.com/wp-content/uploads/2017/02/E3_PATHWAYS_GHG_Scenarios_Updated_April2015.pdf

Figure 10. Four Decarbonization Energy Transitions



The E3 California 2030 PATHWAYS study found renewables accounting for 50-60% of annual energy use by 2030:[28]

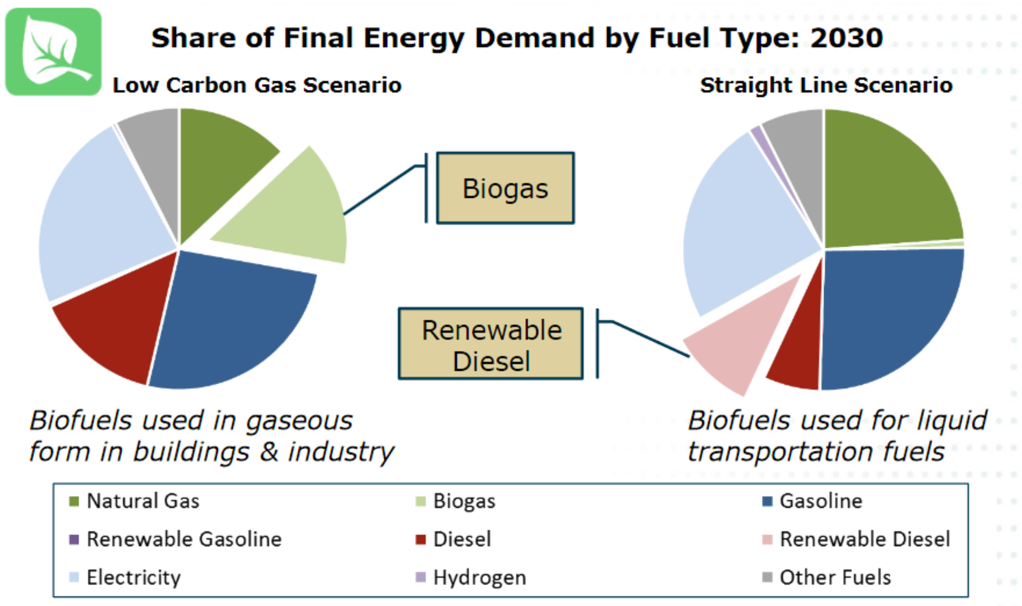
Figure 11. Renewables Equal 50-60% Annual Energy in 2030



[28] Ibid, Slide 12.

The study also found that sustainable biomass is not sufficient to replace both liquid and gaseous fuels:[29]

Figure 12. Share of Final Energy Demand by Fuel Type 2030



Germany Energy Transformation Pathways (2015)

In November 2015, the Fraunhofer Institute for Solar Energy Systems ISE in Freiburg, Germany produced *What Will the Energy Transformation Cost? Pathways for Transforming the German Energy System by 2050*.[30] Similar to E3's PATHWAYS studies, the Fraunhofer modeling found a number of different technically feasible pathways and system configurations to meet targeted reductions; fluctuating renewable energy will play a key role in electricity generation and future energy supply; grid flexibility is required, and combustion systems will be gradually replaced by electric powered units. Electricity generation was projected to grow 20-40%, even with a 25% reduction in electricity consumption from lighting, mechanical drives, etc. Coal-fired electricity generation exits.[31]

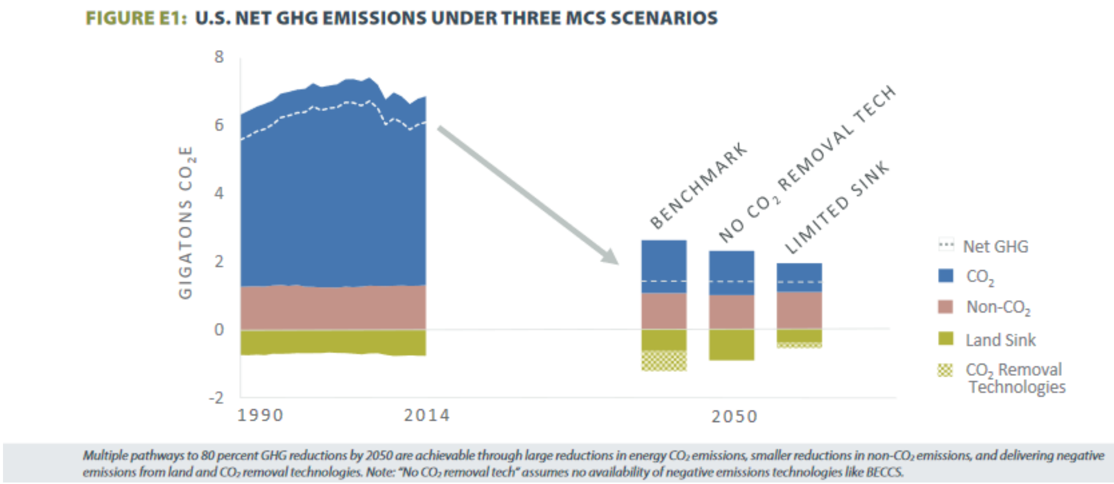
United States Mid-Century Strategy (2016)

One of the Obama Administration's final acts regarding climate policy before leaving office was the release of the *United States Mid-Century Strategy (MCS)* in November 2016,[32] in compliance with the December 2015 Paris Agreement that all signatory countries would produce their individual nationally determined contributions (NDCs) of near-term targets to address GHG emissions. Countries were also invited to submit mid-century, long-term low-GHG emission development strategies.

[29] Ibid, slide 13.
[30] Hans-Martin Henning, Andreas Palzer. November 2015. Fraunhofer Institute for Solar Energy Systems ISE in Freiburg, Germany. "What Will the Energy Transformation Cost? Pathways for Transforming the German Energy System by 2050." https://www.ise.fraunhofer.de/content/dam/ise/en/documents/publications/studies/What-will-the-energy-transformation-cost.pdf
[31] Ibid, pp. 7-8.
[32] United States Mid-Century Strategy. November 2016. http://unfccc.int/files/focus/long-term_strategies/application/pdf/mid_century_strategy_report-final_red.pdf

The MCS identifies three major areas for action to attain deep economy-wide net GHG emissions: 1-transitioning to a low-carbon energy system; 2-sequestering carbon through forest, soils, and CO_2 removal technologies; and 3-reducing non-CO_2 emissions. The figure below shows the importance placed on sequestration techniques:

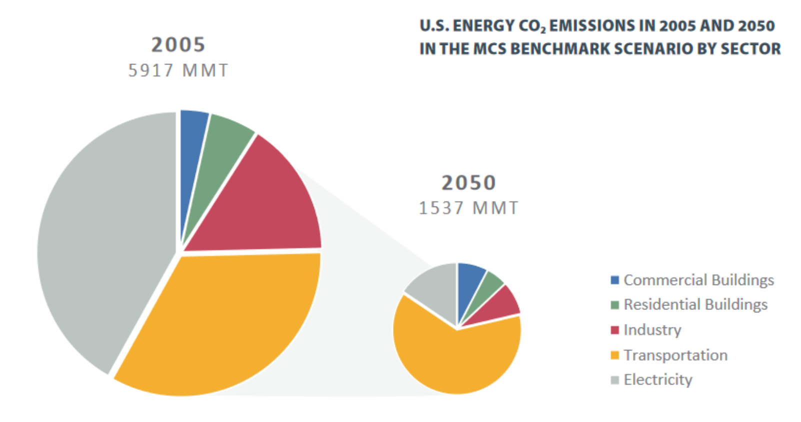
Figure 13. U.S. Net GHG Emissions under Three MCS Scenarios



"The MCS demonstrates how the U.S. can meet the growing demands on its energy system and lands while achieving a low-emissions pathway, maintaining a thriving economy, and ensuring a just transition for Americans whose livelihoods are connected to fossil fuel production and use. It also shows how the momentum of technological progress created by global commitments to low-carbon innovation and policies will enable increasingly ambitious climate action from all countries."[33]

The following figure shows the MCS vision for a low-carbon U.S. energy system in 2050:[34]

Figure 14. U.S. MCS Low-Carbon Energy System in 2050



[33] Ibid, p. 6.
[34] Ibid, p. 42

Risky Business Project (2016)

In 2014, The Risky Business Project, co-chaired by Michael R. Bloomberg, Henry M. Paulson, and Thomas F. Steyer, commissioned a report on the potential economic damages from unmitigated climate change in the United States, called *Risky Business: The Economic Risks of Climate Change in the United States*[35] that concluded that the economic risks from unmitigated climate change to American businesses and long-term investors were significant and unaccepatable.

The Risky Business Project followed up its 2014 study with a second study in 2016*, From Risk to Return: Investing in a Clean Energy Economy*,[36] aimed at addressing how to respond to the risks that climate change presented and contracted with the World Resources Institute and Evolved Energy Research[37] (EER) to use its EnergyPATHWAYS model to develop multiple pathways. The Risky Business Project also retained Regional Economic Models, Inc. (REMI) to use its macroeconomic model to project regional changes in GDP and employment for each pathway. A separate case study was written by EER to understand how autonomous vehicles (AVs) could facilitate deep decarbonization, and how AVs could revolutionize how people conceive of personal mobility, if adopted more rapidly than currently assumed.

The study reached the same conclusions as prior studies in terms of the pathways (moving from fossil fuels to electricity; generating electricity with low- or zero-carbon emission; and using energy more efficiently.) But the report's primary focus was on the required up-front capital investments in clean energy technologies. In this area, the study concluded that "the level of investment required to transition to a clean energy economy in the United States is likely less than either the economic costs of unmitigated climate change or the projected spending if the United States continues to rely on fossil fuels."[38]

Following the three pillars approach (see Figure 15 below),[39] the study found that the share of electricity as a portion of total final energy use more than doubles—from 23% to 51%—including electricity used to produce hydrogen and synthetic methane; the carbon dioxide emissions intensity of generating that electricity drops precipitously from 509 to 2 kg of CO_2/MWh; and the final energy intensity (reflecting energy productivity) decreases by approximately 2/3 (from 3.4 to 1.1 megajoules per dollar of GDP).

[35] Michael R. Bloomberg, Henry M. Paulson, Jr., Thomas F. Steyer; Lead author, Kate Gordon. June 2014. *Risky Business: The Economic Risks of Climate Change in the United States*. https://riskybusiness.org/site/assets/uploads/2015/09/RiskyBusiness_Report_WEB_09_08_14.pdf

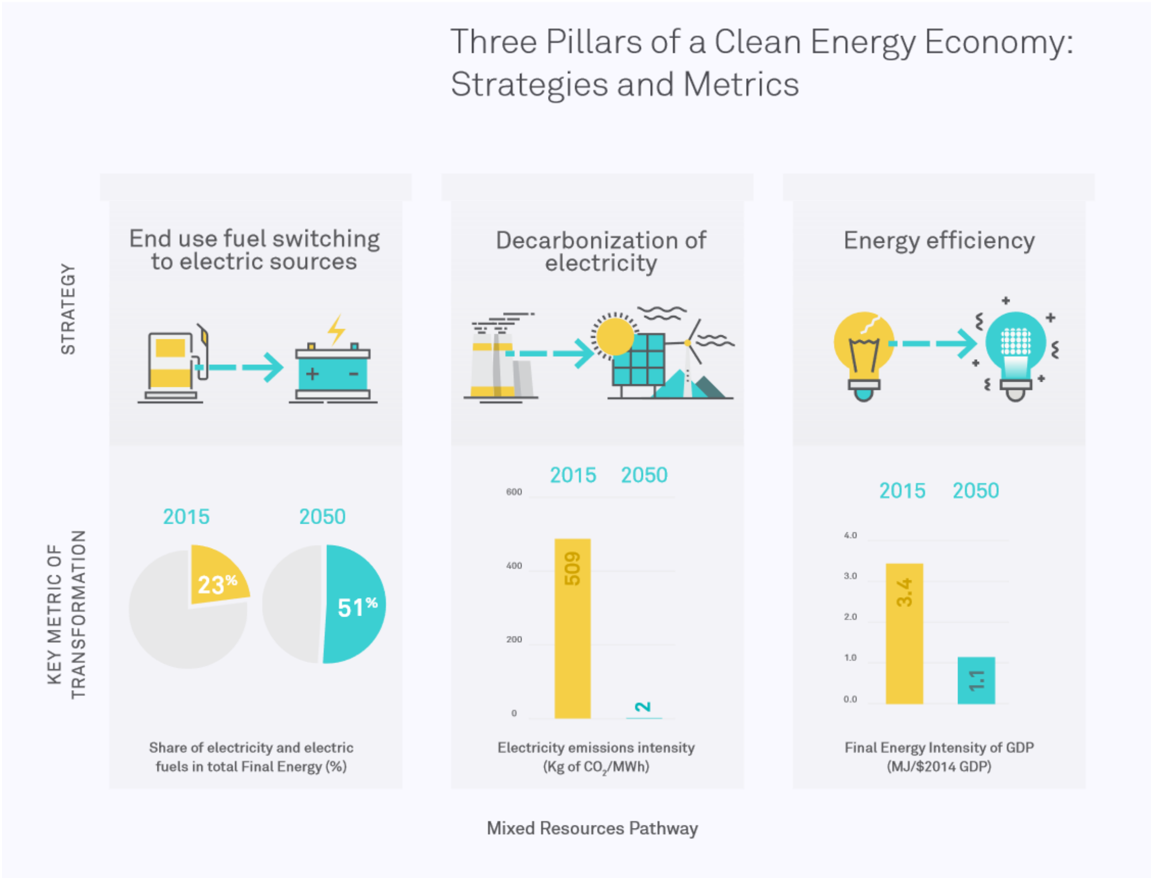
[36] Tim Duane, Jonathan Koomey, Kathy Belyeu, and Karl Hausker. Risky Business Project. 2016. *From Risk to Return: Investing in a Clean Energy Economy.* http://riskybusiness.org/site/assets/uploads/sites/5/2016/10/RBP-FromRiskToReturn-WEB.pdf

[37] Evolved Energy Research was founded in January 2016 by energy analysts who previously worked at E3 to focus on energy sector challenges accelerated by climate change and they developed a new, more extensible model called EnergyPATHWAYS to answer deep decarbonization-related questions,

[38] From Risk to Return, p. 20.

[39] Ibid, p. 22

Figure 15. Three Decarbonization Pillars Approach



Washington State Deep Decarbonization Study (2017)

Evolved Energy Research contracted with the State of Washington Office of the Governor and Office of Financial Management to produce a study using the EnergyPATHWAYS model that was completed on December 16, 2016, *Deep Decarbonization Pathways Analysis for Washington State*.

The purpose of the study was to develop and evaluate technology pathways that achieve deep decarbonization pathways GHG emissions targets by mid-century for the state of Washington in order to (1) quantify the magnitude, scope, and timing of required changes to Washington State's energy system to support recommendations to update Washington's statutory GHG emission limits (currently only aiming for a 50% reduction relative to 1990 by 2050); (2) identify policies and investments consistent with more ambitious emission targets; and (3) facilitate a broader stakeholder discussion.

Figure 16[40] below shows the gap between Washington's existing targets and those that countries and states are aiming for to achieve deep decarbonization:

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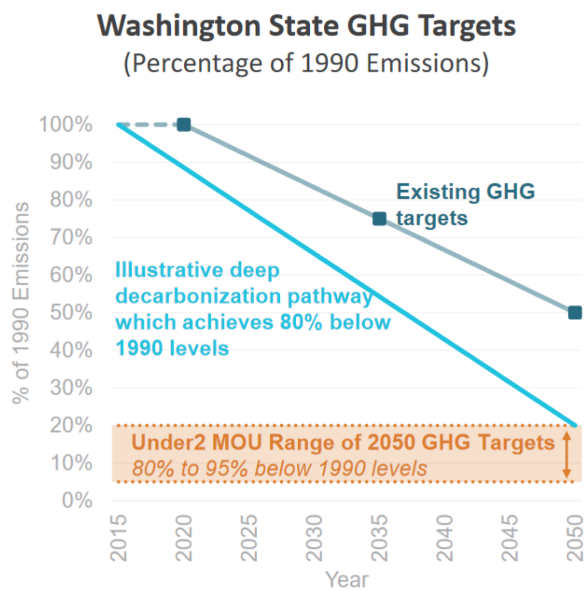
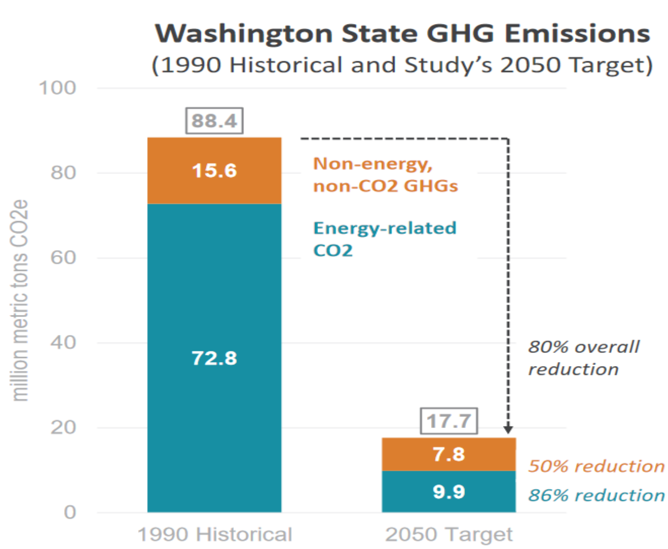
[40] B. Haley, G. Kwok, R. Jones, J. Williams. Evolved Energy Research and Deep Decarbonization Pathways Project. December 16, 2016. *Deep Decarbonization Pathways Analysis for Washington State*. p. 6
http://www.governor.wa.gov/sites/default/files/Deep_Decarbonization_Pathways_Analysis_for_Washington_State.pdf

Figure 16. Gap between Current Washington State GHG Targets and Decarbonization Target



The Washington DDP study is based on the more aggressive target (80% of 1990 levels by 2050). An 80% reduction of overall emissions from 1990 means 17.7 $MMTCO_2$, 9.9 $MMTCO_2$ of which must come from energy-related carbon dioxide emissions, which translates into an 86% reduction in energy-related CO_2 below 1990 levels by 2050 as Figure 17[41] below shows:

Figure 17. Trajectory for Washington State GHG Emissions 80% Reduction of 1990 Levels by 2050



[41] Ibid, p. 7.

The study focuses only on the energy-related CO_2 emissions and developed three DDP cases with alternative reduction strategies and technologies. The study included a detailed representation of the state's energy system, including infrastructure stocks and energy demands for buildings, industry, transportation, and the electric power sector supplemented by a representation of energy infrastructures across other Western states to capture petroleum, natural gas, biofuels, and electricity imports and exports.[42]

The study design accounts for Washington's hydroelectric dominance and energy interconnectedness with neighboring states, its reliance on electricity for home heating, and the disproportionate share of emissions from the transportation sector.

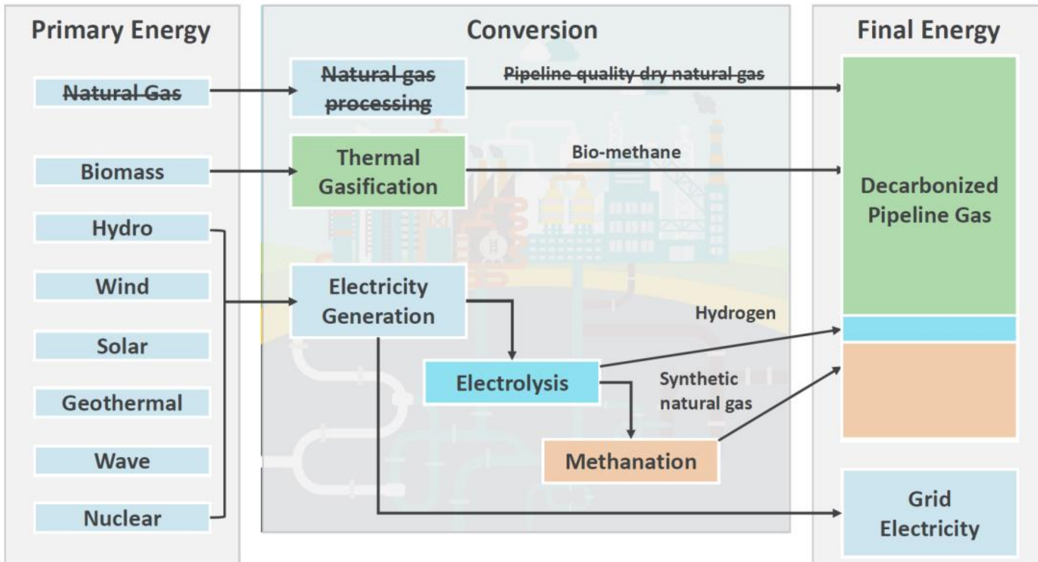
The three DDP cases examined against the reference case of current and planned regulation are as follows:

- **Electrification**, which assumes electrifying as many end-uses as possible and a major reduction in pipeline gas to buildings. Liquid biofuels decarbonize freight trucks, marine, and aviation. Significant new renewable resources are balanced using existing and new pumped hydro storage and new batteries.
- **Renewable Pipeline**, which assumes buildings and industry continue to use pipeline gas, but the gas supply is decarbonized by a mix of biogas, synthetic natural gas and hydrogen. That decarbonized pipeline gas is also used for medium- and heavy-duty vehicles. Power-to-gas facilities are a key balancing resource for electricity.
- **Innovation**, electrification combined with technology breakthroughs in vehicle electrification and hydrogen fuel cells, is used to decarbonize trucking and reduce the need for biomass. Autonomous vehicles electrify the light-duty vehicle sector and wave technology breakthroughs enable 5% of generation. Power-to-gas and electrolysis facilities are deployed for balancing.

One of the interesting aspects of the Washington DDP study is EER's approach to decarbonized pipeline gas and liquid fuels, both of which can be created by using biomass and low-carbon electricity as inputs to fuel production. Figure 18[43] below shows the process by which decarbonized pipeline gas can be created not using natural gas.

[42] Ben Haley, Gabe Kwok, Ryan Jones, Jim Williams. April 2017. *Deep Decarbonization Pathways Analysis for Washington State: Executive Summary*. p.1 http://www.governor.wa.gov/sites/default/files/DeepDecarbonizationPathwaysAnalysisforWashingtonSt.pdf
[43] *Deep Decarbonization Pathways Analysis for Washington State*, p. 29

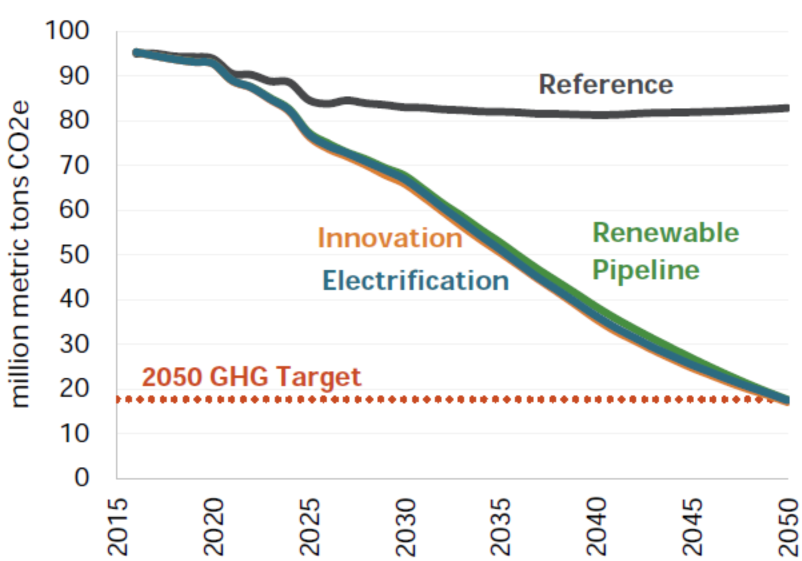
Figure 18. Process for Decarbonizing Pipeline Gas



Note: note all final energy types shown. Size of arrows and box do not correspond to magnitude of energy flows or volume.

The results of the Washington DDP study show all three non-refences cases attaining the 80 percent reduction in GHG emissions below 1990 levels by 2050 emission reduction target.[44] The electrification pathway focuses on electrifying transport and heating; the renewable pipeline pathway substitutes fossil natural gas for decarbonized pipeline gas fuels; and the innovation pathways explores how emerging technologies might enable decarbonization.

Figure 19. Washington DDP Cases Compared to Reference Case GHG Emissions (million metric ton CO_2e)

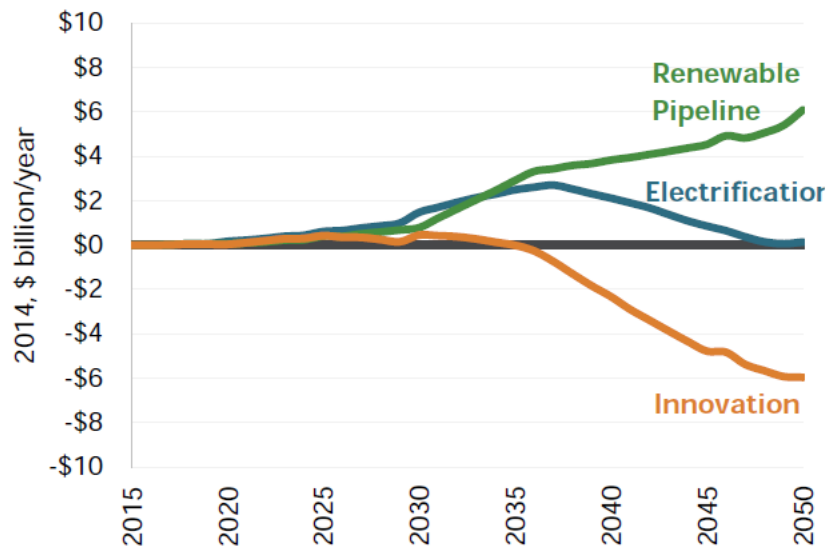


[44] *Deep Decarbonization Pathways Analysis for Washington State: Executive Summary*, p.4

The Washington State DDP study estimated the cost of decarbonizing the state's energy system by comparing the incremental cost of investment in low-carbon and efficient equipment and infrastructure against the savings from avoiding fossil fuel purchases. This net energy system cost metric excludes costs outside of the energy system and the benefits from avoiding climate change and air pollution.

The study found the cost of reduction "likely to be quite reasonable, ranging from $6 billion of costs to $6 billion of savings in 2050. When compared against the state's projected gross state product, these incremental costs are small (-0.6 percent to 0.6 percent)."[45]

Figure 20. Washington State Net Energy System Cost Comparison (2014, $ billion/year)



The study's conclusion offers evidence of the value of conducting a pathways study for the region that would test additional scenarios: "These three DDP scenarios are neither prescriptive nor exhaustive. There are many additional pathways that were not evaluated in our study."[46]

Portland General Electric Decarbonization Study (2018)

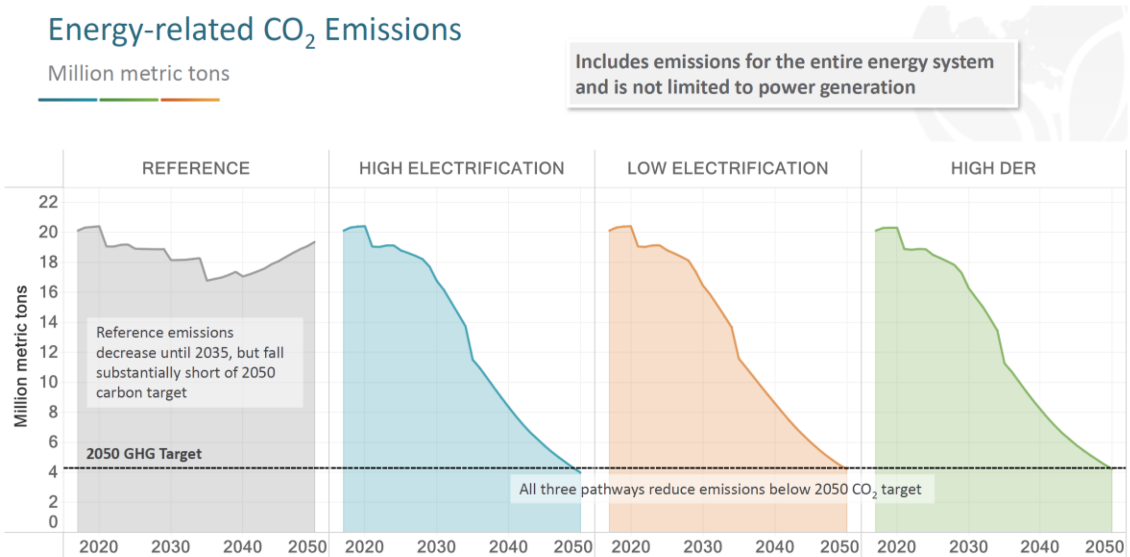
Portland General Electric contracted with Evolved Energy Research to use the firm's EnergyPATHWAYS model to help the utility understand what achieving economy-wide decarbonization might mean for its service territory in Northwest Oregon, which covers approximately 45-47% of Oregon's state population.

The study, *Portland General Electric Decarbonization Study: Summary of Draft Findings*, which looks only at emissions reductions applied to energy CO_2, examined three pathways compared to the reference case, a continuation of current and planned policy, as follows: (1) high electrification—end uses electrified to the extent possible and increase in renewable electricity generation; (2) low electrification—a focus on biofuels and synthetic electric fuels; (3) high distributed energy resources (DER)—in homes and businesses with higher levels of electrification.

[45] Ibid, p. 5
[46] Ibid, footnote p. 3

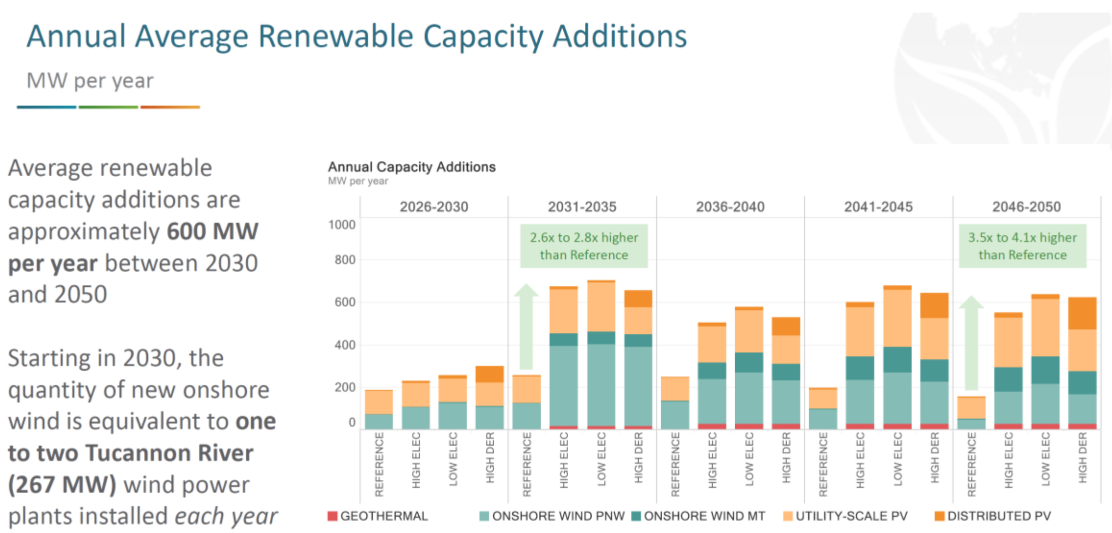
As with the Washington DDP study, all three of the cases in the PGE study attain the emission reduction target as Figure 21[47] below shows:

Figure 21. Portland General Electric's Three DDP Cases



As Figure 22 shows, EER's PGE study found that average renewable capacity additions would need to be approximately 600 MW per year between 2030 and 2050,[48] a hugely significant increase to satisfy demand within PGE's territory. It is possible that a regional approach might reduce the cost relative to a utility-by-utility approach.

Figure 22. PGE Annual Average Renewable Capacity Additions



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[47] Gabe Kwok and Ben Haley. March 23, 2018. *Portland General Electric Decarbonization Study: Summary of Draft Findings*. p. 22. https://www.portlandgeneral.com/our-company/energy-strategy/resource-planning/integrated-resource-planning#

[48] Ibid, p. 33

Lessons Learned from Economy-Wide Pathways Studies

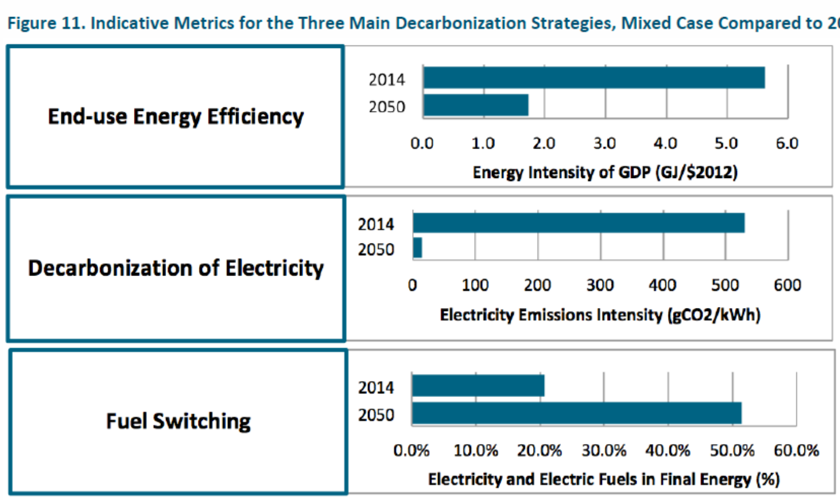
The key lessons learned from the pathways studies conducted from 2010 to the present are as follows:

1. There are three pillars for deep decarbonization of energy systems: (1) energy efficiency; (2) electricity generation decarbonization; and (3) fuel-switching.
2. Sustainable bioenergy is a key strategy for a low-carbon energy system, particularly for currently challenging to electrify sectors such as aviation, freight transportation, and industrial process heat. But supplies of sustainable (net-zero carbon) bioenergy are limited.
3. A deeply decarbonized energy economy results in more spending on technology, such as capital investments in low-carbon equipment and infrastructure, and less spending on fossil fuel, with a relatively small net cost impact.
4. Electricity supply will grow significantly to meet higher demand for heating water and buildings, passenger transportation, and/or producing synthetic electric fuels (hydrogen and synthetic natural gas) despite an overall decrease in energy demand.
5. There are increased challenges in balancing electricity supply and demand to successfully integrate variable renewable generation.

Lesson #1 Three Pillars of Deep Decarbonization

Deep decarbonization of energy systems relies on energy efficiency; electricity generation decarbonization; and fuel-switching from fossil fuels to electricity, electrically derived fuels (hydrogen/synthetic natural gas); or biofuels or low-carbon fuels. Figure 15 above on page 20 from the Risky Business *From Risk to Return* report illustrates the three-pillar framework, as does the following figure from the 2014 *Pathways to Deep Decarbonization in the United States*, which demonstrates the changes in the three pillars from 2014-2050.[49]

Figure 23. Changes in Three Pillars in US DDPP Study 2014-2050



[49] *Pathways to Deep Decarbonization in the United States* (2014), p.23

Here the concepts are laid out in the *United States Mid-Century Strategy* in prose form, with more detail and less eye candy:[50]

Figure 24. U.S. Mid-Century Strategy Three Pillars

TRANSITION TO A LOW-CARBON ENERGY SYSTEM

The energy system—including electricity, residential and commercial buildings, industry, and transportation—is responsible for about 80 percent of U.S. GHG emissions. The MCS envisions deep emission reductions through the following three levers:

- **Cutting energy waste:** Energy efficiency improvements enable the energy system to provide the services we need with fewer resources and emissions. Over the past several years, the United States has demonstrated that programs and standards to improve the energy efficiency of buildings, appliances and vehicles can cost-effectively cut carbon pollution and lower energy bills, while maintaining significant support from U.S. industry and consumers. Technological advancements will further expand the opportunities for cost-effective energy efficiency improvements. "Smart growth" strategies can also reduce the country's structural energy needs, for example, through improved urban design that supports alternative transit options. In the MCS Benchmark scenario, primary energy use declines by over 20 percent between 2005 and 2050.
- **Decarbonizing the electricity system:** By 2050, nearly all fossil fuel electricity production can be replaced by low carbon technologies, including renewables, nuclear, and fossil fuels or bioenergy combined with carbon capture, utilization and storage (CCUS). Current electricity grids can handle near-term rapid expansion of variable energy sources like solar and wind, and with additional flexibility through, for example, demand response, electricity storage, and transmission improvements, variable renewables have the potential to provide the majority of our electricity by mid-century (NREL 2012). Figure E2 shows the annual average additions in electricity generating capacity in the MCS Benchmark scenario. The corresponding electricity generation mix in 2050 includes significant contributions from renewables (55 percent), nuclear (17 percent), and fossil fuels with CCUS (20 percent). While public policies will help to achieve this mix, existing market trends toward lower cost clean electricity will also play a critical role.
- **Shifting to clean electricity and low-carbon fuels in transportation, buildings, and industry:** The vast majority of energy for transportation is currently provided by petroleum, while the industry and buildings sectors are powered by a mix of fuels including natural gas, coal, petroleum, and electricity. With a clean electricity system comes opportunities to reduce fossil fuel usage in these sectors: for example, electric vehicles displace petroleum use and electric heat pumps avoid the use of natural gas and oil for space and water heating in buildings. The electricity generating capacity additions displayed in Figure E2 are therefore needed not only to decarbonize the electricity sector but also to electrify the buildings, transportation, and industrial sectors. Other low-carbon fuels like hydrogen and carbon-beneficial forms of biomass will also play an important role, particularly for energy uses that are difficult to electrify, such as aviation, long-haul trucking, and heat production in certain industrial sectors. In the MCS Benchmark scenario, direct fossil fuel use (i.e., not including electricity generated using fossil fuels) decreases by 58 percent, 55 percent, and 63 percent in buildings, industry, and transportation, respectively, from 2005 to 2050.

[50] U.S. Mid-Century Strategy, p. 8

Perhaps the best graphical display of the three pillars is from the California 2050 Pathways study:[51]

Figure 25. California 2050 Pathways Three Pillars

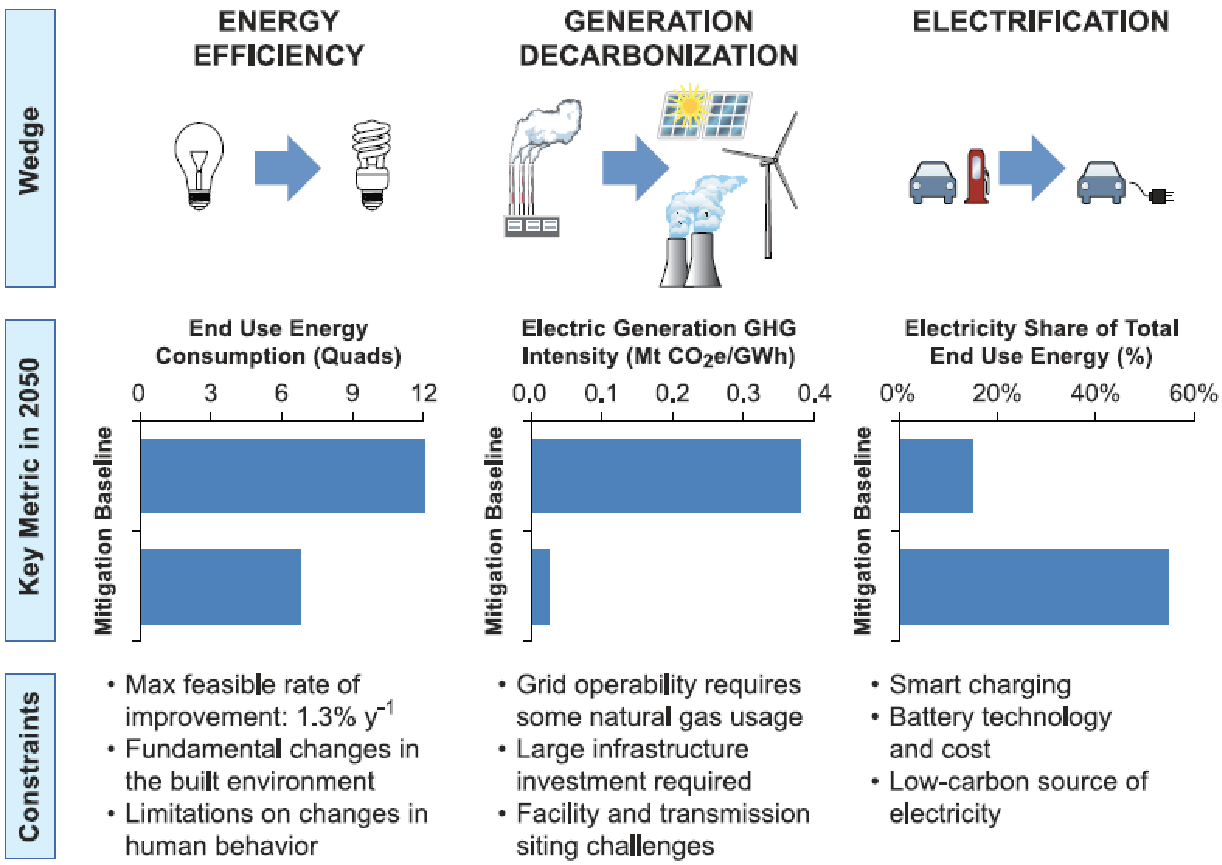


Fig. 2. The three main energy system transformations required to reduce GHG emissions 80% below 1990 levels by 2050 in California. End-use EE must be improved very aggressively (annual average rate 1.3% year^{-1}), electric generation emissions intensity must be reduced to less than 0.02 kg CO_2e/kWh, and most direct fossil fuel uses in transport, buildings, and industry must switch to electricity, raising the electricity share of end-use energy from 15% today to 55% in 2050. Both economics and the current state of technology development suggest a staged deployment in large-scale infrastructural transformation. Without aggressive levels of EE, the scale of decarbonized generation required to simultaneously replace fossil plants and meet both existing and newly electrified loads would be infeasible. Until high levels of electricity decarbonization are achieved, emission benefits from electrification would be limited. Without electrification, constraints on the other measures would limit total reductions to about 50% below 1990 levels.

[51] *The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity*. p 55

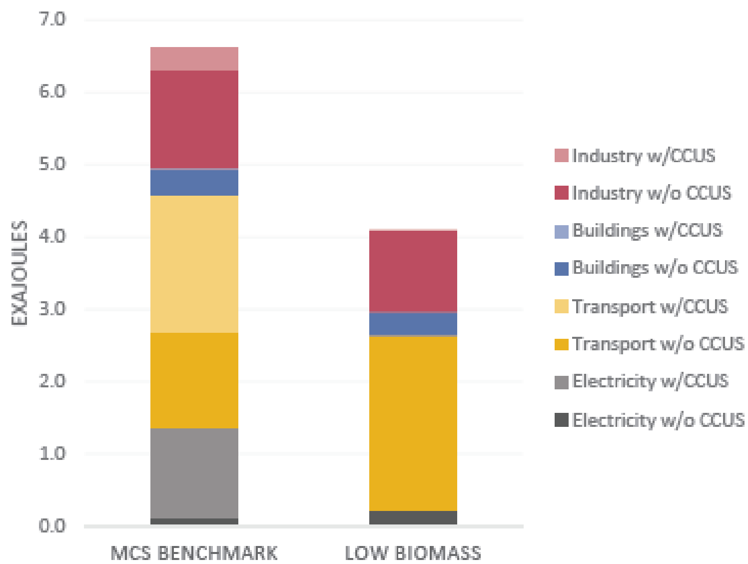
Lesson #2 Sustainable Bioenergy is Key

Sustainable bioenergy is a key strategy for a low-carbon energy system, particularly when used as a "drop in" fuel to replace liquid and gaseous fossil fuels important to energy demand subsectors that are currently challenging to electrify, e.g., aviation, freight transportation, industrial process heat, etc.

The *United States Mid-Century Strategy* found bioenergy consumption in 2050 ranging from 4.1 to 6.6 exajoules, with a large portion of biomass consumption occurring in the hard-to-electrify transportation sector as Figure 26 depicts below (CCUS is carbon capture, utilization, and storage).[52]

Figure 26. Bioenergy Use across the U.S. Energy Sector in the US Mid-Century Strategy

Bioenergy (EJ) in the MCS analysis across electricity, transport, industry, and buildings, 2050. Note that the Low Biomass scenario includes no BECCS by assumption.



Lesson #3 Capital Expense for Technology

A deeply decarbonized energy economy results in more spending on technology, such as capital investments in low-carbon equipment and infrastructure, and less spending on fossil fuel, with a relatively small net cost impact. This graphic from Volume 2 of the U.S. Deep Decarbonization Pathways Report, *Policy implications of deep decarbonization in the United States*,[53] exemplifies this lesson:

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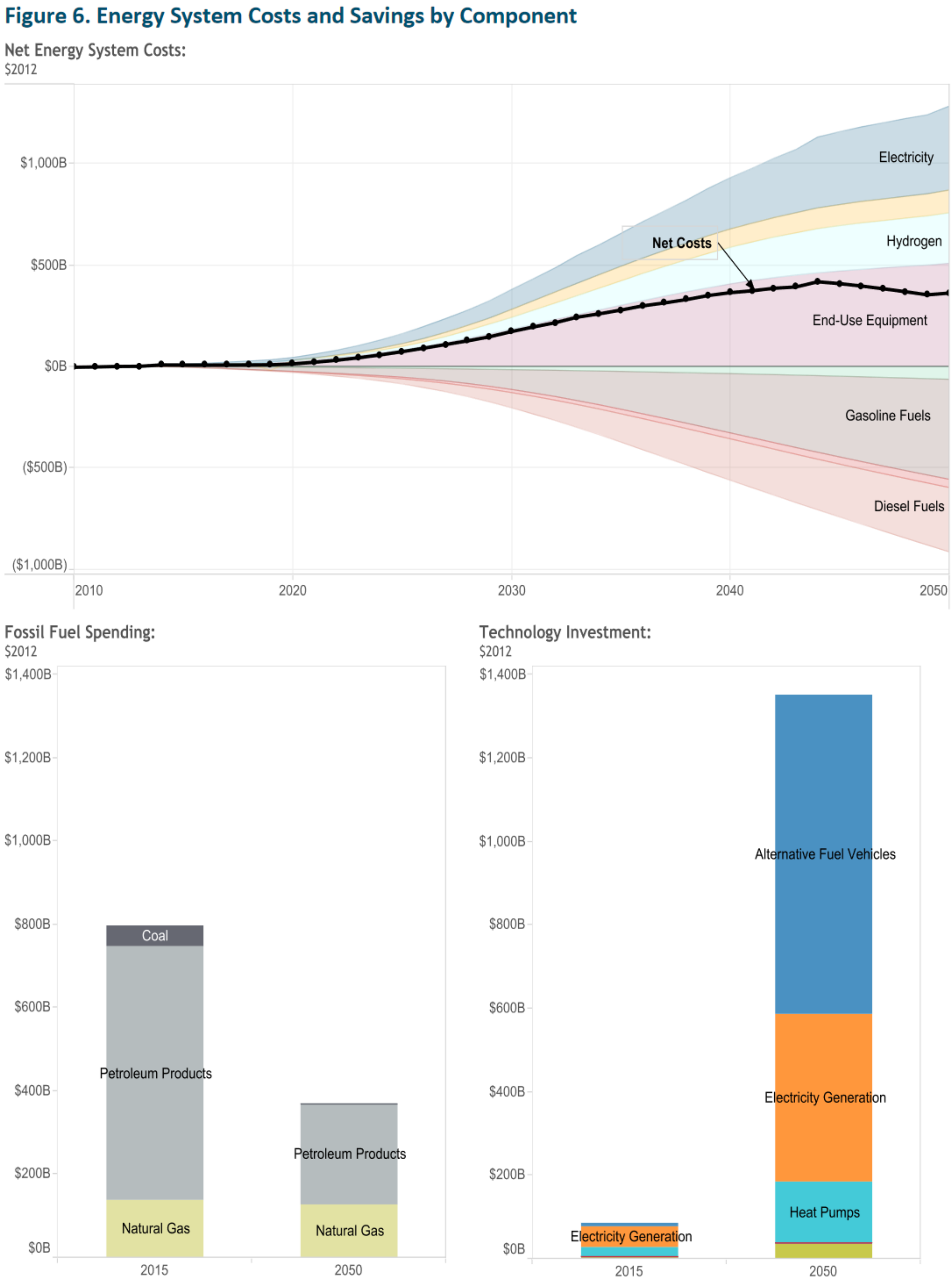
[52] Ibid, p. 59

[53] Williams, J. H., B. Haley, R. Jones (2015). *Policy implications of deep decarbonization in the United States*. A report of the Deep Decarbonization Pathways Project of the Sustainable Development Solutions Network and the Institute for Sustainable Development and International Relations. Nov. 17, 2015. p. 28. http://deepdecarbonization.org/wp-content/uploads/2015/11/US_Deep_Decarbonization_Policy_Report.pdf

Figure 27. Energy System Costs and Savings by Component

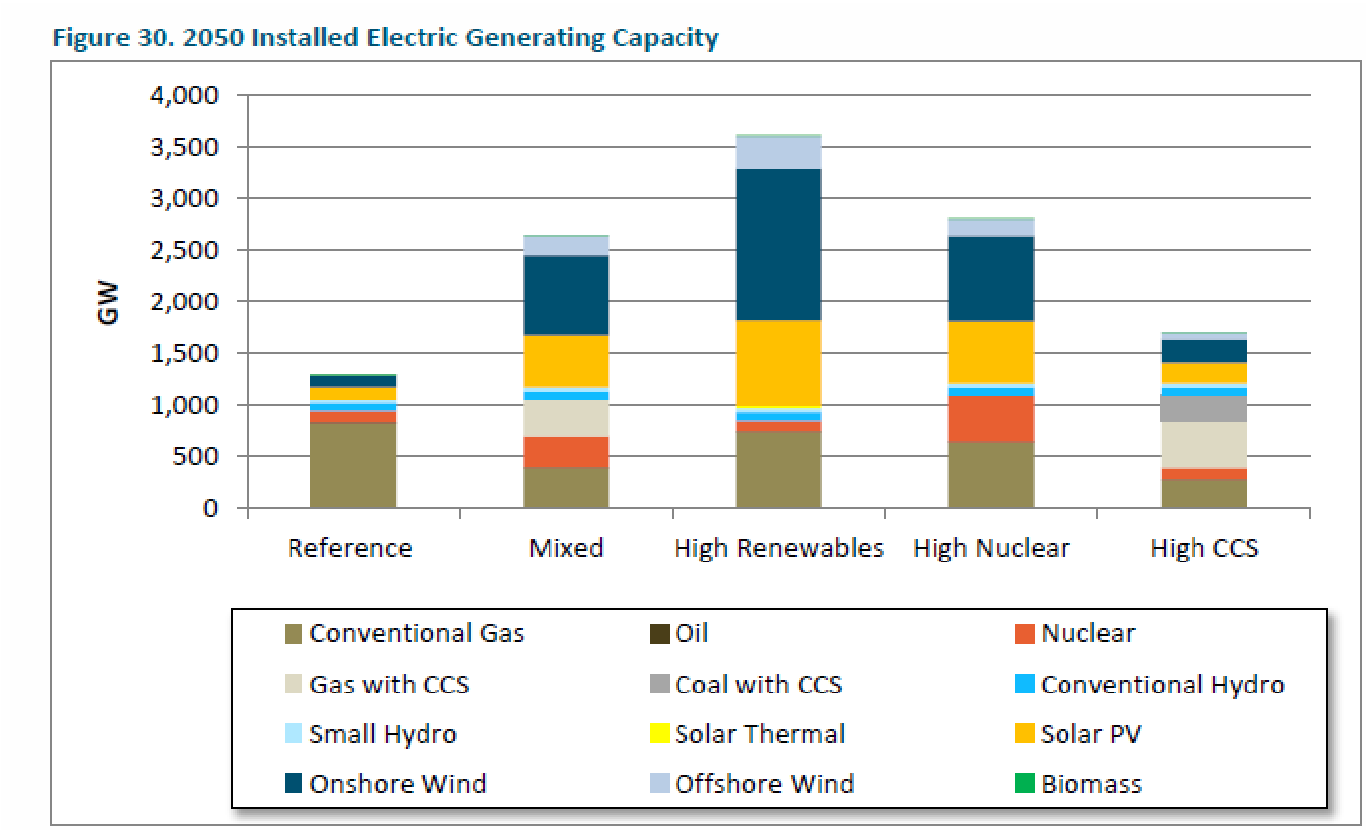


Lesson #4 Significant Increase in Electricity Supply

Electricity supply will need to grow to meet higher demand for heating water and buildings, passenger transportation, and/or producing synthetic electric fuels (hydrogen and synthetic natural gas) despite an overall decrease in energy demand. Substantial investment in low-carbon electricity generation technologies is needed and there will be large growth in variable renewable energy even when nuclear and/or CCS technologies are also deployed.

The graphic below from the *Pathways to Deep Decarbonization in the United States* study shows installed capacity in the United States 2050 with more wind and solar added in all scenarios.[54]

Figure 28. Installed Electric Generating Capacity (US DDPP 2050 Study)



Tale 4 in Figure 29 below from the *Pathways to Deep Decarbonization Pathways 2015 Report* that analyzed 16 countries shows the increase in electric generation capacity by technology from 2010-2050.[55]

[54] *Pathways to Deep Decarbonization in the United States* (2014). p. 36
[55] *Pathways to Deep Decarbonization 2015 Report*. p. 29

Figure 29. Increase Electricity Generation Capacity (DDPP 2015 Pathways Project 16-Country Analysis)

Table 4. Cumulative production of decarbonized units, all DDPP countries*

Technology		2010	2020	2030	2040	2050
Electric Generation Capacity						
Coal w/ CCS	GW	0	3	36	160	362
Fuel Oil w/CCS	GW	0	0	1	1	2
Natural gas w/ CCS	GW	0	12	93	342	798
Nuclear	GW	2	53	259	632	1053
Hydropower	GW	8	190	425	624	813
Wind-Onshore	GW	13	315	1064	2174	3511
Wind-Offshore	GW	1	29	100	268	616
Solar PV	GW	11	275	823	1752	3254
Solar Thermal	GW	0	10	90	294	598
Biomass	GW	1	26	105	221	370
Geothermal	GW	0	4	27	61	97

Lesson #5 Challenges in Balancing Electricity Supply and Demand

Balancing electricity supply and demand to successfully integrate variable renewable generation presents increased technical and economic challenges. Solving the issue of largely non-dispatchable electricity supply (i.e., wind and solar) will require demand to be flexible, the inverse of the system that operates now (dispatchable supply meeting fixed demand).

Balancing resources technologies are required to integrate variable renewable energy. They can include flexible demand met by end uses, such as smart EV charging and smart appliances, or hydrogen production through electrolysis or power to gas, as well as energy storage and hydro and thermal generation (but limited generation). The following two figures from Evolved Energy Research's study for Portland General Electric[56] demonstrates Lesson #5:

[56] *Portland General Electric Decarbonization Study: Summary of Draft Findings.* p. 37 for Figure 30 and p. 38 for Figure 31

Figure 30. Balancing Electricity Supply and Demand (EER's PGE Study)

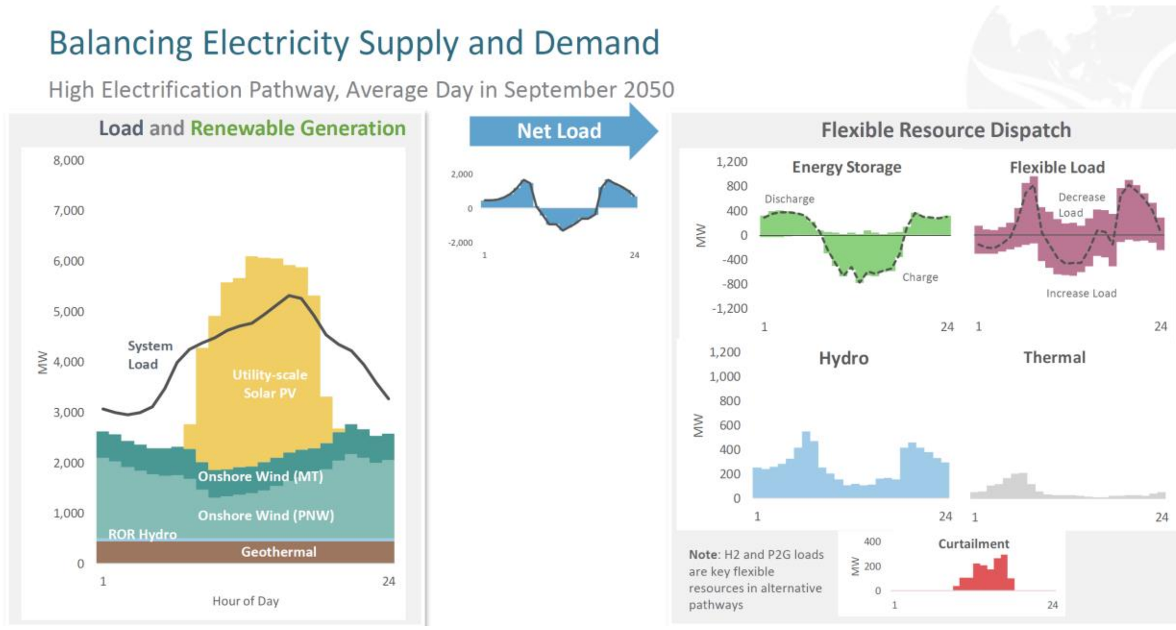
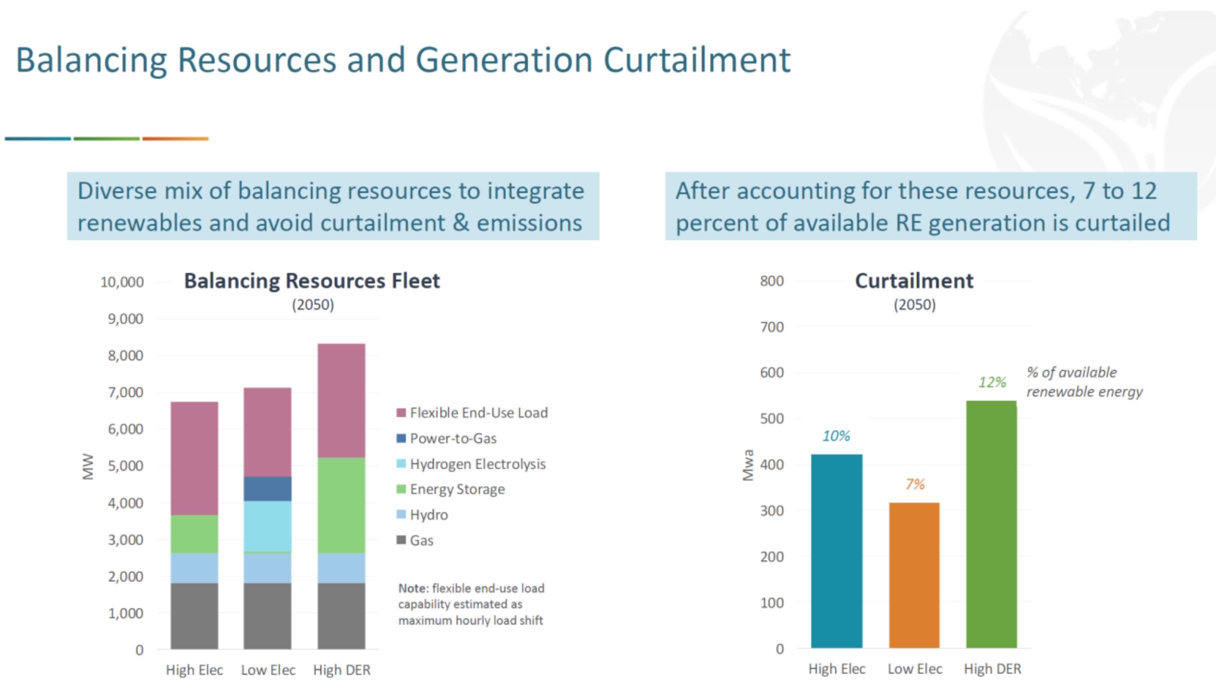


Figure 31. Balancing Resources and Generation Curtailment (EER's PGE Study)



Conclusion

In the past eight years as states and countries have become more serious about reducing carbon emissions on a timeline that might avert catastrophic climate disruption, consulting firms such as Energy+Environmental Economics (E3) and Evolved Energy Research in the United States, as well as other firms and modelers globally have developed and tested models to help governments, utilities, advocates, and policy-makers understand how to deeply decarbonize cities, states, and countries in the 2020-2050 timeframe.

Policymakers in the Northwest are fortunate that at this juncture a robust set of transparent and high-quality technical and economic models exist to evaluate feasible future emission scenarios and assess the environmental and economic implications of different GHG reduction targets and policies designed to achieve them. There are multiple models for California[57] and two pathways studies that have examined slices of the Northwest (Washington State and Portland General Electric) that provide a significant platform from which to launch an economy-wide pathways study for the Northwest that can guide policymakers, funders, legislators, local government officials, and climate advocates in advancing decarbonization strategies in Washington and Oregon.

[57] See both G. Morrison, S. Yeh, A. Eggert, C. Yang, J. Nelson, J. Greenblatt, R. Isaac, M. Jacobson, j. Johnston, D. Kammen, A. Mileva, J. Moore, D. Roland-Holst, M. Wei, J. Weyant, J. Williams, R. Williams, C. Zapata. Climatic Change. DOI 10.1007/s10584-015-1403-5. April 2, 2015. *Comparison of low-carbon pathways for California*. & S. Yeh, C. Yang, M. Gibbs, D Roland-Holst, J. Greenblatt, A. Mahone, D. Wei, G. Brinkman, J. Cunningham, A. Eggert, B. Haley, E. Hart, J. Williams. Energy Strategy Reviews 13-14 (2016) 169-180. October 21, 2016. *A modeling comparison of deep greenhouse gas emissions reduction scenarios by 2030 in California*.

Appendix A. Chronology of Economy-Wide Pathways Studies

Study	Geography	Author(s)	Year
2050 Pathways Analysis	United Kingdom	Department of Energy and Climate Change (DECC)	2010
The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity	California	Jim Williams, et al.	2012
Pathways to deep decarbonization in the United States	United States	Jim Williams, et al. (E3/LBNL/PNNL)	2014
Pathways to deep decarbonization 2015 report	Sixteen countries	Deep Decarbonization Pathways Project (DDPP)	2015
What Will the Energy Transformation Cost? Pathways for transforming the German energy system by 2050	Germany	Fraunhofer ISE	2015
California PATHWAYS: GHG Scenario Results	California	E3/LBNL	2015
Policy implications of deep decarbonization in the United States	United States	Jim Williams, et al. (DDPP)	2015
United States Mid-Century Strategy	United States	The White House	2016
From Risk to Return: Investing in a Clean Energy Economy	United States	Risky Business Project; WRI; EER	2016
Deep Decarbonization Pathways Analysis for Washington State	Washington	EER; Jim Williams (DDPP)	2017
Portland General Electric Decarbonization Study	Northwest Oregon	EER	2018

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Deep Decarbonization Pathways Project (2015). *Pathways to Deep Decarbonization 2015 report*, SDSN – IDDRI. http://deepdecarbonization.org/wp-content/uploads/2016/03/DDPP_2015_REPORT.pdf

Duane, Tim, Jonathan Koomey, Kathy Belyeu, and Karl Hausker. Risky Business Project. 2016. *From Risk to Return: Investing in a Clean Energy Economy.* http://riskybusiness.org/site/assets/uploads/sites/5/2016/10/RBP-FromRiskToReturn-WEB.pdf

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