Economic Analysis of US Decarbonization Pathways

Prepared for:

NextGen Climate America, Inc.

November 5, 2015

This study was prepared by ICF International, using data and inputs obtained from the "Pathways to Deep Decarbonization in the United States" (2014) study, conducted by the Energy and Environmental Economics (E3), Lawrence Berkeley National Laboratory (LBNL) and Pacific Northwest National Laboratory (PNNL). The study used the PATHWAYS model to develop several decarbonization scenarios and ICF was not involved in (and does not endorse) the input assumptions and scenario conclusions generated by the PATHWAYS model. Using E3's input assumptions and key PATHWAYS outputs, ICF conducted this study using REMI to estimate the economic impacts. Questions concerning the PATHWAYS modeling should be addressed to NextGen Climate America and E3.

Funding for this study was provided by NextGen Climate America, Inc.

Outline

- **Introduction**
  - Background
  - Summary of Findings
- **Methodology**
  - Economic Analysis Approach
  - Data Sources
- **Results**
  - Overall National Results
  - Distributional Results (across Regions and Sectors)
- **Conclusion**
- **Appendix**

Introduction

Background

- **E3's "*Pathways to Deep Decarbonization in the United States*" report analyzes different technological scenarios that could reduce greenhouse gas (GHG) emissions**
  - It also estimates levels of investments needed, associated costs, economy-wide energy usage changes, etc.
- **But what are the economic impacts of these changes?**
  - What sectors/regions could benefit from these changes and what sectors/regions could see declines?
- **This study attempts to determine the economic changes that these different technological paths could bring about**
  - National level
  - 9 Census Divisions
  - Different industrial sectors

Summary of Findings

- Study attempts to answer – What impact does climate change mitigation have on the economy?
- Using outputs from the PATHWAYS modeling exercise, results indicate that climate change mitigation could be economically beneficial
- Economy could add more than a million jobs by 2030 and up to 2 million jobs by 2050
- Most of the job gains could be concentrated on construction, certain manufacturing and service sectors relevant for clean energy generation and efficient consumer durables and utilities
- Larger focus on renewable generation appears to provide larger benefits in the long run
- Gains in construction, manufacturing, and other sectors outweigh losses in fossil-fuel industries resulting in a net-gain of employment across the nation
- Household disposable income increases across all regions
- Seven of the nine regions modeled gain jobs, while employment grows more slowly in the remaining two regions compared to the Reference Case (i.e., these two regions are adversely affected)

Methodology

Overall Approach

Approach

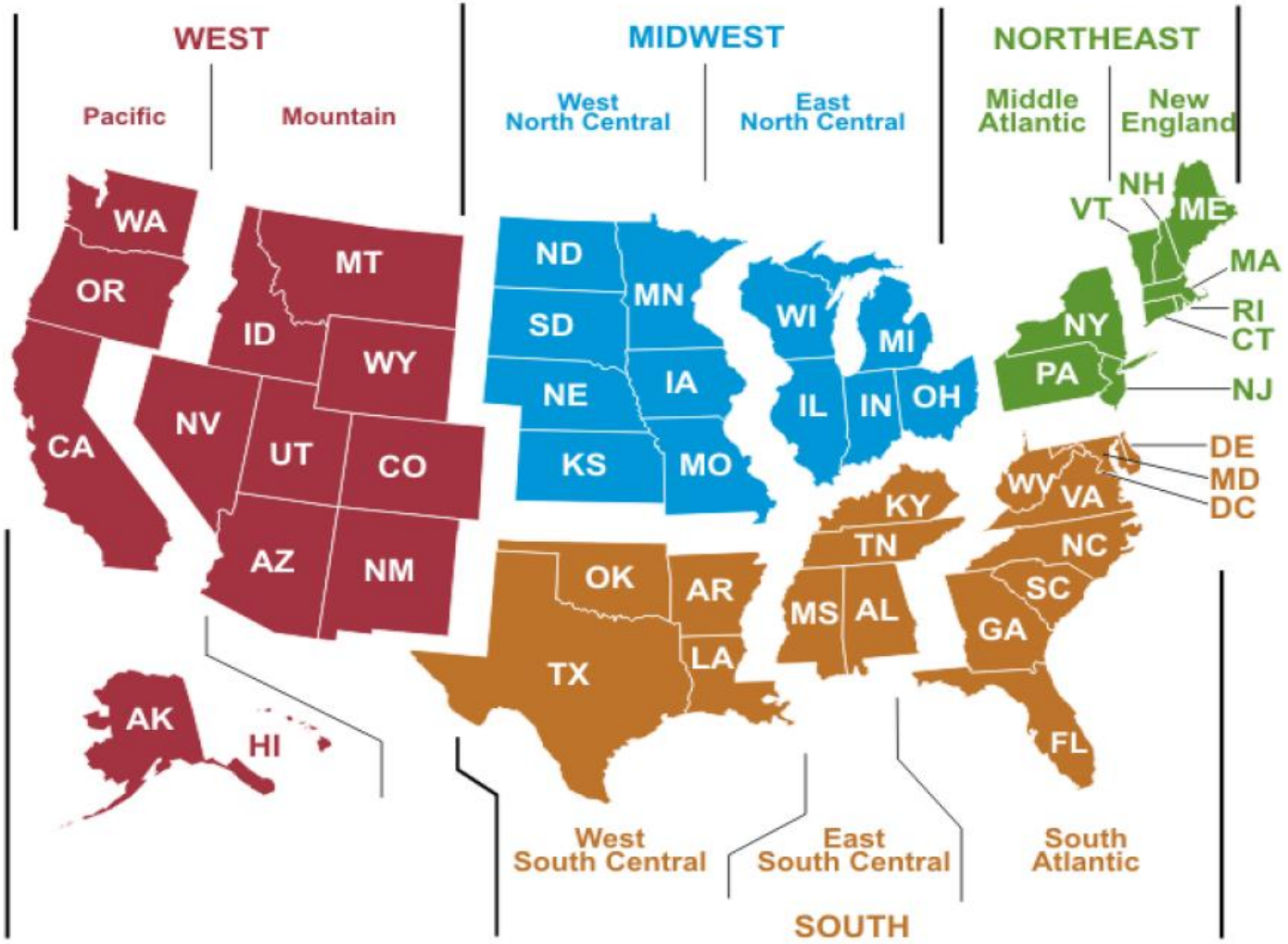
- **Used REMI Policy Insight Plus (PI+) model to analyze different decarbonization scenarios**
  - REMI is a "dynamic" regional economic impact model using a combination of input-output, econometric, and CGE modeling techniques
  - 70 NAICS-based sectors, 9 regions (Census Divisions)
  - Provides the ability to forecast economic impacts over time
  - Results are presented up to 2050 in this study
  - Sectoral and regional resolution provides ability to analyze distributional impacts
  - More details on the REMI model can be found at www.remi.com

Approach

- **Inputs to economic modeling were exclusively derived from E3's *Pathways to Deep Decarbonization in the United States* Report[1] ("Report")**
  - Modeling assumptions in REMI consistent with Report's assumptions on
    - Energy prices
    - Investment quantities
    - Energy usage
  - Obtained detailed data from E3 modelers broken down by regional and annual estimates
    - Detailed data obtained from E3 discussed in the next section
  - Meetings and discussions with E3 to ensure understanding of data and assumptions

[1]http://unsdsn.org/wp-content/uploads/2014/09/US-Deep-Decarbonization-Report.pdf

Modeling Regions in REMI



Calibrating REMI Reference Case

- **REMI Reference Case updated to better reflect current economy and PATHWAYS Reference Case**
  - Ensures consistent starting points in both models
- **Utility sector adjustments**
  - Coal sector in REMI needed updating to reflect actual state of the industry and projected losses in the business-as-usual Reference Case
  - REMI Reference Case assumes a larger decrease in utilities sector than AEO, requiring adjustments
- **PATHWAYS adjustments**
  - Energy spending by households in PATHWAYS Reference Case was different enough from REMI to require updating
  - The motor vehicle industry in REMI was projected differently compared to PATHWAYS Reference Case
    - Additional adjustments to gasoline demand
- **Reference Case adjustments do not account for "costs of inaction" to climate change**
  - Published estimates suggests those costs could be up to 5% of global GDP with confidence intervals extending that from 2.5% to 20%[1]

[1]Tol, R. S. (2014). Correction and Update: The Economic Effects of Climate Change. *Journal of Economic Perspectives, 28*(2), 221-226.

Methodology

PATHWAYS DATA

Decarbonization Strategies

- **Energy Efficiency**
  - Lower energy consumption
  - Appliances, lighting, building shells, engines, and more
- **Energy Supply Decarbonization**
  - Lower GHG emissions from energy sources and fuels
    - Decreases mostly in coal and gas generation
    - Increase in renewable generation, nuclear, natural gas with carbon capture and storage (CCS)
    - Low or zero carbon fuels (synthetic methane, hydrogen)
- **Fuel Switching**
  - Appliances and vehicles electrified
  - Internal Combustion Engine (ICE) vehicles converted to alternative fuels
  - Industrial energy usage changes
    - No coal, reduced natural gas
    - Replaced by electricity and synthetic methane

Additional Infrastructure Investments

- **Additional investments required in fueling infrastructure**
  - Electric vehicle (EV) and Plug-in hybrid electric vehicle (PHEV) charging stations
  - Compressed natural gas (CNG) and liquefied natural gas (LNG) fueling stations
  - Hydrogen fueling stations
- **Significant investments in transmission and distribution network**
  - To support renewable energy sources which are typically not located near load centers
- **Some scenarios require significant hydrogen fuel**
  - Hydrogen production facilities using electrolysis
    - Use of electricity to drive chemical reaction forming hydrogen
  - Synthetic methane production facilities using power to gas
    - Uses electricity to create hydrogen and combine with CO_2 to create methane

High Renewables Case and Mixed Case

- **Decarbonization strategies are implemented differently under two cases**
- **High Renewables Case**
  - Differentiated by significant renewable generation
    - Solar, onshore wind, and offshore wind
  - Electric and plug-in-hybrid electric light duty vehicles
  - Synthetic methane used as pipeline gas in industrial and commercial sectors
    - Requires large investments in production facilities
- **Mixed Case**
  - Electricity generation is balanced between renewables, nuclear, and natural gas with CCS.
  - Electric, plug-in-hybrid, and hydrogen fuel cell light duty vehicles

Energy Efficiency

- **In order to reduce energy demand, high efficiency appliances replace older inefficient appliances**
  - Residential and Commercial appliance purchases benefit retail, installers, manufacturing
- **Utilities often offer rebates for more efficient appliance purchases**
- **Conceptually, they are investments in reducing future energy consumption and future energy costs**
  - Appliance investments are modeled as costs in REMI, reducing consumers' ability to purchase other good and services, assuming constant budget
- **Summary of Appliance Inputs (Change from Reference Case, $ Billions)**

	2025	2030	2050
Increased investment in appliances - Residential			
High Renewables and Mixed	$22	$28	$47
Increased investment in appliances - Commercial			
High Renewables and Mixed	$23	$28	$35

Energy Efficiency

- **Bill savings due to lower energy bills**
  - Efficient end-use of energy in appliances leads to reduced energy demand and lower energy costs or bill savings
  - These savings drive positive economic impacts as the saved money gets spent on other goods and services
  - Reductions in energy use extend beyond the modeling time frame, particularly for appliance purchases occurring towards the end of our modeling period

- **Summary of Consumer Bill Savings (Change from Reference Case, $ Billions)**

	2025	2030	2050
Bill Savings - Residential			
High Renewables	$0.6	$5.3	$41
Mixed	$2.2	$8.8	$51

Energy Supply Decarbonization

- **Shift in construction from conventional to clean generation**
  - Job gains from investments in new types of power plants
  - Job losses from not building conventional plants

- **Investment in New Generation ($ Billions)**

	2025	2030	2050
COAL			
Reference	**$32**	**$33**	**$1**
High Renewables	$11	$9	$0
Mixed	$11	$9	$0
NATURAL GAS			
Reference	**$10**	**$12**	**$38**
High Renewables	$8	$14	$35
Mixed	$12	$29	$105
NUCLEAR			
Reference	**$35**	**$13**	**$0**
High Renewables	$35	$13	$0
Mixed	$73	$50	$37
RENEWABLES			
Reference	**$187**	**$301**	**$413**
High Renewables	$221	$510	$997
Mixed	$217	$399	$671

Fuel Switching

- **ICE vehicles bought in Reference Case are no longer purchased**
  - Replaced by EVs and PHEVs in High Renewables Case and Mixed Case
  - Also replaced by hydrogen fuel cell vehicles (HFCVs) in Mixed Case
  - Heavy Duty and Medium Duty Vehicles to CNG, LNG, and High Efficiency Diesel

- **Summary of Transportation Inputs ($ Billions)**

	2025	2030	2050
ICE VEHICLES			
Reference	**$521**	**$526**	**$665**
High Renewables	$328	$60	$0
Mixed	$377	$162	$41
DECARBONIZED VEHICLES			
Reference	**$5**	**$7**	**$14**
High Renewables	$273	$621	$850
Mixed	$202	$469	$777
ICE FUELS - GAS & DIESEL			
Reference	**$543**	**$565**	**$912**
High Renewables	$460	$358	$89
Mixed	$480	$403	$149
DECARBONIZED FUELS - ELECTRICITY, H2, CNG, LNG			
Reference	**$20**	**$22**	**$38**
High Renewables	$61	$147	$592
Mixed	$51	$125	$496

Fuel Switching

- **Residential and Commercial gas appliances to electricity**
  - For example, gas water heaters replaced with one using electricity
- **Industrial coal, coke, and petroleum to electricity and pipeline gas (synthetic methane)**
  - For example, basic oxygen furnaces converted to electric arc furnaces for iron and steel production
- **Summary of Fuel Cost Inputs (Change from Reference Case, $ Billions)**

	2025	2030	2050
COAL, COKE, PETROLEUM FUELS			
High Renewables	-$16	-$31	-$105
Mixed	-$15	-$28	-$94
PIPELINE GAS			
High Renewables	$2	$12	$121
Mixed	$2	$6	-$41

Additional Infrastructure Investments

- **Infrastructure buildout of transmission and distribution network**
  - Renewable energy sources need to be connected to load centers
- **Fueling and charging stations for new vehicle technologies**
  - Retrofitting existing gas stations or building new stations
- **Production facilities for new fuel types (hydrogen and synthetic methane)**
- **Summary of Infrastructure Inputs (Change from Reference Case, $ Billions)**

	2025	2030	2050
Transmission and Distribution			
High Renewables	$20	$37	$159
Mixed Case	$9	$15	$51
New Fueling and Charging Stations			
High Renewables	$21	$52	$49
Mixed Case	$27	$67	$48
New Fuel Production Facilities			
High Renewables	$3	$72	$117
Mixed Case	$10	$39	$21

Summary of Total Inputs

		2025	2030	2050
Investments ($ Billions)				
	Reference Case GDP	**$20,708**	**$22,765**	**$31,317**
	High Renewables	$50-80	$150-200	$600 - 800
	% Change	*0.2% - 0.4%*	*0.7% - 0.9%*	*1.9% - 2.6%*
	Mixed	$50-80	$150-200	$300 - 500
	% Change	*0.2% - 0.4%*	*0.7% - 0.9%*	*1.0% - 1.6%*

- **PATHWAYS based total investment amounts in the national economy shown above**
  - 2030 investment amounts could top ~$200 billion, or close to 1% of national GDP
  - 2050 amounts could be around 2.5% of the Reference Case GDP in the High Renewables Case, 1.6% in the Mixed Case
  - These investment amounts drive additional economic activities throughout the economy, as resources are transferred between different sectors
  - Also has an effect in crowding out other forms on investments

Modeling Results

Summary National Impacts

National Level Employment (Thousands)

	2020	2025	2030	2040	2050
Reference Case	**193,838**	**194,673**	**194,628**	**204,788**	**214,384**
High Renewables	194,163	195,175	195,737	206,393	216,367
Difference	**325**	**501**	**1,110**	**1,605**	**1,983**
% Change	**0.2%**	**0.3%**	**0.6%**	**0.8%**	**0.9%**
Mixed Case	194,125	195,283	195,635	205,743	215,347
Difference	**288**	**610**	**1,008**	**955**	**963**
% Change	**0.1%**	**0.3%**	**0.5%**	**0.5%**	**0.4%**

- **Significant job gains nationally across both scenarios and over the entire modeling period**
  - High RE could add up to 2 million jobs by 2050
- **Job gains are comparable for both scenarios around 2030 (about a million jobs), but High RE shows bigger gains over the long run than the Mixed Case**
  - Consistent with the patterns of investment needs discussed above

National Level GDP ($ Billion)

	2020	2025	2030	2040	2050
Reference Case	**$18,745**	**$20,708**	**$22,765**	**$26,746**	**$31,317**
High Renewables	$18,772	$20,760	$22,910	$26,959	$31,607
Difference	**26**	**52**	**145**	**213**	**290**
% Change	**0.1%**	**0.3%**	**0.6%**	**0.8%**	**0.9%**
Mixed Case	$18,770	$20,777	$22,909	$26,921	$31,500
Difference	**24**	**69**	**144**	**175**	**183**
% Change	**0.1%**	**0.3%**	**0.6%**	**0.7%**	**0.6%**

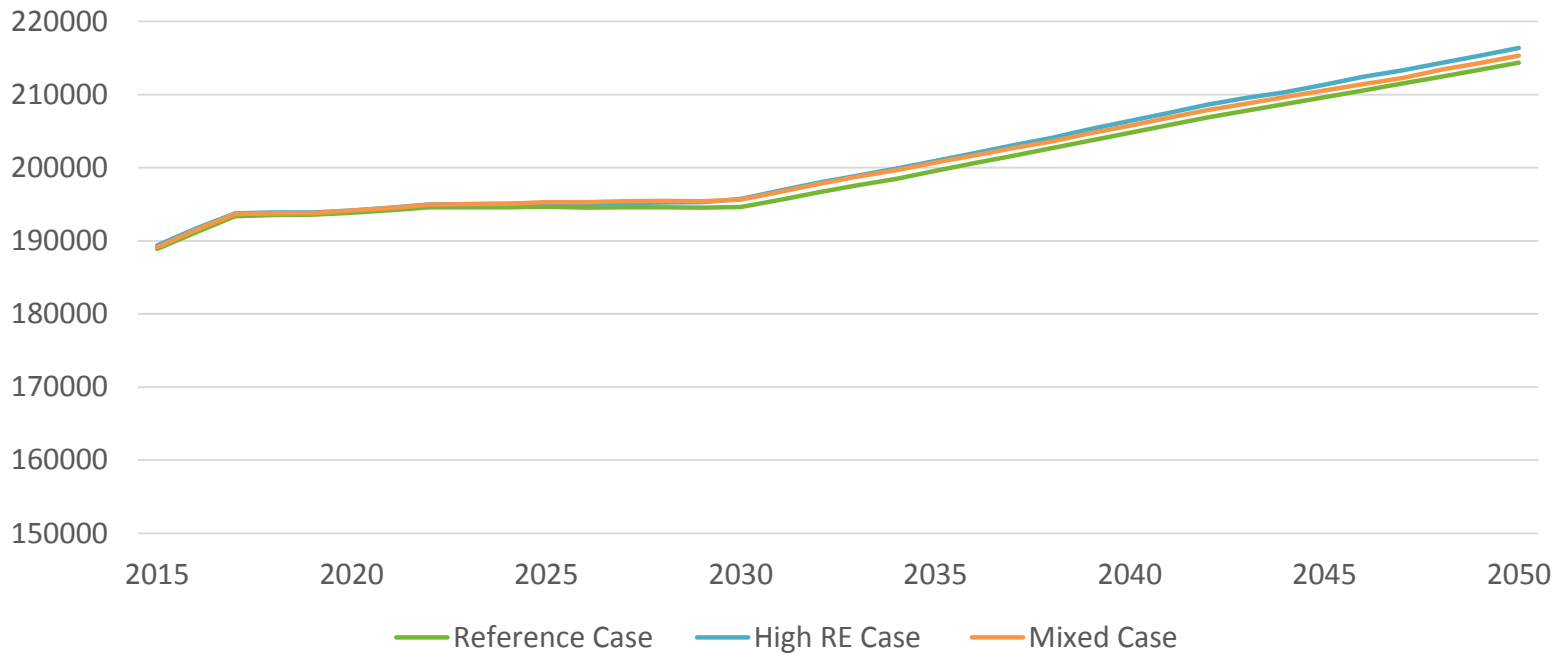
- **GDP impact trends are similar to the employment results**
  - Impacts comparable across both scenarios around 2030
    - About a half percentage point increase over the Reference Case
  - High RE Case shows more pronounced impacts in the long run
    - Close to a full percentage point more than the Reference Case

National Level Disposable Income per Household ($)

	2020	2025	2030	2040	2050
Reference Case	$110,635	$120,597	$129,933	$140,034	$153,600
High Renewables	$110,701	$120,725	$130,318	$140,589	$154,255
Difference	$65	$127	$385	$555	$654
Mixed Case	$110,700	$120,776	$130,283	$140,420	$153,928
Difference	$64	$179	$350	$386	$328

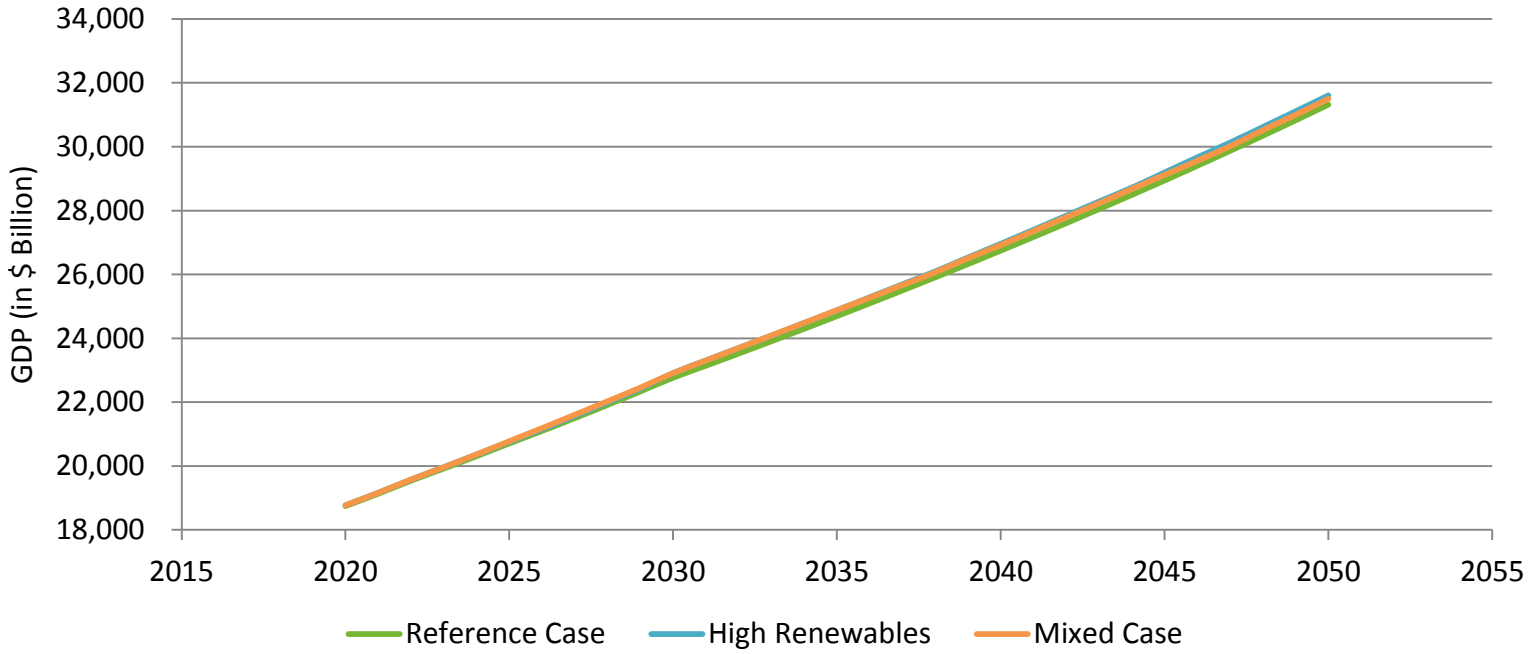
- **Disposable income per household increases from the Reference Case under both High Renewables and Mixed cases**
  - Steadily increases through 2050
- **Increases are larger under the High Renewables Case in the long run**
  - By 2050 the High Renewables Case increase over the Reference Case is about twice as large as the Mixed Case
  - Results are consistent with patterns seen for GDP and employment

Employment Impacts: 2020-2050



- **Economy continues to grow along the same trajectory as Reference Case**
  - But with consistently higher levels of employment throughout than Reference Case
  - Even with some sectors having job losses, discussed below
  - High RE and Mixed Cases track together until diverging around 2035

GDP Impacts: 2020-2050

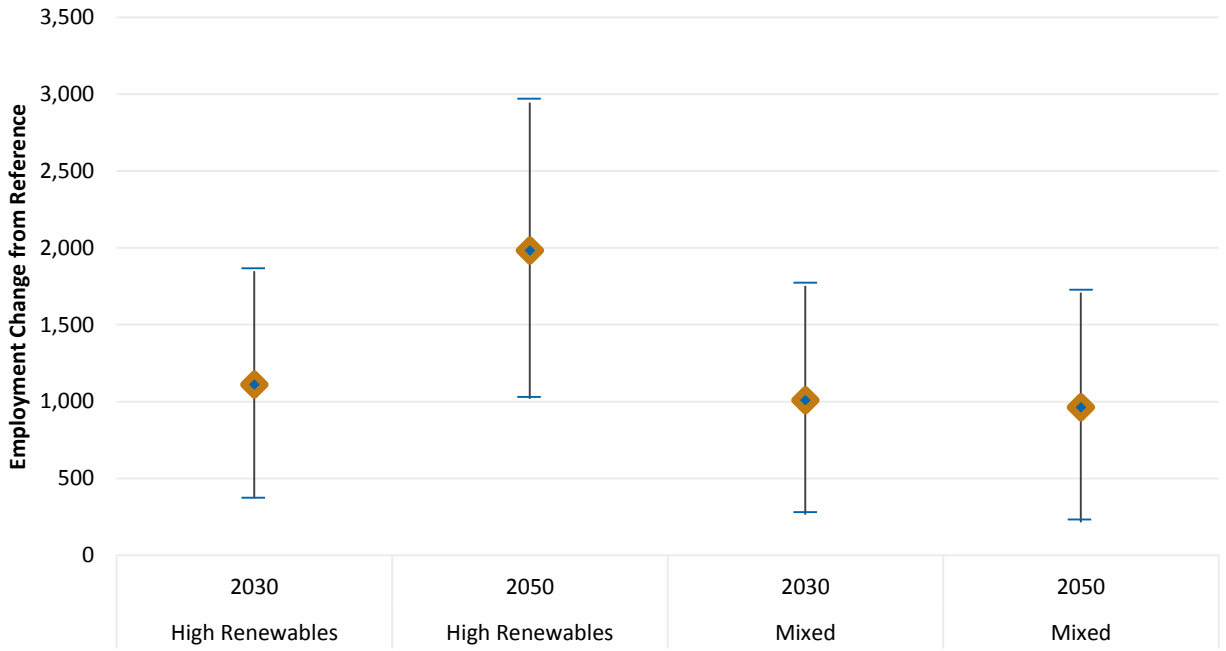


- **Deep decarbonization could be beneficial for economic growth**
  - Under the assumptions of this study, significant investments needed for decarbonization provides a positive boost to the economy
- **Temporal patterns in GDP growth rates are similar to employment**
  - Slightly higher rates of growth under the High Renewables Case than the Mixed Case

Sensitivity of Results

- **Results presented in this study are likely to have significant uncertainties associated with modeling inputs**
  - Formal uncertainty analysis was outside the scope of the current study
- **Modeling incorporates a certain amount of crowding out effect of the significant investment levels required for decarbonization**
  - High levels of investments in decarbonization could increase economy's borrowing costs and crowd out other investment options
- **Modeling assumes investments in clean energy reduces resources available for other non-residential capital spending**
  - Effectively increases the borrowing costs for these investments
  - Crowds out other investment options in the absence of these needs

Sensitivity of Results



- **Considerable uncertainty exists on these countervailing effects**
  - Results indicate net job impacts could vary from about 200,000 to about 2 million in 2030 and from 200,000 to close to 3 million in 2050, depending on how much other investments are crowded out
- **Overall job impacts are modelled to be positive even if borrowing costs are high**

Modeling Results

Sectoral/Regional Impacts

Regional Disposable Income per Household Changes ($)

- Disposable income per household increases across all regions throughout the modeling period
- West South Central sees the largest gain of almost $1,000 per household
  - Likely indication of a smaller labor force due to job losses compared to the Reference Case (discussed below)
  - Could also be driven by improved job quality in the clean energy economy
- In 2030, Mixed Case results are larger than High Renewables Case in 3 regions
- In 2050, High Renewables Case results are larger in all 9 regions

		2030	2050
New England			
	High Renewables	570.2	521.3
	Mixed Case	487.5	337.5
Middle Atlantic			
	High Renewables	584.5	689.1
	Mixed Case	455.3	420.8
South Atlantic			
	High Renewables	454.4	570.0
	Mixed Case	251.5	411.4
East North Central			
	High Renewables	452.5	483.7
	Mixed Case	371.5	227.2
East South Central			
	High Renewables	512.4	976.9
	Mixed Case	396.0	426.8
West North Central			
	High Renewables	338.9	227.6
	Mixed Case	352.0	52.4
West South Central			
	High Renewables	4.5	998.5
	Mixed Case	326.0	316.6
Mountain			
	High Renewables	106.0	468.0
	Mixed Case	247.4	98.0
Pacific			
	High Renewables	346.3	626.6
	Mixed Case	338.7	323.5

Regional Population Changes (Thousands)

- Some population movement occurs across regions as economy transitions to clean energy
  - Changes less than 10k are likely in the noise level
- Regions with significant deep decarbonization benefits see slightly higher population growth compared to Reference Case
  - South Atlantic (in absolute terms) and New England (in percentages) see the largest changes from Ref Case growth
- Regions where fossil-fuel industries see declines face slightly lower population growth compared to Ref Case
  - Regional population still grows over time but rates are slightly reduced compared to Ref Case

		2030	2050
New England	Reference Case Level	16,244	18,340
	High Renewables	+61	+149
	Mixed Case	+30	+94
Middle Atlantic	Reference Case Level	45,860	51,106
	High Renewables	+53	+145
	Mixed Case	-9	+132
South Atlantic	Reference Case Level	69,716	76,122
	High Renewables	+170	+382
	Mixed Case	+163	+112
East North Central	Reference Case Level	49,537	52,959
	High Renewables	+160	+257
	Mixed Case	+113	+38
East South Central	Reference Case Level	20,545	22,044
	High Renewables	+34	+125
	Mixed Case	+47	-6
West North Central	Reference Case Level	23,397	25,936
	High Renewables	+25	+86
	Mixed Case	+24	+38
West South Central	Reference Case Level	44,919	51,151
	High Renewables	-322	-594
	Mixed Case	-190	-392
Mountain	Reference Case Level	26,892	29,902
	High Renewables	-158	-443
	Mixed Case	-126	-163
Pacific	Reference Case Level	58,961	67,164
	High Renewables	-27	-126
	Mixed Case	-55	+133

Regional Employment (Thousands)

- Table shows actual levels of employment changes across various regions
- 7 of the 9 regions show job gains in 2030 and 2050 under both scenarios
- Job gains are larger in 2030 and 2050 under High Renewables Case for 5 regions
- Pacific region shows larger job gains in 2050 under Mixed Case
- West South Central and Mountain region see job losses under both cases in 2030 and 2050

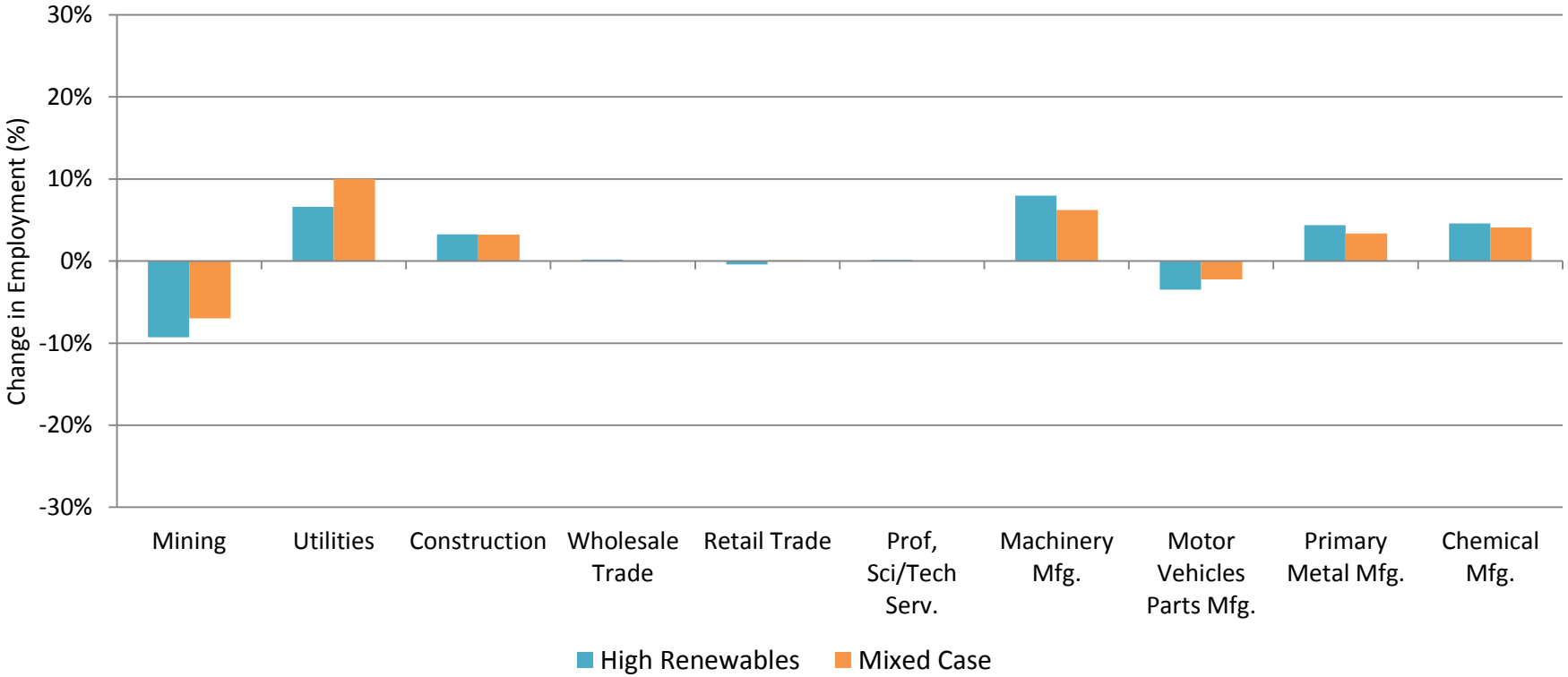
		2030	2050
New England			
	High Renewables	108	187
	Mixed Case	79	113
Middle Atlantic			
	High Renewables	219	369
	Mixed Case	149	257
South Atlantic			
	High Renewables	402	672
	Mixed Case	303	339
East North Central			
	High Renewables	266	384
	Mixed Case	215	101
East South Central			
	High Renewables	99	226
	Mixed Case	93	39
West North Central			
	High Renewables	83	122
	Mixed Case	84	36
West South Central			
	High Renewables	-163	-106
	Mixed Case	-35	-182
Mountain			
	High Renewables	-53	-142
	Mixed Case	-10	-52
Pacific			
	High Renewables	149	270
	Mixed Case	131	312

Regional GDP Changes ($ Billion)

- Changes in GDP similar to employment changes
- 7 Regions show increase in GDP
  - Largest is South Atlantic in 2050 under High Renewables Case
- 2 Regions show decreases in GDP
- Generally, regional GDP gains are larger under the High Renewables case
  - Except Pacific region where gains are larger under the Mixed case

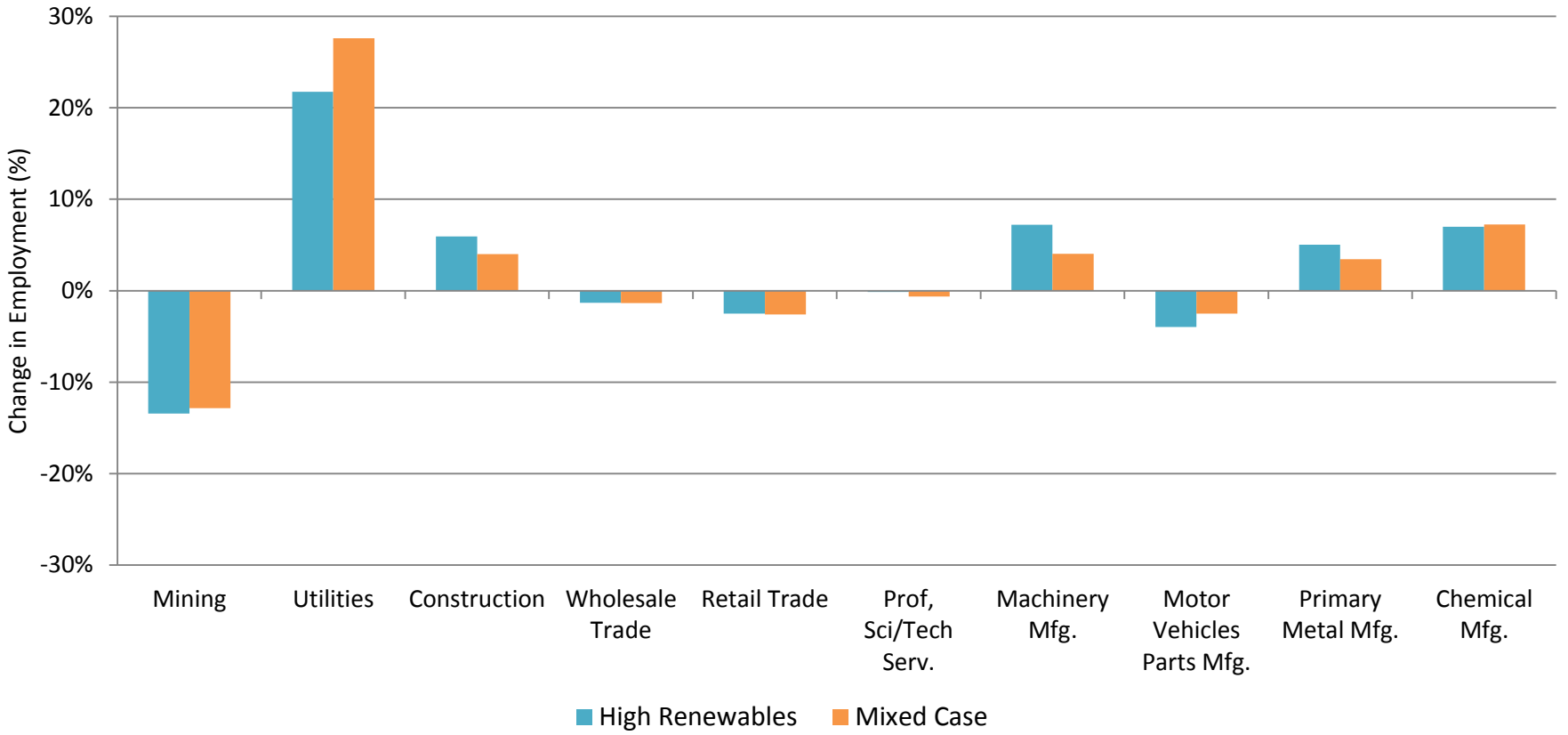
		2030	2050
New England			
	High Renewables	16.0	30.2
	Mixed Case	12.2	20.4
Middle Atlantic			
	High Renewables	31.5	57.2
	Mixed Case	22.2	43.4
South Atlantic			
	High Renewables	51.6	113.3
	Mixed Case	39.8	67.0
East North Central			
	High Renewables	38.9	61.7
	Mixed Case	34.5	26.5
East South Central			
	High Renewables	13.3	34.0
	Mixed Case	13.3	14.9
West North Central			
	High Renewables	11.6	18.9
	Mixed Case	13.3	12.6
West South Central			
	High Renewables	-26.0	-24.8
	Mixed Case	-3.8	-28.9
Mountain			
	High Renewables	-9.3	-29.8
	Mixed Case	-2.7	-12.3
Pacific			
	High Renewables	17.4	29.1
	Mixed Case	15.5	39.5

Sectoral Employment (2030)



- Construction sector shows the largest gains with over 400,000 additional jobs
- Manufacturing also gains, led by machinery manufacturing, as well as some metals and chemicals
- Mining (includes O/G and coal) has the largest job losses among sectors
  - Wholesale/retail trades have some losses under specific scenario/years
- Mining losses are roughly equally spread in absolute terms between O/G and coal

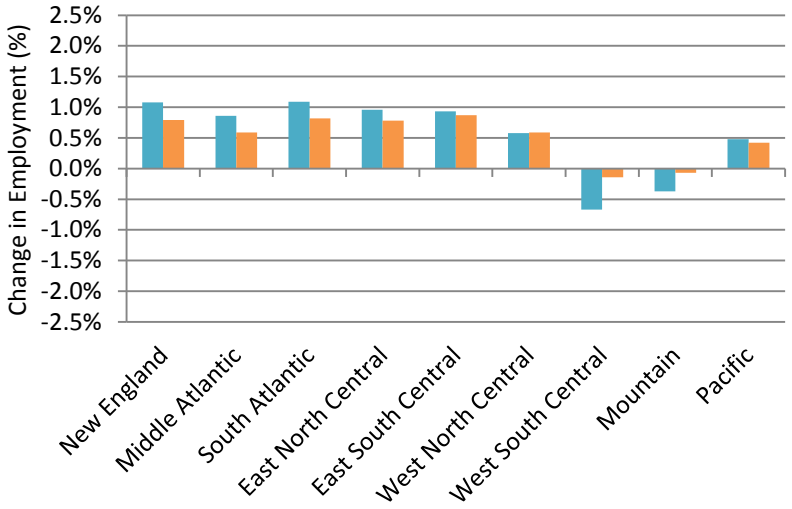
Sectoral Employment (2050)

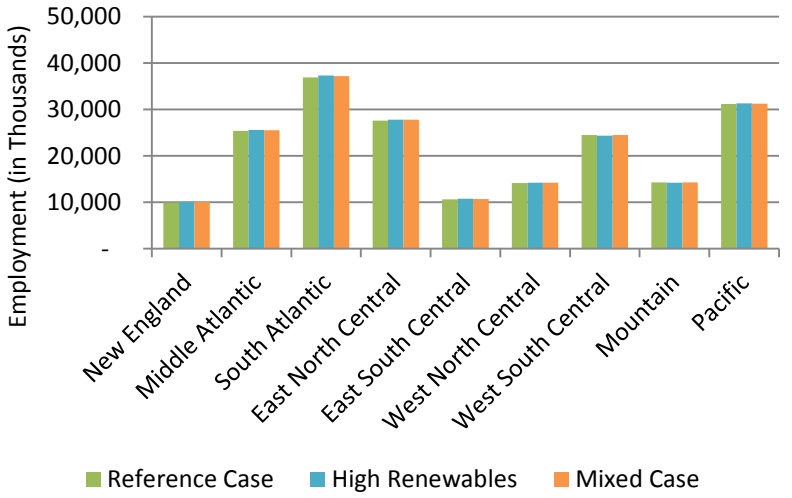


- Construction jobs increase the most, by over 1 million in the High Renewables Case
- Utilities gain around 100k by 2050, which translates to highest gains in percentages

Regional Employment (2030)

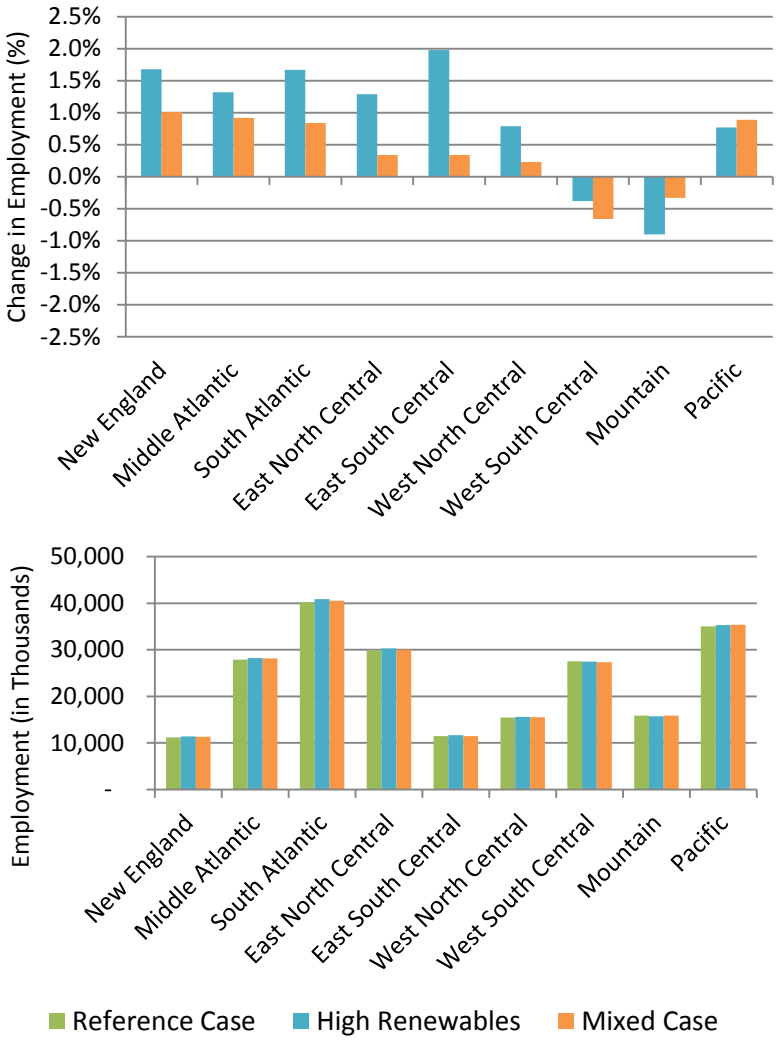
- **Regionally, 7 out of 9 Census Divisions have net positive job gains under both scenarios**
  - Only the Mountain and West South Central regions have net job losses
  - Highly correlated to the shift away from fossil fuels predominant in these regions
- **Differences in absolute employment levels among cases are small across all regions**
  - Including the two regions with job losses





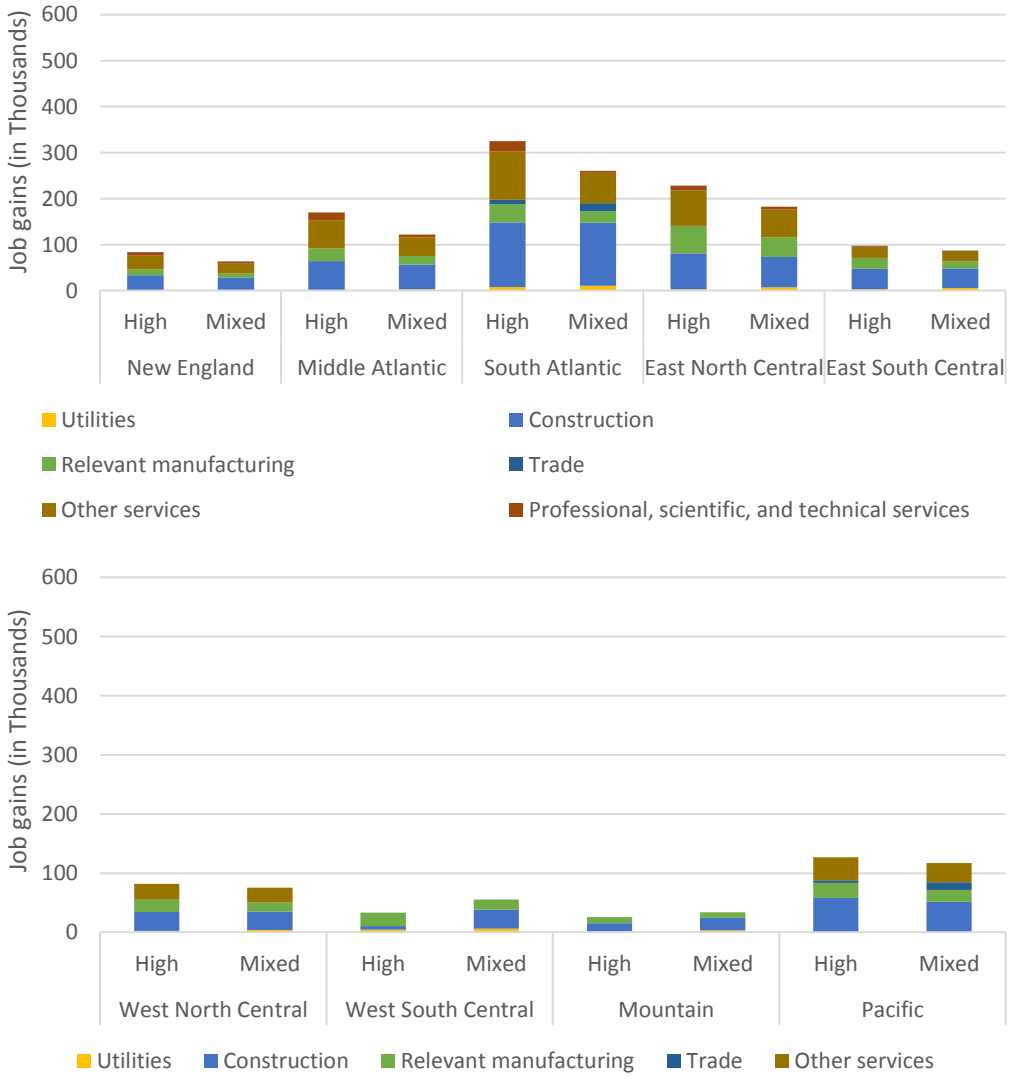
Regional Employment (2050)

- **Similar patterns emerge for 2050, though effects are more pronounced**
  - Highest absolute gains are in the South Atlantic (over 600k) and East North Central (close to 400k)
  - Job gains top almost two percentage points for East South Central (over 225k job gains)
  - Losses for Mountain and West South Central, in absolute terms, are between 50k and 200k in both regions under both scenarios



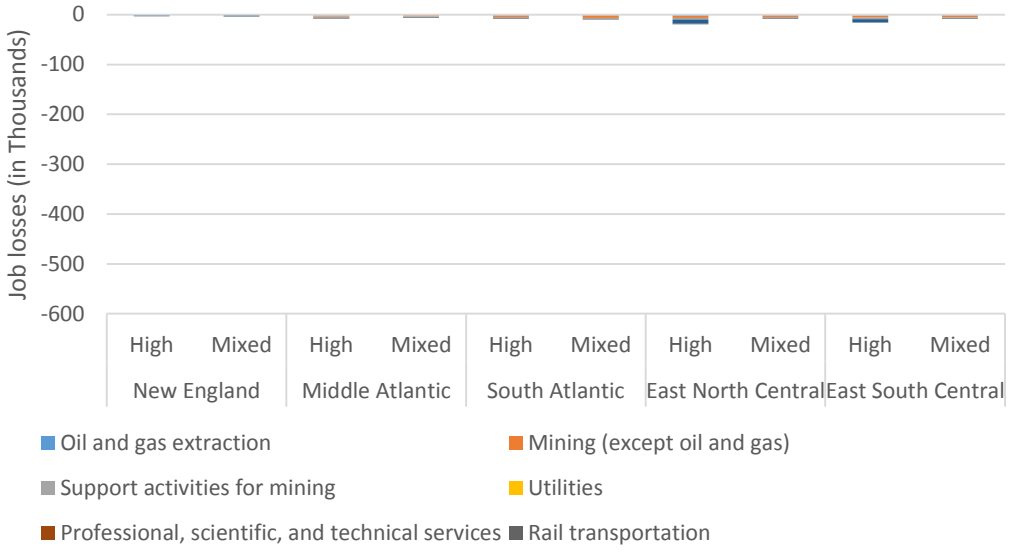
Sectoral Employment: Job Gains (2030)

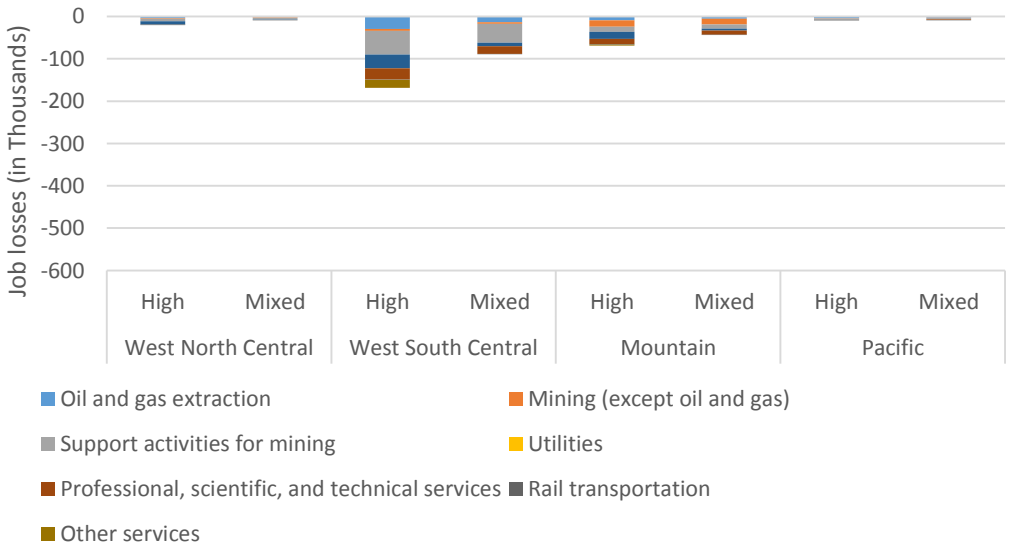
- Construction sector sees job gains in all regions and cases
  - South Atlantic sees largest gains in both cases due to lots of offshore wind being built
- Services sector is the other large gainer in most regions and cases
  - Not just technical services to transition to clean economy but also "support" services like health services, education, etc.
- Utilities also gain across all regions and cases



Sectoral Employment: Job Losses (2030)

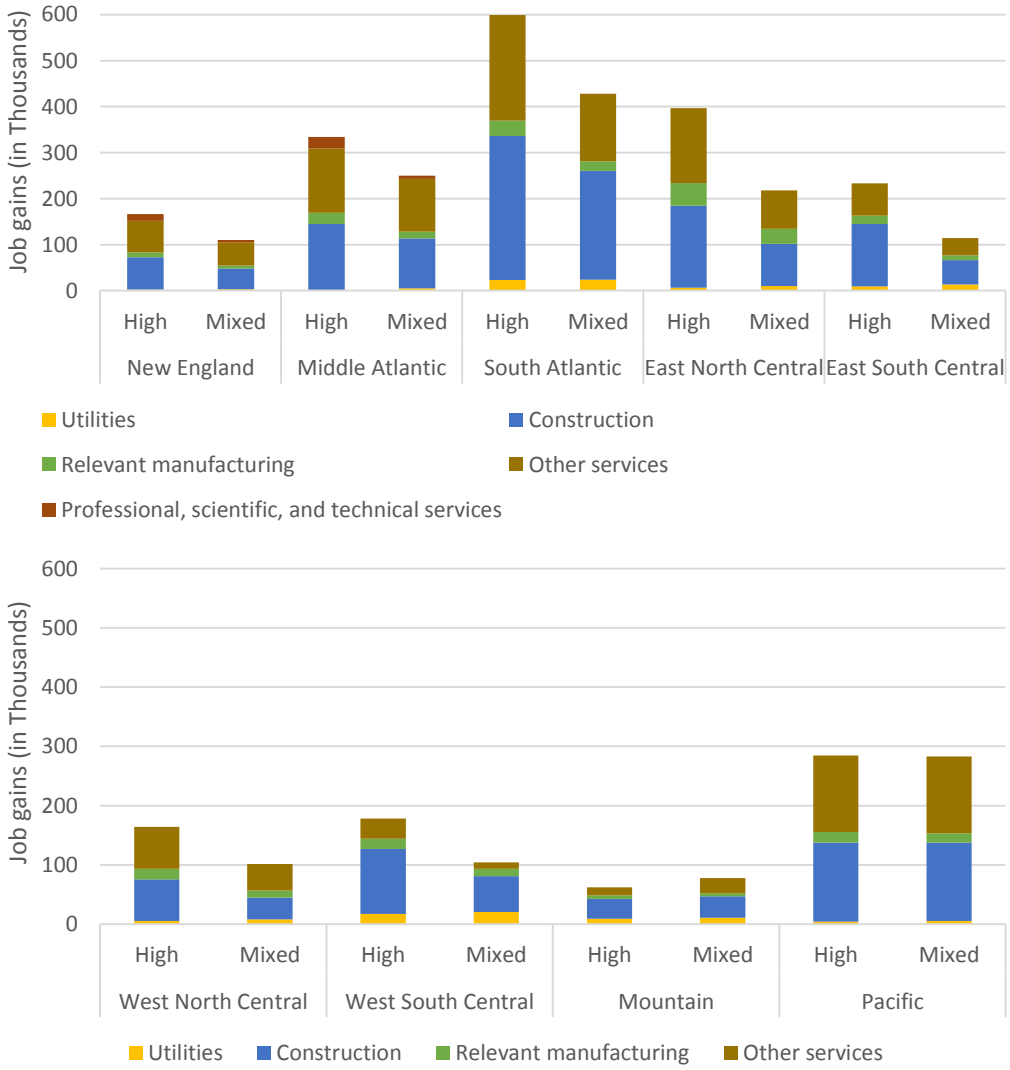
- Losses are primarily concentrated around fossil-fuel based industries
  - Job losses in Eastern Regions (top graph) are very small
- West South Central and Mountain regions see the most declines
- Mining related jobs in the professional, scientific, and technical services sector loses jobs in some regions





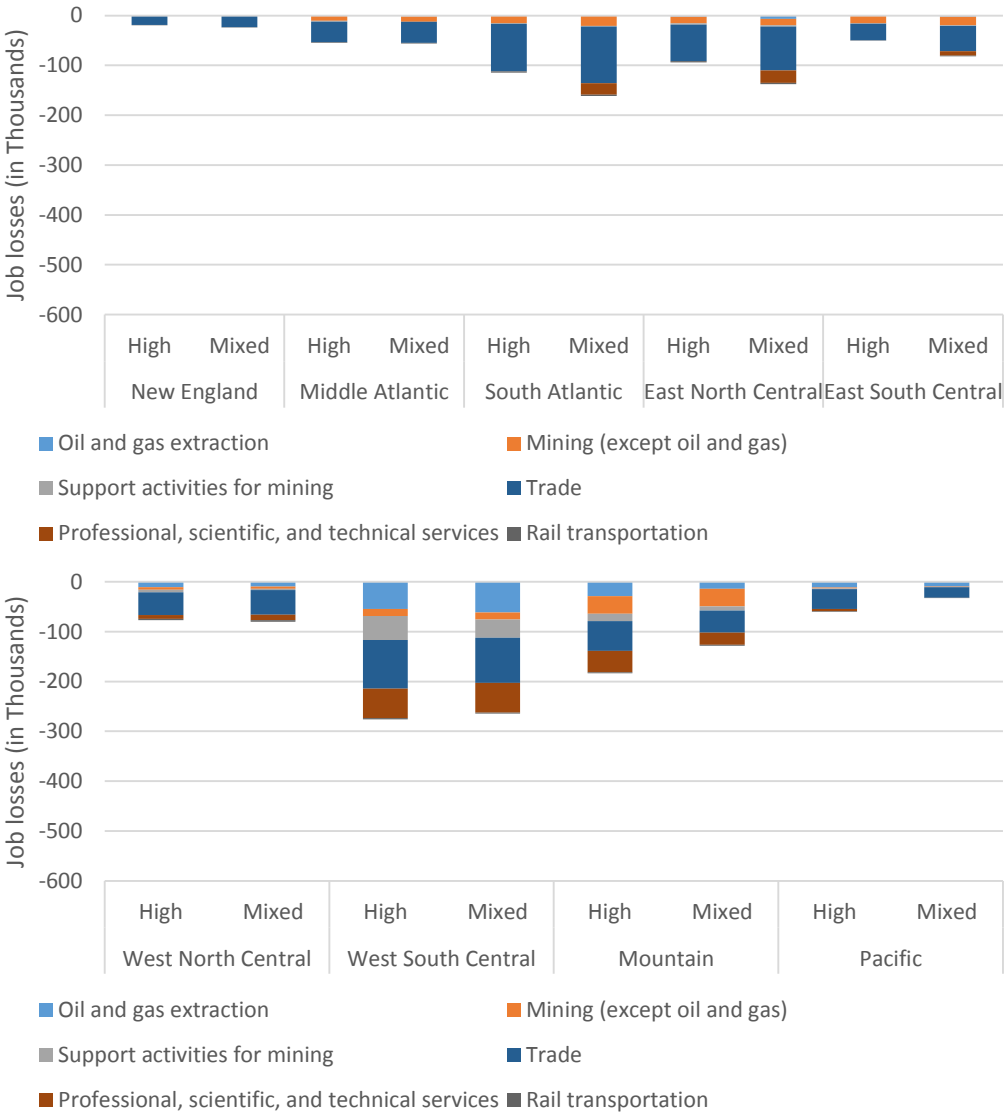
Sectoral Employment: Job Gains (2050)

- Most job gains are still in construction and other services sectors
- Construction gains are larger than in 2030 due to increasing construction of renewables generation and other clean energy infrastructure
- New England and Middle Atlantic see gains in professional, scientific, and technical services sector
- Utilities also gain across all regions and cases



Sectoral Employment: Job Losses (2050)

- Job losses in fossil fuel sectors are visible in all regions as the economy completes transition to clean economy
- Job losses in trade (includes both retail and wholesale) occur across all regions
  - Gas stations shut down (although some are replaced by Hydrogen fueling and EV charging stations), people driving fewer miles
- West South Central region sees the most job losses
  - All losses are highly correlated with fossil-fuel economy that has been replaced



Conclusion

Concluding Thoughts

- Deep decarbonization of the US economy is likely to be economically beneficial overall, using the PATHWAYS based modeling assumptions
  - There could be over a million jobs gained through decarbonization by 2030
  - By 2050, those gains could be up to 2 million under certain scenarios
- Household disposable income is also likely to increase in all regions under both scenarios
- Demand to increase electricity generation from renewable sources leads to significant job gains for building and operating new generating sources
  - Construction, manufacturing, and utilities would be big beneficiaries of decarbonization
- But, there is likely to be job losses in some sectors, related to fossil-based energy production (mining, oil/gas, gas stations, etc.)
  - As more and more energy needs are transferred to an expanded electricity network
  - Workers in the fossil sectors (under the Ref Case) are likely to find jobs in the decarbonized economy with additional training/upskilling
  - New jobs are likely to be better quality than the jobs lost
- Results do not include any costs of inaction under business-as-usual
  - Published estimates suggests those costs could be up to 5% of global GDP with confidence intervals extending that from 2.5% to 20%
  - Also do not include ancillary benefits to public health and national security in decarbonization

Appendix

Supplemental Tables and Figures

Appendix

- The following slides provide additional details on the input data used for the economic modeling
- Appendix also includes additional results, broken down by modeling regions and sectors

Inputs: Investment in New Generation by Fuel Type ($ Billion)

		2030	2050
COAL			
	Reference	**44.26**	**0.51**
	High Renewables	15.61	0.00
	% Change	*-65%*	*-100%*
	Mixed	15.61	0.00
	% Change	*-65%*	*-100%*
NATURAL GAS			
	Reference	**12.60**	**71.38**
	High Renewables	13.75	58.52
	% Change	*9%*	*-18%*
	Mixed	26.15	236.20
	% Change	*>100%*	*>100%*
NUCLEAR			
	Reference	**13.15**	**0.00**
	High Renewables	13.15	0.00
	% Change	*0%*	*0%*
	Mixed	50.53	37.38
	% Change	*>100%*	*>100%*
WIND - OFFSHORE and ONSHORE			
	Reference	**88.06**	**95.28**
	High Renewables	221.63	379.75
	% Change	*>100%*	*>100%*
	Mixed	151.16	222.61
	% Change	*72%*	*>100%*
HYDRO			
	Reference	**4.06**	**2.79**
	High Renewables	4.96	2.36
	% Change	*22%*	*-15%*
	Mixed	4.96	2.36
	% Change	*22%*	*-15%*
SOLAR PV			
	Reference	**6.87**	**24.51**
	High Renewables	44.26	166.03
	% Change	*>100%*	*>100%*
	Mixed	26.21	104.51
	% Change	*>100%*	*>100%*
TRANSMISSION and DISTRIBUTION			
	Reference	**201.86**	**290.21**
	High Renewables	238.88	449.29
	% Change	*18%*	*55%*
	Mixed	217.15	341.24
	% Change	*8%*	*18%*

Inputs: Fuel Costs for Electric Generation ($ Billion)

		2030	2050
COAL			
	Reference	**48.21**	**57.86**
	High Renewables	31.17	0.00
	% Change	*-35%*	*-100%*
	Mixed	32.14	0.00
	% Change	*-33%*	*-100%*
NATURAL GAS			
	Reference	**61.12**	**144.82**
	High Renewables	39.36	20.08
	% Change	*-36%*	*-86%*
	Mixed	48.72	119.24
	% Change	*-20%*	*-18%*
Uranium			
	Reference	**6.76**	**6.76**
	High Renewables	10.51	18.00
	% Change	*55%*	*>100%*
	Mixed	6.76	6.76
	% Change	*0%*	*0%*
OIL			
	Reference	**0.03**	**0.02**
	High Renewables	0.02	0.00
	% Change	*-54%*	*-98%*
	Mixed	0.02	0.00
	% Change	*-47%*	*-92%*

Inputs: Fuel Costs ($ Billion)

- **Totals for residential, commercial, and industrial sectors**

		2030	2050
COAL and COKE			
	Reference	**7.41**	**7.58**
	High Renewables	5.10	0.93
	% Change	*-31%*	*-88%*
	Mixed	5.12	0.96
	% Change	*-31%*	*-87%*
PIPELINE GAS			
	Reference	**155.34**	**261.84**
	High Renewables	174.09	440.63
	% Change	*12%*	*68%*
	Mixed	163.71	238.31
	% Change	*5%*	*-9%*
RESIDUAL FUEL OIL			
	Reference	**13.75**	**20.33**
	High Renewables	9.42	4.99
	% Change	*-31%*	*-75%*
	Mixed	9.42	4.99
	% Change	*-31%*	*-75%*
PETROLEUM BASED (Gas, diesel, kerosene, LPG)			
	Reference	**72.93**	**106.36**
	High Renewables	48.97	23.69
	% Change	*-33%*	*-78%*
	Mixed	51.27	34.47
	% Change	*-30%*	*-68%*

Inputs: Energy Costs by Sector ($ Billions)

		2030	2050
RESIDENTIAL			
	Reference	**298.56**	**435.31**
	High Renewables	293.30	394.34
	Change (% Change)	**-5.26 (-2%)**	**-40.97 (-9%)**
	Mixed	289.77	384.06
	Change (% Change)	**-8.79 (-3%)**	**-51.26 (-12%)**
COMMERCIAL			
	Reference	**267.40**	**390.22**
	High Renewables	276.45	449.76
	Change (% Change)	**9.05 (3%)**	**59.54 (15%)**
	Mixed	273.37	433.11
	Change (% Change)	**5.97 (2%)**	**42.89 (11%)**
INDUSTRIAL			
	Reference	**288.90**	**420.51**
	High Renewables	351.09	766.40
	Change (% Change)	**62.19 (22%)**	**345.89 (82%)**
	Mixed	356.95	655.93
	Change (% Change)	**68.05 (24%)**	**235.42 (56%)**

Inputs : Investments in High Efficiency Appliances ($ Billions)

		2030	2050
RESIDENTIAL			
	Reference	**110.06**	**136.76**
	High Renewables	137.97	183.86
	% Change	*25%*	*34%*
	Mixed Case	137.97	183.86
	% Change	*25%*	*34%*
COMMERCIAL			
	Reference	**150.23**	**184.08**
	High Renewables	177.85	219.40
	% Change	*18%*	*19%*
	Mixed Case	177.85	219.40
	% Change	*18%*	*19%*

Inputs: Investment in Vehicles by Fuel Type ($ Billion)

- **Total investment in light duty vehicles, medium duty vehicles, and heavy duty vehicles**

		2030	2050
ELECTRICITY (EV and PHEV)			
	Reference	**4.25**	**8.05**
	High Renewables	527.27	690.22
	% Change	*>100%*	*>100%*
	Mixed	284.45	459.17
	% Change	*>100%*	*>100%*
HYDROGEN			
	Reference	**0.03**	**0.08**
	High Renewables	16.86	30.99
	% Change	*>100%*	*>100%*
	Mixed	141.07	241.12
	% Change	*>100%*	*>100%*
CNG/LNG			
	Reference	**1.03**	**4.25**
	High Renewables	65.83	111.74
	% Change	*>100%*	*>100%*
	Mixed	34.67	62.54
	% Change	*>100%*	*>100%*
GAS and DIESEL			
	Reference	**526.38**	**664.74**
	High Renewables	59.79	0.00
	% Change	*-89%*	*-100%*
	Mixed	162.18	41.43
	% Change	*-69%*	*-94%*

Inputs: Fuel Costs for Vehicles by Fuel Type ($ Billion)

- **Total fuel costs of light duty vehicles, medium duty vehicles, and heavy duty vehicles**

		2030	2050
ELECTRICITY			
	Reference	**9.74**	**13.20**
	High Renewables	44.33	157.45
	% Change	*>100%*	*>100%*
	Mixed	30.68	114.12
	% Change	*>100%*	*>100%*
HYDROGEN			
	Reference	**0.02**	**0.05**
	High Renewables	22.60	94.25
	% Change	*>100%*	*>100%*
	Mixed	50.89	220.36
	% Change	*>100%*	*>100%*
CNG/LNG			
	Reference	**12.01**	**25.21**
	High Renewables	79.87	340.78
	% Change	*>100%*	*>100%*
	Mixed	43.16	161.05
	% Change	*>100%*	*>100%*
GAS and DIESEL			
	Reference	**564.69**	**911.58**
	High Renewables	357.90	89.45
	% Change	*-37%*	*-90%*
	Mixed	402.73	148.84
	% Change	*-29%*	*-84%*

Additional Results: Changes in National Level Sectoral Employment (Thousands)

		2030	2050
Mining			
	High Renewables	-178.2	-282.3
	Mixed Case	-133.9	-270.2
Utilities			
	High Renewables	27.8	78.7
	Mixed Case	42.1	99.8
Construction			
	High Renewables	465.8	1,186.3
	Mixed Case	462.0	799.5
Wholesale Trade			
	High Renewables	12.2	-78.6
	Mixed Case	-3.3	-80.3
Retail Trade			
	High Renewables	-73.2	-425.0
	Mixed Case	18.3	-443.1
Prof, Sci/Tech Serv.			
	High Renewables	22.2	-28.1
	Mixed Case	-6.2	-136.0
Machinery Mfg.			
	High Renewables	64.8	56.1
	Mixed Case	50.7	31.4
Motor Vehicles Parts Mfg.			
	High Renewables	-23.6	-28.1
	Mixed Case	-15.1	-17.8
Primary Metal Mfg.			
	High Renewables	11.5	10.3
	Mixed Case	8.8	7.0
Chemical Mfg.			
	High Renewables	28.0	29.4
	Mixed Case	24.9	30.4

Additional Results: Changes in Regional Level Sectoral Employment (Thousands)

NEW ENGLAND		2030	2050
Mining			
	High Renewables	-0.1	0.8
	Mixed Case	0.0	0.0
Utilities			
	High Renewables	1.3	2.2
	Mixed Case	1.8	3.0
Construction			
	High Renewables	32.1	70.3
	Mixed Case	26.8	45.1
Wholesale Trade			
	High Renewables	1.2	-1.7
	Mixed Case	0.4	-2.3
Retail Trade			
	High Renewables	-3.5	-16.9
	Mixed Case	-3.3	-21.1
Prof, Sci/Tech Serv.			
	High Renewables	7.7	14.7
	Mixed Case	4.8	5.1
Machinery Mfg.			
	High Renewables	2.9	2.5
	Mixed Case	2.2	1.2
Motor Vehicles Parts Mfg.			
	High Renewables	0.2	0.5
	Mixed Case	0.2	0.6
Primary Metal Mfg.			
	High Renewables	0.5	0.5
	Mixed Case	0.3	0.2
Chemical Mfg.			
	High Renewables	1.3	1.4
	Mixed Case	1.2	1.4

MIDDLE ATLANTIC		2030	2050
Mining			
	High Renewables	-7.0	-12.1
	Mixed Case	-5.9	-11.3
Utilities			
	High Renewables	1.6	1.9
	Mixed Case	2.8	5.1
Construction			
	High Renewables	63.0	143.0
	Mixed Case	53.8	108.5
Wholesale Trade			
	High Renewables	3.9	-4.8
	Mixed Case	0.7	-6.2
Retail Trade			
	High Renewables	-5.0	-36.6
	Mixed Case	-0.9	-36.4
Prof, Sci/Tech Serv.			
	High Renewables	16.9	25.2
	Mixed Case	6.9	6.8
Machinery Mfg.			
	High Renewables	6.3	5.9
	Mixed Case	4.1	2.5
Motor Vehicles Parts Mfg.			
	High Renewables	-0.1	0.3
	Mixed Case	0.1	0.7
Primary Metal Mfg.			
	High Renewables	1.8	1.8
	Mixed Case	1.3	1.1
Chemical Mfg.			
	High Renewables	4.6	4.8
	Mixed Case	4.1	4.8

SOUTH ATLANTIC		2030	2050
Mining			
	High Renewables	-6.2	-5.2
	Mixed Case	-8.0	-20.1
Utilities			
	High Renewables	8.2	23.0
	Mixed Case	10.4	24.0
Construction			
	High Renewables	140.4	313.0
	Mixed Case	137.3	236.3
Wholesale Trade			
	High Renewables	4.9	-14.7
	Mixed Case	0.0	-16.7
Retail Trade			
	High Renewables	4.9	-80.0
	Mixed Case	17.4	-97.1
Prof, Sci/Tech Serv.			
	High Renewables	22.5	36.2
	Mixed Case	4.0	-23.1
Machinery Mfg.			
	High Renewables	8.5	8.0
	Mixed Case	5.3	4.1
Motor Vehicles Parts Mfg.			
	High Renewables	-1.5	-1.1
	Mixed Case	-0.8	-0.3
Primary Metal Mfg.			
	High Renewables	1.2	1.1
	Mixed Case	1.0	0.9
Chemical Mfg.			
	High Renewables	5.0	5.4
	Mixed Case	4.5	5.7

Additional Results: Changes in Regional Level Sectoral Employment (Thousands)

EAST NORTH CENTRAL		2030	2050
Mining			
	High Renewables	-9.5	-18.3
	Mixed Case	-6.9	-22.2
Utilities			
	High Renewables	3.4	6.5
	Mixed Case	7.0	9.8
Construction			
	High Renewables	77.7	178.0
	Mixed Case	66.5	91.8
Wholesale Trade			
	High Renewables	2.7	-10.9
	Mixed Case	0.1	-13.9
Retail Trade			
	High Renewables	-11.3	-62.2
	Mixed Case	1.2	-73.8
Prof, Sci/Tech Serv.			
	High Renewables	10.5	3.5
	Mixed Case	6.3	-25.1
Machinery Mfg.			
	High Renewables	20.3	18.2
	Mixed Case	16.3	10.1
Motor Vehicles Parts Mfg.			
	High Renewables	-14.4	-19.3
	Mixed Case	-10.3	-14.5
Primary Metal Mfg.			
	High Renewables	3.5	3.1
	Mixed Case	2.6	2.0
Chemical Mfg.			
	High Renewables	6.1	6.1
	Mixed Case	5.2	5.9

EAST SOUTH CENTRAL		2030	2050
Mining			
	High Renewables	-8.7	-16.2
	Mixed Case	-7.7	-21.0
Utilities			
	High Renewables	3.4	9.4
	Mixed Case	5.6	13.6
Construction			
	High Renewables	44.5	135.4
	Mixed Case	42.9	52.8
Wholesale Trade			
	High Renewables	-0.2	-5.8
	Mixed Case	-0.4	-6.3
Retail Trade			
	High Renewables	-6.4	-27.4
	Mixed Case	0.3	-44.3
Prof, Sci/Tech Serv.			
	High Renewables	2.1	7.0
	Mixed Case	0.4	-9.0
Machinery Mfg.			
	High Renewables	4.6	4.5
	Mixed Case	3.1	1.5
Motor Vehicles Parts Mfg.			
	High Renewables	-5.5	-6.7
	Mixed Case	-3.8	-4.9
Primary Metal Mfg.			
	High Renewables	1.3	1.1
	Mixed Case	0.9	0.8
Chemical Mfg.			
	High Renewables	1.8	1.9
	Mixed Case	1.6	1.8

WEST NORTH CENTRAL		2030	2050
Mining			
	High Renewables	-11.3	-21.0
	Mixed Case	-7.8	-16.9
Utilities			
	High Renewables	2.4	5.3
	Mixed Case	4.2	7.8
Construction			
	High Renewables	31.9	70.2
	Mixed Case	30.5	36.7
Wholesale Trade			
	High Renewables	0.3	-7.1
	Mixed Case	0.0	-7.1
Retail Trade			
	High Renewables	-8.1	-38.8
	Mixed Case	-0.3	-41.8
Prof, Sci/Tech Serv.			
	High Renewables	0.2	-7.4
	Mixed Case	0.2	-11.2
Machinery Mfg.			
	High Renewables	8.7	8.3
	Mixed Case	7.5	5.2
Motor Vehicles Parts Mfg.			
	High Renewables	-1.2	-1.4
	Mixed Case	-0.6	-0.6
Primary Metal Mfg.			
	High Renewables	0.7	0.6
	Mixed Case	0.5	0.4
Chemical Mfg.			
	High Renewables	1.9	1.9
	Mixed Case	1.6	1.9

Additional Results: Changes in Regional Level Sectoral Employment (Thousands)

WEST SOUTH CENTRAL		2030	2050
Mining			
	High Renewables	-89.8	-116.8
	Mixed Case	-62.3	-112.0
Utilities			
	High Renewables	4.8	16.9
	Mixed Case	6.0	20.3
Construction			
	High Renewables	5.6	109.8
	Mixed Case	32.3	60.4
Wholesale Trade			
	High Renewables	-3.0	-15.6
	Mixed Case	-2.6	-15.0
Retail Trade			
	High Renewables	-29.9	-82.0
	Mixed Case	-5.8	-76.1
Prof, Sci/Tech Serv.			
	High Renewables	-25.9	-59.2
	Mixed Case	-17.5	-59.1
Machinery Mfg.			
	High Renewables	7.8	5.7
	Mixed Case	6.4	3.6
Motor Vehicles Parts Mfg.			
	High Renewables	-1.0	-1.3
	Mixed Case	-0.3	-0.5
Primary Metal Mfg.			
	High Renewables	0.9	0.8
	Mixed Case	0.7	0.6
Chemical Mfg.			
	High Renewables	3.5	3.7
	Mixed Case	3.1	3.7

MOUNTAIN		2030	2050
Mining			
	High Renewables	-36.4	-78.8
	Mixed Case	-28.8	-57.4
Utilities			
	High Renewables	2.1	9.3
	Mixed Case	3.7	10.8
Construction			
	High Renewables	13.2	33.3
	Mixed Case	20.9	35.8
Wholesale Trade			
	High Renewables	-1.7	-10.4
	Mixed Case	-1.7	-7.7
Retail Trade			
	High Renewables	-14.5	-49.4
	Mixed Case	-3.1	-36.7
Prof, Sci/Tech Serv.			
	High Renewables	-12.8	-43.1
	Mixed Case	-9.4	-24.7
Machinery Mfg.			
	High Renewables	1.6	0.4
	Mixed Case	1.6	0.7
Motor Vehicles Parts Mfg.			
	High Renewables	0.4	0.9
	Mixed Case	0.5	1.3
Primary Metal Mfg.			
	High Renewables	0.5	0.3
	Mixed Case	0.4	0.3
Chemical Mfg.			
	High Renewables	1.0	1.2
	Mixed Case	1.0	1.4

PACIFIC		2030	2050
Mining			
	High Renewables	-9.1	-14.8
	Mixed Case	-6.7	-9.3
Utilities			
	High Renewables	0.8	4.1
	Mixed Case	0.6	5.4
Construction			
	High Renewables	57.5	133.4
	Mixed Case	51.1	132.2
Wholesale Trade			
	High Renewables	4.1	-7.6
	Mixed Case	0.3	-5.1
Retail Trade			
	High Renewables	0.5	-31.8
	Mixed Case	12.8	-15.8
Prof, Sci/Tech Serv.			
	High Renewables	1.1	-5.0
	Mixed Case	-1.8	4.3
Machinery Mfg.			
	High Renewables	4.3	2.7
	Mixed Case	4.1	2.6
Motor Vehicles Parts Mfg.			
	High Renewables	-0.5	-0.2
	Mixed Case	-0.2	0.4
Primary Metal Mfg.			
	High Renewables	1.3	1.0
	Mixed Case	1.0	0.7
Chemical Mfg.			
	High Renewables	2.6	3.0
	Mixed Case	2.6	3.9

Questions?

Bansari Saha
617-250-4286
Bansari.Saha@icfi.com


ICF
INTERNATIONAL