The Impact of Clean Energy Innovation

Examining the Impact of Clean Energy Innovation on the United States Energy System and Economy

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An Analysis by Google.org using McKinsey & Company's US Low Carbon Economics Tool

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Executive Summary

Our need for energy must be balanced against the often competing interests of the economy, environment, and national security. Clean, sustainable, safe, and secure sources of energy are needed to avoid long-term harm from geopolitical risks and global climate change. Unless fully cost-competitive with fossil fuels, the adoption of clean technologies will either be limited or driven by policy. Innovation in clean energy technology is thus needed to reduce costs and maximize adoption. But how far can energy innovation go towards meeting economic, environmental, and security needs? This analysis attempts to estimate the potential impact clean energy innovation could have on the US economy and energy landscape.

The analysis assumes aggressive hypothetical cost breakthroughs (BT) in clean power generation, grid-storage, electric vehicle, and natural gas technologies and compares them to Business as Usual (BAU) scenarios modeled to 2030 and 2050. The model also compares innovation scenarios in combination with two clean energy policy paths: 1) comprehensive federal incentives and mandates called "Clean Policy" and 2) a power sector-only $30/metric ton price on CO_2 called "$30/ton Carbon Price." Our modeling indicates that, when compared to BAU in 2030, aggressive energy innovation alone could have enormous potential to simultaneously:

- Grow the US economy by over $155 billion in GDP/year ($244 billion with Clean Policy)
- Create over 1.1 million new net jobs (1.9 million with Clean Policy)
- Save US consumers over $942/household/year ($995 with Clean Policy)
- Reduce US oil consumption by over 1.1 billion barrels/year
- Reduce US total greenhouse gas emissions (GHG) by 13% (21% with Clean Policy)

By 2050, innovation in the modeled technologies alone reduced GHG emissions 55% and 63% when combined with policy, while continuing positive economic and job growth. This analysis indicates that aggressive clean energy innovation could simultaneously help address the US' major long-term economic, environmental, and security goals.

Introduction

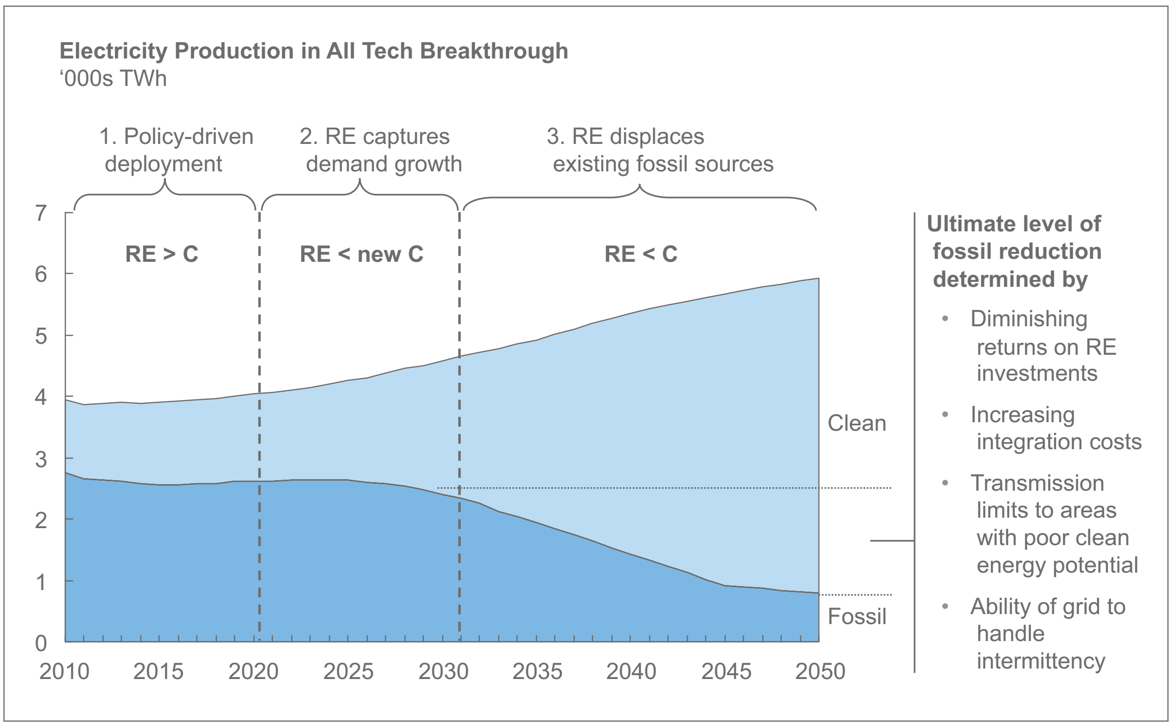
What is the value of clean energy innovation? How much could cheaper clean energy technologies contribute to our economy and energy security? How much could they reduce GHG emissions to mitigate global warming? Examining innovation's potential and limitations in clean energy is critical for understanding its potential role in addressing the world's economic, security and climate challenges.

To attempt to answer these questions, we modeled the impact of breakthroughs in key energy sectors: clean power, energy storage, electric vehicles, and natural gas. Technologies were modeled on their own and in combination with clean energy policies and carbon pricing. This analysis does not attempt to predict innovations, model the best ways to drive innovation, or model the optimal mix of innovation policies. Rather, it sets out to estimate energy innovation's potential impact based on assumed hypothetical breakthroughs.

Based on our modeling, we estimate that by 2030, innovation in the modeled technologies alone could have a transformative impact on the US, adding over $155 billion per year in GDP and 1.1 million net jobs, while reducing household energy costs by $942 per year, oil consumption by 1.1 billion barrels per year, and GHG emissions by 13% relative to BAU. By 2050, annual gains in GDP increase to $600 billion, net additional jobs to 3.9 million, and emissions reductions to 55%.

Figure 1.

U.S. Clean Energy Generation Over Time (All Tech Breakthrough)



Methodology

US energy supply and demand is comprised of five major sectors: electrical generation and use, transportation (primarily oil for vehicles), buildings, industrial use, and agriculture. This analysis looked intensively at electrical generation and transportation, with a more limited assessment of building efficiency. Industrial efficiency and agricultural energy usage were not modeled in detail.

For each sector, we modeled several major technologies (e.g., in the clean power sector: solar, nuclear, geothermal, etc.). For each technology, we developed target "breakthrough" cost-performance levels for 2020 and 2030 through our own analysis and extensive consultation with outside experts. These states of innovation were assumed as fact, then modeled to estimate outcomes of achieving those levels of cost and performance. The modeled breakthrough levels are highly aggressive and would be challenging to reach even with a much more concerted push on innovation than at present.

We used the breakthrough cost-performance levels as inputs to McKinsey & Company's Low Carbon Economics Tool (LCET).[1] The LCET uses detailed micro-economic analysis to determine the impact of technologies and policies on demand and prices (e.g., how large would be the demand for technology X if it reached price Y and were supported by regulation Z?). These impacts are then fed to a macro-economic engine that estimates the resulting impact on GDP, jobs, and other key statistics. The LCET models each sector of the US economy in detail and by state. This analysis relied primarily on the power, transportation, and building units of the LCET.

For the reference control scenario, we modeled a Business As Usual (BAU) case based on technology cost-performance and commodity price assumptions from the US Energy Information Administration's Annual Energy Outlook 2011 and our own perspective on current pricing.[2]

Power Sector

We modeled breakthroughs in utility-scale and rooftop solar photovoltaic (PV), concentrated solar power (CSP), geothermal including Enhanced Geothermal Systems, nuclear, retrofit and new build Carbon Capture and Sequestration (CCS), and on- and off-shore wind. The rate of innovation for each technology was determined by improving capital expenditure, fixed and variable operating expenses, capacity factor, and heat rate (where applicable). This influenced the Levelized Cost of Electricity (LCOE) for each technology.

Figure 2.

Breakthrough LCOE by Technology ($/MWh)

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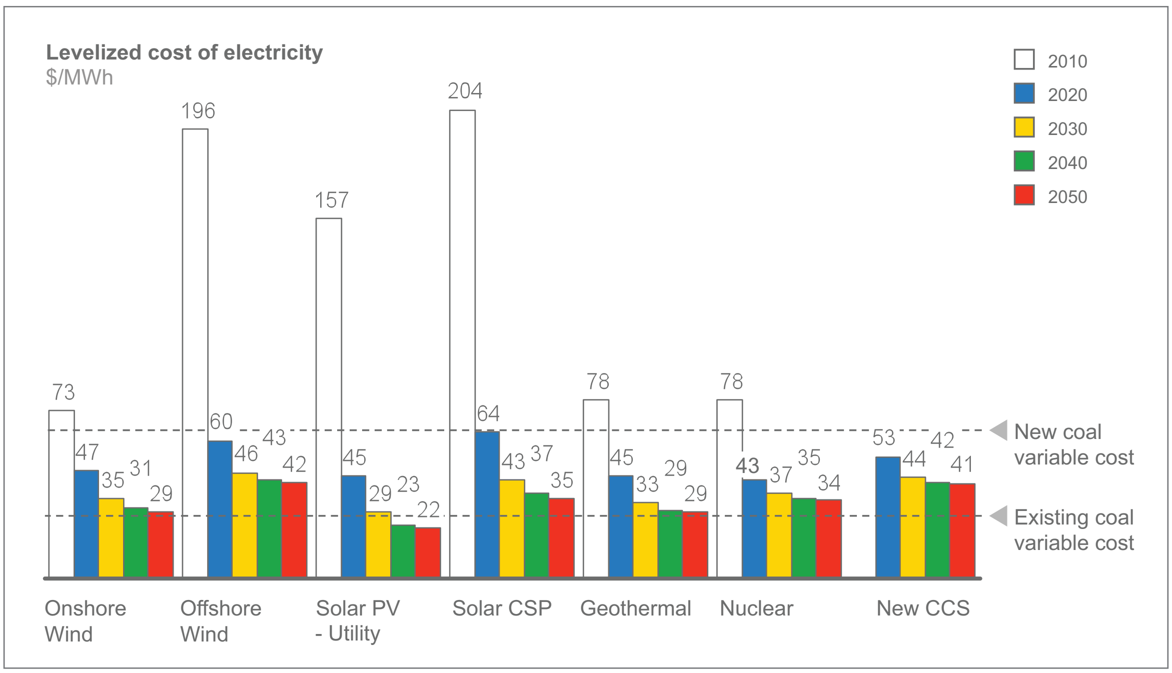


At the core of the power sector model is an hour-by-hour dispatch model that estimates hour-by-hour power dispatch by utility district for the entire US generating fleet and determines power pricing accordingly. Deployment of renewable resources is then modeled from the investor perspective, such that the cost of a new asset is measured against the lifetime returns from either the sale of electricity on the wholesale market or through power purchase agreements (PPAs). In order for an energy source to be deployed, its LCOE must be less than the regional wholesale electricity price, which in most regions is based on the marginal cost of generation from traditional sources such as coal and natural gas.

We optimistically assumed that all necessary transmission is built for new generation. Transmission costs were factored for a given generation source when deployed, which in most cases added between $5–10/MWh to its LCOE. Renewable energy costs were also influenced by resource distribution and availability, based on historical time-of-day generation performance.

1. McKinsey & Company's US Low Carbon Economics Tool: This analysis was prepared by Google.org using McKinsey's US Low Carbon Economics Tool, which is a neutral, analytic set of interlinked models that estimates potential economic implications of various policies using assumptions defined by Google.org. The policy scenarios, input assumptions, conclusions, recommendations and opinions are the sole responsibility of Google.org and are not validated or endorsed by McKinsey. McKinsey takes no position on the merits of these assumptions and scenarios or on associated policy recommendations. More background about McKinsey's US Low Carbon Economics Tool is available at: http://www.mckinsey.com/clientservice/sustainability/low_carbon_economics_tool.asp.

2. US Energy Information Administration, Annual Energy Outlook 2011.

Grid-Storage

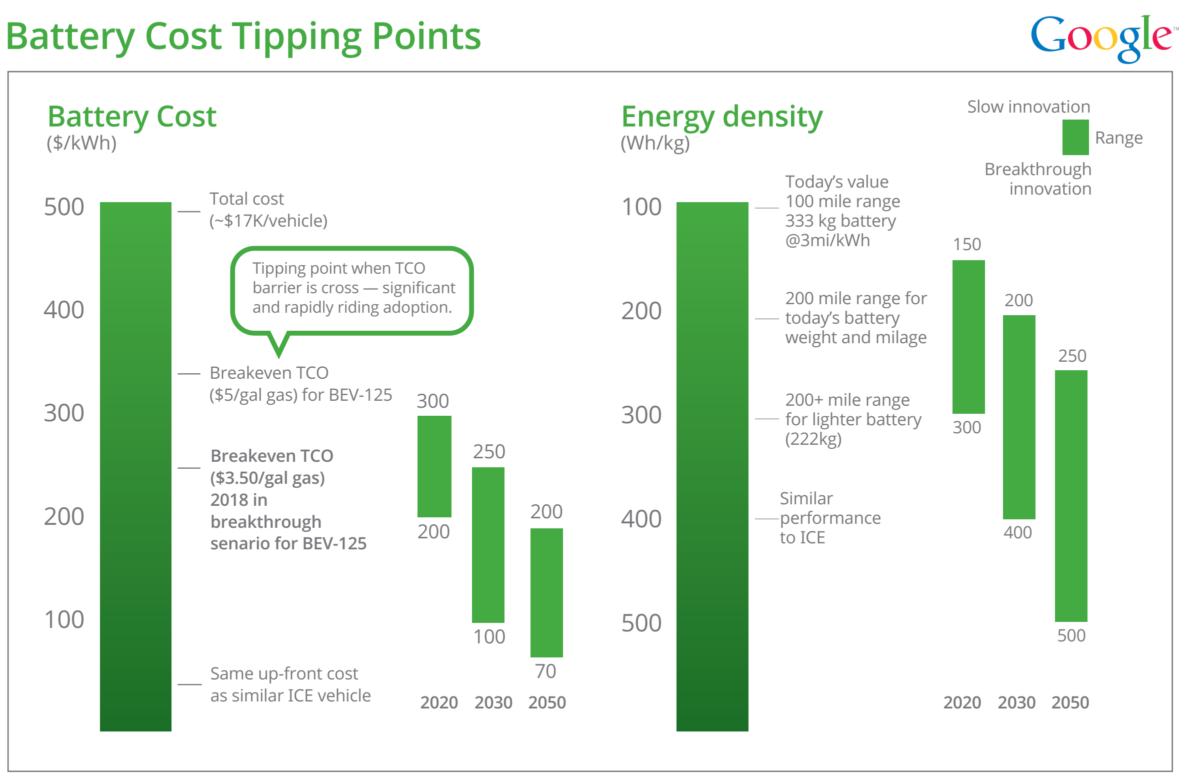
We modeled two primary storage technologies: short duration storage capable of discharging loads for less than one hour; and larger scale storage capable of discharging for over one hour. We then modeled five business cases for storage: 1) Frequency Regulation; 2) Load Following; 3) Price Arbitraging; 4) Capacity Deferment; and 5) Grid Reliability.

Similar to the process described above for new generating capacity, storage deployment is modeled from the investor perspective. Batteries are installed when future cash flow for the five business cases above, less any operating costs over the lifetime of the battery, is greater than the capital cost. Modeling storage is done iteratively as increasing storage capacity eventually degrades the market for its services, inhibiting the deployment of more storage. Some storage capacity can serve multiple business cases, which is also captured by our modeling. For instance, batteries performing price arbitrage by charging at off-peak hours and discharging at on-peak hours could also bid into spinning reserve markets and perform load following.

Transportation

To model breakthroughs in transportation, we set breakthrough cost performance levels for vehicle battery technology. Energy capacity cost ($/kWh), energy density (kWh/kg), duty life (charge cycles), and range (miles) were all improved at optimistic rates. These parameters then influenced vehicle cost and range, which drove vehicle purchasing.

Figure 3.



Our estimate of vehicle adoption relied on a consumer choice model that estimated vehicle purchasing preferences as a function of sticker price, Total Cost of Ownership (TCO), and range, including realistic customer segmentation based on average vehicle miles driven, local climate (which affects heat and air conditioning use), and urban vs. rural driving patterns.

Modeled vehicle options included Electric Vehicles (EV), Plug-In Hybrid Electric Vehicles (PHEV), Hybrid Electric Vehicles (HEV), Compressed Natural Gas (CNG), and Internal Combustion Engine vehicles (ICE) in light, medium, and heavy duty variations (LDV, MDV, HDV). We assumed that charging infrastructure would be built in response to demand and would not act as a bottleneck.

Natural Gas

To model the impact of continued innovation in natural gas extraction and its effect on the energy system, we assumed an optimistically low Henry Hub spot gas price of $3/million British Thermal Units (MMBTU) and held it constant until 2030. We optimistically assumed that all gas demand triggered by the low price is able to be satisfied with production from domestic gas basins. The low natural gas price consequently increases the competitiveness of natural gas generation and Compressed Natural Gas vehicles.

Policy

The impact of innovation was explored within three policy scenarios (see appendix for full descriptions and policy assumptions):

1. BAU (Current Policies), which held existing state and federal energy policies as they exist today and expiring on their approved timeline.

2. Clean Policy, a collection of existing or proposed federal policies including a Clean Energy Standard (25% CCS, renewables, and new nuclear by 2030), Energy Efficiency Resource Standard (EERS), increased Corporate Average Fuel Economy (CAFE), increased EPA regulations on coal, extended Investment and Production Tax Credits, and a Loan Guarantee credit facility capped at $15 billion per year. This scenario optimistically assumes a very high level of effectiveness and efficiency in implementing these policies. For example, we assume that the energy efficiency regulations trigger only the most cost-effective among potential energy-savings measures.

3. $30/ton Price on Carbon, a power sector-only carbon price used to fund a cut in personal income tax rates. The $30/ton price was chosen because it can cause natural-gas generation to be dispatched ahead of coal, since the carbon intensity of coal generation can be more than double that of combined cycle gas turbines. Absent very aggressive cost reductions in clean energy, much higher natural gas prices, or regulation on natural gas, a price on carbon below $30/ton may not sufficiently incentivize cleaner sources.

Since we did not model all potential clean energy policies (e.g. economy-wide cap-and trade, smart grid policies, utility deregulation, etc.) or assess optimal mixes of policies, these scenarios offer a limited assessment of the potential impacts of clean energy policies.

Scenarios Modeled

In total, we examined fourteen different scenarios with various combinations of technology innovation rates, policy conditions, and commodity prices (see appendix for full scenario descriptions).

Scenario	Innovation Rate (Sector)	Policy Condition	Commodity Price
1. BAU	BAU	BAU	BAU (AEO 2011)
2. Clean Power Breakthrough	Breakthrough (Power Only)	BAU	BAU (AEO 2011)
3. Storage Breakthrough	Breakthrough (Storage Only)	BAU	BAU (AEO 2011)
4. EV Breakthrough	Breakthrough (EVs Only)	BAU	BAU (AEO 2011)
5. All Tech Breakthrough	Breakthrough (Power, Storage, and EVs)	BAU	BAU (AEO 2011)
6. Clean Policy	BAU	Clean Policy	BAU (AEO 2011)
7. Clean Policy + Breakthrough	Breakthrough (Power, Storage, and EVs)	Clean Policy	BAU (AEO 2011)
8. $30/ton Price on Carbon	BAU	$30/ton Price on Carbon (Power Sector Only)	BAU (AEO 2011)
9. $30/ton Carbon + Breakthrough	Breakthrough (Power, Storage, and EVs)	$30/ton Price on Carbon (Power Sector Only)	BAU (AEO 2011)
10. High Commodities	BAU	BAU	AEO 2011 + 50%
11. High Commodities + Breakthrough	Breakthrough (Power, Storage, and EVs)	BAU	AEO 2011 + 50%
12. Cheap Natural Gas	BAU	BAU	$3/MMBTU Gas

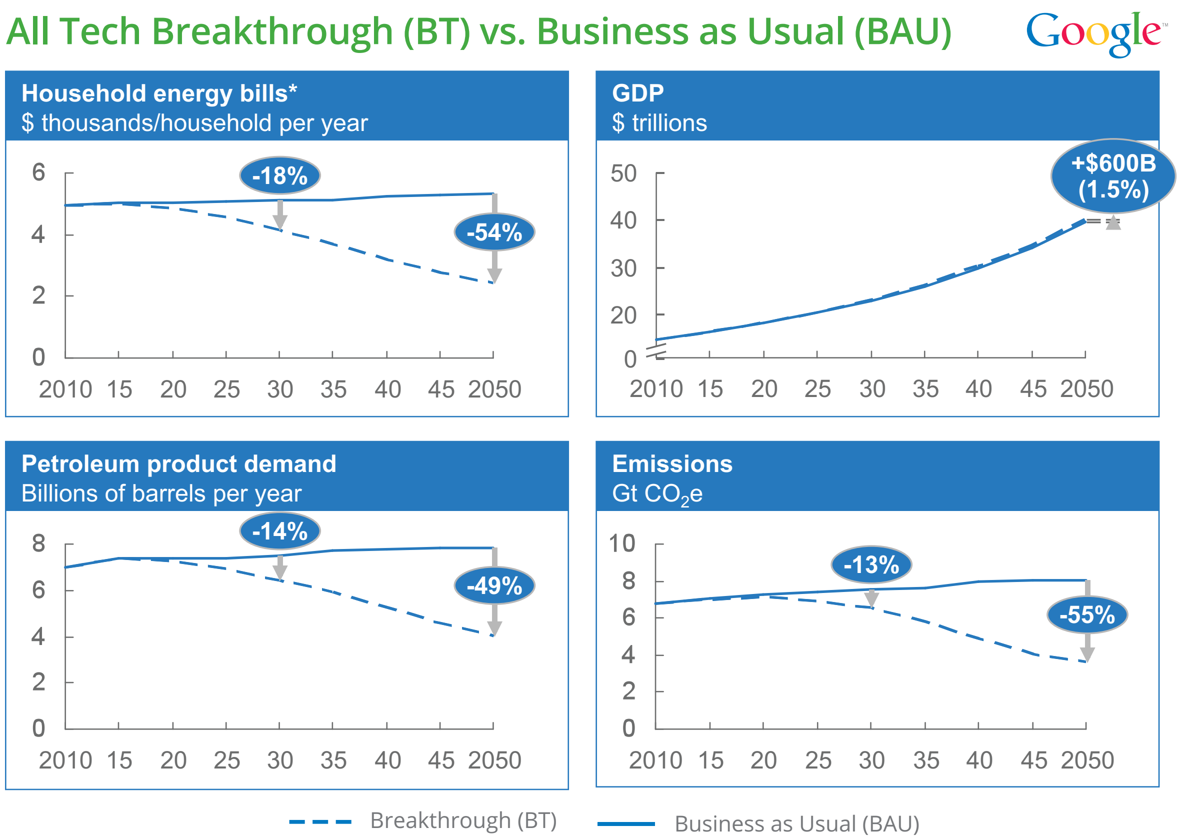
13. Cheap Natural Gas + Breakthrough	Breakthrough (Power, Storage, and EVs)	BAU	$3/MMBTU Gas
14. Delay Breakthrough	All Tech Breakthrough (delayed 5 years)	BAU	BAU (AEO 2011)

Key Findings

I. Innovation Could Pay Off Big

1. Innovation Benefits GDP, Jobs, Security and Emissions. Clean Energy Innovation could accelerate economic growth and improve energy security while significantly reducing carbon pollution. All the breakthrough technology and policy scenarios examined here created substantial economic and net job growth across the country by 2030. Breakthrough innovations in clean energy added $155 billion per year in GDP, creating 1.1 million net jobs, while reducing household energy costs by $942 per year, oil consumption by 1.1 billion barrels per year, and GHG emissions 13% by 2030 vs. BAU.

Figure 4.

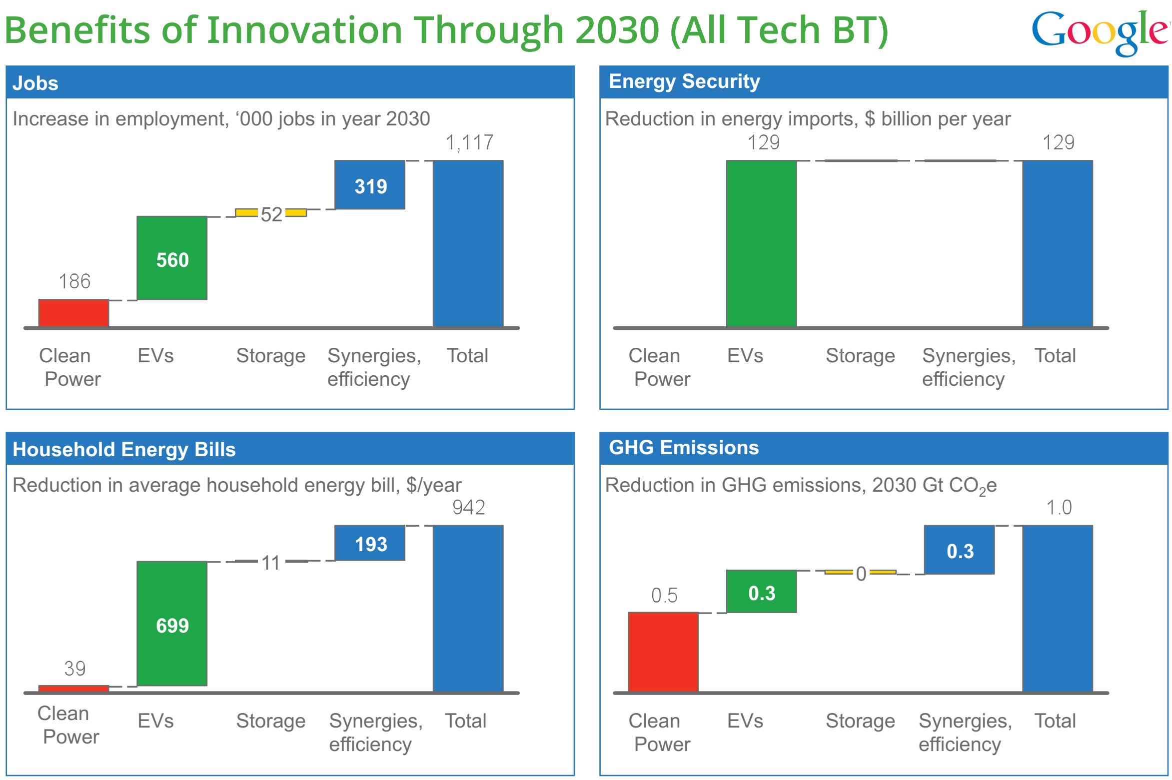


* Electricity, natural gas, and gasoline only

Innovation drove job creation and economic growth in two primary ways. First, innovation reduced energy costs, which increased productivity, competitiveness, and demand. Lower-cost energy also created consumer savings on the order of $942 per household by 2030. These consumer savings, when circulated back into the economy, drove substantial economic and job growth outside the energy sector. Second, lowering the costs of clean technologies increased their deployment – driving associated manufacturing, construction, and operational employment.

The bulk of innovation's benefits by 2030 were attributed to advances in battery technology, enabling adoption of EVs, PHEVs, and HEVs. Overall benefits from power breakthroughs were less than EVs by 2030 for two reasons. First, most consumers spend less on electricity than on gasoline, leading to less household savings from cheaper power. Second, due to the very low cost of coal in the US, clean power technology did not attain as large a cost advantage over fossil alternatives as was the case in the transportation sector with electric vehicles by 2030 .

Figure 5.

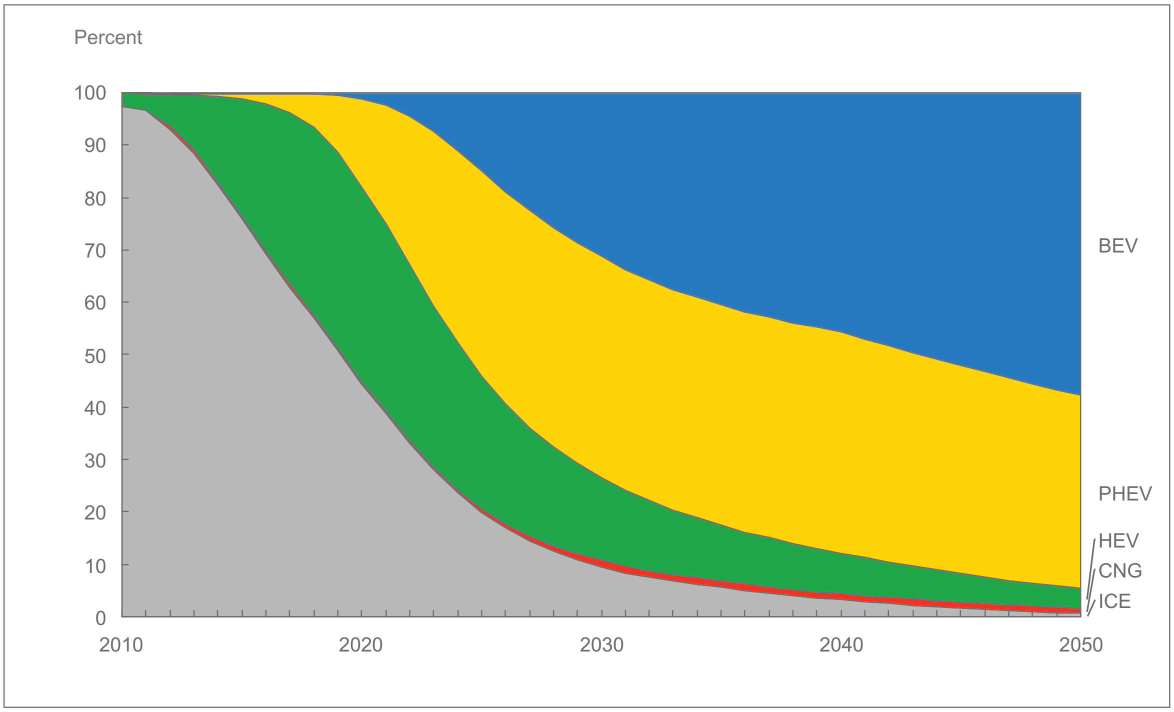


The benefits of breakthroughs pay even larger dividends out to 2050. By 2050, annual gains in GDP increased to $600 billion, net additional jobs to 3.9 million, reduced oil consumption by 3.7 billion barrels per year, and emissions reductions of 55% vs. BAU.

2. Reaching tipping points in Electric Vehicle (EV) battery technology could be transformative. Breakthroughs in battery technology could push EVs over cost-performance tipping points, enabling mass adoption. In our model, rapid decreases in battery costs and increases in energy density by 2030 enabled the production of electric vehicles with 300 mile range and a total cost of ownership (TCO) lower than that of internal combustion vehicles. This led to EVs, Hybrid Electric Vehicles (HEVs) and PHEVs achieving 90% market share of new light duty vehicle sales in 2030, reducing oil consumption by 1.1 billion barrels per year — or more than Canada's entire 2009 production.

Figure 6.

Light Duty Vehicle Sales by Type (All Tech BT)

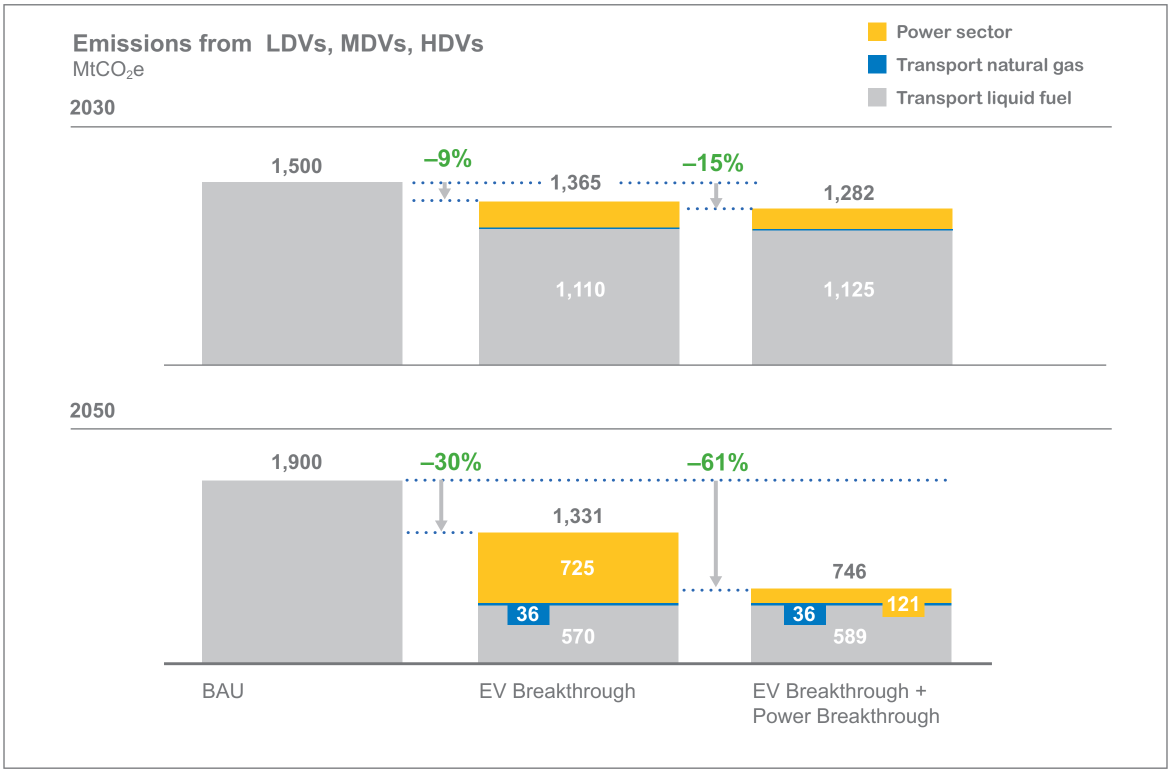


The outcomes of battery breakthroughs are striking. By rapidly reaching TCO and driving range tipping points, battery breakthroughs enabled EV, PHEV, and HEV light duty vehicles to comprise 58% of the US light duty vehicle fleet by 2030. The high rate of sales held even when EV breakthroughs were modeled against increasingly efficient internal combustion vehicles mandated by (CAFE) standards. Gasoline prices also heavily affected the hurdle for EV adoption. For example, at gasoline costs of $3.50/gal., breakeven TCO is reached at battery costs of ~$255/kWh for a 125 mile range BEV, while at $5/gal., breakeven TCO is reached at ~$355/kWh.

Electrifying transportation, even in scenarios where coal remained the dominant source of electricity, still reduced total transportation emissions (from all energy sources including electricity) by 9%, despite increasing electricity consumption by 13%. This resulted from two factors. First, much of the incremental electricity demand was met with incremental generation from natural gas and (in some scenarios) renewables sources. Second, electric drivetrains have a higher conversion efficiency (i.e., the power plant that generates the incremental electricity has a higher thermal efficiency than a vehicle's internal combustion engine).

Figure 7.

Transportation Emissions With and Without Power Breakthroughs



Oil consumption was cut by 1.1 billion barrels per year by 2030 in the EV breakthrough scenario. This equals a reduction of nearly 14% vs. BAU demand and over 26% of projected US oil imports in 2030.[4]

By replacing high cost gasoline with cheap electricity, battery breakthroughs in our model also yielded substantial economic benefits from new manufacturing and consumer savings. GDP increased by $86 billion per year by 2030 and jobs by 560,000. Perhaps most compelling, EV breakthroughs alone generated net savings of $699 per household by 2030.

3. Cheap Grid-Storage: Significant Opportunity and Unintended Consequences. In the long run, cheap grid-scale electricity storage can create large economic and environmental benefits for the US. Storage improved power quality and reliability, lowered power prices by allowing more efficient dispatch, and enabled much higher penetrations of intermittent solar and wind than would otherwise be possible.

In the absence of storage, wholesale prices in regions rich in renewable resources can plummet when wind or solar energy peaks and supply overwhelms demand. For example, this has already forced some wind farms in Texas to shut down at night, inhibiting additional deployment. Storage can alleviate this constraint by charging at times when renewable sources are strongest and then discharging when other demand is available. When storage and power breakthroughs were combined, we estimated that storage enabled an additional 35% renewables generation by 2050.

In the short term, much cheaper storage, absent innovations in wind and solar that reduce their cost to below coal, could actually drive an increase in coal consumption. Cheaper storage would enable already cheap coal units to run at peak efficiency 24 hours/day, store energy at night and dispatch it during the day — reducing the demand for load-following natural gas capacity and ultimately resulting in a slight (0.3%) increase in CO_2 emissions.

When storage breakthroughs were modeled alone, electricity prices decreased by 1%, job creation was modest at 52,000 jobs, and emissions slightly increased by 0.06 GT, or 0.3% by 2030. Storage

4. US Energy Information Administration, International Energy Outlook 2010.

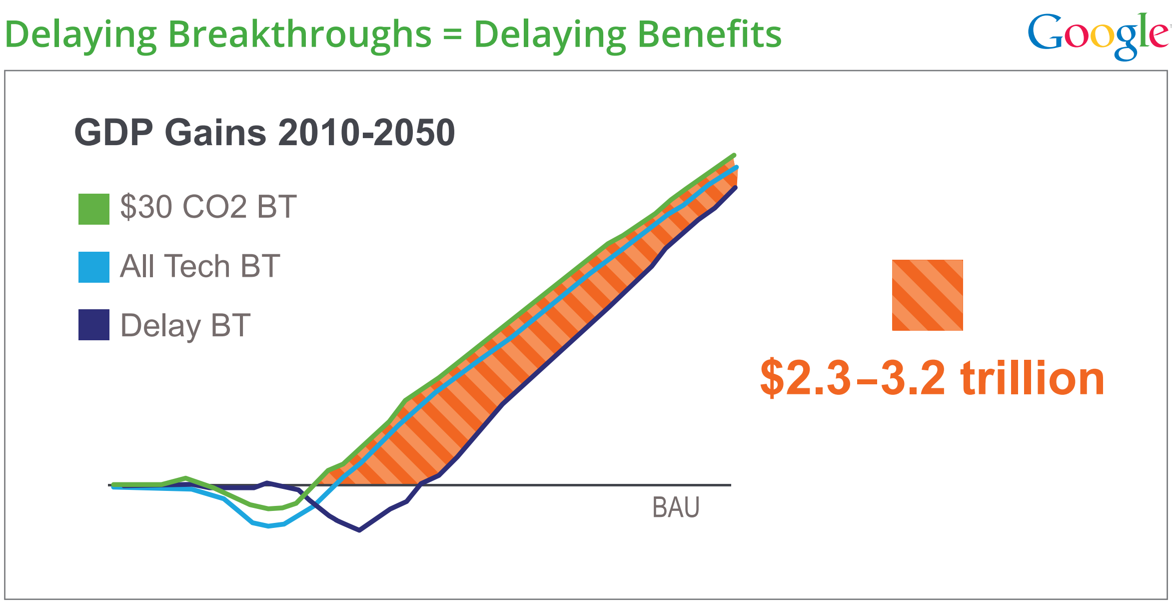
alone created $8.6 billion in annual economic opportunity by 2030, with $4.4 billion accounted for by grid reliability services. However, when combined with power breakthroughs, storage enabled significant increases in wind and solar generation after 2030. When combined with storage, onshore wind, offshore wind, solar PV, and CSP accelerate from 18% of total generation in 2030, to 48% of total generation by 2050.

II. Speed Matters

4. Delaying Breakthroughs = Delaying Benefits. Breakthroughs in clean energy can provide enormous benefits to the economy, national security, the environment, and the job market. But the longer we delay achieving those breakthroughs, the greater the benefits we stand to give up.

In the delay scenario, the same rates of innovation were assumed as in the All Tech Breakthrough scenario (Power, EVs, Storage), except that they started in 2015 from the projected 2015 BAU level, rather than in 2010.

Figure 8.

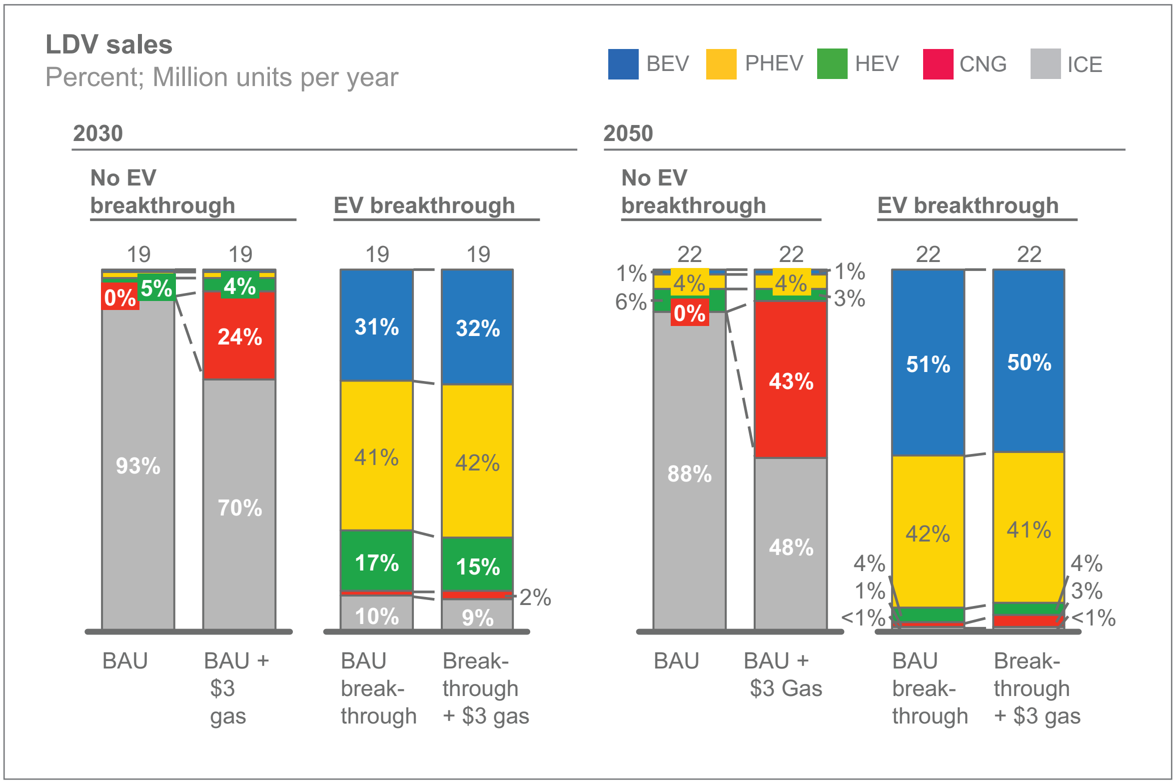


In our model, a mere five year delay in starting aggressive cost reduction curves could cost the economy an aggregate $2.3–3.2 trillion in unrealized GDP gains,1.2–1.4 million net jobs and 8-28 gigatons of potential avoided CO_2 emissions by 2050 (Delay Breakthrough vs. All Tech Breakthrough and $30/ton Carbon + Breakthrough)

5. Technologies that Innovate Fastest Win. The technologies that become cheaper than coal and oil fastest will dominate our clean energy future. An "innovation arms race" between clean technologies will encourage healthy competition, while benefiting consumers.

Figure 9.

Cheap Natural Gas vs. EV Breakthroughs



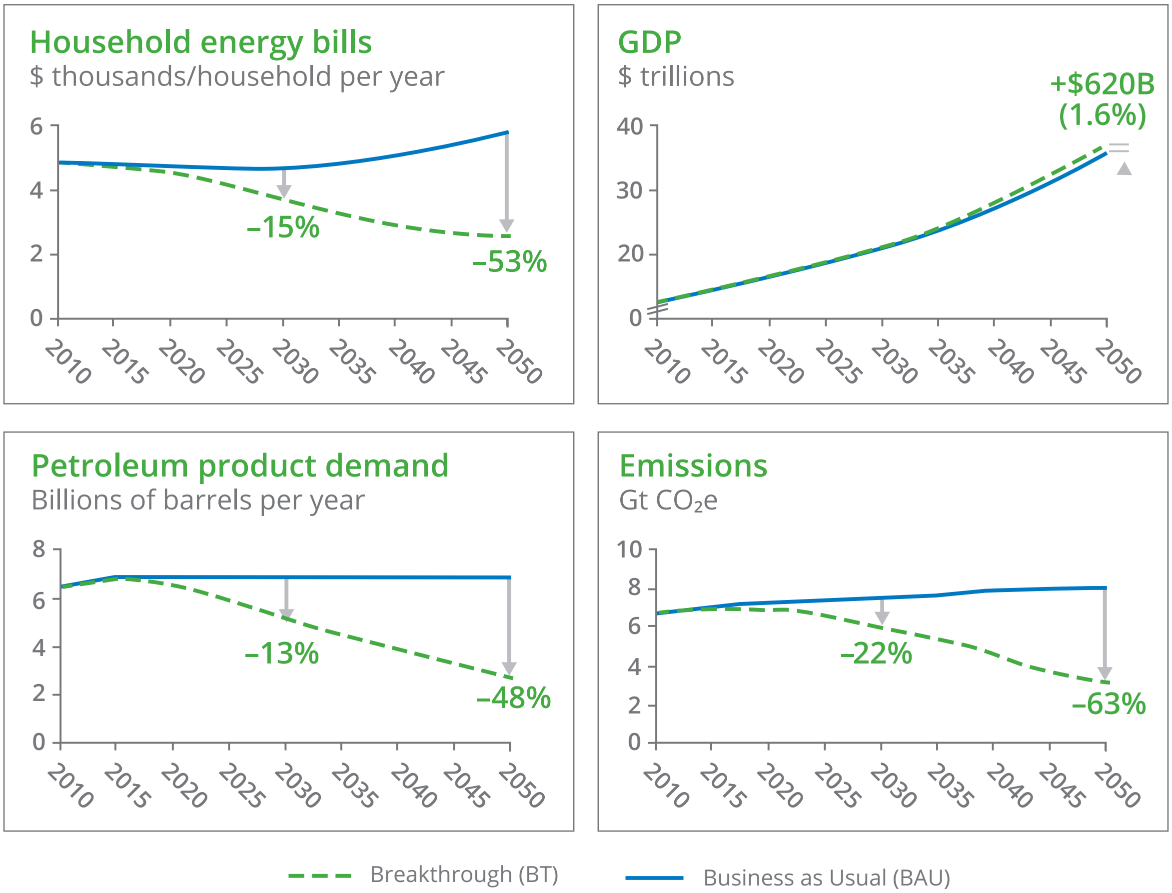
For example, in transportation, we explored EV and PHEV competition against Compressed Natural Gas (CNG). In the EV Breakthough scenario, EVs rapidly became cost competitive against CNG, leading to dominant market share for EVs, PHEVs, and HEVs. However, in a sustained era of cheap gas ($3/MMBTU), if EV breakthroughs do not happen quickly, CNGs will dominate the market and make it much harder for EVs to reach scale.

III. Policy and Innovation Can Enhance Each Other

6. Smart Energy Policies and Breakthroughs are Mutually Beneficial. Breakthroughs in clean energy technology can reduce the cost associated with implementing policies such as Clean Energy Standards or carbon prices — growing the economy while de-carbonizing our energy use. Policies can also amplify the economic, security, and pollution benefits of breakthroughs by creating markets, dis-incentivizing the highest-emitting technologies, and leveling the playing field for clean energy, leading to increased adoption.

Figure 10.

$30/ton CO_2 + All Tech Breakthrough vs. BAU



When $30/ton carbon price on the power sector was modeled on its own, with revenues returned to consumers through a cut in personal income tax rates, by 2030 annual GDP and job growth numbers were $53 billion and 558,000 respectively, while GHG emissions dropped by 9%. Consumer energy bills increased $152 per household by 2030 in this scenario. But, when combined with All Tech Breakthroughs, GDP growth increased to $182 billion, job growth to 1,558,000, while also reducing emissions 22% vs. BAU. Consumers now saved $761 per household when combined with breakthroughs.

When Clean Energy Policy was modeled on its own without breakthroughs, by 2030 annual GDP and job growth were positive at $37 billion and 458,000 respectively, while achieving a 16% reduction in GHG emissions. When combined with All Tech Breakthroughs, GDP growth increased to $244 billion, job growth to 1,959,000, while reducing emissions 21% vs. BAU. Consumer savings for the combined scenario was $995 per household.

Breakthroughs on their own did not create as much value as when combined with policy. In the All Tech Breakthrough scenario, by 2030 annual GDP and job growth were slightly higher than Clean Policy at $155 billion and 1,117,000 respectively, and achieved a 13% reduction in GHG emissions vs. BAU.

The differences between All Tech Breakthrough's impact with and without policy, were due to the difficulty reducing coal-fired generation without policy support for the technologies modeled. The marginal cost of coal is so low that existing coal was displaced only when cost breakthroughs were almost fully realized, which occurred after 2030 for most renewable generation technologies.

On the other hand, policy was a much stronger lever for reducing carbon from coal in the near term — either through pollution regulation, mandated retirements, or a carbon price. However, without the cheaper technologies produced by innovation, policy-only options led to fewer jobs and lower GDP than when combined with aggressive innovation.

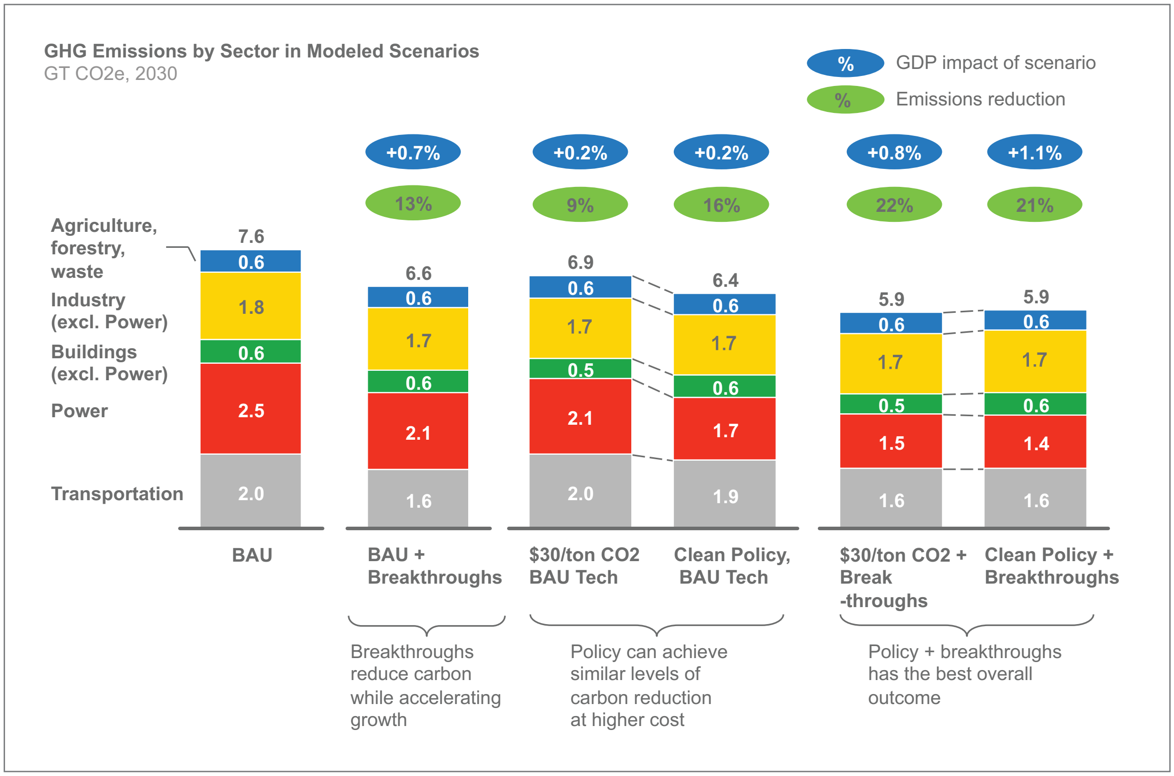
7. Reaching 80% reductions in GHG emissions by 2050 requires multiple solutions based on the scenarios and technologies we modeled. We set very optimistic rates of innovation, pushing technologies hard on cost and performance. Even with aggressive breakthroughs, by 2050 we achieved only a 49% reduction in GHG emissions vs. 2005 emissions in the All Tech Breakthrough scenario, well short of the standard, IPCC-inspired reduction targets of 80% by 2050.[5 6]

However, we only modeled innovations in a limited group of energy technologies. We did not model innovations in many promising sectors, including low-carbon fuels, internal combustion engines, industrial efficiency, advanced building materials, advanced building energy management, or agricultural practices. Since the subset of technologies we modeled achieved 49% emissions reduction, it is possible that a more comprehensive mix of innovations could achieve 80% reductions.

Energy policies alone also did not develop trajectories for 80% reductions by 2050. But when carbon pricing was combined with breakthroughs, reductions reached 59% vs. 2005 levels. This indicates that policy and innovation combined likely increase the potential for reaching climate mitigation targets.

Figure 11.

2030 GHG Emissions by Scenario



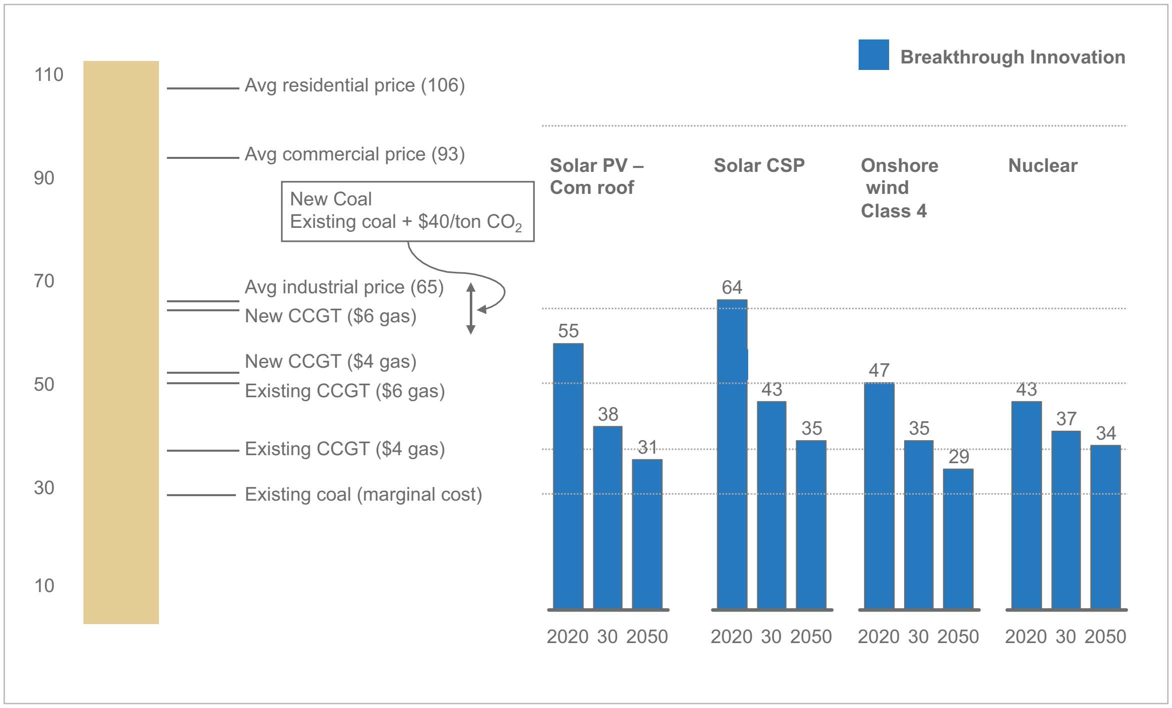
Reaching 80% reductions by 2050 will be difficult and likely require much more aggressive innovation and policy than we currently have today. Thus, this analysis supports the need for a multi-pronged US strategy, combining both aggressive innovation and policy to mitigate climate change while growing the economy.

8. Coal is Very Hard to Displace on Economics Alone: Coal power is abundant and cheap, especially from older and fully depreciated plants. Major displacement of coal generation did not occur until clean energy became cheaper than the marginal cost of coal, which occurred predominately after 2030 even with breakthroughs.

5. Environmental Protection Agency, inventory of US GHG Emissions Sinks: 1990–2005.
6. Intergovernmental Panel on Climate Change, Climate Change 2007: Synthesis Report.

Figure 12.

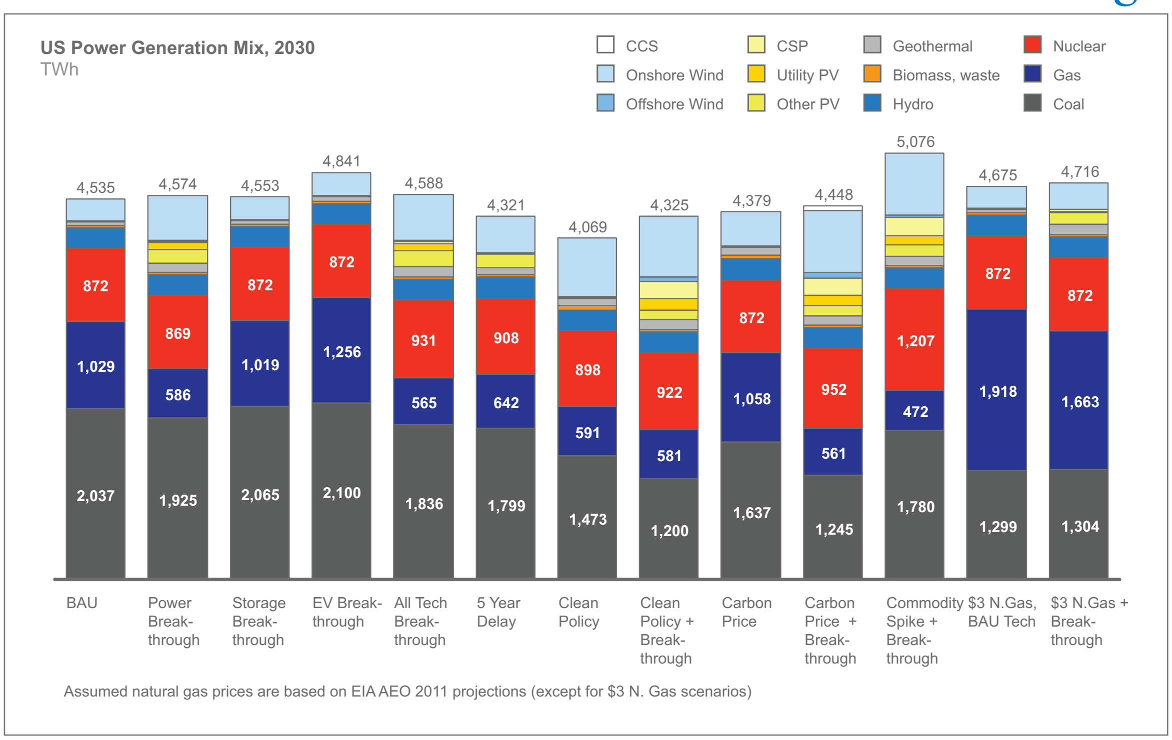
Generation Cost Tipping Points LCOE



We used LCOEs of $66/MWh and $28/MWh for new and existing coal respectively. In BAU, coal use is held roughly flat to 2020 by existing state CES laws and EPA regulations. But once RPS targets are achieved, coal use increases again in tandem with demand, rising a net 12% by 2030.

Figure 13.

2030 US Power Generation Mix by Scenario



Only our breakthrough assumptions for Solar PV and Geothermal were cheap enough to replace existing coal by 2030. Thus, none of the breakthrough-only runs reduced 2030 coal generation by more than 5%.

Policies alone also did not reduce much coal use by 2030. Clean Policy reduced coal use 17% and $30/ton Carbon reduced coal by 15% vs. BAU. Clean Policy's higher impact was driven by aggressive EPA regulations, increasing compliance costs, and driving retirements of existing coal units. The highest reductions seen were from the $30/ton + Breakthrough scenario, which achieved nearly 20% reductions vs. BAU.

Post-2030, breakthroughs in generation become cost advantaged and start to pay off significantly. As clean power reaches its lowest price points, displacement of coal accelerates rapidly from 2030 to 2050. By 2050, All Tech Breakthrough reduced coal 66%, and the $30/ton CO_2 + Breakthrough scenario reduced coal use 87%.

9. Cheap natural gas could reduce GHG emissions in the short term but also slow the deployment of clean energy sources in the long term. Initially, the improved economics of natural gas in our hypothetical $3/MMBTU price environment led to coal-to-gas switching and made coal plant retirements more economical. In the long term, when prices were held low, gas out-competed carbon-free energy. By 2030, in our Cheap Gas scenario, total generation from gas surged by 86%, overall emissions were reduced slightly by 6% from coal displacements, and households saved an average of $555 through switching to CNG vehicles and cheaper electricity. But cheap gas on its own reduced the total deployment of renewables, CCS and nuclear by 47% vs. All Tech Breakthrough and 57% vs. Clean Policy + Breakthrough.

When combined with breakthroughs, the benefits of cheap gas increased. As EV breakthroughs kicked in, EVs became advantaged vs. CNG vehicles, leading to higher household energy and oil savings. The cheaper electricity prices created by cheap gas actually increased EV, PHEV, and HEV combined sales by 100,000 vehicles per year. By increasing EV penetrations and some breakthrough low-carbon generation, Cheap Gas + Breakthroughs reduced overall emissions 15% by 2030.

However, the breakthrough renewables, CCS, and nuclear technologies needed for deep long-term GHG reductions, struggled in competition with cheap gas. Even with breakthroughs, their deployment was reduced 26% vs. All Tech Breakthrough and 40% vs. Clean Policy + Breakthrough by 2030.

Our hypothetical future of cheap gas is clearly optimistic as gas prices are notoriously volatile. But the advent of abundant and cheap unconventional resources has pushed gas spot-prices to the low $4/MMBTU range. Thus, it is critical to understand the impact sustained cheap gas could have on the energy system.

Conclusion

Energy innovation is a powerful tool capable of simultaneously addressing society's goals of economic growth, enhanced energy security, environmental health, and de-carbonization.

This project's analysis suggests that breakthroughs in clean energy technologies could meaningfully improve the quality of our lives. Some of these benefits could accrue quickly, such as switching away from oil to electric transportation. Others, like lower-cost clean generation technologies, are long-term investments which begin paying enormous dividends around 2030, increasing through 2050.

Getting there will take the right mix of effective policy, a major sustained national investment in innovation by public and private institutions, and the increased mobilization of the private sector's entrepreneurial energies.

The benefits are clear, so let's go!

Appendix A

About

Google's Energy Initiatives: Google supports the development and deployment of clean energy through a variety of initiatives. Our commitment starts with our operations. We went carbon neutral in 2007. We have installed the largest corporate electric vehicle charging infrastructure in the country, developed some of the most efficient data centers in the world, and buy and use renewable energy whenever possible, including long-term power purchase agreements for over 200 MW of wind energy generation. Our investments in the clean energy sector total more than $780 million in large-scale renewable energy projects spanning a wide range of technologies, and over fourteen venture-backed technology start-ups. For more information, visit **google.com/green**.

Limitations of this Analysis: We conducted this analysis to evaluate — at a basic economic level — the benefits of breakthroughs in clean energy technology.

This analysis does not represent a comprehensive assessment of energy technology or technology broadly. For example, we did not model breakthroughs in building science, industrial efficiency, smart grid, or biofuels. We also did not estimate spill-over or convergence effects of breakthroughs (e.g. the combination of fiber optics and the Internet enabling online video and telephony), which can multiply wealth creation from a given technology. Lastly, we did not quantify potential positive externalities — such as reduced health care costs from avoided pollution. This was a function of our own time constraints and not of the merits of those questions. Thus, while our breakthrough scenarios were inherently optimistic, our conclusions may significantly underestimate the value of clean energy innovation.

Since predicting the probability, timing and magnitude of breakthroughs is likely to be impossible we assumed breakthroughs as fact and modeled their impact. We did not examine the likelihood of breakthroughs occurring, the exact improvements required to achieve our modeled breakthrough levels, the most effective policy drivers of innovation, the cost of achieving these breakthroughs, or which technologies should be prioritized over others. These are critical questions which demand their own investigation.

Upon the project's completion, we were so compelled by energy innovation's potential that we wanted to share our analysis and the associated data (**google.org/energyinnovation**), in the hope that it encourages further discussion and debate about these important issues.

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Appendix B

Scenario Descriptions:

1. Business As Usual (BAU): BAU uses the projected technology costs, gasoline and natural gas prices, demand, and learning rates of technologies as defined by the US Energy Information Administration's Annual Energy Outlook 2011. In some cases, such as solar PV, CAPEX and OPEX, prices were adjusted to better reflect the market. Policy frameworks were held to existing state and federal policies expiring on their current schedule. For example, we assumed a state RPS that terminates in 2025 would not continue after that date. BAU operates as our control scenario in this exercise.

2. Clean Power Breakthrough: Major clean energy technologies that are at or near commercial readiness, have substantial resource bases, or are being pursued aggressively by industry were modeled. Included were nuclear, solar PV (Utility and Rooftop), solar CSP, onshore and offshore wind, geothermal including Enhanced Geothermal Systems (EGS), and new and retrofit Carbon Capture and Sequestration (CCS). In each case, we selected an extremely aggressive CAPEX, OPEX, LCOE and performance target defined as the "breakthrough" for 2020 and 2030. These rates were set by our own aspirational estimates of each technology's potential, informed by technical cost models and industry experts. State and federal policies remained the same as BAU.

3. Storage Breakthrough: Two basic types of breakthroughs in grid-storage were modeled: short duration storage capable of discharging loads for less than 1 hour; and larger scale storage capable of discharging for over 1 hour. We then modeled five business cases for storage: 1) Frequency Regulation; 2) Load Following; 3) Price Arbitraging; 4) Capacity Deferment; and 5) Grid Reliability. State and federal policies remained the same as BAU.

4. EV Breakthrough: Cost factors were driven by total cost of ownership (TCO), energy density, cycle life, and total unit cost for vehicle batteries. Impacts of battery technologies on PHEV, HEV, and EV technologies were assessed. Vehicle adoption was driven by a consumer choice model that was triggered by TCO and vehicle range, in competition with Compressed Natural Gas (CNG) and conventional internal combustion engine vehicles (ICE). Impacts were modeled for both the light duty and medium duty vehicle segments. Breakthrough energy densities were not high enough to displace long-haul heavy trucks, so they were not covered by this model. State and federal policies remained the same as BAU.

5. All Tech Breakthrough: A combination of the clean power, storage, and EV breakthrough scenarios. This scenario observes the impacts of simultaneous breakthroughs, the convergence effect of cheaper storage and renewables. As in each of the breakthrough scenarios, only cost/performance levels of technologies are adjusted. All state and federal policies are the same as BAU.

6. Clean Policy: The Clean Policy scenario modeled a collection of existing and proposed federal mandates, regulations and incentives. The modeled package is far less aggressive than a major comprehensive policy such as an economy-wide cap-and-trade program. We modeled the Clean Policy scenario to explore the potential impact of non-carbon based policies on CO_2 emissions and the economy. It includes: a national CES of 15% by 2020 and 25% by 2030; national EERS of 5% by 2020 and 10% by 2030 (roughly 20% capture of total energy efficiency potential); extension of PTC and ITC through 2030 capped at $10 billion annually along with loan guarantees for all techs capitalized at $15 billion; CAFE standards increased by 4%/year from 2016 to 2025, 1%/year thereafter for LDVs; and coal retirements of roughly 55GW by 2020 based on strict EPA regulations along with tightening of SOx/NOx caps, MACT/HAPs, transport rule 316b (cooling towers), and CCR (ash disposal).

7. $30/ton Price on Carbon: A $30/ton CO_2 price was implemented on the power sector only and was similar to proposed tax and dividend structures. Revenues generated through the fee were collected by the federal government, then rebated to taxpayers in proportion to their tax receipt. The $30/ton price was chosen because it is high enough to push the LCOE of coal above natural gas and thus lead to coal-gas switching.

Only our breakthrough assumptions for Solar PV and Geothermal were cheap enough to replace existing coal by 2030. Thus, none of the breakthrough-only runs reduced 2030 coal generation by more than 5%.

Policies alone also did not reduce much coal use by 2030. Clean Policy reduced coal use 17% and $30/ton Carbon reduced coal by 15% vs. BAU. Clean Policy's higher impact was driven by aggressive EPA regulations, increasing compliance costs, and driving retirements of existing coal units. The highest reductions seen were from the $30/ton + Breakthrough scenario, which achieved nearly 20% reductions vs. BAU.

Post-2030, breakthroughs in generation become cost advantaged and start to pay off significantly. As clean power reaches its lowest price points, displacement of coal accelerates rapidly from 2030 to 2050. By 2050, All Tech Breakthrough reduced coal 66%, and the $30/ton CO_2 + Breakthrough scenario reduced coal use 87%.

9. Cheap natural gas could reduce GHG emissions in the short term but also slow the deployment of clean energy sources in the long term. Initially, the improved economics of natural gas in our hypothetical $3/MMBTU price environment led to coal-to-gas switching and made coal plant retirements more economical. In the long term, when prices were held low, gas out-competed carbon-free energy. By 2030, in our Cheap Gas scenario, total generation from gas surged by 86%, overall emissions were reduced slightly by 6% from coal displacements, and households saved an average of $555 through switching to CNG vehicles and cheaper electricity. But cheap gas on its own reduced the total deployment of renewables, CCS and nuclear by 47% vs. All Tech Breakthrough and 57% vs. Clean Policy + Breakthrough.

When combined with breakthroughs, the benefits of cheap gas increased. As EV breakthroughs kicked in, EVs became advantaged vs. CNG vehicles, leading to higher household energy and oil savings. The cheaper electricity prices created by cheap gas actually increased EV, PHEV, and HEV combined sales by 100,000 vehicles per year. By increasing EV penetrations and some breakthrough low-carbon generation, Cheap Gas + Breakthroughs reduced overall emissions 15% by 2030.

However, the breakthrough renewables, CCS, and nuclear technologies needed for deep long-term GHG reductions, struggled in competition with cheap gas. Even with breakthroughs, their deployment was reduced 26% vs. All Tech Breakthrough and 40% vs. Clean Policy + Breakthrough by 2030.

Appendix C
Assumptions

Power Generation

	Scenario	BAU			Breakthrough				
Technology		2010	2020	2030	2010	2020	2030	2040	2050
New Build CCS									
	Overnight Capital Cost ($/kW)		4,684	3,721		1,800	1,600	1,540	1,522
	Fuel Cost ($/MMBtu)		2	2		2	2	2	2
	Variable O&M ($/MWh)		4.5	4.5		4.5	4.5	4.5	4.5
	Fixed O&M ($/kW/yr)		47	47		47	47	47	47
	Heat Rate if Applicable (BTU/kWh)		10,000	8,300		9,000	6,000	6,000	6,000
	Capacity Factor		85%	85%		85%	85%	85%	85%
	LCOE ($/MWh)		93	77		53	44	42	41
Retrofit CCS									
	Overnight Capital Cost ($/kW)		1,670	1,300		1,000	900	870	861
	Fuel Cost ($/MMBtu)		2	2		2	2	2	2
	Variable O&M ($/MWh)		0.7	0.7		0.7	0.7	0.7	0.7
	Fixed O&M ($/kW/yr)		4	4		4	4	4	4
	Heat Rate if Applicable (BTU/kWh)		2,500	2,500		2,500	2,500	2,500	2,500
	Capacity Factor		85%	85%		85%	85%	85%	85%
	Delta LCOE ($/MWh)		28	24		20	18	18	18
Onshore Wind									
	Overnight Capital Cost ($/kW)	2,000	1,900	1,800	2,000	1,300	1,000	910	883
	Fuel Cost ($/MMBtu)	-	-	-	-	-	-	-	-
	Variable O&M ($/MWh)	-	-	-	-	-	-	-	-
	Fixed O&M ($/kW/yr)	31	31	31	31	25	15	10	8
	Heat Rate if Applicable (BTU/kWh)								
	Capacity Factor (class 4)	35%	35%	35%	35%	36%	36%	36%	36%
	LCOE ($/MWh)	73	69	66	73	47	35	31	29
Offshore Wind									
	Overnight Capital Cost ($/kW)	6,100	5,347	4,320	6,100	1,600	1,300	1,210	1,183
	Fuel Cost ($/MMBtu)	-	-	-	-	-	-	-	-
	Variable O&M ($/MWh)	-	-	-	-	-	-	-	-
	Fixed O&M ($/kW/yr)	86	86	86	86	62	56	53	52
	Heat Rate if Applicable (BTU/kWh)								
	Capacity Factor (class 6)	39%	41%	43%	39%	41%	45%	45%	45%
	LCOE ($/MWh)	196	166	133	196	60	46	43	42

	Scenario	BAU			Breakthrough				
Technology		2010	2020	2030	2010	2020	2030	2040	2050
Solar PV - Utility Scale									
	Overnight Capital Cost ($/kW)	3,100	2,950	2,876	3,100	800	500	410	383
	Fuel Cost ($/MMBtu)	-	-	-	-	-	-	-	-
	Variable O&M ($/MWh)	-	-	-	-	-	-	-	-
	Fixed O&M ($/kW/yr)	20	20	20	20	15	10	8	7
	Heat Rate if Applicable (BTU/kWh)								
	Capacity Factor (Arizona)	23%	23%	23%	23%	23%	23%	23%	23%
	LCOE ($/MWh)	157	150	147	157	45	29	23	22
Solar PV - Rooftop									
	Overnight Capital Cost ($/kW)	4,000	3,500	3,000	4,000	1,000	700	610	583
	Fuel Cost ($/MMBtu)	-	-	-	-	-	-	-	-
	Variable O&M ($/MWh)	-	-	-	-	-	-	-	-
	Fixed O&M ($/kW/yr)	20	20	20	20	15	10	8	7
	Heat Rate if Applicable (BTU/kWh)								
	Capacity Factor	23%	23%	23%	23%	23%	23%	23%	23%
	LCOE ($/MWh)	200	176	152	200	55	38	33	31
Solar CSP									
	Overnight Capital Cost ($/kW)	8,000	6,429	5,714	8,000	2,857	2,143	1,929	1,864
	Fuel Cost ($/MMBtu)	-	-	-	-	-	-	-	-
	Variable O&M ($/MWh)	-	-	-	-	-	-	-	-
	Fixed O&M ($/kW/yr)	90	80	80	80	65	45	40	37
	Heat Rate if Applicable (BTU/kWh)								
	Capacity Factor (including effect of storage)	48%	50%	55%	48%	60%	66%	69%	70%
	LCOE ($/MWh)	204	159	130	201	64	43	37	35
Geothermal									
	Overnight Capital Cost ($/kW)	4,500	4,050	3,600	4,500	3,000	2,500	2,350	2,305
	Fuel Cost ($/MMBtu)	-	-	-	-	-	-	-	-
	Variable O&M ($/MWh)	-	-	-	-	-	-	-	-
	Fixed O&M ($/kW/yr)	225	175	135	225	125	75	60	60
	Heat Rate if Applicable (BTU/kWh)								
	Capacity Factor	87%	90%	95%	87%	95%	98%	98%	98%
	LCOE ($/MWh)	78	64	52	78	45	33	29	29
Nuclear									
	Overnight Capital Cost ($/kW)	4,750	4,500	4,300	4,750	2,300	1,700	1,520	1,466
	Additional Capital Costs (over-runs, etc.)	15%	10%	5%	15%	0%	0%	0%	0%
	Variable O&M Including Fuel ($/MWh)	10	10	10	10	10	10	10	10
	Fixed O&M ($/kW/yr)	90	90	90	90	90	90	90	90
	Heat Rate if Applicable (BTU/kWh)								
	Capacity Factor	90%	93%	94%	90%	95%	98%	98%	98%
	LCOE ($/MWh)	78	70	65	78	43	37	35	34

Transportation

	Scenario	BAU			Breakthrough				
Technology		2010	2020	2030	2010	2020	2030	2040	2050
EV Batteries									
	Energy Capacity Cost ($/kWh)	500	300	250	500	200	100	80	70
	Energy Density (Wh/kg)	100	150	200	100	300	400	450	500
	Max Calendar Lifetime (years)	10	10	10	10	10	20	20	25
BEV Car (compact sedan) - Other Assumptions									
	Efficiency (miles/kWh)	3.0	3.5	4.0	3.0	5.0	6.0	6.5	7.0
	Range (miles)	100	200	300	100	200	300	350	400
	Electric Drivetrain Cost ($/vehicle)	5408	4,058	3,290	5408	4,058	3,290	2,667	2,162
	Battery Cost ($/vehicle)	16,667	17,143	18,750	16,667	8,000	5,000	4,308	4,000
	Other Costs - body, chasis, labor ($/vehicle)	13,800	13,800	13,800	13,800	13,800	13,800	13,800	13,800
	Total Capital Cost ($/vehicle)	35,874	35,001	35,840	35,874	25,858	22,090	20,775	19,962
	Maintenance and Repairs (cents per mile)	2.0	1.9	1.8	2.0	1.9	1.8	1.7	1.6

Grid Storage

	Scenario	BAU			Breakthrough				
Technology		2010	2020	2030	2010	2020	2030	2040	2050
Grid Storage - Short Timescale (<1 hr)									
2010 Based on Today's Li ion	Battery Cost ($/kWh)	500	400	300	500	100	50	35	30
	Min Charge Time (hr)	1.0	1.0	1.0	1.0	0.5	0.1	0.1	0.1
	Round-Trip Efficiency	85%	90%	93%	85%	94%	95%	95%	95%
	Cycle Lifetime @ 80% DoD (cycles)	3,000	3,500	4,000	3,000	10,000	20,000	40,000	80,000
	Max Calendar Lifetime (years)	10	10	10	10	15	20	20	20
Grid storage - long timescale (>1 hr)									
2010 Based on Today's Li ion	Energy Capacity Cost ($/kWh)	500	400	300	500	100	50	35	30
	Min Charge Time (hr)	7.0	7.0	7.0	7.0	5.0	3.0	0.1	0.1
	Round-Trip Efficiency	80%	80%	80%	80%	85%	90%	95%	95%
	Cycle Lifetime @ 80% DoD (cycles)	2,000	2,500	3,000	2,000	10,000	20,000	40,000	80,000
	Max Calendar Lifetime (years)	15	15	15	15	20	25	20	20

Clean Energy Policy

	BAU	Clean Policy	$30/ton CO2
Description	EIA AEO + existing state and federal policies	More aggressive CES, EE, CAFE, incentives and regulation	Same as BAU
CES	No federal CES, existing state RPS' only	National CES: 15% by 2020; 25% by 2030; eligible sources are renewables, CCS, and new nuclear; no exemptions	Same as BAU
Efficiency	Existing national mandates, standards and state EERS	National EERS: 5% by 2020, 10% by 2030 (~20% of capture potential)	
Clean Incentives	Existing PTC, ITC expire on authorized timelines	Extend PTC and ITC through 2030 capped at $10B annually, loan guarantee for all clean techs capitalized with $15B	Same as BAU
Transportation	Existing CAFE – Proposed NHTSA rule: 34.6 mpg for "passenger vehicles" (cars and light trucks combined) for model year 2016, no improvements thereafter	CAFE + 4%/yr. improvement from 2016–2025, 1%/yr. Thereafter for LDVs: CAFE + 4%/yr. in 2016–2025, +1%/yr. after 2025. For MDVs/HDVs: proposed fuel efficiency rules in 2007–2022, +1%/yr. after 2022.	Same as BAU
Coal Retirements	Announced retirements + uneconomic coal plants given existing regulations (~20 GW of retirements)	55GW by 2020, strict EPA regulations includes tightening SOx/NOx caps, MACT/HAPs, transport rule 316b (cooling towers); and CCR (ash disposal)	Same as BAU
Carbon Price	None	None	$30/ton CO_2, power sector only. Revenues distributed to states based on proportional tax receipts

Glossary

AEO – US Energy Information Administration's Annual Energy Outlook 2011

BEV – Battery Electric Vehicle. A type of electric vehicle that uses entirely electric propulsion, with energy stored on-board in battery packs.

Break over Point – The crossover point at which one technology becomes cheaper than another.

Breakthrough – In this study, breakthrough is used to represent a highly aggressive cost/performance level. Practically, it does not represent a single technical innovation but rather represents the sum of multiple major advances in a given technology.

Business As Usual – Continuation of status quo (policy and technology).

CAFE Standards – Corporate Average Fuel Economy Standards. Federal regulations that set baseline minimum average fleet efficiency for miles per gallon (mpg) of cars sold in the United States. Historically CAFE standards have applied to cars and light trucks, but beginning in 2011 the standards will begin to expand to other vehicles. Current standards (2011) require cars to achieve at least 30.2 mpg and light trucks to achieve at least 24.1 mpg.

CAPEX – Capital Expense. Expenditures that are designed to provide future benefits. Occurs when businesses spend money to buy fixed assets or add value to existing assets that will have a life that extends beyond a taxable year.

Cap and Trade – Cap-and-Trade is a policy mechanism for emissions management, which sets a mandatory cap on emissions and creates tradable emissions credits which emitters can purchase or sell as needed to comply with the cap.

CCS – Carbon Capture and Sequestration, a process by which CO_2 emissions are captured and then sequestrated. In this study, CCS refers to CCS for coal fired generation.

Clean Energy Standard – Federal mandate for 25% of all generation by 2030 to be met with renewable sources, new nuclear generation, and carbon capture sequestration.

CNG – Compressed Natural Gas vehicles. Vehicles that use CNG as a substitute for gasoline or diesel fuel in conventional internal combustion engines.

CO_2 – Carbon Dioxide. CO_2 is a greenhouse gas that traps heat from solar radiation in the Earth's atmosphere.

CSP – Concentrated Solar Power also known as Concentrated Solar Thermal (CST). Systems that use mirrors or lenses to concentrate a large area of sunlight onto a small receiver. Electrical power is produced when the concentrated solar energy heats a working fluid, producing steam which powers a turbine that generates electricity.

Emissions Regulation – Requirements that set specific limits to the amount of pollutants that can be released into the environment. In the United States these standards are set by the Environmental Protection Agency (EPA).

Energy Efficiency Resource Standard – A state (and potential federal) requirement that utilities meet a mandated portion of load with efficiency rather than generation.

Energy Storage – Storage from devices or natural processes of some form of energy to perform useful tasks at a later time.

GDP – Gross Domestic Product. Refers to the market value of all final goods and services produced within a nation over a given period of time. GDP is a common indicator of national standard of living.

Geothermal – The use of the earth's natural heat to produce heat and power. Two primary geothermal resources were included in this study: Hydrothermal, the naturally occurring but limited geothermal systems like hot springs; and the potentially much more abundant Enhanced Geothermal Systems (EGS) in which geothermal reservoirs are artificially created.

Gigaton – One Billion Metric Tons.

HDV – Heavy Duty Vehicle. A vehicle that when operated has a gross weight of of 32,000 pounds or greater.

HEV – Hybrid Electric Vehicle. A vehicle that combines an electric propulsion system with an internal combustion engine (ICE).

High Commodity Prices – The sustained increase in price of commodities such as oil, metals, and other natural resources. In our High Commodity Scenario, commodity prices were held 50% above AEO estimates to 2030.

Household Energy Consumption – The amount of energy consumed annually by the average American household including heating fuels (natural gas, oil, wood etc.), transportation (gasoline, diesel etc.), and electricity.

ICE – Internal Combustion Engine

Investment Tax Credit – An investment tax credit equal to 30% of a project's cost of development.

IPCC – Intergovernmental Panel on Climate Change

Jobs – Job numbers reflect net new full-time positions created, including both direct and indirect employment.

kWh/kg – Energy to Weight ratio used as a common measure of energy density in storage technologies.

LCOE – Levelized Cost of Electricity, sometimes called the fully burdened cost of power. LCOE incorporates the costs of a generation facility's development, operation, finance, and required transmission over its operating lifetime. LCOE in this model is the $/MWh price an operator can sell power at and remain Net Present Value positive.

LDV – Light Duty Vehicle. A US classification for trucks or light trucks that have a payload capacity of less than 4,000 pounds.

Loan Guarantee – A loan guarantee is a government promise to assume private debt obligations if the private enterprise defaults. These guarantees are typically used by governments to correct market failures or stimulate investment in higher-risk projects of national interest.

MACT/HAP – Maximum Achievable Control Technology Standards and Hazardous Air Pollutants.

Marginal Cost – Change in the total cost that arises when the quantity produced changes by one unit. The cost of producing one more unit of a good.

MDV – Medium Duty Vehicle. A vehicle that when operated has a gross weight that is greater than 14,000 pounds but less than or equal to 32,000 pounds.

Megawatt – A unit of power that measures the rate of energy conversation. A megawatt is equal to one million watts. A watt is defined as one joule per second.

Nuclear – Nuclear power is the sustained use of nuclear fission to generate heat which is then converted to electricity. In this study, nuclear refers to any fission or fusion process capable of achieving breakthrough cost/performance levels.

OPEX – Operating Expense. Refers to the ongoing cost for running a product, business, or system.

Other Renewables – This grouping includes hydrothermal geothermal, EGS, biomass, biomass co-firing, and waste-to-energy.

PHEV – Plug-in-Hybrid Vehicle. A hybrid vehicle that that uses batteries that can be recharged by connecting to an external electrical source, in combination with an internal combustion engine (ICE).

Production Tax Credit – Tax credit that incentivizes the production of renewable energy. Qualifying renewable energy sources are eligible for a 2.1 cent per kilowatt-hour credit for the first decade of the facility's operation.

Solar PV – Solar Photovoltaic. A method of generating electrical power by converting solar radiation into direct current through the photovoltaic effect. Solar PV in this study refers to any solar material or conversion system (e.g. photochemical, mono or poly silicon, Thin-Film, CIGS) capable of achieving the assumed breakthrough cost/performance levels.

TCO – Total Cost of Ownership. TCO is a financial estimate that estimates total lifetime direct and indirect cost of a product or system to consumers.

Vehicle Range – The distance that can be traveled by a vehicle on either a full tank of fuel or a single battery charge.

Wind Energy – The use of devices (typically mechanical turbines) based on land and at sea to convert the wind's energy into electricity. Wind in this study refers to any method of converting wind to electricity (e.g. high-altitude kites, turbines, aerial propellers etc.) capable of achieving the breakthrough cost/performance level.