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CURC-EPRI Advanced Fossil Energy Technology Roadmap

CURC CARBON UTILIZATION RESEARCH COUNCIL

ADVANCING FOSSIL ENERGY SOLUTIONS

EPRI ELECTRIC POWER RESEARCH INSTITUTE

2018 CURC-EPRI Roadmap Key Takeaways

The CURC-EPRI Roadmap represents a plan for delivering low- or zero-carbon emission, fossil-fueled power plant technologies between 2025-2035 that can be cost-competitive with other sources of electricity under future market conditions.

Several technologies identified in the Roadmap are readying for large-scale pilot testing and a few are preparing for commercial demonstration. It is critical that a program for piloting and demonstrating these technologies be implemented for these technologies to be successfully commercialized. This means annual federal budgets should increase in the next several years to support the scale-up effort.

The macroeconomic benefits to the U.S. and the global environmental benefits far outweigh the federal investment recommended in the Roadmap.

There is historical evidence of public-private partnerships developing new energy technologies that resulted in significant emissions reductions and are estimated to have resulted in a $50 billion economic benefit through 2005.

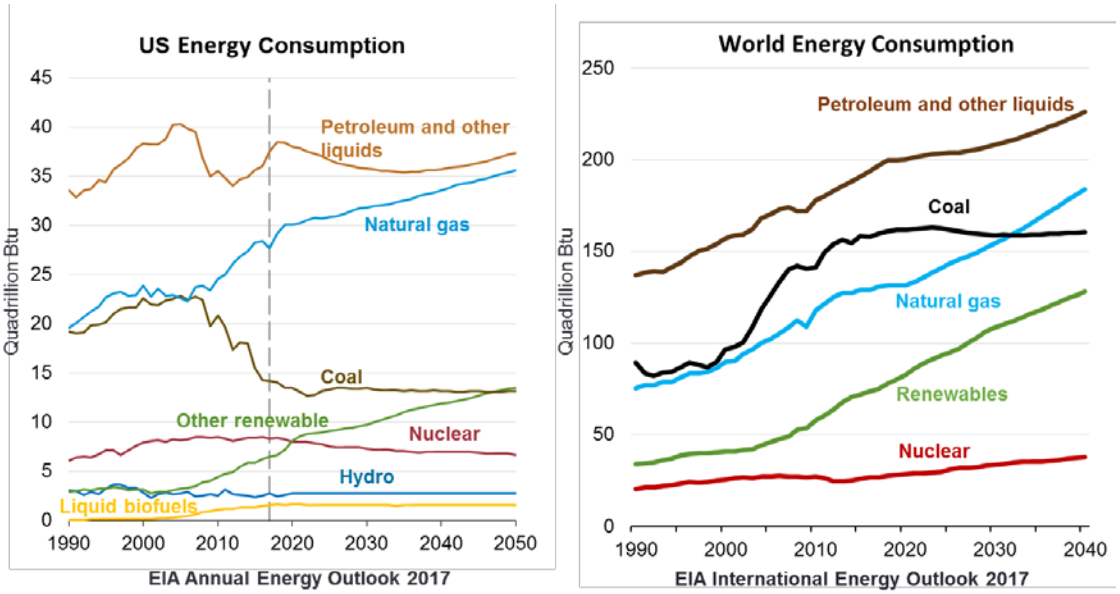
Nearly 75% of the technology developments identified in the Roadmap will support both coal and natural gas power generation applications, which can result in a diverse portfolio of cost-competitive, low-carbon generating options in the future.

Executive Summary

Background

Our nation's fossil fuels play a significant role in the global and domestic energy economy as they provide easily accessible, reliable and low-cost energy. Domestically, coal and natural gas comprised 43% of total U.S. energy consumption and 47% of our net electric generation in 2017 (see Figure ES-1 and Figure ES-2).[1] The U.S. Energy Information Administration (EIA) estimates that coal and natural gas will provide 56% of total U.S. net electricity generation in 2040. Globally, consumption of coal and natural gas are projected to supply 50% of total global energy consumption by 2040. The use of fossil fuels is projected to grow as many emerging economies increase their demand for electricity to fuel their economic growth.

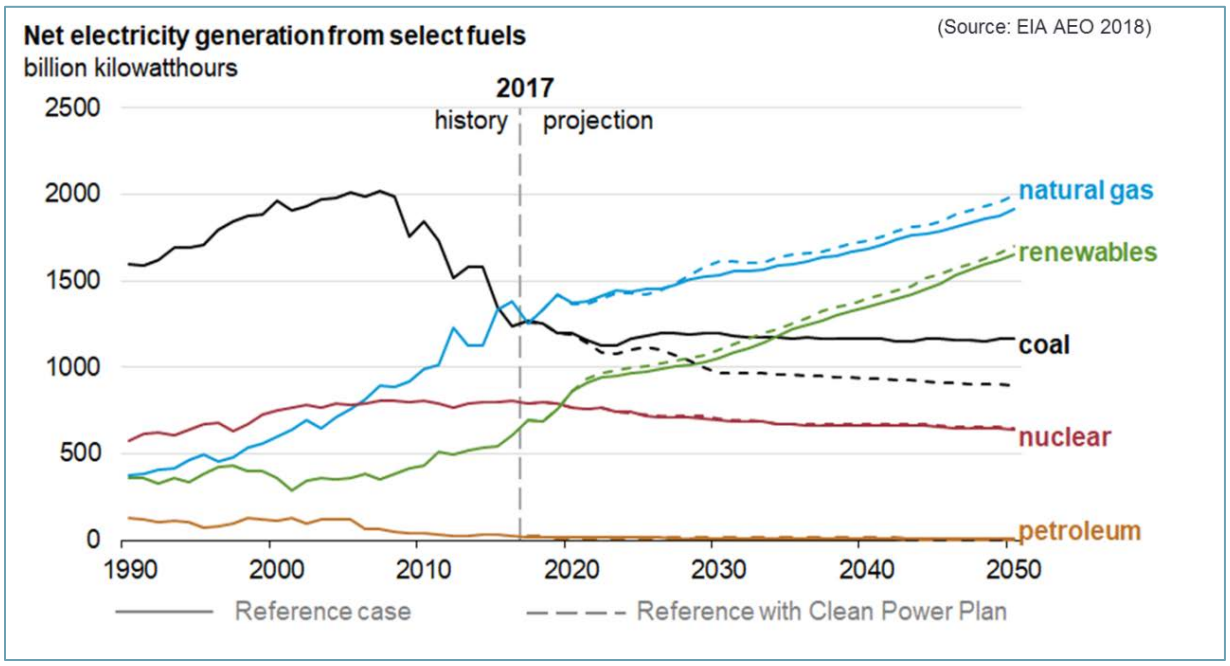
Figure ES-1 - Domestic and International Fossil Fuel Consumption



Because of the value fossil fuels contribute to our economy, the U.S. has invested in technologies to improve the use coal and natural gas in electric power generation. The U.S. has made significant strides in the development of advanced coal and natural gas technologies over the last two decades. Similar to how a new car today can travel further on a single gallon of gasoline than one built in the 1980s, the most advanced coal units operating in the U.S. today are 25% more efficient than the previous generation of coal units. With further technology improvements, additional efficiency gains of similar magnitudes can be achieved for both coal and natural gas combined cycle systems.

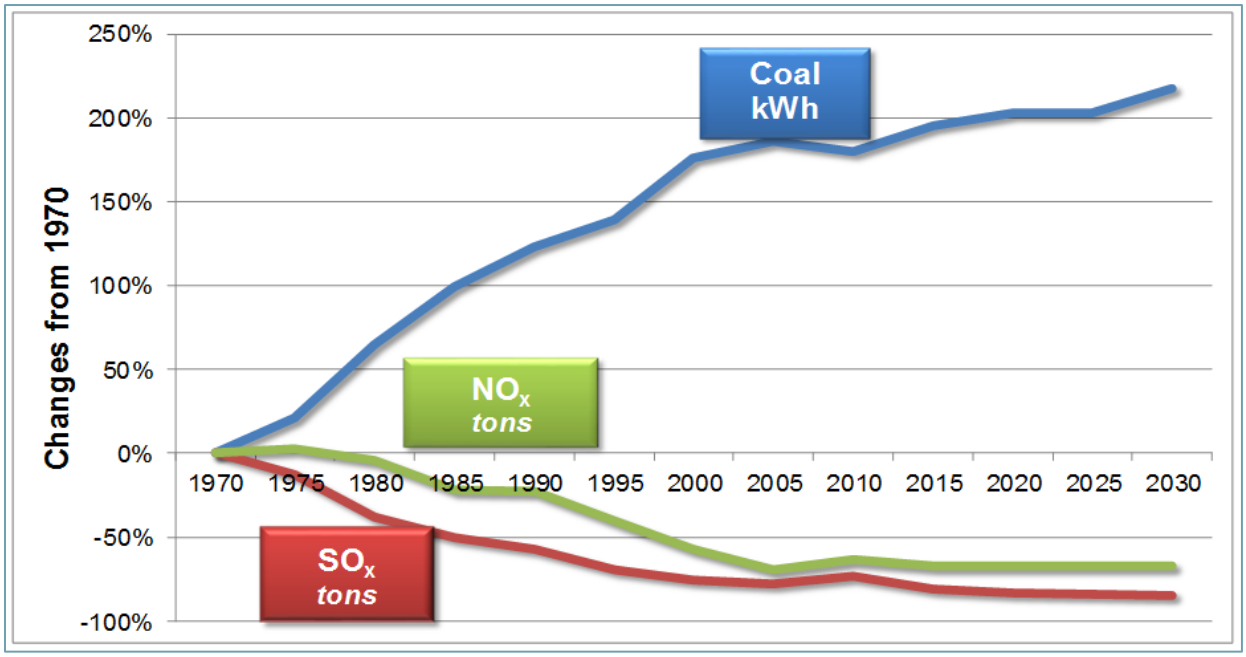
[1] *See* Energy Information Administration, *Annual Energy Outlook 2017 with Projections to 2050* (Jan. 5, 2017) (EIA AEO 2017, https://www.eia.gov/outlooks/aeo/pdf/0383(2017).pdf; Energy Information Administration, *International Energy Outlook 2017*, at 19 (Sept. 14, 2017) (EIA IEO 2017), https://www.eia.gov/outlooks/ieo/pdf/0484(2017).pdf.

Figure ES-2 - U.S. Net Electricity Generation[2]



New technologies have also resulted in significant emissions reductions since the early 1970s, even while fossil use substantially increased. Additionally, technology has substantially reduced the use and discharge of water from fossil fueled power plants (see Figure ES-3).

Figure ES-3 - Historical Improvements in Coal Plant Emission Reductions[3]



[2] Energy Information Administration, *Annual Energy Outlook 2018 with Projections to 2050*, at 89 (Feb. 6, 2018) (EIA AEO 2018), https://www.eia.gov/outlooks/aeo/pdf/AEO2018.pdf.

[3] National Energy Technology Laboratory, Department of Energy, Large Demonstrations, Coal-Fired Generation Emission Rates: https://www.netl.doe.gov/research/coal/large-scale-demonstrations

There is increasing international consensus that technologies to address the growing use of fossil fuels must be developed and deployed to reduce the carbon footprint of fossil fuels. Models show the need for technologies that significantly reduce carbon dioxide (CO_2) emissions profiles to meet global climate targets. Yet cost-effective, commercially-tested technologies to enable a transformational change in the conversion of fossil fuels to electricity with carbon capture, utilization and storage (CCUS) are not available today.

As a result, more recent technology efforts have focused on technologies to reduce carbon dioxide emissions. There is a first-of-a-kind (FOAK) carbon capture project successfully operating on a coal-fired power plant in the U.S. today that is selling its carbon dioxide to enhance recovery of oil in a nearby oil field – the Petra Nova project in Texas. This innovative FOAK project relied on federal financial support to launch. While research is advancing that will result in lower cost technologies, carbon capture is not yet economic for widespread application in the power sector today.

The 2018 CURC-EPRI Advanced Fossil Energy Technology Roadmap (or "Roadmap") is a plan developed by the Carbon Utilization Research Council (CURC) and the Electric Power Research Institute, Inc. (EPRI) that identifies the research, development and demonstration (RD&D) needs to commercialize a suite of technologies that will transform the way fossil fuels are converted to electricity. If implemented, the Roadmap identifies technologies that can be available by the 2025-2035 timeframe that generate electricity from fossil fuels with low or no emissions at a cost competitive with other sources of electricity generation.

2018 Roadmap Overview

The 2018 Roadmap reflects the technology development needs that can support an evolving U.S. power sector impacted by several emerging trends driving innovation and investment decisions for new generation, including:

- Increased and low-cost domestic supplies of natural gas
- Slow, and in some areas of the country declining, load growth and electricity demand
- Ability to rapidly adjust to cycling load demands with increased intermittent renewables on the grid
- Integration of new generation sources with distributed power systems
- Rapidly evolving customer requirements for purchasing electricity
- Need for generation sources with low or no CO_2 emissions that meet state, regional and pending federal regulatory requirements
- An aging fleet driving the need for accelerated development of new, transformational fossil energy technologies to ensure replacement options are available

The 2018 Roadmap continues to evaluate development needs for the existing fossil-fuel fleet; updates efforts to accelerate development of "transformational" technologies that will deliver significantly higher value in terms of cost, efficiency, flexibility and environmental performance from the use of fossil fuels; and promotes continued support of large-scale pilots for testing new technologies under real operating conditions at a scale beyond laboratory- and bench-scale, and before testing technologies in a commercial-scale demonstration.

The 2018 Roadmap builds on prior Roadmap objectives by identifying the technology development needed to cost-effectively implement technologies that will result in a reduced environmental footprint, including near or zero emissions of CO_2, from the use of coal and gas resources in power generation. It

was determined that many of the technologies identified in the 2015 CURC-EPRI Coal Technology Roadmap are applicable to both coal- and natural gas-fired power generation, through which public-private sector funding and support can be leveraged to develop technologies for applications using both resources. Table ES-1 summarizes the technology programs more fully described in the report.

Table ES-1 – Technology Programs Supported in the Roadmap

Transformational Advanced Energy Systems		
Technology	**Fuel**	**Description**
Pressurized Oxy-Combustion (P-Oxy)	Coal and Natural Gas	Oxy-combustion power plants remove nitrogen from air cryogenically and perform the combustion of fossil fuels with oxygen and recycled flue gas to produce a stream largely comprised of CO_2 and water, greatly simplifying carbon capture. P-Oxy operates at elevated pressure, improving efficiency and allowing smaller components that combine to potentially reduce costs.
Chemical Looping Combustion (CLC)	Coal and Natural Gas	CLC is a form of oxy-combustion in which oxygen from air is separated using a metal oxide or limestone oxygen carrier, eliminating the need for cryogenic air separation and its significant energy penalty, while maintaining the relatively easy carbon capture provided by oxy-combustion.
Direct-Fired Supercritical CO_2 (sCO_2) Cycles	Coal and Natural Gas	A form of oxy-combustion, direct-fired sCO_2 cycles burn natural gas or syngas (provided by coal gasification) in a high-pressure oxy-combustor, producing very high-temperature CO_2 and water that drive a sCO_2 turbine to make power. Water and CO_2 (at pipeline pressure) are then removed downstream to conserve mass, producing a high efficiency, potentially low-cost carbon capture system.
Indirect-Fired sCO_2 Cycles	Coal and Natural Gas	Replace steam-Rankine cycles with sCO_2 cycles which, due to the superior thermodynamic qualities of CO_2, have higher efficiency and utilize more compact turbomachinery. Can be used on any cycle that currently uses a steam-Rankine one, including solar thermal, geothermal, nuclear, biomass and any type of fossil fuel. The process results in 2–5 percentage point higher efficiencies and can be coupled with a low-cost carbon capture system.
Gasification	Coal	Coal can be gasified in either an air- or oxygen-blown gasifier to produce synthetic gas (syngas) that can be used in an efficient integrated gasification combined cycle (IGCC) system. Pre-combustion carbon capture can also be added. New, highly efficient, compact gasifiers can be used in poly-generation plants that combine electricity generation with co-production of transportation fuels, fertilizer and/or other chemicals to improve the overall economics.
Compact Hydrogen Generator	Natural Gas	New, highly efficient method for producing hydrogen (alternative to steam-methane reforming).
Cross-Cutting Technologies		
Technology	**Fuel**	**Description**
Advanced Ultra-supercritical Materials (A-USC)	Coal and Natural Gas	A-USC materials are needed to allow working fluid temperatures up to 760°C to support highly efficient combustion and heat exchange systems for both steam-Rankine and sCO_2 power systems and other high-temperature technologies. Can be applicable to both new and existing plants.
Turbines	Coal and Natural Gas	RD&D and testing of steam turbines, combustion turbines, sCO_2 turbines and pressure-gain combustion (PGC), all in an effort to improve efficiency, reliability and flexibility and support power systems evaluated in the Roadmap.

Cross-Cutting Technologies		
Technology	Fuel	Description
CO_2 Capture	Coal and Natural Gas	Advances in solvents, sorbents and membranes for both pre- and post-combustion carbon capture focused on lowering energy requirements and overall cost of capture including capital, operating and maintenance costs. Technologies will need to be adjusted to handle the differences between coal and natural gas flue gas, which include different CO_2 concentrations and trace species. R&D is also focusing on flexibility of operations of carbon capture systems to accommodate ramping cycles.
CO_2 Storage	Coal and Natural gas	Saline reservoirs, enhanced oil and gas recovery and other geologies are being explored for storing CO_2 both onshore and offshore. RD&D as well as large-scale CO_2 storage and regional infrastructure strategies related both to storage and transportation in the U.S. are needed.
Existing Plants	Coal and Natural Gas	RD&D to support flexibility and reliability of operations of existing plants.
Cross-Cutting	Coal and Natural Gas	RD&D on technologies that support all Roadmap areas, including: • Advanced manufacturing • Breakthrough technologies • Sensors and controls • Water management

Projected Benefits

Successful implementation of the Roadmap can result in significant environmental, economic and energy security benefits including:

1. Aggressive reduction of water use and air pollutants, including nitrogen oxides (NOx), sulfur dioxide (SO_2), mercury (Hg) and particulate matter (PM)
2. Reduction of CO_2 emissions
3. Production and preservation of affordable electricity essential for U.S. competitiveness through a diverse generation technology portfolio
4. Significant growth in gross domestic product (GDP) and jobs due to the macroeconomic impacts of increased domestic oil production and reductions in the cost of electricity (COE)
5. Improved energy security by:
    a. Generating affordable power for electricity consumers including increased industrial and advanced manufacturing customers
    b. Improving the operational flexibility of existing and future generating plants to ensure continued electricity grid reliability and stability
    c. Using captured CO_2 as a commodity to recover crude oil, thereby increasing domestic oil production

CURC and ClearPath Foundation, with support from the International Brotherhood of Boilermakers, Iron Ship Builders, Blacksmiths, Forgers & Helpers, the International Brotherhood of Electrical Workers, and the United Mine Workers of America, with primary analyses conducted by NERA Economic Consulting and Advanced Resources International, have published the results of a study that projects the

macroeconomic benefits of new, lower-cost CCUS technologies to the U.S.[4] Under the scenarios evaluated, the study, entitled "Making Carbon a Commodity: the Potential for Carbon Capture RD&D", estimates that if an aggressive RD&D program is implemented that achieves the cost targets identified in this Roadmap, market-driven deployment of 62 to 87 GW of power-sector projects with installed carbon capture technologies can be enabled by 2040 without any additional environmental regulations or mandates.

Under an aggressive RD&D scenario that achieves those cost targets, the macroeconomic impacts of low-cost power sector carbon capture technologies that sell CO_2 for use in enhanced oil recovery (EOR) can:

- Increase coal production by as much as 40% between 2020 and 2040
- Contribute 100 to 923 million barrels of annual domestic oil production
- Add 270,000 to 780,000 new jobs and $70 billion to $190 billion to the annual GDP relating to increased oil production
- Decrease the retail cost of electricity 1.1 to 2.0% by 2040, which on its own creates an additional 210,000 to 390,000 jobs and adds $30 to $55 billion in GDP

Cost of the Roadmap Effort

Achieving the objectives of the Roadmap will require a combined public and private sector partnership over approximately 15 years. The projected federal investment averages $760 million per year (see Table 6). Current funding levels remain well below these recommendations; the technology programs outlined in the CURC-EPRI Roadmap were appropriated at only $430 million in FY 2018. Although the recommendations are a significant increase over current levels, the resulting DOE annual Fossil Energy RD&D budget would still be less than current allocations to the Department's renewable energy equivalent. Moreover, the federal investments in advanced power systems and carbon capture technologies are expected to generate significant returns as outlined in the CURC and ClearPath Carbon Report.[5] These projected benefits likely understate their macroeconomic potential because they do not include other CO_2 utilization or sequestration storage options, or evaluate scenarios under a potential future climate policy or regulation.

Federal funding support to incentivize the deployment of new and improved fossil-fueled generating plants will also help ensure U.S. engineering and manufacturing expertise grows, drive development of a robust U.S. supply chain and better position the U.S. to be a global leader in innovative fossil fuel technologies. Federal support and policies to incentivize these investments in today's electricity markets are critical to ensuring the U.S. can achieve these benefits.

What Next?

Since the 2015 Roadmap, there has been growing support for policies that favor CCUS and the technology recommendations that achieve the Roadmap objectives, including a program for large-scale pilots. In FY 2017, Congress appropriated $50 million for the U.S. Department of Energy (DOE) to undertake a new, transformational coal pilot program. The DOE program has solicited projects for both processes and components, along with post-combustion carbon capture, aimed at enabling step-change

[4] CURC and ClearPath Foundation, *Making Carbon a Commodity: the Potential of Carbon Capture RD&D* (July 2018) (CURC and ClearPath Carbon Report), http://www.curc.net/curc-clearpath-report-rollout-briefing.
[5] Ibid.

improvements in coal-powered system efficiency, COE and carbon capture performance.[6] The program will be carried out in three phases, with the first phase nearing completion with nine projects having been selected to develop initial design concepts.[7] The intent of the program solicitation is to ultimately design, construct and operate two large-scale pilots with these transformational attributes. Congress appropriated an additional $35 million in FY 2018 to support the total $100 million program.[8]

In addition, legislation was moved in the last Congress to authorize a new RD&D program through the America COMPETES Act (H.R. 1806) and the Energy Policy Modernization Act (S. 2012). Each of these bills included provisions reflecting the 2015 Coal Technology Roadmap programs. While the House and Senate each passed their version of comprehensive energy bills, the Conference Committee did not agree to a final package. The Senate reintroduced its comprehensive energy bill in this Congress, S. 1460, which includes the Fossil Energy RD&D provisions from the earlier bill, S. 2012. This year, the "FUEL Act" (S. 2803) was also introduced, which amends the S. 2012 RD&D provisions to reflect updates from the 2018 CURC-EPRI Roadmap. In the House, H.R. 5745 has been introduced, which would likewise authorize several programs that align with the direction of the 2018 CURC-EPRI Roadmap technology program.

Additional efforts have focused on financing deployment of CCUS, which is important to reduce CO_2 emissions from the use of fossil fuels across many industries – not just the power sector. In February 2018, Congress enacted the FUTURE Act to extend and expand Section 45Q tax credits for CCUS from any industrial source. The new 45Q provisions are designed to catalyze a CCUS industry and help promote economies of scale for the application of the technology in the future. The provisions are designed to provide greater financial certainty for commercial projects and will act to stimulate CCUS innovation. While the new 45Q tax credits provide a significant incentive for CCUS, the tax credits do not fully cover the costs of applying CCUS in a power sector application. The technology development outlined in the Roadmap will result in lower-cost technologies targeted at closing that cost gap. Several of those technologies are readying for testing at pilot-scale or in large, commercial-scale demonstrations, and will only be successful with the federal support proposed in this Roadmap.

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[6] *See* U.S. Department of Energy, *Department of Energy Announces $50 Million for Large-Scale Pilot Fossil Fuel Projects* (Aug. 24, 2017), https://www.energy.gov/articles/department-energy-announces-50-million-large-scale-pilot-fossil-fuel-projects

[7] U.S. Department of Energy, *Department of Energy to Invest $6.5 Million for Large-Scale Pilot Fossil Fuel Projects* (Feb. 15, 2018), https://www.energy.gov/articles/department-energy-invest-65-million-large-scale-pilot-fossil-fuel-projects.

[8] *See* H.R. 1625, Consolidated Appropriations Act of 2018: https://docs.house.gov/billsthisweek/20180319/BILLS-115SAHR1625-RCP115-66.pdf; *see also* Congress.gov, H.R. 1625, Consolidated Appropriations Act, 2018, https://www.congress.gov/bill/115th-congress/house-bill/1625