DEPLOY, DEPLOY, DEPLOY: UNPACKING THE STRATEGY TO ACHIEVE NET ZERO BY 2050

The Inflation Reduction Act (IRA) (*see* my previous briefing note, available here) and the Infrastructure and Investment Jobs Act (IIJA) (*see* my previous briefing note, available here) together are poised to unlock close to half a trillion dollars in investments in clean energy. A study undertaken by Princeton University entitled "Net-Zero America: Potential Pathways, Infrastructure, and Impacts" (*see* Princeton Final Report and Princeton Final Report Summary) sets out a framework to evaluate how to most effectively make use of funds that are becoming available under the game-changing legislation.

Specifically, the study sets out, in the words of the authors, for the benefit of political, business and societal conversations, what it would take for the United States to achieve an economy-wide net zero GHG emissions target by 2050 – that is an economy that emits no more GHGs than are permanently removed and stored each year, in order to achieve the Paris Agreement goals. Reaching the 2050 target will mean eliminating or offsetting approximately 6 billion tons per year of GHGs. The study posits that reaching net zero will require unprecedented rates of deployment of multiple technologies and immediate, large-scale mobilization of capital, policy and societal commitments, including at least $2.5 trillion in additional capital investment (relative to business as usual) over the next decade into energy supply, industry, buildings and vehicles. The study is timely roadmap for responding to Energy Secretary Jennifer Granholm's call to arms to "deploy, deploy, deploy."

The Pathways

The study sets out five pathways premised on three key elements: the extent of end-use electrification in transport and buildings (E), the extent of solar and wind electricity generation (RE) and the extent of biomass use for energy (B). The authors do not endorse a particular pathway. Each is different, but all achieve the same goal and all rely, to greater or lesser extent, on six pillars of decarbonization. The pathways, each with different assumptions about energy-demand and energy-supply technology options available in the future, are:

E+	**High Electrification**: assumes aggressive end-use electrification (transport and buildings), but energy-supply options are relatively unconstrained for minimizing total energy-system cost to meet the goal of net-zero emissions in 2050; no land-use change for biomass allowed
E-	**Less-High Electrification**: less aggressive end-use electrification (transport and buildings), but same supply-side options as E+; no land-use change for biomass allowed
E- B+	**High Biomass**: electrification level of E-, but higher biomass supply allowed (converting agricultural land from food to energy crops) to enable possible greater biomass-based liquid fuels production to help meet liquid fuel demands of non-electrified transport
E+ RE-	**Renewable Constrained**: electrification level of E+; on the supply-side, RE (wind and solar) rate of increase constrained to 35 GW/y (~30% greater than historical maximum single-year record). More CO_2 storage allowed to enable the option of more fossil fuel use than in E+
E+ RE+	**100% Renewable:** electrification level of E+; supply-side constrained to be 100% renewable by 2050, with no new nuclear plants or underground carbon storage allowed, existing nuclear plants retired and fossil fuel use eliminated by 2050

In short, and starting from a base of oil, gas and coal representing 85% of the primary energy supply in 2020, and representing 75% by 2050, with 2020 serving as the reference point if no new policies were introduced (REF):

- In all five cost-minimized energy-supply pathways, coal use is essentially eliminated by 2030. Reduction of nearly all coal-fired capacity reduces GHG emissions by roughly 1Gt/y of CO_2.
- Overall, fossil fuels in the primary energy mix decline by 62%-100% from 2020 to 2050 across scenarios. Oil and gas decline 56%-100%.
- In pathways with aggressive electrification (E+, E+RE-, and E+RE+) use of petroleum-derived liquid fuels declines more rapidly than with less-aggressive electrification (E-, E-B+). Natural gas use also declines.
- Oil & gas contributions in 2050 are largest in E+RE-, where fossil, nuclear and renewables each account for about one-third of primary energy.
- Renewable energy (primarily wind & solar power) accounts for the majority of primary energy in 2050 (60-68%) in the other scenarios, and supply 100% of primary energy in the case of E+RE+.
- Nuclear power is maintained at roughly today's levels in the least-constrained cases (E+, E-, E-B+), expands significantly when renewable energy deployment is constrained (E+RE-) and is eliminated by 2050 in a 100% renewable energy pathway (E+RE+).
- All pathways rely on large-scale CO_2 capture and utilization or storage. In E+RE+, 0.7 Gt/y of CO_2 is captured and utilized as a carbon source for synthetic liquid and gaseous hydrocarbons needed to replace fossil fuels. In all other scenarios, more than 1Gt/y of CO_2 is captured with the majority being stored in geologic formations.
- Annualized energy spending across the full 30-year transition as a fraction of GDP is similar to spending levels experienced during recent prosperous periods, but all net-zero pathways are much more capital intensive than historical energy sector capital spending.

The study identifies five key areas of transformation, with a range of sub-pillars, listed below.

The Areas of Transformation

- ***Physical infrastructure – six pillars of decarbonization***
    - ***End-use energy efficiency and electrification***, which has both a **consumer element** (light-duty electrical vehicles (in E+, EV stock grows to 17% of all light-duty vehicles by 2030 and 96% by 2050) and residential heat pump heaters (residential heat pumps grow from 10% in 2020 to 80% (E+) or 54% (E-) by 2050) and an **industrial element** (energy intensity declines (assumed to drop 15-20% below REF by 2050), steel-making moves to electric arc furnaces, and electricity and hydrogen from carbon-free sources replace some industrial fuel uses). These are critical to reduce the required build-out of the energy-supply system to meet demand, and to reduce demand for liquid or gaseous fuels, which are more costly/difficult to decarbonize than electricity.

Equipment replacements are made at economic end-of-life; for long-lived assets, next end-of-life replacement would be with a low-carbon option. These include bulbs, other appliances, air conditioners and heaters, vehicles and industrial boilers.

- ***Clean electricity***: wind and solar generation, transmission capacity and firm power (firm generation being power on demand, any time of year, for as long as required).
  - Electricity generation grows 2x to 4x by 2050. Low or no-carbon electricity goes from 37% in 2020 to 70-85% by 2030, and 98-100% by 2050.
  - Wind (onshore and offshore) and solar power are the lynchpins. Generation grows more than 4x by 2030 to supply approximately half of US electricity in four of the five scenarios; E+RE- sees 3x growth by 2030 to supply one-third of US electricity. By 2050, wind and solar power provide 85-90% of generation in E+, E-, and E-B+ (44% in E+RE- and 98% in E+RE+). Wind/solar capacity deployment rates set new records year-on-year (unless constrained, as in E+RE-), with extensive deployment across the country.
  - Nearly all coal-fired capacity is retired by 2030.
  - Some nuclear plants are operated 80 years, except in E+RE+ where existing plants retire after 60 years, and no new construction is permitted. New advanced nuclear generation capacity is added in all scenarios except E+RE+; expansion is modest in E+, E- and E+B+ with 10-20 GW deployed in the 2030s and 2040s. The E+RE- scenario expands new nuclear capacity rapidly from 2025-2050, deploying 260 GW by 2050, requiring historically unprecedented build-out rates in the 2040s.
  - Natural gas generation declines, except in E+RE-, by 2-30% by 2030, while installed capacities increase 10% over the 2020 level. In E+RE-, gas-fired generation grows through 2035 (up 30% from 2020) before declining to just 7% of 2020 levels by 2050, even as total installed capacity grows to be one-third higher than in 2020.
  - As wind and solar capacity grows, so too must transmission capacity grow by 2050: in E+ 3x 2020 levels, in E- 2x 2020 levels and in E+RE+ 5.1x 2020 levels. Today's transmission grid evolved over a century. In effect, the size of the transmission grid will have to at last double in the next 15 years, and double again in the following 15 years.
  - To ensure reliability, all cases maintain 500-1,000 GW of firm generating capacity through all years (compared to 1,000 GW today); gas plants burn hydrogen blends and with declining utilization rates through 2050. When wind and solar expansion is constrained (as in E+RE-), natural gas plants with CO_2 capture and nuclear plants expand to pick up the slack.
- ***Clean (zero-carbon) fuels: bioenergy, hydrogen and synthesized fuels.*** By 2050, half to two-thirds of our end-use energy will still be fuels, not electricity, but unlike today, the fuels will need to be clean – such as hydrogen and hydrocarbons synthesized from sustainably grown biomass.

Hydrogen is a key carbon-free intermediate and final fuel. Biomass is important as it removes CO_2 from the atmosphere as it grows, meaning that that hydrocarbon fuels made with sustainable-biomass carbon results in no net GHG emissions. The biomass supply in four of the five scenarios consists of agricultural and forest residues, plus transitioning land growing corn for ethanol today to growing perennial grasses or equivalent for energy. This supply scenario thus includes no conversion of land currently used for food or feed production.

- ***CO_2 capture/utilization or storage.*** CO_2 capture and utilization is deployed at large scale in all scenarios. Capture and geological storage is deployed at large scale in all except E+RE+, where all captured CO_2 is used for synthetic fuels. CO_2 capture is deployed on cement production, gas- and biomass-fired power generation, natural gas reforming, biomass derived fuels production and in some cases from direct atmospheric air capture. The majority of geologic sequestration takes place in the Texas gulf coast region. The CCUS industry is enabled by 100,000 km of new CO_2 pipelines. Some capture plants are operational by 2030, followed by rapid growth over the next two decades, and significant trunk lines/spur lines must be installed to keep pace with plants coming online.
- ***Reduced non-CO_2 emissions (methane, N_2O and fluorocarbons).*** Non-CO_2 GHG emissions must be compensated by removal of an equivalent amount of CO_2 from the atmosphere. Negative emissions can be achieved by permanent storage underground (or in long-lived plastics or similar products) of CO_2 derived from biomass or directly captured from the air, or by uptake in soil and trees (*see* next pillar).
- ***Enhanced land sinks (forest management and agricultural practices).*** Land carbon sinks (removal of carbon from the air and permanent storage in soil or trees) are critical to all scenarios, because they offset positive GHG emissions from elsewhere in the economy. The last unit of GHG emissions avoided from the energy/industrial system is the most expensive to mitigate. Thus, land sinks avoid using the most costly measures for GHG emissions reductions in the energy/industrial system.

- ***Capital mobilization.*** The scenarios are 2x-4x more intensive than REF in terms of capital investment. For example, E+ requires at least $2.6 trillion of energy supply-side risk capital before 2030 and at least $10 trillion by 2050. To avoid lock-in and reduce costs of transition to net zero, the scenarios envision capitalizing on the timing of stock turnover of long-lived assets.
- ***Land use***. Direct land use for wind-turbine pads in net-zero scenarios is small, but the (visual) footprint of wind farms is significant. The footprint is largest for E+RE+ at 1 million km^2, or the equivalent of Arkansas, Iowa, Kansas, Missouri, Nebraska and Oklahoma combined. Wind projects are concentrated in the Great Plains, Midwest and Texas, primarily on crop, pasture and forested lands. Land use for solar farms in 2050 is much smaller than the visual footprint of wind farms, but directly impacted lands are greater, ranging from the equivalent of the area of Connecticut for E+RE- to that of Virginia for E+RE+. Solar deployment is greatest in the Northeast and Southeast, and forested lands make up the largest directly impacted land cover type.

- ***Energy workforce***. To support a net-zero transition, the supply-side energy workforce expands by 15% in the first decade and by 1.2x to 3x by 2050. Net-zero pathways support a net increase of 0.3-0.6 million jobs by 2030 relative to REF. Net job losses in fossil fuel sectors across the transition are more than offset (in aggregate) by increases in low-carbon sectors, especially solar, wind and electric-grid sectors. Construction comprises an increasing proportion of jobs over time, and mining (*i.e.*, oil, gas and coal upstream activities) comprises a declining portion.
- ***Air pollution and public health***. As a result of changes in coal and natural gas electric power, on-road vehicles, commercial and residential heating and cooling, gas stations, coal mining, and oil and gas production on the path to economy-wide net-zero emissions by 2050, it is estimated that approximately 40,000 to 45,000 premature deaths ($370-410 billion in damages) are avoided in the net-zero scenarios (relative to the REF scenario) in the 2020s and approximately 260,000 to 410,000 premature deaths ($2.3-3.7 trillion in damages) are avoided from 2020 to 2050.

The Risks to be Mitigated

The successful transition to net zero by 2050 is premised on mitigating four risks, namely failure:

- ***to deploy physical assets and infrastructure at unprecedented rates*** (*e.g.*, adding utility-scale solar and wind capacity by 2030 means installing 38 to 67 GW/y on average; the record to date achieved in 2020 was the addition of 25 GW) – with approval processes that must be updated to accommodate the scale and urgency;
- on the part of governments and the private sector ***to mobilize capital investment at unprecedented rates*** (an estimated $2.5 trillion above REF across energy supply, building, appliances, vehicles and industry – much of it upfront costs, not operating costs, by 2030), including in terms of order of magnitude estimates:
    - **Electricity**: wind ($430 billion), solar ($380 billion), natural gas ($10 billion);
    - **Networks**: electricity transmission ($310 billion), CO_2 transportation ($130 billion), electricity distribution ($30 billion), EV charging ($10 billion) and CO_2 storage ($10 billion);
    - **Buildings and appliances**: residential building shells ($120 billion), residential heat pumps for water and heat ($70 billion), commercial ventilation ($70 billion), commercial heat pumps ($40 billion), commercial appliances and lighting ($70 billion) and residential appliances and lighting ($50 billion);
    - **Vehicles**: electric vehicles (EVs) ($190 billion) and hydrogen fuel cell vehicles ($60 billion);
    - **Industry and fuels conversions** ($360 billion); and
    - **Option creation** ($140 billion).
- ***to gain and sustain community support*** in face of visual and other impacts of wind, solar and grid expansion, carbon sequestration, bioenergy industrialization and nuclear power, and drive consumer uptake of electrification alternatives (EVs and heating); and
- ***to mitigate disruptions to the fossil fuel workforce*** (while many states will see net job gains, a few will face net losses in jobs as fossil fuel industries decline).

The Blueprint for the Remainder of the Decade

The study recommends that the following priority actions be taken up to 2030:

- Get an estimated roughly 50 million EVs on the road and install 3 million or more public charging ports nationwide, and double (at least) the share of electric heat pumps in home heating and triple heat pumps in commercial buildings (with the advantage that EVs and heat pumps not only drive the transition to clean electricity but they also drive reductions in final energy use due to greater efficiencies). In residential buildings, the use of natural gas for space and water heating and cooking is nearly fully replaced by electricity by 2050 across the net-zero transitions, and final energy use is dramatically lower as a result of heating (and air conditioning) using heat pumps. The commercial sector's final energy use also declines, but not as significantly as for the residential sector.
- Grow wind and solar electricity capacity fourfold (to approximately 600 gigawatts), to supply half of US electricity.
- Expand high-voltage transmission capacity by roughly 60% to deliver renewable electricity to where it is needed. Electrification of vehicles and space and water heating will increase electricity demand and require upgrades to electricity distribution networks. Flexible demand, including smart charging of EVs and automation of heat pump systems, can reduce coincident peak demand and stress on distribution networks, minimizing costly upgrades.
- Increase uptake of carbon stored permanently in forests and agricultural soil by 200 million metric tons of CO_2e/yr.
- Reduce non-CO_2 GHG emissions by at least 10%.
- Invest in enabling infrastructure and innovative technologies to create real options to complete the transition to net zero beyond 2030:
    - plan and permit additional electricity transmission to enable further wind and solar expansion;
    - plan and begin building a national CO_2 transportation network and permanent underground storage basins; and
    - invest in maturing key technologies to make them less expensive, scalable and ready for widespread use after 2030, including:
        - carbon capture for various industrial processes and power generation technologies;
        - low-carbon industrial processes;
        - clean "firm" electricity technologies, including advanced nuclear, advanced geothermal and hydrogen combustion turbines;
        - advanced bioenergy conversion processes and high yield bioenergy crops; and
        - hydrogen and synthetic fuel production from clean electricity, and from biomass and natural gas with carbon capture; and direct capture of CO_2 from the air.

The Importance of Transmission

A key element of reaching the GHG emissions potential of the IRA is improving the US high-voltage transmission system, according to another Princeton University-led study, released last week, entitled "Electricity Transmission is Key to Unlock the Full Potential of the Inflation Reduction Act," as part of its REPEAT Project (Repeat being Rapid Energy Policy Evaluation and Analysis Toolkit). This study posits that:

- To unlock the full emissions reduction potential of the IRA, the pace of transmission expansion must more than double the rate over the last decade to reach an average of 2.3% per year. That rate of expansion is comparable to the long-term average rate of transmission additions from 1978-2020.
- Failing to accelerate transmission expansion beyond the recent historical pace (~1% per year) increases 2030 US GHG emissions by 800 million tons per year, relative to estimated reductions in an unconstrained IRA case. Emissions are 200 million tons higher if transmission growth is limited to 1.5% per year.
- Over 80% of the potential reduction in GHG emissions delivered by the IRA in 2030 are lost if transmission expansion is constrained to 1% per year, and roughly 25% are lost if expansion is limited to 1.5% per year.
- New clean electricity must be rapidly added to both meet growing demand from electrification and reduce fossil fuel use in the power sector. Constraining transmission growth severely limits the expansion of wind and solar power.
- If electricity transmission cannot be expanded fast enough, power sector emissions and associated pollution and public health impacts could increase significantly as gas and coal-fired power plants produce more to meet growing demand from EVs and other electrification spurred by IRA.
- If transmission capacity cannot be expanded faster than recent historical rates, growing demand from EVs and other electrification spurred by IRA will result in over 110 million tons of additional coal consumption in 2030 above the no-IRA case and roughly 250 million tons more than if transmission expansion is unconstrained.
- Expanding transmission more rapidly enables growth of wind and solar power and substantially reduces natural gas consumption, which falls 17% from 2021 levels in the unconstrained IRA case. In contrast, if transmission expansion is limited to 1% per year, natural gas use increases to 4% above 2021 levels in 2030 and remains elevated through 2035.

Senator Joe Manchin had proposed legislation (as part of a continuing resolution, agreed in July to get Manchin's approval for the IRA) designed, among other things, to reform the Federal permitting regime. Provisions of the National Environmental Policy Act can be used to block or delay approval of energy projects, which would include new clean energy projects; however, the permitting regime allows the Department of Energy to designate proposed transmission projects to be in the national interest and for the Federal Energy Regulatory Commission to approve them if they meet certain conditions. The legislation would have required the president to designate 25 strategically important energy and mineral projects that would receive priority federal review. There was opposition to the legislation, both from progressives (in spite of White House support), based on concerns that the reforms would weaken environmental reviews of energy infrastructure, particularly for fossil fuel-related projects, and from Republicans – the combination forced its removal yesterday from the stopgap funding bill.

Concluding Thoughts

Efforts to combat the climate crisis, starting with, but by no means limited to, passage of the IIJA and the IRA, highlight the sheer complexity of this existential undertaking. There will be winners and losers, countless new entrants and a scramble for legacy participants to align with the direction of travel. The Princeton University conveys in a far more granular manner the complexity of the undertaking as well as pathways to achieving targeted goals of net zero by 2050.

This effort is not about rebuilding the entire edifice but rather unleashing the powers of technological innovation and incentivizing capital investment. These efforts will need the support of multi-stakeholder engagement between business, and government, investors, unions, community groups and environmental NGOs as the conversations turn, in the words of the authors of the Princeton study, from "if" to "how." A critical element of these conversations will be the building of awareness of the challenges if we do not act and of the pathways to act and overwhelming benefits of acting with urgency.

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