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Can a CO_2 price decarbonize the United States?

By driving technological innovation, the CLC plan would reduce US CO2 emissions by 57% by 2035 (vs. 2005), unlock $1.4tn of new investment, create 1.6M jobs and enhance US competitiveness.

- ***CLC Plan as Basis for Modelling:*** Thunder Said Energy modelled the consequences of a $43/ton CO_2 price in the US starting in 2021, then rising by 5% above inflation each year, reaching $112/ton by 2035. Our bottom-up analysis assessed the impact on the costs and potential benefits of 30 different energy technologies. This summary is drawn from our longer report.
- ***Emissions Reductions of 57% by 2035:*** Based on the cumulative emissions reductions of 30 different decarbonization technologies, unlocked at different price points, the CLC plan would reduce US CO_2 emissions by 57% from the EPA's 2005 CO_2 baseline. See Figures 1 and 2.
- ***$1.4 Trillion of New Capital Investment in Technological Innovation:*** The plan would produce an initial investment surge of $95bn of new spending in 2023 and create 195,000 direct new jobs that year. By 2035, the CO_2 price would unlock a total of $1.4tn of new capital investment in energy-related technological innovation. See Figure 3.
- ***Up to 1.6 Million Jobs Created:*** As per Figure 4, the plan would create 195,000 direct new energy-related construction and operational jobs in 2023, increasing to 255,000 direct new jobs in 2035. Cumulatively, this would lead to the creation of up to 1.6 million new jobs by 2035, including multiplier effects.
- ***Renewable Output Rises 3.3x:*** The longer-term energy system would be transformed. Renewable output would rise 3.3x to 1,350TWH by 2035, moving from 10% to 29% of the net electricity grid, saving 330MT of CO_2 per year. See Figure 5.
- ***Revenue Raised:*** In the first year, the CLC plan could raise $230bn in gross CO_2 fees, which can be returned to all Americans as equal quarterly dividends. That revenue could increase to $340 billion in 2035. See Figure 6.
- ***900TWH of Electricity Generation Would Switch from Coal to Gas*** by 2023, displacing 440MTpa of coal, stoking gas use by 13bcfd (+15% from 2019) and saving 600MTpa of CO_2 (10% of total US emissions). Gas demand would remain above 80bcfd all the way to 2035. All coal used in 2035 would be in plants fitted with CCS.
- ***Renewables Would Reach 30% of the Gross Grid*** by 2035 as wind and solar spending would continue near its record 2019 pace of $55bn of investment. Increased CO_2 prices would accelerate deployment of new wind and solar generation, which increased at 40TWH per annum in 2014-19 and which would rise at 50TWH per annum in 2020-25 and 70TWH per annum in 2025-2030. See Figure 5.

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- ***Industrial Efficiency Gains Would Double:*** Industrial efficiency would grow 2% per year, helping to save another 300MTpa of CO_2 and limiting future growth in US energy demand. Novel technologies would progress faster, advancing the US' competitiveness: most notably, additive manufacturing could save 6% of global CO_2 and re-shore manufacturing supply chains from emerging markets back to the US.
- ***Decarbonization Would Become a Competitive Sector:*** A rising price on carbon would allow a wide range of decarbonization technologies to become cost-effective, including yet unknown solutions, further incentivizing technological innovation.
- ***Levelling the Playing Field:*** One of the greatest advantages of a CO_2 price is that it creates a level playing field for different decarbonization technologies to compete. Thus, the most economical technologies can gain traction. By contrast, if policymakers seek to incentivize individual technologies, there is a danger of selecting overly expensive ones while stifling the emergence of superior alternatives.
- ***Most Efficient Companies Would Win:*** As rising CO_2 prices would steepen cost curves, the most carbon-efficient companies would benefit, particularly in energy-intensive and low-margin sectors, such as refining and basic materials.
- ***Competitive Advantage for US Companies:*** Manufacturing currently occurring in Southeast Asia, or other emerging market countries, would be incentivized to return to the US, closer to the products' point of use. Manufacturing goods in the US using the most efficient and lowest carbon technologies would benefit from a border carbon adjustment.
- ***Inducing Emissions Reductions in Other Countries:*** For global coal-to-gas switching to reach its full potential, delivering 20% of the world's decarbonization by 2050, it would be necessary for other countries to switch coal to gas too. In Europe and Asia, $40/ton is required to encourage this, as gas is 2x more expensive than the US average. The CLC's proposed border carbon adjustment could accomplish this.
- ***Accelerating Electrification:*** The CLC plan would accelerate the electrification of light passenger vehicles. Electric vehicles are already economical without a CO_2 price. CO_2 prices could create a $500-1,000 per annum financial incentive to 'go electric' in 2030-35, deducting a further 2.5Mbpd from our prior 2035 assumptions.
- ***Incentivizing Additive Manufacturing:*** The rising carbon price would lead to steep 65-90% CO_2 savings on manufacturing and distributing certain industrial components, while also returning jobs to the United States. These jobs are not captured by the study and represent additional upside job creation.
- ***Major Reduction in Gas Flaring:*** In addition to CO_2 reductions, one of the largest industrial efficiency opportunities would be capturing flare gas. At 2019's run rate, flaring 15bcm in the US would incur $1.5bn pa of penalties at $50/ton, worsening OPEX for heavy flarers by c$1.3/bbl vs. light flarers. A $90/ton CO_2 price could potentially eliminate US gas flaring.

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Introduction: the rationale and mechanism for CO_2 prices?

CO_2 is an externality. In 2019, US CO_2 emissions ran at 5.9 bn tons[1], due to the consumption of 20Mbpd of oil, 86bcfd of gas and 530MT of coal. Emitters derive economic benefits from their energy consumption. But the climate consequences are incurred by the country's 330M inhabitants, and the world's 7.5bn inhabitants.

The most effective antidote to externalities is to tax them. This would entail emitters paying for their CO_2. These payments can be redistributed to individuals who bear the costs of climate change. A direct tax is also an effective incentive to improve efficiency, invest in new technologies and reduce emissions.

Perhaps the greatest advantage of a CO_2 price is to create a level playing field for different decarbonization technologies to compete. Thus, the most economic technologies can gain traction. Conversely, there may be a danger, if policymakers seek to incentivize individual technologies on a case-by-case basis, of selecting and 'kingmaking' overly expensive technologies, while unintentionally stifling the emergence of superior alternatives that did not receive favourable policy support.

Relying on CO_2 pricing thus produces the most cost-effective path to decarbonization. Keeping energy prices affordable, while decarbonizing the energy system, may be a requirement for preserving political will, in a thirty-year decarbonization process. Hence, our focus on the costs of different energy technologies in our models.

We have modelled the consequences of a CO_2 price, as proposed by the Climate Leadership Council (CLC), a bipartisan policy institute based in Washington DC. Their proposal is a $40/ton CO_2 price (in 2017$), beginning in 2021. This is equivalent to adding 40c/gallon onto US gasoline prices, which averaged $3.0/gallon over the past decade; or adding $2.2/mcf to US natural gas prices, which averaged $10.6/mcf for residential purchases in 2019, $7.6/mcf for commercial and $3.9/mcf for industrial purchases; or equivalent to adding 1.5c/kWh to power prices, which averaged 11c/kWh for residences and 4c/kWh wholesale at ERCOT in 2019. Future CO_2 prices are then assumed to rise at 5pp above inflation.

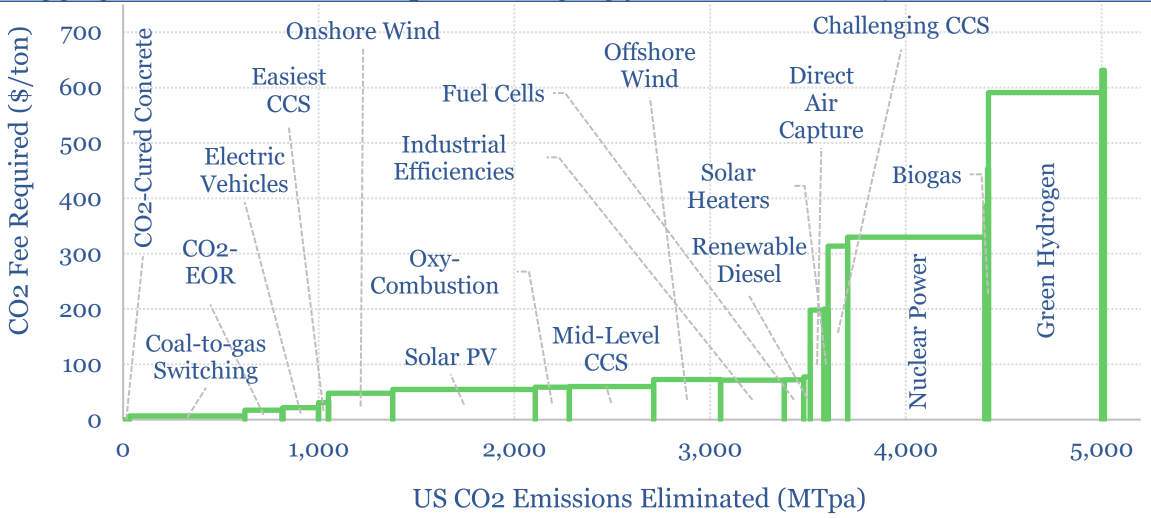
The Benefits of the CLC Plan

These CO_2 prices could unlock enough new investment to eliminate 50% of the United States' 2019 CO_2 emissions, based on sixty economic models constructed by Thunder Said Energy, and available here. **Fig 1** is a cost curve showing the CO_2 price required to generate a 10% IRR deploying each technology.

50% of the US's CO_2 emissions could be eliminated by 2035 purely through a $40/ton (2017$) CO_2 price in 2021, which escalates to $86 real ($112/ton nominal) by 2035 (**Fig 2**).

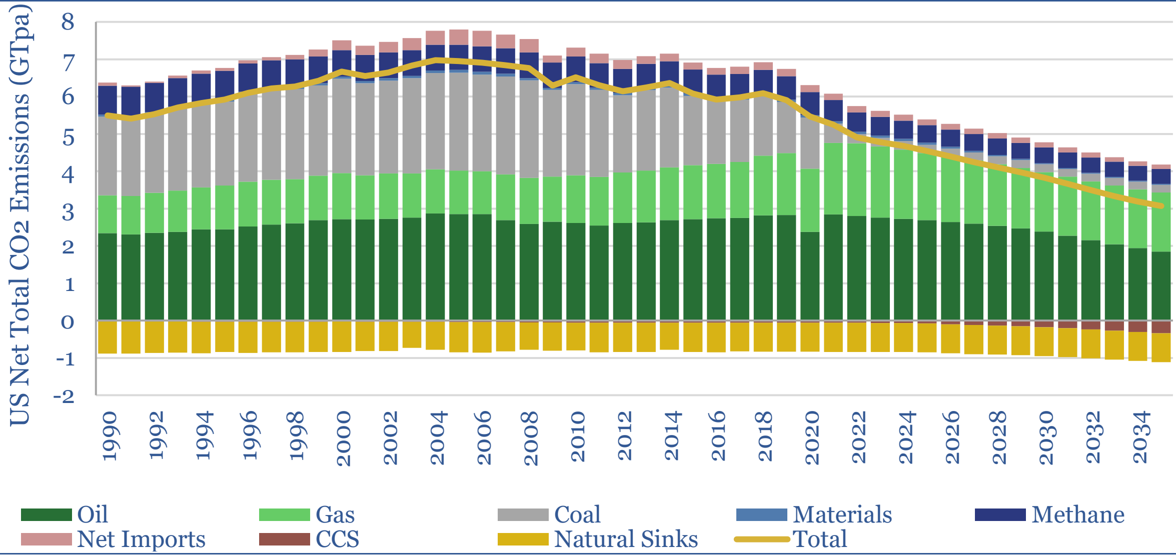
[1] Please see Appendix II, at the end of this report, for additional notes and modelling assumptions.

***Fig 1.** Technologies could eliminate over 5bn tons of CO_2 emissions from the US energy system, with incentive prices ranging from zero to $750/ton*



Source: Thunder Said Energy (see Fig 1 to 3 in Annex 1 for a more granular breakdown)

***Fig 2.** Purely by implementing a CO_2 fee, the US could reduce its emissions 57% by 2035 compared to 2005.*



Source: Thunder Said Energy [Download the data?]

\$230bn of gross CO_2 fees could be raised in 2021, which could be redistributed to Americans. CO_2 fee revenues rise to \$340bn by 2035, as CO_2 prices rise (**Fig 3**). An initial investment surge takes place in late 2021 and peaks in 2023. \$95bn of new annual investment is unlocked in 2023, rising to \$130bn per year in 2035 (**Fig 4**). A total of \$1.4tn of new investment is unlocked from 2021 to 2035. 195,000 jobs are also created by 2023, ramping to 255,000 jobs by 2035 (**Fig 5**).

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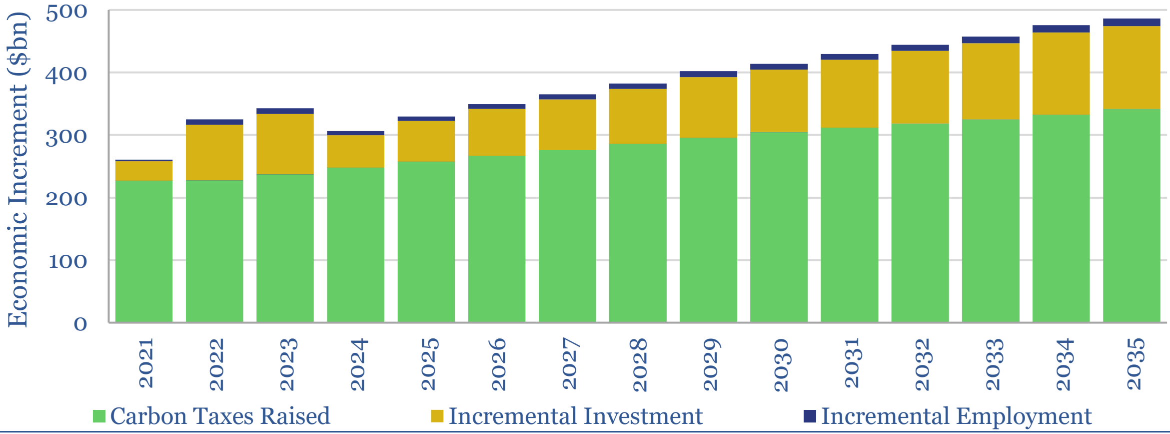
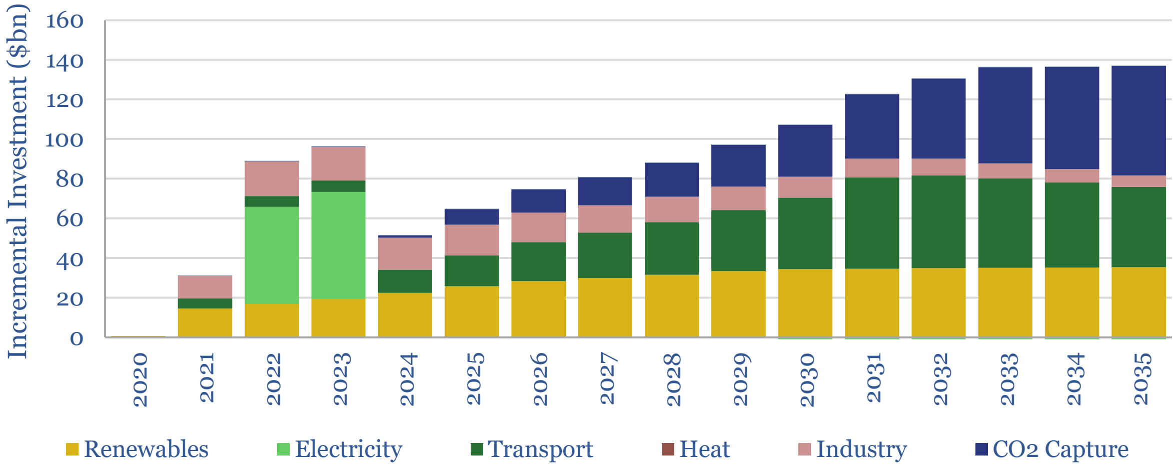
Fig 3. *CO_2 fee revenues could escalate from \$230bn in 2021 to \$340bn in 2035*



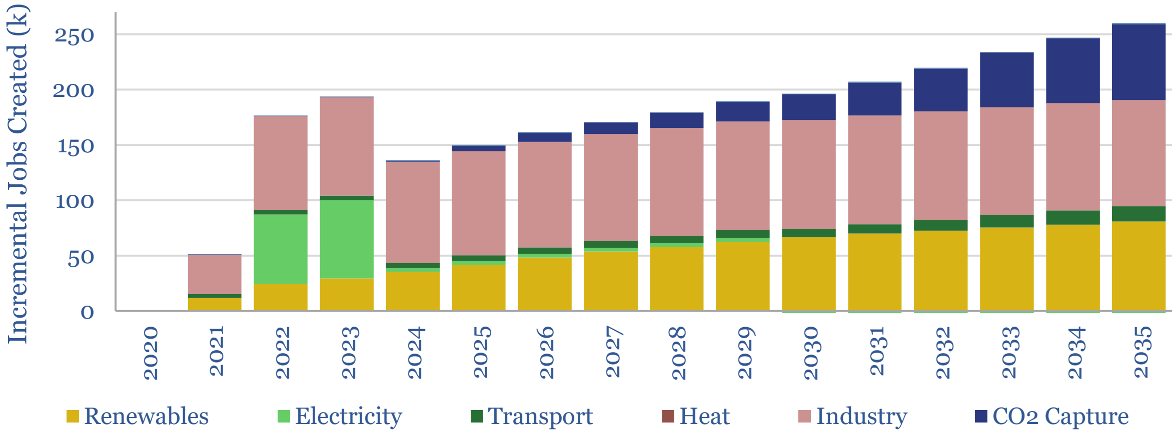
Source: Thunder Said Energy [Download the data?]

Fig 4. *Incremental annual investments escalate over time, with an initial surge to \$95bn in 2023, rising to \$100bn in 2030 and \$130bn in 2035*



Source: Thunder Said Energy [Download the data?]

Fig 5. *195,000 incremental jobs would be created in 2023, in an initial investment surge, while long-term job creation ramps up gradually to 255,00 jobs by 2035*



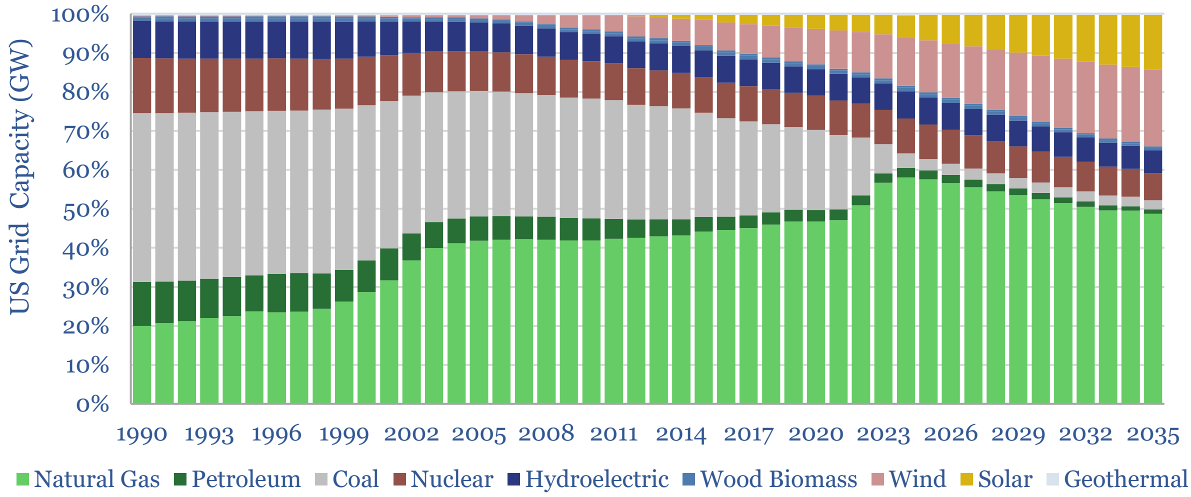
Source: Thunder Said Energy [Download the data?]

We will now explore the consequences of CO_2 prices on the US economy, assessing the impacts of CO_2 prices on power, industry and transportation.

Impacts on the power sector: renewables and gas dominate

A vast acceleration of renewables and natural gas would re-shape the US power mix, shortly after implementing a $40/ton real CO_2 price. For context, in 2019, the US grid was 38% gas, 23% coal, 19% nuclear, 7% hydro and 10% wind and solar. In our analysis existing nuclear power plants are assumed to continue in operation through 2035.

Fig 6. *CO_2 prices help renewables rise from 10% to 30% of the US grid, while switching 440MTpa of coal to 13bcfd of gas saves almost 600MTpa of CO_2*



Source: Thunder Said Energy — Download the data?

Renewables reach an impressive 30% of the gross grid by 2035 as wind and solar spending continues near its record 2019 pace of $55bn, as the new CO_2 price supersedes prior fiscal incentives. This 30% gross share translates into a 29% net share after curtailment, which is still assumed to be insignificant at these levels of grid penetration. Underlying our figures is an acceleration of new wind and solar generation, which increased at 40TWH per annum in 2014-19 and is now seen rising at 50TWH per annum from 2020-25 and 70TWH per annum between 2025 and 2030. These are phenomenal numbers, but it will still take time to materially reconfigure a grid that comprised 4,150 TWH of electricity demand in 2019 and accelerates to 4,700 TWH by 2035 due to the electrification of road transport, discussed below.

Adding batteries to a grid do not materially reconfigure the economics of scaling renewables. Specifically, for a lithium ion battery system to yield a 10% IRR, it must earn a spread of 18c/kWh between its charging power price and its discharging power price (model here). This assumes a capital cost of $1,550/kW by 2025 and 280 charge-discharge cycles per year, which is the number of sunny days in California. To continue providing 1-4 hours of solar energy beyond sundown each day, 0.1GW of

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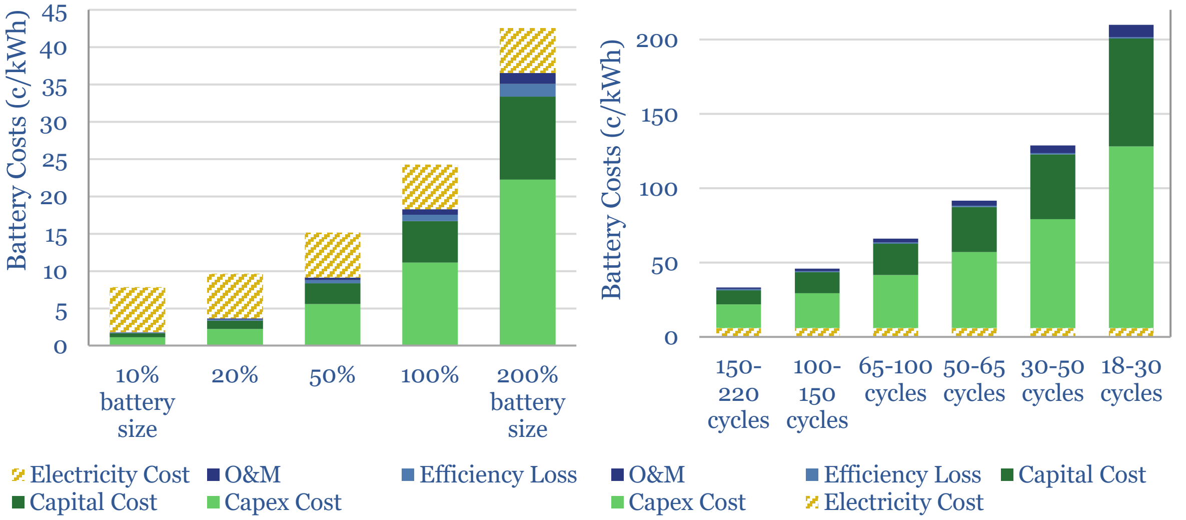
battery capacity is required per 1GW of renewable capacity (i.e., a "10% battery size"). Accordingly, these battery costs amplify the total costs of renewables by 1.8c/kWh. This is not overly expensive and may unlock another 1-2% share of net generation for renewables, before extensive curtailment is required. This is reflected in our numbers. However, costs become exponentially larger to ramp renewables to 40-50% shares in the longer-term electricity markets (**Fig 7**).

Fig 7. *Battery electric storage costs rise exponentially with size and infrequency*



Source: Thunder Said Energy [Download the data?]

The other major change in the grid is the acceleration of natural gas, to backstop volatile renewables. Gas is well suited to this role. It is the cleanest fossil fuel. It is also a competitive advantage for the US, with 420TCF of proved gas reserves, 6% of the world's total, vast further unconventional resources and wholesale US gas prices likely to run 50% below European and Asian gas prices for the foreseeable future. Generating 1 MWH of power from an efficiently configured gas plant emits 0.30 tons of CO_2 per MWH, while up to 1.1 tons of CO_2 are emitted per MWH of coal generation. In other words, a $40/ton CO_2 price detracts 4c/kWh from the spark spread of a coal plant and 1.5c/kWh from the spark spread of a gas plant. This incentivizes higher utilization of gas plants over coal plants in the short-term and new construction of efficient gas plants in the longer-term (**Fig 10**).

Of crucial importance to the scale up of natural gas is mitigating methane leaks, as methane is a 25-120x more potent greenhouse gas than CO_2, depending on the timeframe of measurement. 2-3% of global gas production is leaked across the value chain, including substantially at the final distribution stage. In the US, according to EPA disclosures, the combined leakage rate is 0.6%, equivalent to c18kg/boe (**Fig 8**). This remains c65% lower than the methane emissions that result from coal mining in Virginia, West Virginia, or Pennsylvania.

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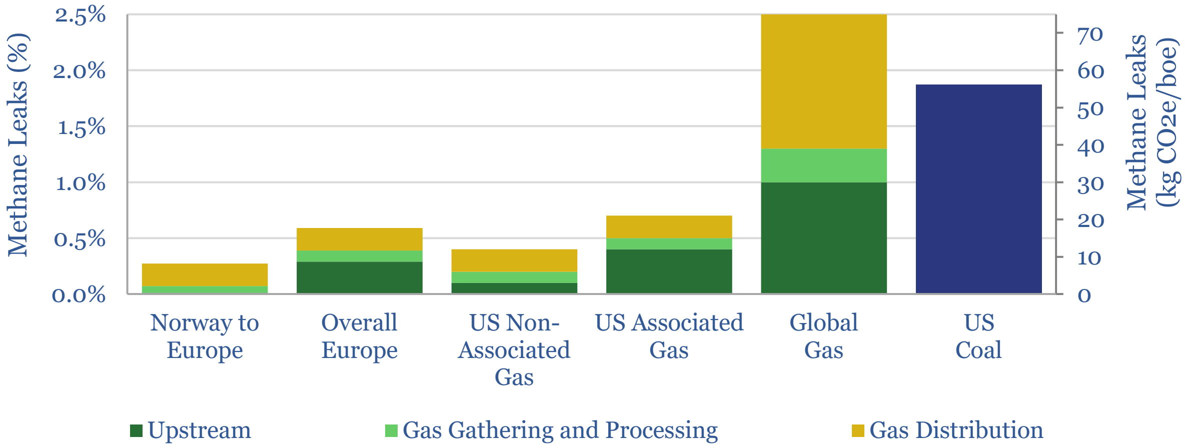
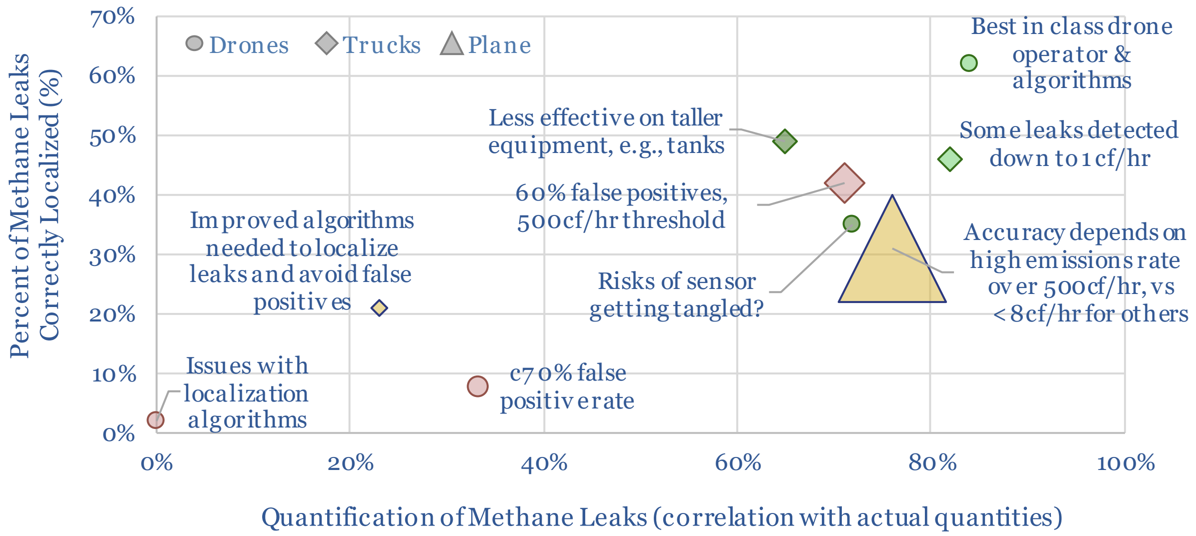
We have also reviewed 35 technologies to lower methane leaks well below 0.3%, to safeguard the scale-up of gas. Operators are beginning to fly drones over their assets, with the best trials detecting practically all leaks above 1cf/hour, and localizing 85% (**Fig 9**). At least three satellites will be in orbit by the early 2020s, promising sufficient resolution to detect 100-1000 kg/hr leaks from space in an area as small as 50m x 50m. Next-generation sensors are also being employed. BP has cut methane emissions in Wyoming by 74% using Kelvin's AI-solutions.

Fig 8. *35 companies and technologies in the methane mitigation value chain*



Source: EPA, Technical Papers, TSE [Read the Report?]

Fig 9. *Nine next-generation methane monitoring drones were screened in 2019*

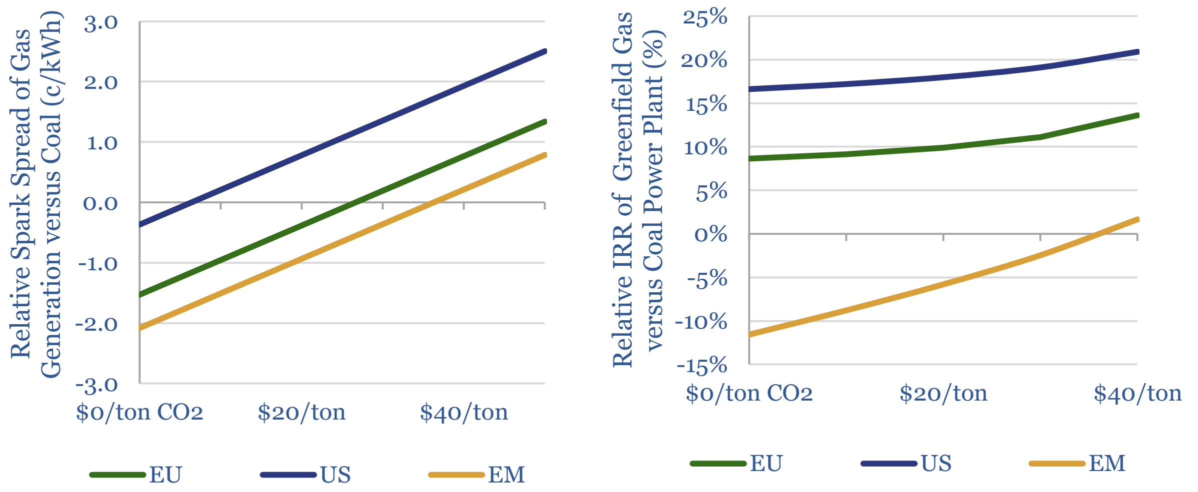


Source: Stanford/EDF, TSE [Download the Data]

The US can be a leader in gas-switching, as shown in **Fig 10**. For global coal-to-gas switching to reach its full potential, delivering 20% of the world's decarbonization by 2050, it would be necessary for other countries to switch coal to gas too. While a $5-10/ton CO_2 price is sufficient to spark coal-to-gas switching in the US, \$40/ton is required in Europe and Asia, as gas is 2x more expensive. Hence, if the US's own CO_2 price translates through to an equivalent tax on the embedded CO_2 of imports, other regions globally would be incentivized to switch coal to gas.

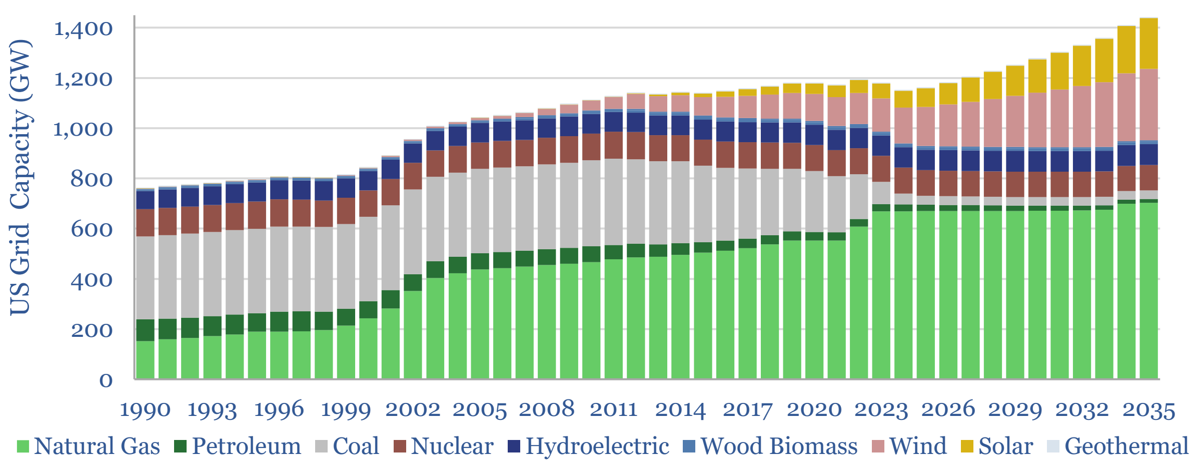
Overall, our model generates 600MTpa of CO_2 savings, or 10% of the US's total decarbonization, by switching 440MTpa of CO_2-intensive coal to 13bcfd of less CO_2-intensive gas in the power sector. In turn, this requires a surge in activity to construct 130GW of new gas-fired power generation capacity, at a CAPEX cost of \$885/kW, unlocking \$100bn of new investments before 2023. The 2035 grid, comprises c35% renewables, 47% gas and 7% nuclear as shown in **Fig 11**.

Fig 10. *A \$5-10/ton CO_2 price is sufficient to incentivize US coal-to-gas switching. \$40/ton would be required outside the United States as gas prices are higher*



Source: EIA, Thunder Said Energy [Download the data?]

Fig 11. *The 2035 grid is 14% larger than 2019 in gross terms, comprising 30% wind and solar (up 3.3x from 2019 levels) and 47% natural gas (up 40%).*



Source: TSE (note: Transmission and grid upgrade costs are not included in our models)

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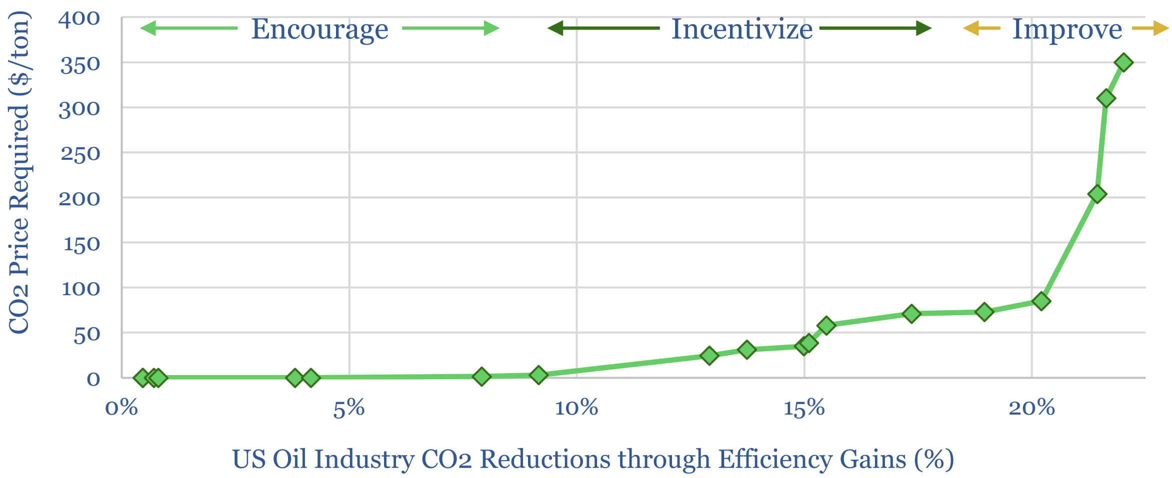
Industrial competitiveness: efficiency gains are amplified

The pace of industrial efficiency gains could double from their historical rate of 1% per annum, we estimate, if the US implements a CO_2 price of $40-80/ton. This matters as industry comprises c30% of global CO_2 emissions, of which c20% is heat and c10% is wasted. These efficiency gains deliver another 300MTpa of CO_2 reductions in our models of the future US energy system, or 5% off 2019's baseline.

Examples are shown from the US oil and gas industry in **Fig 12**, which is interesting to study as it comprises 500MTpa of total US emissions and is thus one of the sectors most in need of decarbonization. It should already be economical to obviate 10% of the sector's emissions, but these projects are complex and potentially disruptive, so they have not taken place to-date without the encouragement of a CO_2 price. Cutting another c10% of the sector's emissions requires a CO_2 price as an economic incentive in order to earn a double-digit return.

Fig 12. *A $40-100/ton CO_2 price unlocks 15-20% efficiency gains from oil and gas*

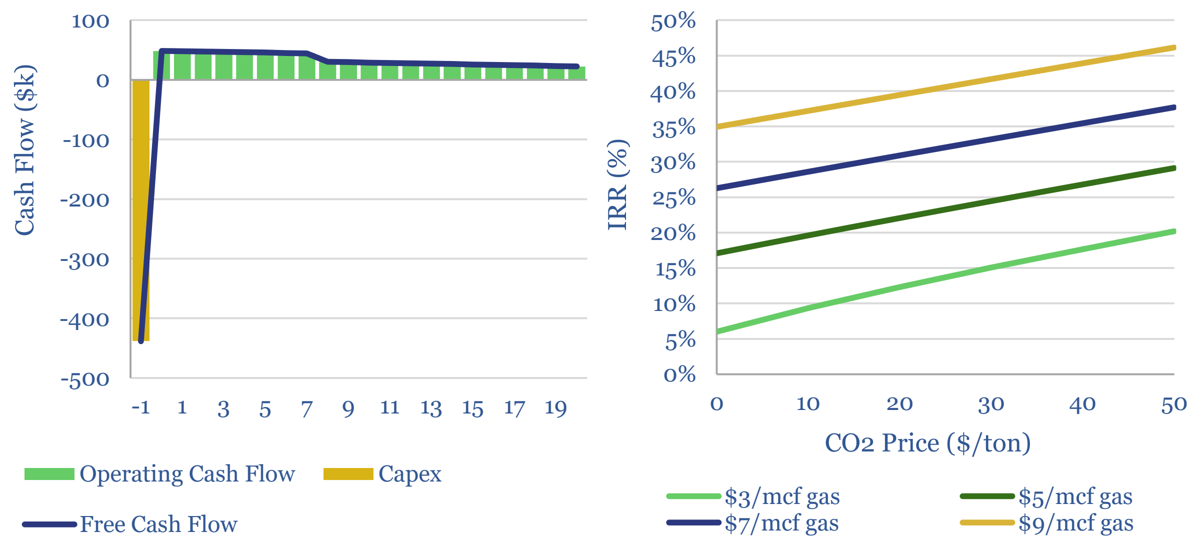


Source: Thunder Said Energy — Download the data?

- ***The largest opportunity is capturing waste heat*** by installing new heat exchangers. A $50/ton CO_2 price uplifts marginal 6% IRRs into solid 20% IRRs. A $50/ton CO_2 price also adds $0.5/bbl onto the refining costs of less efficient refiners relative to more efficient refiners, which is a powerful economic incentive to improve in an industry that tends to earn $1-2/bbl net profit margins (**Fig 13**).
- ***The second largest opportunity is capturing flare gas***. At 2019's run rate, flaring 15bcm in the US would incur $1.5bn pa of penalties at $50/ton, worsening OPEX for heavy flarers by c$1.3/bbl vs. light flarers. A $90/ton CO_2 price could potentially eliminate US gas flaring (**Fig 14**). Potential reductions in methane emissions associated with flaring are not reflected in this analysis.
- ***Other efficiency gains would emerge from the woodwork***, around the oil and gas industry, including further digitization projects (**Fig 15**), methane

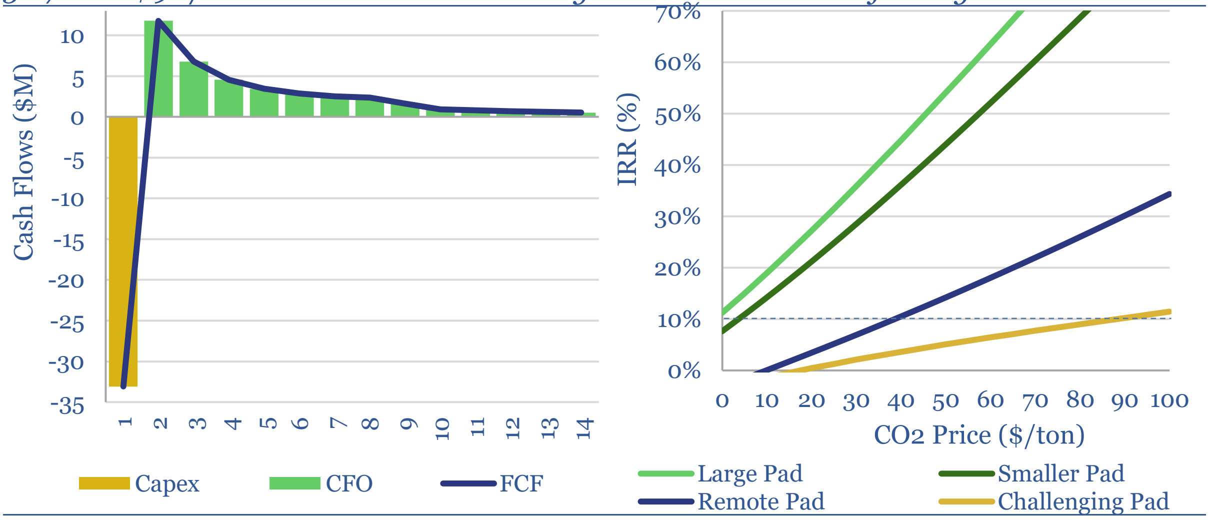
mitigation and other new technologies. Adopting these technologies and upgrades are likely to improve the long-term competitiveness and efficiency of US industry.

Fig 13. *A 6% IRR is generated in our base case assumptions for a small waste heat recovery project at an industrial asset. A $50/ton CO_2 price uplifts the IRR to 20%.*



Source: Thunder Said Energy Modelling [Download the data?]

Fig 14. *IRRs for capturing and commercialising gas at a typical shale pad run at 5-17%. A $90/ton CO_2 could theoretically eliminate US shale flaring.*

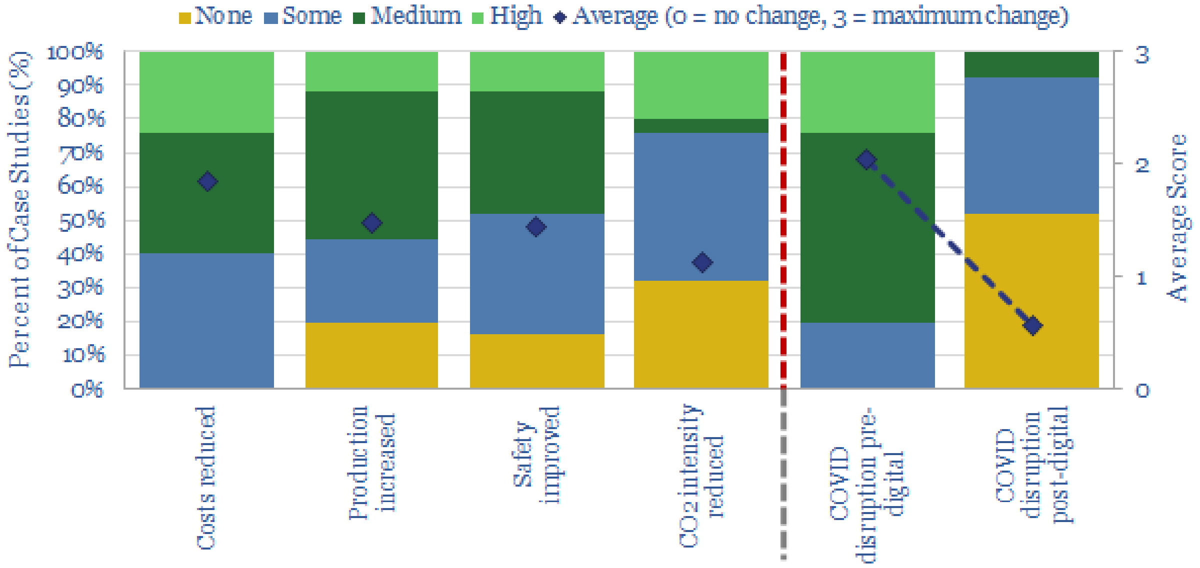


Source: Technical Papers, Thunder Said Energy [Download the data?]

Similar efficiency gains can be generated by similar means in other industries. Cutting edge technologies that promote efficiency would also be incentivized by a carbon price.

One important example is additive manufacturing, which could lead to steep 65-90% CO_2 savings on manufacturing and distributing particular industrial components, while also returning jobs to the United States. These jobs have not been included in our numbers above; hence they offer incremental upside.

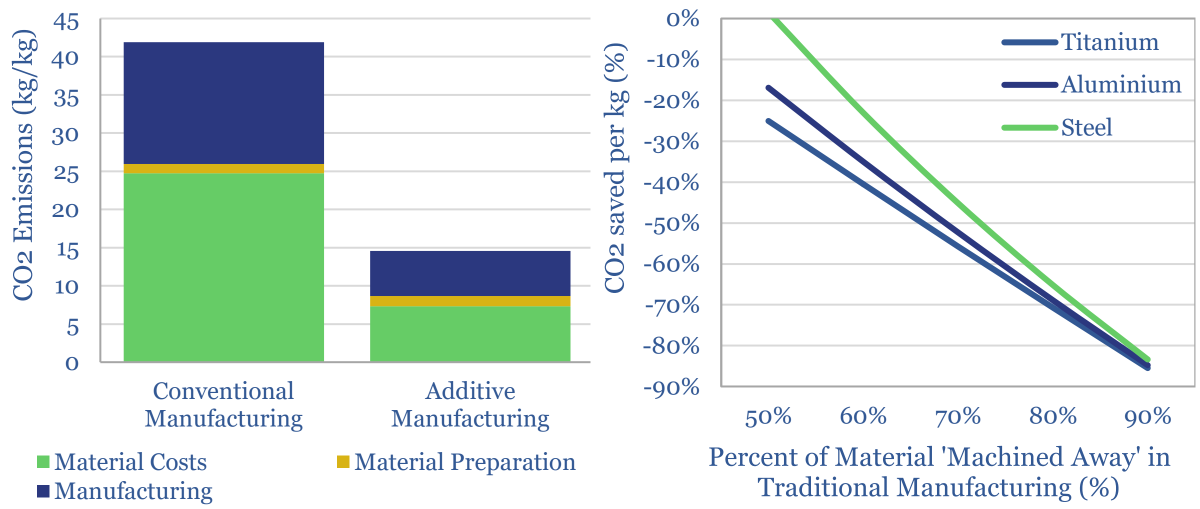
Fig 15. *The most common benefit of digitization initiatives is to lower costs, followed by increasing production, improving safety and lowering CO_2 intensity*



Source: Thunder Said Energy [Download the data?]

Specifically, manufacturing metal components can be extremely energy intensive, emitting 50-250kg of CO_2 per kg of finished parts, as 60-95% of original materials are machined away in the manufacturing process. By contrast, additive manufacturing (AM), also known as 3D printing, only uses up the material that is needed for each part, while unused materials can be largely recycled. Hence AM is typically able to deliver c65% CO_2 savings, per kg of manufactured materials (**Fig 16**). The savings will be greater for more energy-intensive material inputs and when >80% of materials are machined away in the manufacturing process.

Fig 16. *Additive manufacturing of steel components is 65% less CO_2-intensive than conventional machining under our base assumptions; 80-90% savings are possible*



Source: Technical Papers, Thunder Said Energy [Download the data?]

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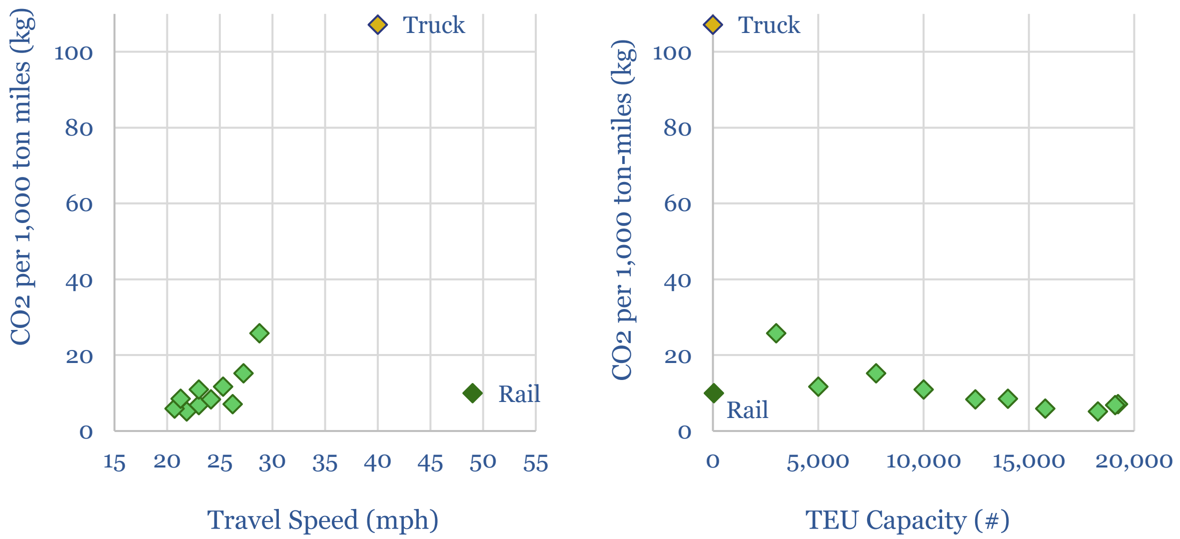
Simplifying supply chains through AM can also yield cost and CO_2 savings. Consider the example of an Airbus 320[2]. Raw aluminium is obtained from Alcoa in Pittsburgh, USA. It is transported 7,750-miles to a Tier-1 supplier in Taiwan. 90% of these materials are lost during machining and discarded. The finished parts are then transported 6,450 km to Toulouse for assembly. To produce a 1-ton part, requires 84,000 ton-miles of transportation. This freight requirement could be reduced to 4,100 miles, if aluminium powder were transported directly from Pittsburgh to Toulouse. Eliminating c80,000 ton-miles is equivalent to saving c650kg of shipping emissions per ton of finished product (or higher if the materials move faster, on smaller ships or on trucks/rails) (**Fig 17**).

A broader macro-economic implication is that manufacturing currently occurring in Southeast Asia, or other emerging market countries, may return to the US, closer to products' point of use, with a combination of CO_2 prices and advanced manufacturing technologies. Manufacturing goods in the US using the most efficient and lowest carbon technologies would save the material costs of a border tax applied to the CO_2 embedded in US imports. Globally, we calculate that additive manufacturing could reduce CO_2 emissions by 6%, and the full opportunity is explored in our recent note, linked here.

Fig 17. *Large container ships average 8kg of CO_2 emissions per thousand ton-miles, rising to 10kg for trains and 110kg per thousand ton-miles for trucks*



Source: Companies, TSE — Download the data?

Further disruptive efficiency technologies are likely to emerge with a CO_2 price. They can be hard to quantify ex ante, which highlights the importance of research into energy technologies as part of the energy transition.

[2] Verhoefa, L. A., Buddeb, B. W., Chockalingamb, C., Nodarb, B. G., & van Wijkc, A. J. M. (2019). The effect of additive manufacturing on global energy demand: An assessment using a bottom-up approach. Energy Policy.

Impacts on transportation: electrification accelerates

Total US demand for oil products ran at 20.5Mbpd in 2019, per the IEA (**Fig 18**). Last year, we considered how emerging technologies could disrupt the oil markets, concluding that US demand could fall to c10Mbpd by 2050 (note here). This scenario already assumed that 200M out of the US's 300M passenger vehicle fleet would be electric by 2050. Moreover, stringent fuel standards for automakers were assumed to continue improving ICE fuel economy by 1.8% pa. Thus, on our numbers, US gasoline demand would already have declined from 9.3Mbpd in 2019 to 5.8Mbpd in 2035.

Conversely, heavy-duty vehicles such as trucks (2.2Mbpd in 2035) and planes (2.6Mbpd in 2035) are harder to electrify. Lithium ion batteries currently store 200Wh of energy per kg of battery materials. This would give a Boeing 747 a range of approximately 60 miles before needing to land and re-charge (calculations here). Likewise, the battery materials required to electrify a Class 8 heavy truck could otherwise have been used to electrify 40 passenger vehicles. Any change to this picture would require a breakthrough in battery technologies, which we have not assumed.

The impact of a CO_2 price is to accelerate the electrification of light passenger vehicles. As we will show below, electric vehicles are already economic without a CO_2 price. CO_2 prices could create a $500-1,000 per annum financial incentive to 'go electric' in 2030-35, deducting a further 2.5Mbpd from our prior 2035 assumptions. Overall, our numbers assume another 580TWH of power is required to charge electric vehicles by 2035, equivalent to expanding the US electricity grid by 14% from 2019.

Another cutting edge technology example is the use of drones for last mile delivery, which could unlock sharing economics and save 150MTpa of CO_2 in the US (note here). For analysis on new vehicle concepts see here and here. For our analysis on possible upside to oil demand after COVID-19, please see here.

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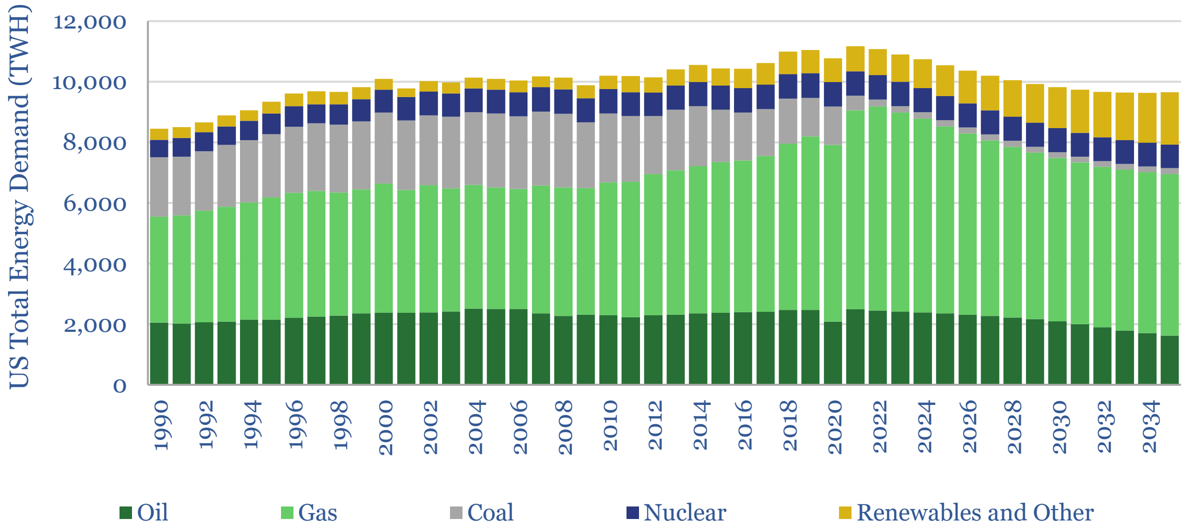
Conclusions on the future US energy system

A cost-optimized combination of the methods above can eliminate over 50% of the United States' CO_2 emissions. Final energy consumption would be 13% lower in 2035 versus 2019, at 9,650 TWH of useful energy.

Looking across the energy mix, we find that renewable generation rises 3.3x to 1,350 TWH by 2035. Coal demand falls by 85% to c80MTpa, all burned at plants with CCS. Oil demand falls 35% to 13.4Mbpd, of which 3.3Mbpd is light vehicle transport, 2.6Mbpd is aviation, 2.3Mbpd is trucking and 1.6Mbpd is as a feedstock for materials. Gas demand rises from 86bcfd to a peak of 101bcfd in 2023, then gently declines back down to 80bcfd in 2035 (**Fig 18**)

Fig 18. *Energy mix of the United States on our economic models*



Source: Thunder Said Energy [Download the data?]

We conclude that a $40/ton (2017$) CO₂ price, instated in 2021, inflating thereafter at 5% above inflation, has the potential to encourage a 50% economic decarbonization of the United States compared to 2019, unlocking investment, creating jobs and incentivizing the adoption of technologies that will promote US industrial efficiency.

The immediate impact of the plan is a surge in new investment, which peaks in 2023, with $95bn of annual investment and 195,000 new jobs created.

Most importantly, these policies would turn decarbonization into a competitive sector, allowing the most cost-effective solutions to emerge. Efficient companies and technology leaders stand to benefit most.

Appendices: *Appendix I discusses some of the technologies that featured in our Cost Curve. Appendix II lays out our methodology and modelling assumptions.*

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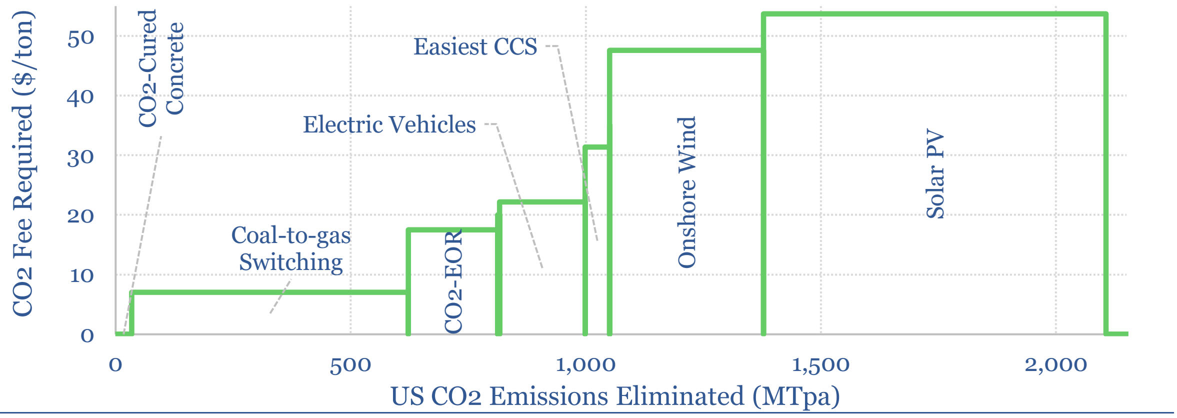
Appendix 1 – Options for US decarbonization ranked by cost

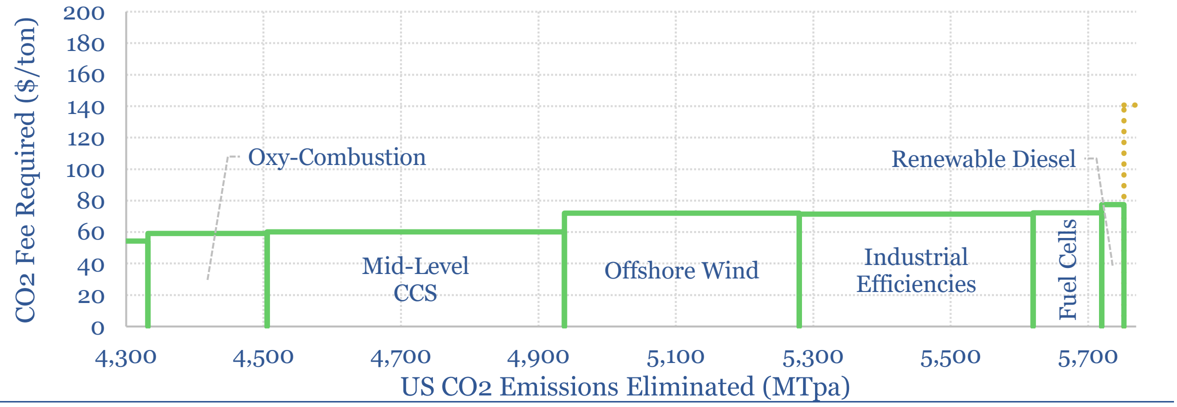
In this appendix, we review the low, medium and high cost technologies available to decarbonize the United States, based on the economic models in our analysis.

Fig 1. *Low cost options for US decarbonization can cut 4.4bn tons pa for <$50/ton*



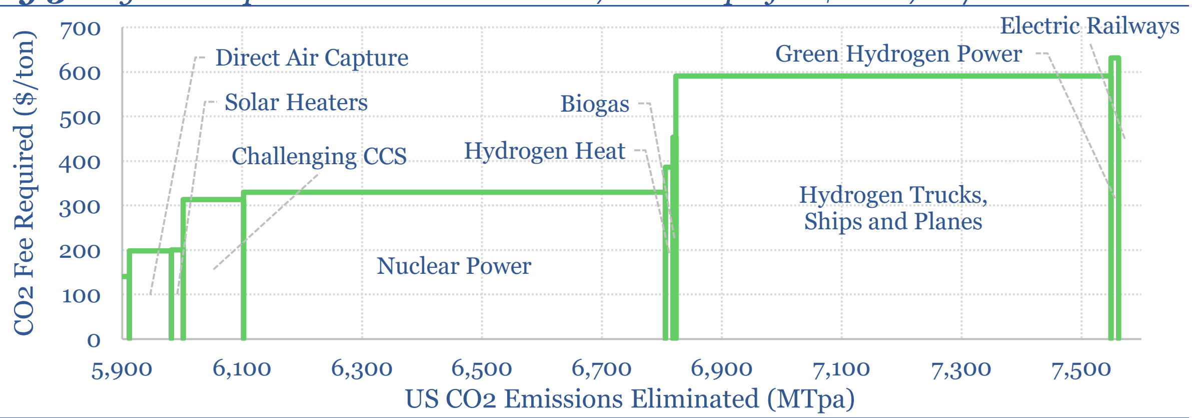
Source: Thunder Said Energy [Download the data?]

Fig 2. *Medium cost options can cut another 1.5bn tons pa for $50-100/ton*



Source: Thunder Said Energy [Download the data?]

Fig 3. *High cost options can cut another 1.7bn tons pa for $200-700/ton*



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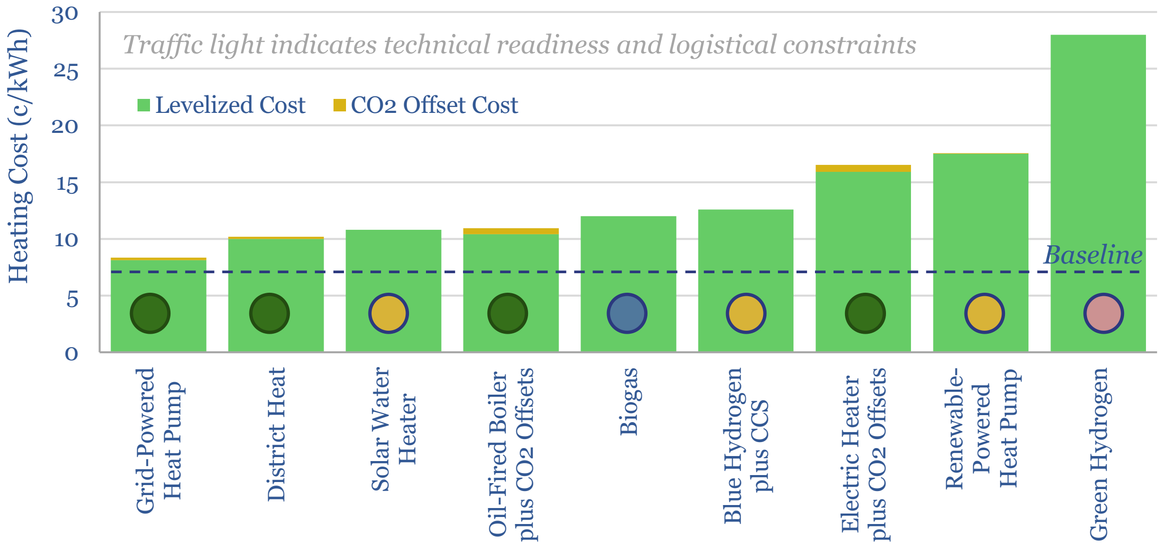
By identifying these different cost levels, we can illustrate how relying on the use of carbon pricing can produce the most cost-effective energy transition.

The importance of a cost competitive energy transition is illustrated clearly in the decarbonization of heat. A typical household in the US consumes 12,500 kWh of heat per year, costing $750-950 and emitting 2.6 tons of CO_2. We have modelled nine opportunities to reduce the CO_2 intensity of household heating. These technologies have starkly different consequences for consumers (**Fig 4**).

Lower cost options for decarbonizing heat include heat pumps, district heating and solar water heating, which will tend to raise heating prices by 1c, 2.7c and 3.5c/kWh respectively. This is tantamount to increasing the average household heating bills by $110, $340 or $440 per household.

Higher cost options for decarbonizing heat include biogas, relying exclusively on renewable energy or green hydrogen, which will trend to raise heating prices by 4.7c, 10c and 21c/kWh respectively. This is tantamount to increasing the average household heating bill by $600, $1,300 or $2,600 per household.

Fig 4. *Costs matter to consumers: lower cost options in the decarbonization of heat add 1-3c/kWh to household heating bills; higher cost options add 5-20c/kWh*



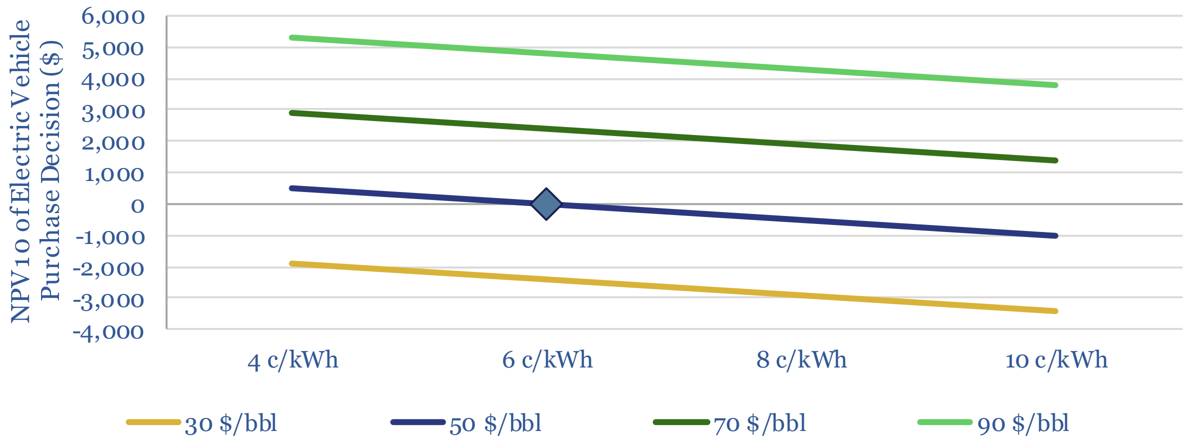
Note: biogas is marked blue due to its CO_2 content, which limits full substitution with gas in all contexts, as discussed below

This exercise can be repeated for other parts of the energy system. The key is to identify the different low, medium, and high costs options for decarbonization.

Lower cost options for US decarbonization

Electric vehicles are among the low cost technologies in the energy transition, as a new electric vehicle purchase is already economic at a $50/bbl long-term oil price and a 6c/kwh wholesale power price (**Fig 5**) However, no material grid upgrade costs are assumed in these numbers. Displacing 6Mbpd of gasoline demand would save 850MT of CO_2 per year. An important modelling consideration is that 120mcf-equivalents of gas energy are needed to assemble an electric vehicle battery, thus an EV takes 3.7 years to repay the up-front energy costs of manufacturing it.

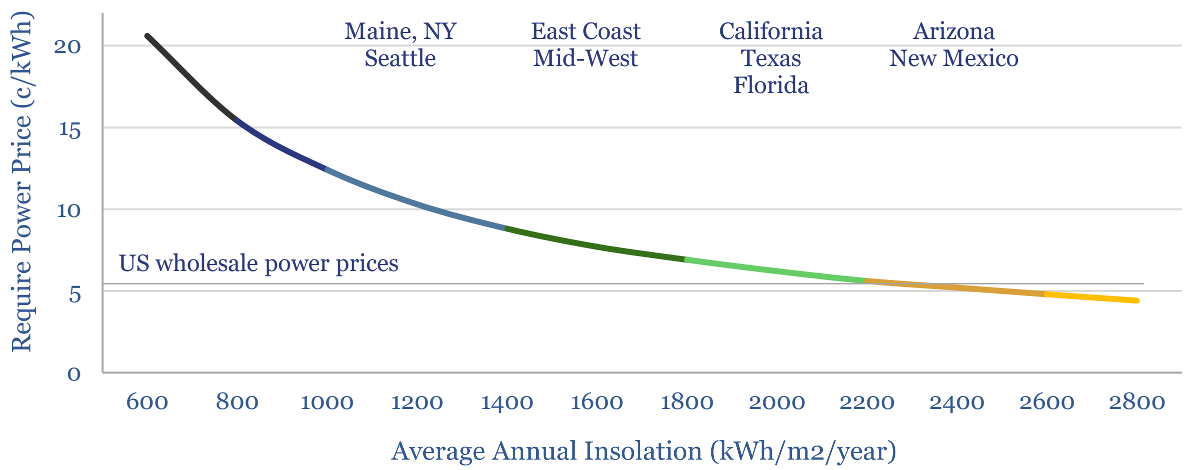
Fig 5. *The 'breakeven' on an electric vehicle is 6c/kWh power and a $50 oil price*



Source: Thunder Said Energy Modelling Download the model?

The ramp up of renewable energy achieves 1bn tons of decarbonization in our models. Levelized costs can be very low. However, the economics are location dependent, as illustrated in **Fig 6**. Assuming $1.3/W of total CAPEX (including installation costs), utility scale solar does not require any tax support in the sunniest parts of Arizona and New Mexico to achieve 10% IRRs. c$10/ton CO_2 prices are required in Texas and California. But $70/ton CO_2 prices are required for deployment across the US on average, assuming 1,700 kWh/m2/yr of insolation.

Fig 6. *Utility-scale solar economics vary state-by-state as a function of insolation*



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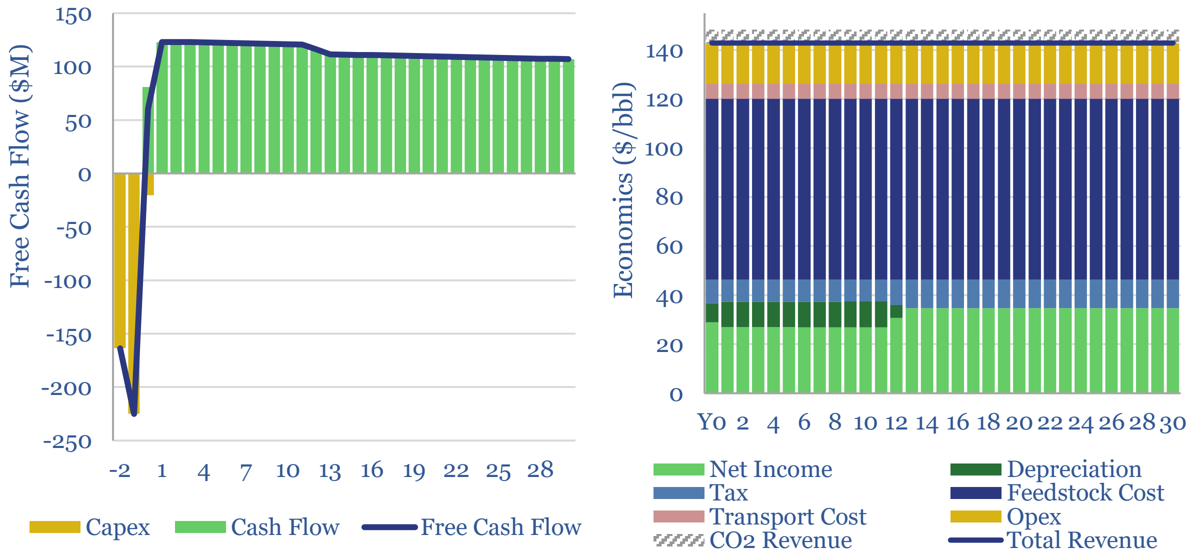
Intermediate cost options for US decarbonization

Renewable Diesel is an example of an intermediate cost technology in the energy transition. It is also an example for how ad hoc policies can act as 'kingmakers' for specific technologies. A new, 10kbpd renewable diesel plant currently generates a 25% IRR off c$40M/kbpd CAPEX, helped by a c$1/gallon pricing premium, guaranteed by the US's Blenders' Tax Credit. In other words, this means renewable diesel is already receiving a CO_2 subsidy equivalent to $200/ton. Without the Blenders' Tax Credit, an $80/ton CO_2 price is required for a 10% IRR. Renewable diesel is also not 'zero carbon', as we estimate its production still emits c150kg/boe, versus c430kg/boe for regular diesel. Our numbers assume 30MTpa of decarbonization via the production of 350kbpd of renewable diesel by 2035, limited by the availability of feedstocks.

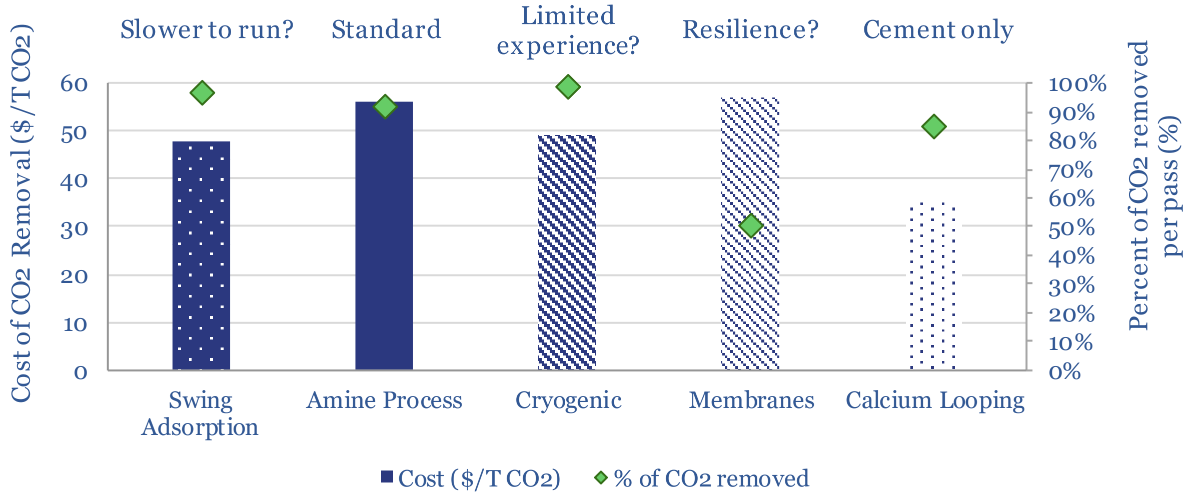
Fig 7. *A 10kbpd renewable diesel project currently generates a 25% IRR, helped by $1/gallon of price support under the Blenders' Tax Credit*



Source: Thunder Said Energy Modelling [Download the Data]

Carbon capture and storage is assumed to sequester 65MTpa of CO_2 in our models of decarbonization by 2035, at a long-term cost of $60/ton. This assumes a benefit of scale, as a relatively nascent sector is expanded from 22MTpa of capacity in the US today and 44MTppa by 2030 under current proposals. Currently, the most widely used technology to capture CO_2 from industrial exhaust flues is the amine process. This technique uses amines to absorb and purify CO_2 from post-combustion waste gases, such as nitrogen and residual oxygen. Costs average $50/ton, plus the costs for disposing of CO_2, which range from $7-50/ton (model here). Regenerating CO_2-absorbing amines requires steam-treating them, which is energy intensive, and also absorbs 15-30% of the energy whose combustion emissions are being captured, requiring more fossil fuels to deliver the same net energy. Costs may also be higher to install CCS at pre-existing power assets as additional retrofits are needed.

***Fig 8.** Today's CO_2 capture technologies typically cost c$50/ton and come with an energy penalty of 15-30%, as well as operational challenges with each method*



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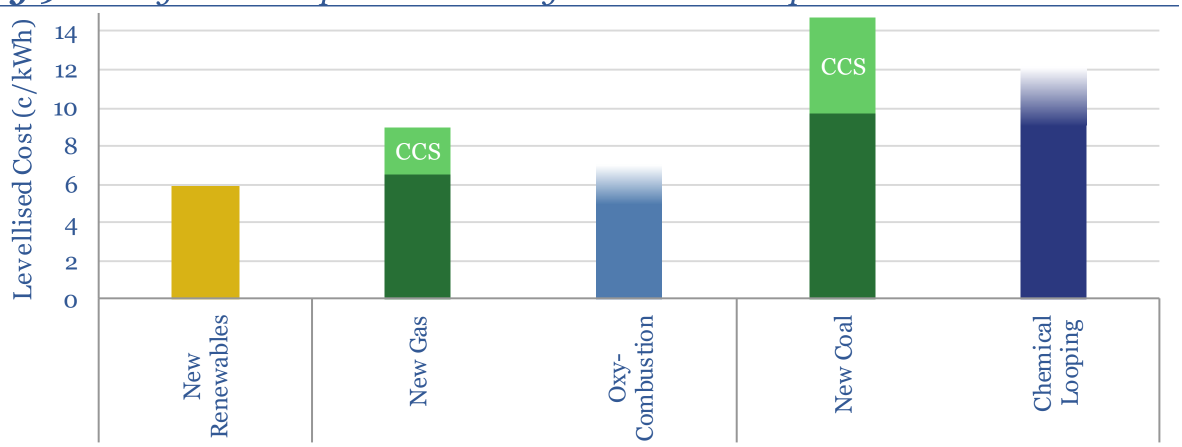
Allam Cycle Oxy-Combustion is an emerging gas-to-power technology, which burns CO_2 in an inert atmosphere of CO_2 and oxygen, yielding an exhaust gas of pure CO_2 and water, which can be sequestered immediately, without requiring the challenging nitrogen separation step that hinders conventional CCS. As a working fluid, CO_2 yields impressive, c60% gross efficiency. Hence, we model IRRs of 10% in the US and 14% in Europe, assuming a $40-60/ton total CO_2 price. Occidental and McDermott are invested in the leading company, NET Power, which started testing a 25MWe pilot in LaPorte, Texas in May 2018. We are optimistic on this technology, and it is ascribed 30MTpa of decarbonization potential in our model by 2035. A similar technology, 'chemical looping combustion', also avoids the costs of nitrogen separation by oxidizing fossil fuels in the presence of a metal oxide, to produce pure CO_2 plus a metal, which can be recycled and re-oxidized in the presence of air.

***Fig 9.** Next-generation power technologies are cost-competitive and zero-carbon*



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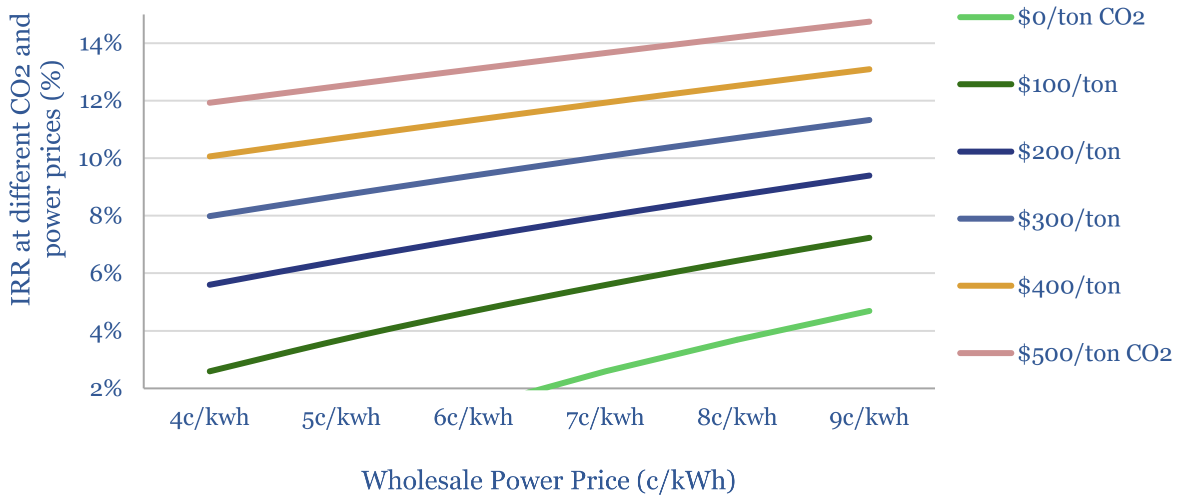
Higher cost options for US decarbonization

Nuclear technology has vast potential to drive decarbonization of the power sector, but we find the economics of new plants require very high CO_2 prices, around $330/ton, in order to generate 10% IRRs in the US. The first reason is high CAPEX costs, which typically run at $6,000/kW for a new nuclear plant, compared with $800/kW for natural gas. Second, construction schedules are very long, between 5-10 years, which makes it challenging to earn a high IRR, as cash flows are discounted further into the future. Third, and not reflected in our numbers, is a troubled history of cost overruns. Future nuclear plant designs may address some of these problems, but they are in an early stage of technical readiness.

The largest nuclear plant in the world has 8.2GW of capacity per year. If the US built one plant of this magnitude each year to 2035, it could unlock 115GW of incremental capacity, enough to offset 310MTpa of emissions.

Fig 10. *A $330/ton CO_2 price is needed to generate a 10% IRR for new US nuclear*

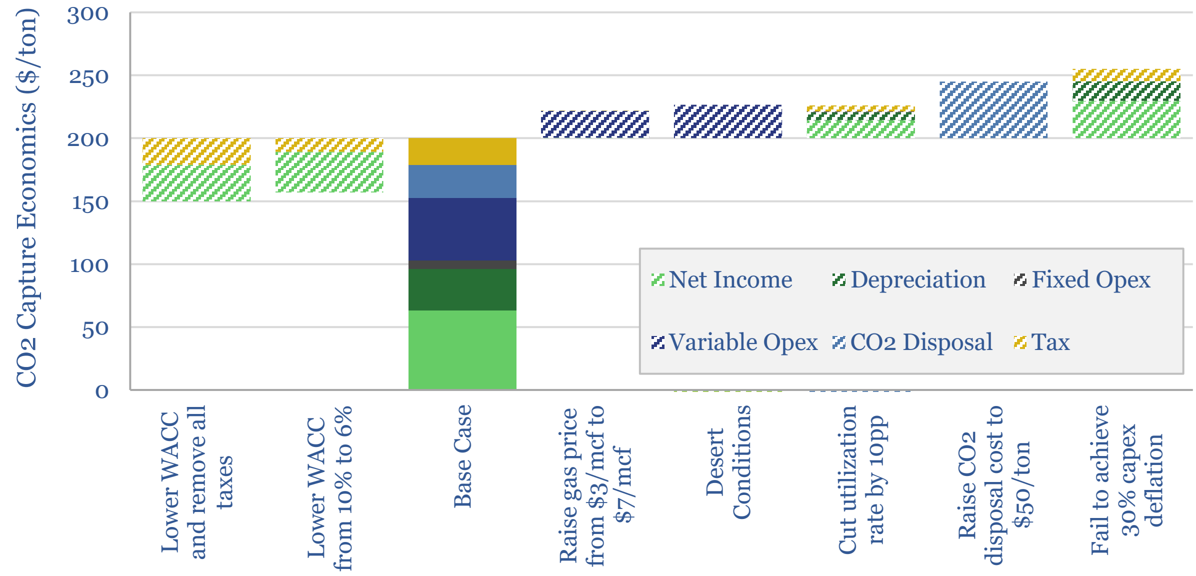


Source: Technical Papers, TSE [Download the Data]

Direct Air Capture uses alkali solution in a large industrial 'contactor' to pull CO_2 out of the air. We model CO_2 prices would need to reach $200/ton to earn a 10% unlevered IRR on a DAC plant, within a likely range of $150-300/ton (**Fig 11**).

A challenge is that the DAC process is resource-intensive, requiring 5.4mcf of gas per ton of CO_2 captured, to heat a calciner to 900°C, and 5 tons of water per ton of CO_2, due to evaporation from the air contactor. Our base case financial estimates assume a CO_2 price of $750/Tpa, which is broken down line-by-line in our economic model, based on technical disclosures from Carbon Engineering. However, our numbers are generous in accepting aspirations to build future air contactors for 80% lower cost than prior proposals.

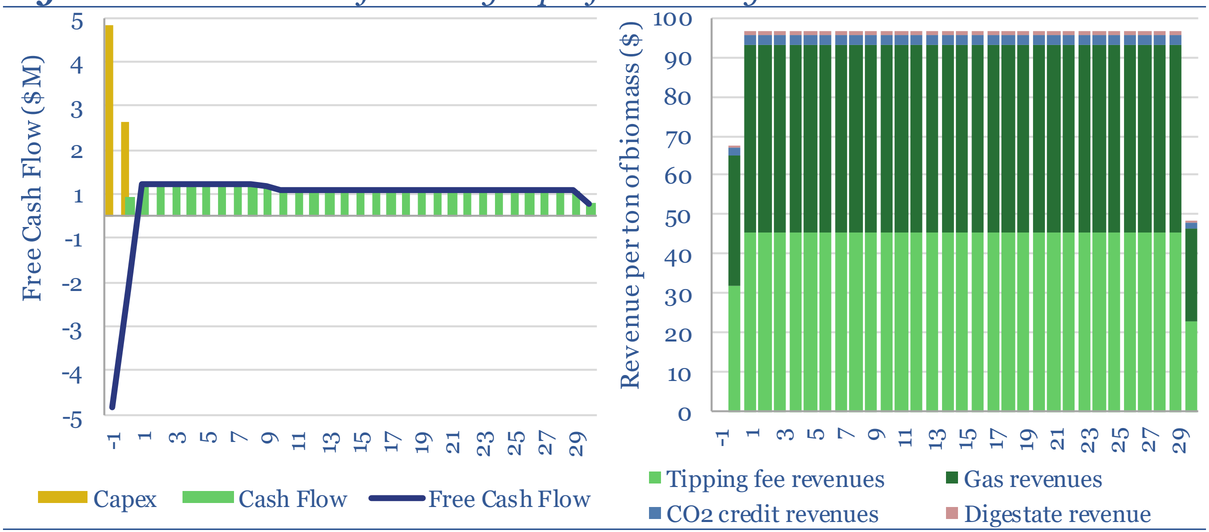
***Fig 11.** CO₂ price required for an economic Direct Air Capture project*



Source: Technical Papers, TSE [Download the Data]

Biogas is another candidate with potential to displace natural gas in heating, offering a lower-carbon alternative. Biogas is derived from the anaerobic conversion of waste organic matter. This makes it a renewable fuel. Albeit it is c35% CO_2 by volume, which means it cannot substitute perfectly for pipeline-grade gas without further upgrading. Some commentators see potential for a vast scale-up of biogas to displace c10-20% of conventional gas in developed world gas grids. But the economic costs of biogas are high. An anaerobic digester will typically cost c$430/Tpa to construct (**Fig 12**)

***Fig 12.** Economic model for a biogas project earning a 10% unlevered IRR*



Source: Technical Papers, TSE [Download the Data]

We model that to earn a 10% unlevered return on this CAPEX requires revenues of $95/ton of biomass, through a combination of gas price surcharges,

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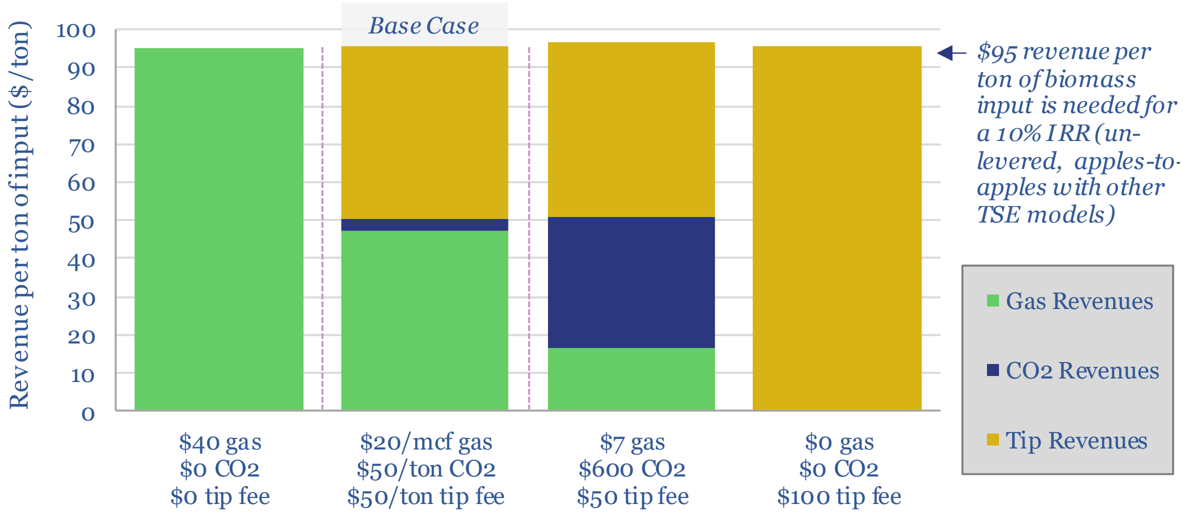
tipping fees and CO_2 prices (**Fig 13**). Even with modest tip fees, we estimate a CO_2 price of $525/ton is required for a competitive 10% IRR in the US.

Fig 13. *Converting organic waste to biogas requires $95/ton of revenue to earn a 10% unlevered IRR; for example, via $20/mcf gas, $50 CO_2 and a $50/ton tip fee*



Source: Technical Papers, TSE Download the Data

Voltaire famously said that the Holy Roman Empire was neither holy, nor Roman, nor an Empire. It is tempting to say the same of the green hydrogen energy economy. It is neither green, nor hydrogen 'energy', nor economical. Different hydrogen technologies are summarized in **Fig 14**.

Hydrolysing water using renewable energy is the most optimistic scenario, yielding truly 'green' hydrogen. This would most likely involve powering a hydrolyser with excess wind and solar electricity. Research is also ongoing into direct conversion of solar energy into hydrogen, using semiconductors or photocatalytic particles in an aqueous electrolyte, but these systems are in an early stage of technical readiness, with stability in the tens or hundreds of hours. We model economic green hydrogen production to require a hydrogen price of $7.5/kg (over $60/mcf-equivalent), in order to earn a 10% IRR (**Fig 15**)

The largest challenge is efficiency, as the round trip from renewable electricity, to hydrogen, and back to electricity is likely c50% efficient. Another challenge is utilization rates. If renewables are only generating excess electricity c50% of the time, then it is challenging for a green hydrogen hydrolysis plant to surpass 50% utilization rates. This is a catch-22. Low utilization rates inflate costs per kWh. But if an alternative fuel is used to boost utilization rates, then green hydrogen is not truly green. Further costs would also be incurred building hydrogen distribution networks. We model that a total CO_2 price above $600/ton is necessary to incentivize hydrogen, hence it is not included at scale in our models.

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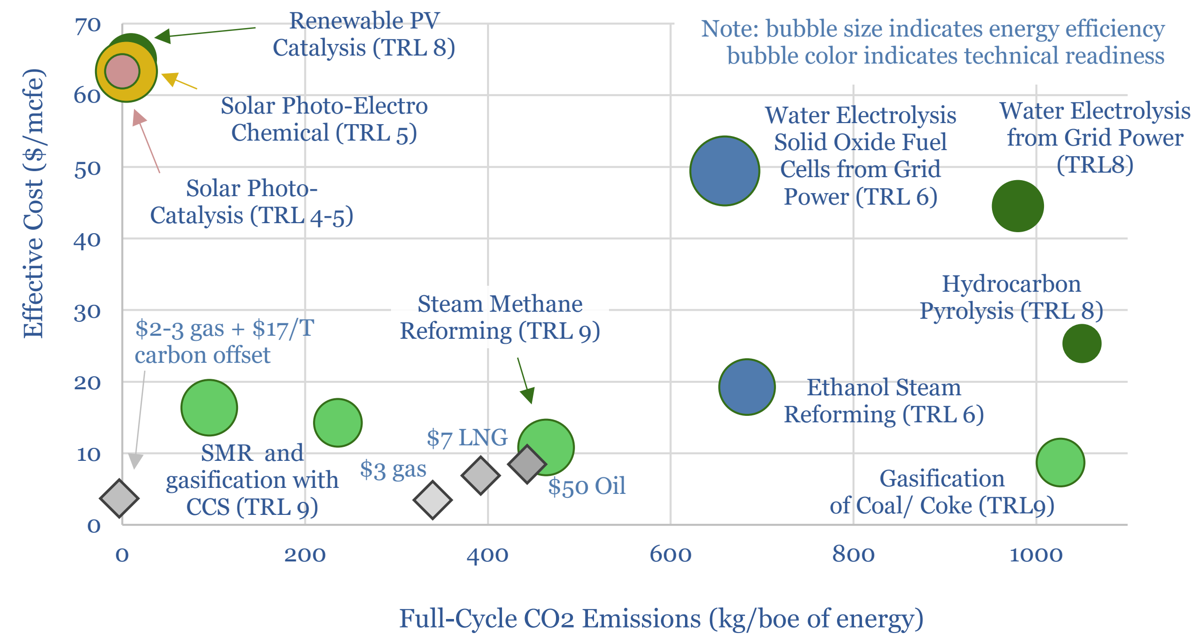
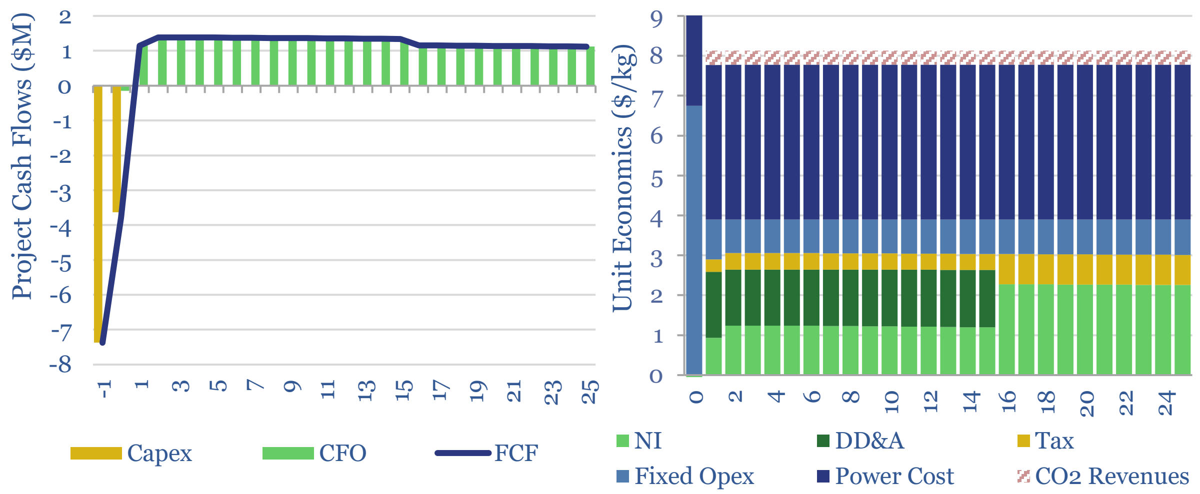
Fig 14. *Costs and CO_2-intensities for different hydrogen production technologies*



Source: Technical Papers, TSE [Download the Data]

Fig 15. *A $7.5/kg hydrogen price is required to earn a 10% IRR on green hydrogen*



Source: Technical Papers, TSE [Download the Data]

Appendix II – Additional Notes and Modelling Assumptions

Economic inputs to our models are as follows: US population grows at 0.57% per annum, which is two-thirds of the trailing 20-year CAGR to 2019 due to demographic changes; and GDP per capita continues rising at 1.25% per annum, in line with its trailing twenty years rate. Energy consumption is linked to population and GDP.

Inflation is assumed to run at 2% per annum. All numbers quoted above are quoted in nominal terms, unless marked otherwise. We model that carbon prices could unlock $1.4-1.5tn of total nominal investments between 2021-35, in nominal terms, while this is equivalent to $1.2-1.3tn in real terms.

Our model is constructed by considering the incentive price for thirty energy technologies, over time, based on economic models constructed by Thunder Said Energy. When CO_2 prices are above a technology's incentive price, we assume activity accelerates. We then model investment, job creation and consequences on oil, gas, coal and power demand per unit of activity.

CAPEX and jobs numbers quoted in this report are calculated *incrementally*, i.e., directly comparing the consequences of a CO_2 price with our baseline assumptions prior to instating a CO_2 price. Some categories see marginally lower spending or fewer jobs in some years of the analysis, with CO_2 prices versus without them, but these negative bars are not shown in **Fig 4** - **Fig 5** of the main section.

CO_2 emissions from the United States can be defined under multiple scopes. The US EPA reports CO_2 emissions of 5.4bn tons in its most recent, 2018 data, and 6.1bn tons in 2005, which is the year relevant to the Paris Climate Accord. Our own estimate of pure CO_2 emissions for 2018 is also 5.4bn, which is calculated based on the consumption of coal, gas, oil and emissions from the materials sector (mostly cement), multiplied by CO_2 conversion factors per unit of each fuel.

Base year. Generally, in this report, we have used 2019 as our base year, finding it is possible for the US to eliminate about 50% of 2019's CO_2 emissions with an escalating CO_2 price. Rounding is appropriate given the uncertainties of global events, policies and technologies. The unrounded number is 49.5% relative to 2019 which equates to 57.5% relative to the EPA 2005 baseline.

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