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Opportunities in the Green Economy

The Problem

Here we look at what will be one of the key drivers of the world economy over the next thirty years – the technological transition driven by the need to limit emissions of greenhouse gases. Our point of view is that of an investor interested to understand how this transition will effect investment opportunities. Our interest in policy debates is limited to their likely economic impacts. We advocate for no particular course of action. Our focus is limited to the United States. In fact, the transition is a global one. However, to have considered its international aspects would have doubled the length of this report.

Background

The current energy economy is dominated by combustion of fossil fuels: coal, oil and natural gas. These three fuels provide more than 70% of the energy used in the United States. Massive capital is devoted to extracting, transporting, refining, distributing and combusting these fuels. In the United States capital so employed amounts to about 10% of GDP. Unfortunately combustion of fossil fuels produces carbon dioxide gas as a waste product and also allows some leakage of uncombusted natural gas into the atmosphere. Both gasses effect the physical processes in the atmosphere in such a way as to raise the mean surface temperature of the earth – the so called greenhouse effect. Natural gas (mainly methane) is approximately 30 times more potent than carbon dioxide, molecule for molecule, in raising the earth's temperature. But natural processes also scrub methane from the atmosphere 3 to 10 times times faster than carbon dioxide. As a result the cumulative heating effect from these two gasses is attributable 83% to carbon dioxide and 17% to methane. A number of other gases also contribute to climate warming in lesser degree. Collectively such gases are known as greenhouse gases. It is typical to measure the amount of gas emitted in a certain period by stating it as the amount of carbon dioxide which would produce an equivalent heating effect. The relevant unit for measuring emissions on an economy wide scale is millions of carbon dioxide equivalent metric tons per year, or – for short – equivalent megatons per year. The Environmental Protection Agency (EPA) is the government department charged with tracking these emissions. Our discussion will draw heavily on their publication US Greenhouse Gasses Emissions and Sinks 1990-2018. In particular, whenever giving the amount of emissions from a certain source we shall be drawing the value from this publication for the year 2018.

As long ago as the Nixon administration it was realized that greenhouse gasses would drive a change in the world climate which could require massively costly adaptations. For instance one consequence is to raise sea levels during storm surges. The Navy, whose port facilities are naturally located at sea level, has estimated costs on the order of one trillion dollars to move its facilities to higher ground. Another consequence is to cause a northward shift of climate zones. The consequent costs absorbed by the agricultural sector are on the order of tens of trillions of dollars.

Since this basic realization was first arrived at, fifty years of research has gone into understanding the phenomena, tracking its progress and attempting to estimate its speed of progression. The primary conclusion is that the climate system is composed of a number of interlocking subsystems. When perturbed by the addition of greenhouse gases from human sources, the first response of the system is to resist perturbation. Eventually, however, the system can be pushed to the point where certain subsystems begin to reinforce the perturbation. For instance, natural reservoirs of sequestered carbon dioxide can be released

by the warming of permafrost and that source of carbon dioxide would continue to drive the heating effect even in the absence of further human generated release of greenhouse gasses.
For a system such as the climate is there is not much long term predictability and little assurance that changes will be proportionate to the initial driving forces. No one is particularly eager to absorb the enormous cost of moving off the fossil fuel economy which has generated a century and a half of profound human progress. But gradually a consensus has emerged worldwide that exactly that transition needs to be completed within the next thirty years.
Considerable engineering work has gone in to developing climate friendly sustainable technologies and in driving their costs down to the point where the transition is affordable. In general, in the development of a new technology there are certain well marked stages

Research – one sees the possibility of developing a certain technology, but how well it can ultimately perform is unknown.

Technical feasibility – the technology has demonstrated that it can actual perform the task assigned to it but the cost of that performance is not yet demonstrated to be acceptable

Economic feasibility – the cost/performance characteristics of the technology have improved to the point where the technology is a potentially feasible solution for at least part of the market need.

Commercially proven - products embedding the technology are voluntarily purchased in the marketplace without government subsidy or mandate.

Competitively proven – in commercial competition against alternate technologies the technology has established itself as the dominant technology for a certain market segment.

In the first three stages (research through economic viability) the focus is generally on improving the cost-performance characteristic of the product itself. In becoming commercially proven the focus shifts to solving problems of cost efficient manufacturing and maintenance and in demonstrating acceptable full life cycle costs and operational reliability. Then in becoming competitively proven the technology must establish a role for itself in the world within the total ecosystem of products and practices.

In general one technology is never an exact replacement for a prior technology. Rather it delivers a different package of features at a cost such that some part of the market prefers the new technology to the old. To give an example, digital photography generally delivered lower image quality than film photography, but it delivered higher convenience and immediacy. As a result, once it was able to deliver acceptable image quality at a low enough price, it was able rather quickly to displace film photography from the consumer photography market. Its adoption by the commercial photography market, where greater emphasis attached to image quality than to immediacy, was much slower. Once a technology becomes competitively proven the revenues from that product generally drive further product improvements/cost reductions such that alternate technologies cannot keep up and are driven out of the market. Thus in the photographic market, the consumer segment represented the bulk of photography revenue. Once film photography lost its hold on the consumer market its technical improvement basically came to a stop. Digital photography was then able to catch up with the image quality of film and displace film from the commercial photography market as well. This dynamic makes technology adoption somewhat path dependent. It can happen that the theoretically better technology fails to reach its potential because an acceptable technology was able to become competitively proven sooner and it thereafter suppresses the better technology. When technologies are still in the research or technical feasibility stage it is often difficult to predict which technology will emerge as the dominant solution for a given market segment. As technologies move to the point of economic feasibility or being commercially proven it is often possible to compare two candidate solutions and draw some reliable inferences about which one is more likely to reach the point of being competitively proven. For that reason, our discussion here tends to focus on the technologies which are furthest along the path from research to commercial dominance. Indeed, at this point the likely shape of a post-fossil fuel economy can be seen with fair degree of definition.

In terms of economic impacts there are six sectors of key importance: electric power production, transportation, industrial processes, agriculture and land management, buildings and hydrocarbon production. We will review each sector in turn and then form a view of the economy as a whole.

The Electric Power Segment

Most electrical power in the United States is generated by regulated utility companies. Relatively minor contributors to power production are electricity produced in industrial plants as a by product of their main operation and consumer production of electricity through rooftop solar installations. Our current discussion will focus on utility generated power.

Table 1 summarizes the current state of play for different electrical generating technologies. The primary point of comparison is the full life cycle unsubsidized cost of producing a megawatt hour of electrical power. This is not an apples to apples comparison as each technology has its special qualities. And the cost is generally a range rather than a point estimate as costs depend on specifics of where the plant is sited as well as the technology chosen. However, the basic picture is clear enough.

Currently wind and solar (photo-voltaic) power are the cheapest technologies for new built plant. Coal and nuclear plants are no longer economic to build. Hydroelectric plants are not being built as the suitable sites have already been exploited. For already built plants, the cost of running nuclear and hydroelectric plants is low and competitive. Established coal plants are marginally competitive to run but they are the worst carbon emitters. Currently the coal fleet is being retired at about 10% per year. Single cycle natural gas plants survive in the niche role of peak demand power producers. However, their very high costs make them subject to retirement as described in the next paragraph. High efficiency natural gas fired combined cycle plants are currently the dominant technology. However, new plant builds are only marginally competitive. They are also carbon emitters. Currently the cost of scrubbing carbon dioxide from their smokestack stream would raise the price of such power to noncompetitive levels. If these plants are to have a long term future the cost of carbon capture and sequestration must be reduced. Absent progress on carbon abatement, fossil fuel producers and thermal plant builders face a wind-down future.

Table 1: US Electric Power Production

Technology	Full Life Cycle Cost of Electricity ($/Mwh)			Annual Production		
	New Build	Already Built	CO2 Pollution (tons/Mwh)	Electricity (Mwh)	Electricity (% Total)	C02 (million tons)
Climate Altering						
...coal	65-129	38.4	1.105	965,000,000	23.8%	1,066
...gas single cycle ("peaker")	151-198	142.8	0.84	145,000,000	3.6%	122
...gas combined cycle	44-73	48.9	0.455	1,441,000,000	35.6%	656
...gas combined cycle + carbon abatement	66-113	n.a.	0.0546	0	0	0
Total				2,551,000,000	63.0%	1,844
Climate Benign						
...nuclear	118-192	29.6	0	809,000,000	20.0%	0
...hydroelectric	n.a.	34.2	0	288,000,000	7.1%	0
...wind	26-54		0	295,000,000	7.3%	0
...solar (photovoltaic)	29-42		0	104,000,000	2.6%	0
Total				1,496,000,000	37.0%	0
Grand Total				4,047,000,000	100.0%	1,844

Source: Lazare (costs), EPA (emissions), EIA (production)

The primary obstacle to adoption of wind and solar power is one of load cycle management rather than production cost. Whereas fossil fuel power is produced, solar and wind power are harvested. The US demand cycle is subject to significant daily, weekly and seasonal variation which only partially matches the power harvesting cycle. Currently about 45% of consumption occurs during nighttime hours when solar production is offline. There are several mechanisms for bringing supply and demand in balance. Time of day metering rewards consumers with load flexibility for shifting their demand to the cheapest to service part of the cycle. Transmission of power from regions with excess supply to regions with excess demand can be economical even over transcontinental distances. There are three technologies capable of storing significant quantities of power: battery, thermal and pumped hydro storage. Two battery chemistries are suitable to this application: lithium ion and vanadium. Lithium ion technology has advanced rapidly driven by the consumer electronics and electrical vehicle markets. Vanadium technology is currently somewhat less developed but may eventually prove to scale to utility size operations better than lithium. Thermal storage comes in both hot and cold versions. In the cold version electrical power is used to liquefy air which is stored in an insulated tank. When power is required either ambient heat or waste heat from an industrial plant is used to boil the liquid air and drive a gas turbine to produce power. In the hot version, power is used to melt salt or metal and the hot material is stored. Electrical power is extracted from the hot mass by creating steam to drive a conventional generator. Currently the liquid air storage is proving its commercial viability at scale while hot thermal storage is still in research/technical feasibility stage. Finally pumped hydro uses electrical power to pump water uphill where it is retained by a dam. Power is generated by releasing the water through a conventional hydroelectric plant. This technology is currently deployed at scale, but there are a limited number of sites at which it can be built. Accordingly, it is unlikely to be the main power storage technology in the future. For all storage methods, the cost of stored power has two components. The first component is the cost of the plant amortized over the electric power delivered during its life. The second component is the cost of the power stored by the plant. Since the round-trip efficiency is less than 100%, more than one unit of electricity must be purchased to deliver a unit of electricity and so the price per delivered unit is increased by the storage premium over the price of the charging power. The spot price of power can vary considerably during the day, however, and may even be zero. A storage plant charged opportunistically may end with an essentially zero charging cost, and then its cost of delivered power is just the plant cost. Table 2 summarizes the basic facts for the different technologies. We show cost of delivered power in three situations: zero charging cost (i. e. just plant cost), charging with wind power and charging with solar power. Transmission has a low storage premium and a plant cost half that of other technologies so it is always the cheapest method. When power is sourced opportunistically it is competitive with already built combined cycle gas. Fed with purchased solar or wind power it is competitive with new built combined cycle gas. The other storage methods have roughly comparable plant costs. Over the next decade it is possible that technological improvement will cut the plant cost of batteries by a quarter and of thermal storage by a half. If so these methods will become competitive with combined cycle gas with carbon abatement. In the opportunistic power purchase case they would likely be more expensive than transmission but at a significant cost advantage to carbon abated combined cycle. Currently stored power fed from purchased wind and solar is cost competitive to gas peakers. We anticipate an emerging push to retire the nation's peaker fleet, which is often old and poorly sited for current land use. Overall this analysis suggests that the best hope for gas to retain a substantial role in power production is to develop plants which remain highly efficient and low emitting when used in a load following role. Even so gas could face increasing competition from stored wind and solar if this technology achieves substantial progress in reducing storage costs.

Table 2: Diurnal Load Balancing

	Costs of Storage			Cost of Delivered Power			
Technology	Storage Premium (%)	Plant Cost ($/Mwh)		Wind ($/Mwh)		Photovoltaic ($/Mwh)	
		minimum	maximum	minimum	maximum	minimum	maximum
500kv transcontinental transmission line	15.00%	44	57	74	119	77	102
liquid air storage	67.00%	100	140	143	230	148	241
liquid air with industrial waste heat	43.00%	100	140	137	217	141	241
lithium battery	11.00%	102	134	131	194	134	237
vanadium battery	25.00%	126	211	159	279	162	338
pumped hydro	18.00%	92	151	123	215	126	244

Source: Lazare

The politics of the power sector are both complex and significant (see table 3.) States where fossil fuel production is currently an important part of the economy are 9 in number and dispose of 75 electoral votes. Eight of these are strong red states. For Republican presidents this is a critical voting block whose interests they find it difficult to ignore. The Democratic power base, by contrast, makes that party more oriented to the discontents of the rate payers. These alignments may change as wind and solar become more important to the economy. States with renewable resource potential are 17 in number and dispose of 211 electoral votes. Interestingly there is high overlap between fossil fuel power and wind power states. Also interestingly states with high solar potential are all blue states while states with good solar potential are all red states. Uniquely Wyoming has interests in both gas and coal with strong potential in both wind and solar. However the energy transition plays out, Wyoming can prosper. Alaska and West Virginia, by contrast, have strong interests in fossil fuels but limited potential in renewables. For them the energy transition is problematic. State and federal regulators both play an active role in the industry. Rate of return regulation awards construction risk to utility companies and technological obsolescence and regulatory risks to ratepayers. This division of risks has made the power sector one where innovation is driven by government mandates and subsidies rather than by commercial analysis. Failure to create a regulatory incentive for carbon abatement is one reason why cost effective abatement technology has not emerged and the fossil fuel providers and steam plant manufacturers now face a foreshortened future. Transmission line projects usually require government eminent domain powers to move forward. As a result, the US currently has several regional power grids loosely tied together by capacity constrained interconnects rather than a true national grid. We expect this sector to remain politically led.

Table 3: States With Interest in the Current & Emerging Energy Economy

	State Politics		Fossil Fuel Production		Potential Renewable Production	
State	Electoral Votes	Party Vote 2020	Value % State GDP	Mix	Wind	Solar
Alaska	3		20.59%	O&G		
Arizona	11					high
California	55					high
Colorado	9		4.14%	O&G		high
Florida	29					good
Iowa	6				good	
Kansas	6		1.33%	O&G	high	good
Louisiana	8		4.19%	O 23% G 77%		
Minnesota	10					high
Montana	3		5.36%	O 47% C 49%	high	
N Dakota	3		56.85%	O&G	good	
Nebraska	5				high	
Nevada	6					high
New Mexico	5		23.35%	O&G	good	high
Oklahoma	7		10.01%	O&G	good	good
Pennsylvania	20		2.48%	G 88% C 10%		
S Dakota	3				high	
Texas	38		7.06%	O&G	high	good
Utah	6		1.72%	O&G 83% C 17%		good
West Virginia	5		12.92%	G 54% C 36%		
Wyoming	3		51.48%	O&G 46% C 54%	good	good

Source: Energy Information Agency and News Reports

Overall the future for the sector is promising. The US has abundant wind and solar resources to harvest, whereas most high quality fossil fuel reserves are already played out. In 2021, already 40% of electricity production will be free of carbon production. Over the next decade carbon emissions will decline by between 35% and 64% depending on the mix of combined cycle gas and wind and solar which replace the coal and gas peaker plants being retired. Efficient load balancing rather than primary production cost is the main obstacle to a clean low cost power sector.

Over the years a number of possible technologies have been discussed for the power sector. Our discussion here incorporates only technologies which are commercially proven or which are highly likely to be proven in the next three years. The following are technologies which we do not anticipate playing more than a marginal role in the US power sector: ultra supercritical coal, advanced nuclear, breeder reactors, fusion power, tidal plants, coal gassification, blue or green hydrogen, offshore wind, concentrated solar power, magnetohydrodynamic generators, geothermal, compressed air energy storage and lead acid batteries. For a technology to enter commercial service it must go through a process of engineering refinement that carries it to the point of economic viability before its role is captured by an alternate technology of approximately equal merit. Most of these technologies are so capital intensive or already face such entrenched competition that no path to commercial viability is evident at this time. Others have highly specialized site requirements that limit the technology to a marginal role.

The Transportation Sector

Overall this sector contributed 28% of US emissions in 2018. As shown in table 4 the sector consists of many sub-sectors each with its own characteristics. However road transportation of people and freight accounts for almost 70% of emissions. We believe the lithium battery powered electrical vehicle will be the dominant solution for this category. A battery pack stores less power per kilogram than gasoline but it leads to a simpler and better performing drive train. Electric vehicles have lower operating costs from savings on fuel and maintenance but somewhat higher capital costs. In the passenger car segment engineers have already been able to deliver competitive designs to the marketplace. We expect they will roll out competitive designs in the other categories of road vehicles over the next five years. Indeed electric delivery van builders are already claiming full life cycle costs which are half that of diesel vehicles. The segment which is most challenging for the battery powered vehicle to address is heavy long distance road haulage. However delivery of electric power to moving vehicles through overhead wires tapped by a pantograph is already demonstrated technology for trams and trains. Wiring up key sections of the interstate highway system with such a supply so that heavy trucks can conserve and recharge their batteries in transit is a simple solution for converting even this market segment to electrical power. An alternate solution is to swap out tractor units at truck depots, much as post riders used to swap horses at relay posts.

Aviation accounts for 11% of emissions. Here there is no immediately viable carbon free technology. Biofuels present the best remedial solution. When plants grow they extract carbon dioxide from the air. They can then be harvested for oils or fermented to produce ethanol. Burning these plant derived fuels generates carbon dioxide but over the total life cycle there are no net emissions of carbon dioxide. Today's biofuels must be mixed with either aviation gas or jet fuel to create a mixture which can be used in current aircraft engines. As a result this is only a reduction in carbon emissions and not full elimination. That residual carbon emission can be offset currently by capturing carbon dioxide through reforestation projects. Currently the cost of reduction and offsets about doubles fuel cost. Over time fuel and engine manufacturers will likely coordinate their efforts to reduce that cost.

Rail and pipelines account for about 4% of emission. Current rail traction is mainly diesel electric traction with some electric traction. Conversion of main lines to electric traction with diesel equipment being shifted to short line work is an obvious solution for this sector. The primary obstacle is actually property tax law rather than technical or economic. Electrified rail lines are assessed at a higher rate for property taxes while not delivering sufficient offsetting benefits to the rail operators. With pipelines the main issue is powering pumping stations along the pipeline. Retrofitting these to electrical power is a significant capital project which, however, can be implemented incrementally. Again, tax law which favored such improvements would materially accelerate the transition.

As recently as 2013, coal represented 25% of rail freight tonnage. Today that amount has been cut in half and as noted, coal tonnage is likely to disappear entirely over the next decade. Given this adverse business development, railroads are likely to need financing support from the government to engage in significant electrification. Cost of electrification is estimated at $1 million per mile. At that rate electrifying a transcontinental main line would cost a few billion dollars. Efficient rail operation requires equipment to be interoperable throughout the system. One way to achieve this would be to attach an electricity tender behind a diesel electric locomotive. This car would tap power from the overhead lines, run it through power conditionning equipment and feed it to the locomotive which would idle its diesel engine while traveling under supplied electric power. On track sections without electric power, the diesel would be throttled up to provide power.

Table 4: Green House Gas Emissions By US Civil Transportation in 2018

Category	Type	Use per year	Emissions (by weight)	Specific Emissions	Emissions (% total)
Passenger	Cars & Motorcycles	3,752,907	781.4	0.21	34.96%
	Light Trucks	664,495	328.3	0.49	14.69%
	Buses	368,430	13.4	0.04	0.60%
	Domestic Airline	722,415	119.6	0.17	5.35%
	International Airline	450,680	81.6	0.18	3.65%
	Subtotal	5,958,927	1,324.3	0.22	59.25%
Freight	Regional Trucking	1,181,074	254.3	0.22	11.38%
	Interstate Trucking	852,847	183.6	0.22	8.21%
	Rail	1,729,638	39.4	0.02	1.76%
	Domestic Shipping	491,800	41.2	0.08	1.84%
	Ocean Shipping	497,768	41.7	0.08	1.87%
	Air Freight	15,969	11.2	0.70	0.50%
	Pipelines	979,343	49.2	0.05	2.20%
	Subtotal	5,748,439	620.6	0.11	27.77%
Other Commercial	General Aviation	26	32.8	1285.97	1.47%
	Farm Equipment	793	40.0	50.42	1.79%
	Construction Equipment	1,363	68.7	50.42	3.07%
	Lubricants	n/a	9.3	n/a	0.42%
	Other International	n/a	77.7	n/a	3.48%
	Other Domestic	n/a	94.4	n/a	4.22%
	Subtotal		290.1		12.98%
	Grand Total		2,235.0		100.00%

Notes:
Emissions by weight are in CO2 equivalent million metric tons per year
Use is measured in millions of passenger miles (passenger), millions of ton miles (freight) and millions of engine hours (other)
Specific emissions are in kilograms per unit of use, e.g. cars are measured in kilograms per passenger mile
Other International is fishing boats and other non-freight marine. Other domestic includes mobile power generation and similar uses.
Emissions % total are percent of total weight

Source: Federal Highway Administration

Shipping accounts for about 4% of emissions. Similar to aviation there is not yet a demonstrated technological solution. At one time ships moved under sail power, which of course is emissions free. A number of experiments are underway to incorporate sails as an auxiliary power source in modern ships and so reduce fuel consumption. Moving to cleaner fuels is also under study. Here the candidates include biofuels and liquefied natural gas. The ocean shipping segment is regulated by the International Maritime Organization and its policies will determine the pace at which this sector evolves.

A variety of other commercial vehicles account for about 11% of emissions. Most of these are currently diesel powered. Some can be switched to electric power. Otherwise transition to biofuels or compressed natural gas may offer the best remedial solutions. This is a small complex market segment and it will probably be among the slower to transition.

The primary government interventions are likely to be raising excise taxes on disfavored fuels, providing easy loan terms for purchase of clean vehicles, mandating fleet wide emission standards, adjustment of tax law and providing targeted subsidies for emergent technologies. Interestingly, the government sits on both sides of the table in this transition. As the owner of the nation's road network the government holds a massive capital asset which is maintained currently by fuel taxes. As electric vehicles increasingly bypass that tax, the government will ultimately need to transition to a new revenue model.

Hydrogen has been much touted in the past as the solution for the transportation sector. Currently hydrogen can be generated at reasonable cost from natural gas feed stock. This method, however, results in some carbon dioxide emissions. Hydrogen can also be derived in an emission free manner from water by electrolysis driven from clean electric power. This route to hydrogen is currently three times more expensive than the natural gas method. However, it is believed that technical improvements could reduce that cost to the current cost of natural gas derived hydrogen in about a decades time. In the vehicle, hydrogen can be converted to electrical power in fuel cells with high efficiency and that electric power then applied to generate motive force. This has already been demonstrated in certain categories of vehicles (e. g. buses.) Given the advances which have been made in lithium batteries, however, it now looks as if hydrogen's role will be limited to sectors where batteries are not viable solutions – namely aviation and shipping. Those uses would avoid the need for an extensive network of fueling stations – which is what has stalled adoption of hydrogen for passenger vehicles. Possibly hydrogen will prove viable for heavy trucks and some commercial vehicles as well. Again the ability to introduce the technology in the absence of an extensive fueling network will assist adoption.

Mass transit is another much talked about technology. Certainly electric trams and low emission buses are easily deployed available technologies. However, mass transit is mainly a solution for congestion rather than for decarbonization. In the developed world mass transit has already been deployed in most markets where there is a sound investment case for it. The trend in the developed world is now towards population density reduction through greater telecommuting. The growth market for mass transit is in the still developing world rather than in the developed world.

Similarly moving walkways, cable lines and various forms of light rail are niche transport solutions for specific situations rather than major tools for decarbonization.

Currently the vehicle manufacturing industry is structured as a small number of vehicle manufacturers relying on a large complex network of suppliers who manufacture parts, components and subassemblies. The final vehicle manufacturers design, perform final assembly and market the finished vehicle. But the suppliers are responsible for the engineering refinement of their particular components. In this manufacturing ecosystem, the disruption of switching from internal combustion engines to electric drive will mainly be concentrated in the power train and brake manufacturers. The other suppliers will incur modest redesign of their components for the new vehicles, but their business should not be disrupted. The power train manufacturers will be variously impacted depending on the technological direction for the vehicle. Where electric drive becomes dominant, the demand for the diesel or gasoline engine winds down. Where instead the major change is in the fuel mix (aeroplane and marine engines) the impact on the engine supplier is much less drastic. Finally in electric drive vehicles the braking system becomes a higher value added component, representing both a challenge and an opportunity for the suppliers of this component. We expect most of the major vehicle manufacturers to successfully transition to the new technological paradigm. In the process some may gain or lose market share, but we are not expecting a dramatic shift in industry players. Accordingly, we also feel openings for new firms may be limited. Such openings as exist are more likely to be in design/engineering shops than in final vehicle manufacturing. The best chance for new manufacturers to establish themselves as final vehicle builders is in small production run specialty vehicles where vehicle performance engineering is more important than manufacturing process engineering.

The transportation sector makes heavy capital investment in equipment with different expected lives. Cars and light trucks have economic lives of about seven years. Heavy trucks last twice as long. Locomotives have 25-35 year lives. Aircraft and ships have forty year lifespans. Operators of a long lived equipment naturally want to know what the future regulatory framework will be. Shorter lived equipment is retired quickly and can respond more flexibly to government policy. Several countries have adopted dates around 2035 for ending sale of new gasoline powered passenger cars. Diesel vehicles have an additional problem of particulate emissions and are likely to be phased out sooner in urban areas. Once phaseout of a major category of vehicle begins then fueling and maintaining the old fleet is likely to get progressively harder and more expensive. These rising burdens then accelerate adoption of the new technology. The transportation sector is already at the point where it needs government to provide a clear road map for the transition so the capital invested in this complex sector can be properly allocated. The good news, however, is that technologies capable of eliminating 80% of this sector's emissions at reasonable cost are already available.

The Industrial Sector

We continue our study of the carbon transition by an examination of the industrial sector. The fossil fuel industry merits its separate treatment so we do not include that industry in this discussion. We will, however, include the waste management industry in this section. Overall industrial uses account for 23% of emissions. There are essentially three separate sources of emissions in this sector. First, many industries operate power plants to generate process heat, steam or electricity. Often industry operates cogeneration plants where heat or steam is the primary product and electricity is created as a byproduct either for internal use or for sale to the grid. From an emissions perspective such cogeneration plants are among the most efficient in the sense of economic benefits per pound of emissions. Second, some industries operate processes which create carbon dioxide as a waste product of the industrial process separate from combustion for power purposes. Third, industry emits a whole range of gases other than carbon dioxide which have greenhouse gas effect. For instance, sulfur hexafluoride is a gas primarily used as an insulator in high voltage equipment. Pound for pound, it has 23,900 times the the atmospheric heating potential of carbon dioxide and its atmospheric dwell time has a half-life of 800-3200 years. Emissions of this obscure gas are largely limited to unintentional equipment leakage, but so potent are its physical characteristics that it contributes 0.2% to the annual emissions budget stated in carbon dioxide equivalent tons. These diverse issues make the industrial sector an unusually complex one. As shown in table 5, the major emission issues are concentrated in a small handful of industries:

Table 5: Greenhouse Gas Emissions, Industrial Sector, exclusive of power generation

Industry	Emissions (C02 equivalent metric megatons)			Industry	
	CO2 Emissions	Other Emissions	Total	Revenue (B$)	Intensity ($/Ton)
Refrigerants		171.2	171.2	9.5	55
Landfills		110.6	110.6	64.0	579
Basic Chemical Industry	55.5	25.5	81.0	21.0	259
Iron & Steel	42.6		42.6	113.0	2,653
Cement	40.3		40.3	10.0	248
Petrochemicals	29.4	0.3	29.7	55.0	1,852
Wastewater Treatment		19.2	19.2	63.0	3,281
Electrical & Electronics		8.9	8.9	500.0	56,180
Other Waste		4.7	4.7	8.9	1,894

Source: EPA Inventory of US Gas Emissions and Sinks 1990-2018

The single biggest source of greenhouse gas emission is leakage of refrigerants from equipment. These leaks are not especially large but the gases involved are particularly potent greenhouse gases. Initially industry relied on chlorinated fluorocarbons (CFCs) such as Freon for its refrigerants. However those chemicals were recognized as injurious to the earth's ozone layer and an international treaty, the Montreal Protocol of 1987, has mandated their phaseout. The replacement was hydrofluorocarbons (HFCs) but these in turn were recognized as injurious greenhouse gases. The 2016 Kigali amendment to the Montreal protocol establishes a phaseout regime for HFCs. The plan is to switch over to environmentally benign refrigerants over a thirty year period. Ratification of the Kigali protocol is pending and broadly supported.

The second biggest source of emissions is methane released from landfills. Methane is also produced by sewage treatment plants, but much less intensely. Fortunately burning methane converts it to carbon dioxide which has only 4% of the warming power of methane. So capturing and flaring the methane is an effective means of reduction. The methane is produced by decomposition of organic matter in the landfill, so segregating organic and inorganic waste streams is a valuable first step to controlling this emission.

The chemical industry is the third largest emitter. Its emissions derive largely from production of ammonia, lime, other carbonates, urea and a dozen other minor sources. In addition it is an emitter of nitrous oxide, primarily in the manufacture of nylon and nitric acid. It is economically feasible to scrub nitrous oxide from smokestacks. Scrubbing carbon dioxide has not yet been demonstrated on an industrial scale but it is estimated to cost $100/ton. Compared to product sales of about $259 per ton of emission this is a fairly significant cost. While the chemical industry runs a dozen different processes that emit greenhouse gases, each process runs at only a handful of plants. This is in marked distinction to the electric power industry which emits greenhouse gases at hundreds of sites or the transportation industry which emits gases from millions of vehicles. The small number of sites in the chemical industry means that solutions can be handcrafted for each plant if warranted.

The iron and steel industry is the fourth largest emitter. Most of these emissions derive from coal fired blast furnaces. The industry has been evolving away from blast furnaces and towards electric arc furnaces and its emissions are dropping in consequence.

The cement industry is the fifth largest emitter. Unfortunately there is no apparent way to avoid these emissions and the cost of scrubbing is high relative to revenue per ton of emissions. Mandating remediation for this industry could raise cement costs about 40%. However, it is believed that economies could be achieved in utilization of cement such that the end consumer impact would be less. In any case, the absolute impact – about $4 billion – is small relative to the size of the economy.

Petrochemicals, electronics and waste incinerators are the final sources of emissions. Reduction and remediation of emissions are small costs relative to industry revenues.

To these process emissions we must add emissions from industrial power plants. These amount to 833 metric megatons of emissions. The break-down by fuel source is coal 50, petroleum 269 and natural gas 515. Theoretically replacing coal and petroleum by natural gas would reduce emissions by about 114 megatons per year. Practically, however, complete replacement is not possible. For instance, one reason industry uses a relatively high percentage of liquid fuel is that its sites are remote from gas distribution systems and it must rely on fuel brought in by ship, train or truck. In general the remediation track for industrial power plants is similar to other power generators. By preference move to gas or emission free energy either generated onsite or delivered by transmission lines. Where those solutions are not possible then biodiesel offers some immediate reduction and LNG or hydrogen may be longer term solutions.

As a final remark, we note that the problem of managing waste lithium batteries is an emergent issue. It will be much increased by mass adoption of electric vehicles. Lithium batteries gradually wear out over time. Batteries which have aged to the point that they are no longer suitable for vehicles may still be reusable for stationary electric power storage. Eventually the batteries can be recycled. Currently batteries are poorly engineered for recycling, but this issue will no doubt be addressed as the waste stream grows more substantial.

The Agricultural and Land Management Sectors

Agriculture is responsible for emitting 619 million metric tons of CO_2 equivalent gases, which is 9.3% of gross emissions (or 10.5% of net emissions.) Other land management is responsible for absorbing 774 million metric tons, which reduces gross emissions by 11.6%. Netting Agriculture and land use results in a 155 megaton reduction in emissions per year.

In Agriculture there is a massive natural flux of carbon dioxide. Plants absorb carbon dioxide from the air as part of their growth cycle and store it during their lives. After the plants dies the process of decomposition returns the carbon to the environment. However, this natural flux has little net effect on atmospheric greenhouse gases and is not considered as part of the emission flux from Agriculture. The primary greenhouse gas impact of Agriculture comes from practices which convert carbon, ultimately sourced from the atmosphere, into methane which has 25 times the warming impact of carbon dioxide. The other impact of Agriculture comes from emissions of nitrous oxide which has 298 times the warming power of carbon dioxide. The primary Agricultural sources of greenhouse gases are given in table 6 in terms of millions of metric tons of CO_2 equivalent emissions.

Table 6: Greenhouse Gas Emissions From Agriculture

Source	Emissions (Megatons CO2 equivalent)				
	Carbon Dioxide	Methane	Nitrous Oxide	Total	% Sector
Soil Management					
...nitrogen enrichment	4.6		338.2	342.8	55.42%
...soil conditioning	3.1			3.1	0.50%
Crop Practices				0	
...rice cultivation		13.3		13.3	2.15%
...burning field residue		0.4	0.2	0.6	0.10%
Livestock Management				0	
...cattle raising		207.4	15.3	222.7	36.01%
...pig raising		25.0	2.0	27.0	4.37%
...other livestock		6.9	2.1	9.0	1.46%
Total	7.7	253	357.8	618.5	100.00%

Source: EPA Inventory of US Greenhouse Gas Emissions and Sinks 1990-2018

Over half of emissions are nitrous oxide emissions resulting from digestion of soil nitrogen by bacteria living in the soil. Farmers deliberately add nitrogen to the soil by fertilizing with either synthetic fertilizer or animal manure or by growing certain plants which fix atmospheric nitrogen (e.g. legumes.) The intention of this nitrogen enrichment is to support crop growth, but crops must compete with bacteria for the available nitrogen.

The second largest source of emissions is raising beef and dairy cattle. The feed consumed by cattle is fermented in their fore stomach by bacteria which generate methane. This methane is then burped out by the cattle. Each animal produces between 75 and 125 kilograms of methane per year (170 to 280 pounds.) Choice of breed and feed both effect the amount of methane produced per year. A recent report suggests that enriching the feed by 0.2% by weight with certain seaweeds can eliminate 95% of the methane production. Seemingly the cattle benefit from losing the bloat as they are claimed to exhibit better meat and milk production. Interestingly this result came from observing the feeding habits of cattle with natural access to the seaweed on beaches. If these results are confirmed in general practice then this impressively large source of emissions can be dealt with rather easily. A secondary source of emissions from cattle is bacterial fermentation of manure to nitrous oxide. When cattle are pasture raised then the manure is digested aerobically with little nitrous oxide production. When cattle are kept in feedlots or barns, however, the manure is washed out with water and ends up in waste ponds. Here it is digested anaerobically and nitrous oxide is produced. More careful waste management can reduce this source of emissions.

A handful of other agricultural practices are minor sources of emissions. Raising pigs and other livestock presents the same issues as cattle but on a smaller scale. Growing rice in flooded fields creates conditions favorable to methane generating bacteria. Spreading carbonate minerals on fields to adjust soil acidity results in some release of carbon dioxide. Burning crop residue left standing in fields after the harvest is a highly visible but not important source of emissions.

Agricultural systems are highly complex assemblages of interacting natural organisms. We can expect that research into different practices will gradually permit us to tune our agriculture so as to reduce harmful emissions while maintaining productivity. However, remediation in this area is likely to progress more slowly than in the other sectors we have looked at due to the complexity of the systems dealt with.

Next we consider the impact of land use on emissions of greenhouse gases. The surface area of the United States is classified into several types depending on the dominant use of the land as shown in table 7. Here managed refers to lands at least loosely under human control, while unmanaged refers to true wildlands.

Table 7: Land Use in the United States

Type	Thousands of Hectares				CO2 Absorbed	
	Managed	Unmanaged	Total	Total %	Megatons/year	tons/hectare/year
Forestland	886,513	8,208	894,721	53.87%	564.5	0.63
Grassland	336,863	26,608	363,471	21.89%	(11.2)	-0.03
Cropland	281,546	0	281,546	16.95%	16.6	0.06
Settled	44,797	0	44,797	2.70%	31.5	0.70
Wetland	39,132	4,165	43,297	2.61%	4.4	0.10
Other	0	32,944	32,944	1.98%	0.0	0.00
Total	1,588,851	71,925	1,660,776	100.00%	605.8	0.36

Note: excludes the US territories, which represent 0.1% of US landmass
Source: EPA *Inventory of US Greenhouse Gas Emissions and Sinks 1990-2018*

Perhaps surprisingly, the United States is a forest nation with more than half its surface area given up to forests. In fact, the United States is virtually tied with Canada to possess the world's third largest forest. Only the forests of Russia and Brazil are appreciably larger. Tree growth in that forest absorbs an enormous quantity of atmospheric carbon dioxide each year – amounting to 565 megatons per year. Unexpectedly the settled areas of the country are an even more intense absorber of carbon dioxide. But, except for the desert cities of the Southwest, American cities are heavily tree covered. In fact, the typical American city is about 35% tree covered. The growth of this urban forest absorbs 32 megatons of carbon dioxide per year. The other land types are minor sources and sinks of carbon dioxide.

Land use changes gradually through time. From the seventeenth through nineteenth century homesteaders were busy clearing forestland to create cropland. As agriculture became more capital intensive at the end of the nineteenth century the focus shifted to developing the most productive acreage. In the twentieth century the trend has been to re-purposing marginal croplands. Landowners extract the greatest value from the conversion of cropland to settlement and that is the primary flow (table 8.) In fact, the settled area is growing considerably faster than the population as dense urban centers continue to spread out into suburbia.

Table 8: Change in Use of Managed Land

Original Use	Final Use: Forestland	Grassland	Cropland	Settled	Wetland	Other	Losses
Forestland	0	545	58	541	54	90	1,288
Grassland	992	0	12,609	3,352	836	2,331	20,120
Cropland	135	16,600	0	2,452	440	678	20,305
Settled	26	346	99	0	25	16	512
Wetland	25	308	104	46	0	121	604
Other	93	2,442	179	197	118	0	3,029
Gains	1,271	19,696	12,991	6,047	1,419	3,146	
(Losses)	-1,288	-20,120	-20,305	-512	-604	-3,029	
Net Gains	-17	-424	-7,314	5,535	815	117	
Gains (%)	0.00%	-0.12%	-2.60%	12.36%	1.88%	0.36%	

Source: EPA *Inventory of US Greenhouse Gas Emissions and Sinks 1990-2018*

Net changes in the other land uses are fairly modest, although there is some considerable churn in grasslands. Changing the use of land often releases carbon dioxide stored in soils and tends to increase emissions (table 9.) This, however, is partially offset by increased tree growth in the forest and settled areas.

Table 9: Emissions Resulting From Change in Land Use

Original Use	Final Use: Forestland	Grassland	Cropland	Settled	Wetland	Total
Forestland	0.00	15.90	48.70	62.90	0.00	127.50
Grassland	(9.70)	0.00	8.50	11.30	0.00	10.10
Cropland	(46.30)	(18.00)	0.00	5.90	0.00	(58.40)
Settled	(38.90)	(0.90)	(0.10)	0.00	0.00	(39.90)
Wetland	(0.90)	0.30	0.60	0.40	0.00	0.40
Other	(14.90)	(21.90)	(2.20)	(1.20)	(4.40)	(44.60)
Total from Gain	(110.70)	(24.60)	55.50	79.30	(4.40)	(4.90)
Total from Loss	127.50	10.10	(58.40)	(39.90)	0.40	
Net	16.80	(14.50)	(2.90)	39.40	(4.00)	34.80

Source: EPA *Inventory of US Greenhouse Gas Emissions and Sinks 1990-2018*

The net effect of 35 megatons of greenhouse gases emitted per year is quite modest. Overall, land use is a massive absorber of atmospheric carbon dioxide. Encouraging tree growth and paying some attention to drainage when land is converted to settled use are the principal interventions for maximizing this beneficial effect.

The timber industry harvests trees annually amounting to about 20% of a year's growth. This harvested wood is often kiln dried and operating the kilns results in an unknown quantity of greenhouse gas emissions. Except for timber converted to paper or fuel, most of the harvested timber is incorporated into long lived products such as furniture and houses. These store the tree's carbon long term. As a result, this wood harvesting does not create major emissions. Eventually harvested wood ends up in landfills and the emissions resulting from its decomposition there was included in the total for landfill emissions. Wood burned as fuel contributes 237 megatons per year of emissions of which 8 megatons are methane and nitrous oxide. Only this eight megatons is considered a net addition to greenhouse gas emissions.

One rather visible sources of emissions is fires (table 10.) For most of the twentieth century the forest service intervened to limit and suppress wildfires.

Table 10: Emissions From Fires

Fire	Emissions
Type	Megatons/year
Forest wildfire	142.6
Forest controlled burns	8.6
Grassland fires	0.6
Total	151.8

Source: EPA *Inventory of US Greenhouse Gas Emissions and Sinks 1990-2018*

Gathering ecological knowledge called this practice into question. The forest and grassland ecosystems evolved with fires as a natural part of the system. When fires are suppressed the ecosystem is thrown out of balance. As a result forest service practice shifted to nonintervention in fires not immediately threatening settled areas. However, one consequence of the long period of fire suppression was the accumulation of an unnatural amount of tinder. As a result, fires in formerly fire suppressed areas have often developed into devastating megafires. The thinking is developing that it is not enough to abruptly switch from intervention to nonintervention. Rather controlled burns and gradual release of suppressive measures may be called for. Practice will continue to evolve here. Meanwhile, the emissions noted in table 10 are incorporated into the emission data of table 7 and they are not an additional source of emissions.

The Building Sector

Table 11: Emissions from Residential and Commercial Structures

	Use	Emissions (Megatons C02 equivalent)				
Fuel	% BTU	CO2	Other	Total	% Total	% Residential
Natural Gas	67.53	466.3	1.2	467.5	78.90%	58.7
Propane	8.852	46.24	0.28	46.52	7.85%	54.9
Fuel Oil	13.278	69.36	0.42	69.78	11.78%	54.9
Coal	0.15	1.8	0	1.8	0.30%	0
Wood	10.19	62	6.9	6.9	1.16%	85.9
Total	100.0	645.7	8.8	592.5	100.0%	60.7

Source: EPA *Inventory of US Greenhouse Gas Emissions and Sinks 1990-2018*

The building sector is divided into residential and commercial sectors. Total emissions of greenhouse gases by buildings are 592.5 million metric tons of carbon dioxide equivalent gases. This is 10% of net emissions of greenhouse gases in the US. These emissions derive from combustion of fuels to generate heat, primarily to warm buildings and secondarily to drive appliances such as stoves and water heaters. The details are in table 11. Natural gas provides almost 70% of the heat generated and it is the most efficient fuel from an emissions perspective. Propane is used mostly in rural buildings remote from gas grids. Fuel oil is used in both urban and rural settings. Converting all of the fuel oil users to gas would reduce emissions from this sector by only 4%. Coal was once the dominant heating fuel in the US, but its use today is vestigial. Wood is used as a fuel mainly in rural homes. Carbon dioxide emitted in that process is ultimately of atmospheric origin and so it is not included in the total of greenhouse gas emissions. However, methane and nitrous oxide emissions from wood burning are considered greenhouse gases. These derive mostly from incomplete combustion. Upgrading from fireplaces and older heating (Franklin) stoves to more modern heating stoves would reduce this minor source of emissions. This sector is already the most efficient from an emissions perspective in terms of its fuel mix and so relatively little improvement can be made in that regard. Longer term, substituting emissions free electricity or hydrogen for fossil fuel combustion could more substantially reduce emissions. Considerable progress has been made in improving building insulation – particularly in the residential sector. However this gain has been largely offset by a gradual enlargement of residential size with rising incomes. Consequently, we see little net emissions reduction occurring from that source.

The best near term prospect for buildings to contribute to greenhouse gas reduction is through addressing their air conditioning usage. Currently a great deal of building electrical use is devoted to air conditioning loads. Not only is this electricity supplied from power plants which are greenhouse gas emitters but the greatest demand comes at peak hours which are generally supplied from less efficient peaker power plants. Emissions from this source are estimated to amount to 117 megatons per year. However the air conditioning load is an excellent match for the production cycle of roof top photo-voltaic cells. Situating the cells on roof tops basically eliminates any real estate expense associated to such installations. In addition, generating the power at the points of use eliminates transmission losses. Finally older air conditioning equipment is an important source of leaking refrigerants
which we have noted as important greenhouse gases. A program of upgrading less efficient old equipment to more efficient better insulated new equipment with benign refrigerants and powered from a roof top installation represents the most effective way for buildings to reduce greenhouse gas emissions currently.

An obstacle to the suggested program is the difficulty of getting consumers to invest in economic capital improvements. The public is both capital constrained and lacks the capacity to evaluate the economic case for the improvement. They respond by applying very healthy discounts to vendor projections. It is estimated that the internal rate of return must reach 33% before mass consumer adoption occurs. Utilities, by contrast, are allowed only an 8% return on capital. This circumstance opens the possibility of an arbitrage in which the utility provides the capital for the improvement in return for a split of benefits with the homeowner. In recent years regulators have been increasingly favorable to such arrangements.

We have noted that cement production is an unavoidable source of greenhouse gas emissions. Commercial buildings are the major users of cement. The consumption of cement is largely set by safety standards established by regulators and a prevalent practice of building to twice the standard. In addition, a planned building life of 60 years is used which is significantly less than physical life. Reviewing safety standards, reducing overbuilding and extending building lives would all economize on cement usage and thus reduce emissions. However, total emissions from cement manufacture are only 40 megatons per year, so the scope of reductions is limited.

The Fossil Fuel Industry

In our review of the effort to control greenhouse gas emissions we come finally to the industry most centrally effected – the producers of hydrocarbon fuels. This industry divides into miners of coal and drillers for oil and gas. Unsurprisingly the extraction and transportation of fossil fuels gives rise to various leaks and spills which are a source of greenhouse emissions independent from the emissions caused by use of the fuels. Total emissions are 314 megatons per year or about 5% of net US emissions.

As shown in table 12 over 95% of the emissions derive from active facilities and only 13 megatons from retired facilities. Fugitive methane from production of natural gas is the major emission, but oil production and underground coal mining are also important sources. As the hydrocarbon industry winds down the emissions from active facilities will be eliminated. It then remains only to ensure proper capping of abandoned wells and sealing of closed mines to limit the emissions from retired facilities.

Table 12: Greenhouse Gas Emissions by the Hydrocarbon Industry

Source	Emissions (metatons CO2 Equivalent per year)				
	Carbon Dioxide	Methane	Nitrous Oxide	All	% Total
Active Facilities					
...oil	36.8	36.2	0.1	73.1	23.28%
...natural gas	35.0	140.0	0.0	175.0	55.73%
...underground coal	0.0	44.2	0.0	44.2	14.08%
...surface coal	0.0	8.5	0.0	8.5	2.71%
...total	71.8	228.9	0.1	300.8	95.80%
Retired Facilities					
...oil & gas	0.0	7.0	0.0	7.0	2.23%
...underground coal	0.0	6.2	0.0	6.2	1.97%
...total	0.0	13.2	0.0	13.2	4.20%
Grand Total	71.8	242.1	0.1	314.0	100.00%

Source: EPA *Inventory of US Greenhouse Gas Emissions and Sinks 1990-2018*

As we have suggested, wind down is the most likely fate of this industry. Let us review the reasons for this conclusion. First, the coal industry is already in wind down. The only important use of coal is electric power production. As we saw in our review of the electric power industry, coal is more expensive than other fossil fuels and than emission free sources of power. The utility industry is phasing it out without need for government action. As the dirtiest source of electric power coal is sure to be an early target in a government push to control emissions.

Second, we must consider the oil and gas industry. Historically, oil was the more prized resource and gas was something of a by product. A talented refining industry is adept at turning oil into various products and the petrochemical industry takes that alchemy a step further by transforming oil and gas feed stocks into plastics, fibers and synthetic rubbers (see table 13.) The overwhelming use for oil, however, is to produce fuels for transportation. As we saw in the review of the transportation industry a technological paradigm shift has occurred in which the battery driven electric road vehicle can deliver better performance at lower life cycle cost than hydrocarbon driven road vehicles. The technology of electric vehicles is still advancing rapidly while the hydrocarbon fueled vehicle is a mature product not susceptible to significant further improvement.

Table 13: Market For Petroleum Products 2019

Product	Market Share	
	% Volume	% Value
Gasoline	45.31%	57.17%
Diesel	14.67%	18.60%
Jet Fuel	8.48%	9.39%
Heating Oil	5.30%	7.09%
Propane	5.28%	2.00%
Petrochemical Feedstock	11.54%	3.10%
Other	10.96%	2.56%

Note: Other includes asphalt, lubricants, waxes and coke
Source: EIA

The competitive advantage of the electric vehicle will grow progressively greater and we can anticipate a major market shift as existing vehicles wear out and need to be replaced. This shift will be accelerated by government action. Several governments have announced deadlines for terminating sales of hydrocarbon fueled passenger cars. This circumstance forces the automotive industry to either field electric vehicles or cede its market share in those jurisdictions. Once manufacturers are producing both electric and gas powered vehicles, but only the electric product line is growing the manufacturer's preference shifts to pushing full adoption of the electric vehicle as the way to maximize the efficiency of its operations. These considerations suggest that the major market for oil derived fuels will have disappeared by 2040.

Currently that market accounts for about 75% of oil company revenues. We do not know the exact trajectory it will follow, so a reasonable expectation is the market will steadily shrink at about 3.5% per year. That leaves oil with a collection of smaller markets: jet fuel, heating oil, propane, petrochemical feed stock, asphalt and lubricants. Even here, over a twenty year horizon, it must contend with technological developments that could reduce the jet fuel and heating oil markets. The remaining demand for oil as a chemical feed stock may hold steady, but that amounts to only about 5% per cent of the current market by value. It is clear that the industry is headed towards a situation of massive over supply and falling prices. In that situation only the lowest cost producers can survive long term. Worse yet, there are a number of nationalized firms which governments may prop up with subsidies in the medium term. This artificial competition will make the environment untenable for even the most efficient private firms without access to low cost reserves. That description pretty much characterizes the American and European oil producers, and so we expect them to be relatively early casualties of a contracting market.

These considerations leave only natural gas as a long term viable sector. Initially the demand picture for gas is strong. It is the cleanest of the hydrocarbon fuels and also the most economical to use for electric power generation. The market for gas can expand for five to ten years as it displaces coal and oil from power generation. However, over the same time frame we anticipate that utility scale electrical storage technologies will prove out. Wind and solar power will then begin to displace gas from the electrical power generation market. Electrical power will then begin to displace direct use of gas from heating buildings. In this view gas demand will decline steadily over the 2030-2050 time frame much as oil demand declines over the 2020-2040 time frame.

There is a route to long term survival for the oil and gas industry. It is economically feasible to convert natural gas to hydrogen. However the process also creates substantial carbon dioxide emissions. If the industry can solve the problem of capturing and sequestering this carbon dioxide economically then it can have a long term future of producing emission free hydrogen. However, it will have to compete with hydrogen produced by electrolysis driven from emission free electric power. It is not clear at this point which technology will prevail. If the industry can deliver clean hydrogen it must then develop the market for this fuel. Unfortunately, electric battery technology has developed rapidly and benefits from an electrical power distribution system which is already in place. Hydrogen, by contrast, is stymied by the lack of a distribution system. This limits hydrogen initially to niche markets – heavy vehicles and possibly airplanes. Whether it can displace the battery from the dominant position in personal transportation is fairly doubtful. Long term prosperity for the oil and gas industry would seem to require clearing three difficult technical and economic hurdles. Worse yet, these hurdles have to be cleared at a time of decreasing revenues and in the face of skepticism from regulators and potential technology adopters.

If this strategy cannot be developed successfully, then we think the likeliest future for the oil and gas industry is a steady market contraction that leaves the low cost producers of the Arabian peninsula as the long term survivors serving the residual demand. This picture implies an extended wind down of the US petroleum, refining and petrochemical industries playing out over the next thirty years. Probably the decline will be gradual enough that needed workforce reductions can be handled through natural retirement and attrition rather than through massive career terminations. However, it definitely implies a decline for local economies closely tied to this sector. Given the future we project, we have considerable skepticism towards projects to bring high cost reserves such as high arctic oil or Canadian oil sands online. Even if the Arabian producers were to drop the price of oil in an effort to slow the technological migration away from petroleum, those high cost reserves would still be untenable. Given instead the likelihood that mounting anxiety about climate change is likely to accelerate the move away from fossil fuels, such high risk projects look closer to folly than to strong investment cases.

It is worth noting that we have been here before. In the 1880s an effective electric light was developed and over the next twenty years it displaced kerosene from domestic lighting. In this way, it eliminated what was then the principal market for the oil industry. However, the oil industry solved the engine knock problem and reinvented itself as a provider of transportation fuels. As the electric vehicle now threatens to displace the industry from that market it is possible that the industry will successfully reinvent itself again.

Whether wound down or reinvented, we believe the oil and gas industry is in for some wrenching changes. Substantial reductions in exploration, write-offs of unrecoverable reserves and reductions in workforce are inevitable. Credit downgrades are to be expected. Investment will likely be redirected away from refineries, distribution and petrochemicals. Attention to cash flow generation will be paramount. Oil stocks will likely trade on a yield basis with a portion of the yield regarded by the market, if not by the tax collector, as a return of capital. Firm consolidations will be common in the face of ever greater pressure for efficiency.

Summary

Let us now summarize our sector based review into an economy wide perspective on the technological transition we face. We tabulate the different sources of emissions we have discussed and assign them to the time horizon at which we believe they will become addressable (table 14.) In the now column we list emissions for which commercially proven solutions currently exist. These include retiring coal generated electricity and emissions that result from coal mining, replacing peaker power plants by by battery storage, converting cars and light trucks to electric vehicles and converting to gas heat those buildings currently reliant on coal and fuel oil. Addressing just these issues would eliminate 40% of current emissions.

Table 14: Remediation Horizon

	Emissions (Megatons CO2 Equivalent/year)				
Source of Emissions	Now	Medium Term	Long Term	Never	Total
Electric Power Production					
...coal fired	1,066.00				1,066.00
...peaker	122.00				122.00
...combined cycle gas		656.00			656.00
Transportation					
...passenger vehicles	1,109.70				1,109.70
...heavy trucks		437.90			437.90
...rail	39.40				39.40
...shipping			82.90		82.90
...airline			201.20		201.20
...air freight			11.20		11.20
...pipelines		49.20			49.20
...general aviation			32.80		32.80
...farm and construction equipment			108.70		108.70
...lubricants				9.30	9.30
...other			172.10		172.10
Industry					
...refrigerants		171.20			171.20
...landfill		50.00		60.60	110.60
...air freight					0.00
...basic chemical		40.00	20.00	20.00	80.00
...iron & steel		20.00		22.60	42.60
...cement				40.30	40.30
...petrochemicals			9.70	20.00	29.70
...waste water		10.00		9.20	19.20
...electrical & electronics			8.90		8.90
...other waste				4.70	4.70
Agriculture					
...soil treatment				345.90	345.90
...crop practices		7.00		6.90	13.90
...livestock		220.00		38.90	258.90
Buildings	71.60		467.50	53.40	592.50
Hydrocarbons				20.00	20.00
...active coal mines	52.70				52.70
...active oil and gas			241.30		241.30
...inactive facilities				20.00	20.00
Total	2,461.40	1,661.30	1,356.30	671.80	6,150.80
%Total	40.02%	27.01%	22.05%	10.92%	

The medium term is emission sources which we believe will become addressable once technologies currently in technical/economical feasible stage are commercially proven. Prominent among these are utility scale electric storage, electrification of road freight, and adjusting animal feed to minimize methane production. At this medium term horizon we include the already legislated plan to move to benign refrigerants. Partial cleanup of certain industrial processes and pipelines rounds out the projects addressable in the medium term. These projects eliminate 27% of current emissions, or 67% cumulatively to this point. At the long term horizon we list projects which require additional technical breakthroughs. Preeminent among these is a cost acceptable supply of emission free hydrogen and conversion of various end user markets to utilizing this product. Success here would eliminate 22% of emissions, or 89% cumulatively. Finally there is a certain set of emissions for which no viable road to remediation is in sight. However, those emissions amount to only 10% of current emissions. These contribute 672 megatons of emissions per year. However existing tree growth and other carbon sinks currently absorb 608 megatons per year. So our net emissions would be only 63 megatons – 1% of our current emission level. Within rounding error this would achieve the goal of zero net emissions of greenhouse gases.

Political Considerations

When the problem of converting away from the hydrocarbon economy was first identified, economists urged a tax on carbon emissions as the best regulatory intervention. They were reluctant to see the government write a massive rule book and they felt the free market could be harnessed to find the cheapest way forward. Revenues from the tax would be applied to ameliorating displacement and subsidizing technology development and deployment.

However, industry was not comfortable with this proposal. From the perspective of industry, if government mandated change and provided a transition period then all firms would face similar costs and so these costs could be passed on to consumers without much damage to profitability. With a carbon tax, however, every long term capital budgeting decision would involve forecasting the path of the tax. Firms which had either better forecasters or better connections to government would gain competitive advantage,. Firms felt the efficiency gain inherent in the carbon tax would not accrue to them while their business risks would increase. So they were cool to this proposal.

Economists came back with the idea of tradeable emissions permits. Rather than a carbon tax which would apply economy wide, they proposed regulating just key industries. The government would initially license firms to emit their current level of greenhouse gasses ("cap") but then would progressively lower the total allowed emissions. Firms could take one of three courses – shut facilities, remediate them to reduce emissions or buy up emission permits from other firms. Again the market would be harnessed to guiding the transition. Such a cap and trade system was actually introduced in Europe with mixed success. Again industry was not keen on a regulatory scheme which left them carrying all the economic risks of the transition.

In the US the policy argument was at about this point when Trump took power. Trump's election was dependent on the electoral votes of hydrocarbon producing states. Protecting the fossil fuel industry became his mission. He launched an attack on the science of climate change and actively promoted fossil fuels and especially coal which is the worst of the hydrocarbon fuels from an emissions viewpoint. The results were two. First, effective policy making was halted for the four years of his presidency. Second, Trump's policy making was dominated by the fossil fuel producers and the wider business community did not have a place at the table.

By default, policy thinking was left to the Democratic party. Two separate strains of thought emerged - the Inslee plan and the Green New Deal. The Inslee plan focused on the major sources of emissions and what could be done to address them today. As a result, the plan was not technology based – i. e. focusing on the immediately addressable issues first. The Green New Deal combined a missionary zeal to save the planet with a practical political idea of funneling vast sums of government money to labor unions involved in remediation work. For instance, one of the central programs of the Green New Deal is to remediate 3% of existing structures each year to drive emissions from the structure sector down to zero over a thirty year period. Implementing this implies creating a lot of jobs in the construction industry.

To our mind, neither the Inslee plan nor The Green New Deal exhibit an adequate appreciation of the relative difficulties of different courses of action. To give an example, let us zero in on the problem of emissions from cattle raising. In theory a simple solution would be to stop eating beef. In principle this could be implemented in a week's time, the herd would quickly shrink and this source of emissions would go away. But as food companies will tell you it takes massive marketing expenditure to persuade the public to alter what they put in their mouths. And as priests and doctors will tell you, the public doesn't curb its animal appetites based on alleged distant benefits. So this is a massively difficult to implement idea. In addition it bankrupts the cattle industry which of course will mobilize against the idea. Consider instead the idea of feeding cows seaweed supplements. Implementing this requires only doing some research at agricultural colleges, distributing the supplement through existing feed distributors and having a certifying organization certify the beef as coming from green cows so that the consuming public voluntarily pays a premium for such meat resulting in higher profits for cattlemen. Everyone – even the cows – are happier and the costs of implementation are dramatically lower. Because too many of the proposals in the Inslee and Green New Deal plans were high friction proposals, it was difficult for their proponents to build broad support for their plans.

President Biden has developed his own plan to address climate change. It draws on earlier thinking, but it dramatically dials back on some of the heavy politicized spending of the earlier policies. For instance, structure remediation is provided for at one tenth the rate of the Green New Deal.

We have evaluated the Biden plan in the light of our technological survey. We find that it can be divided into three parts: rational ideas inline with economic realities, more aspirational but not obviously foolish ideas, and ideas which appear more driven by the desire to throw a bone to political constituencies than by a genuine focus on the climate. We expect that in the horse trading of enactment some ideas will be traded away in return for progress elsewhere. If Biden's commitment to the environment is sincere – and we have no reason to believe it is not – it is the ideas in the third group which should perish so that the ideas in the first group can live.

In the group of rational ideas three are of preeminent importance. The first is a committed plan for reaching carbon neutrality by 2050. This is exactly the clarity the business community requires in its capital budgeting. The second is a commitment to carbon neutral electricity by 2035. The pace is a bit accelerated but probably achievable and in line with economic reality. It does assume success at utility scale electric energy storage. It will also require significant investment in the electric grid. Importantly, it implies that coal fired plants currently being retired will be replaced by wind or solar power rather than by combined cycle gas power plants. The third is a strong push on electric passenger vehicles supported by investment in recharging stations. This is less firm than other governments which have promulgated phase out deadlines for gasoline powered cars. It also is vague on heavy trucks. We would not be surprised to see objectives firm up in this area, however, as political consensus builds. Indeed, as this document was being written General Motors announced it would exit the gasoline powered vehicle market by 2035. Attention to capping emissions from retired hydrocarbon facilities and for improving agricultural waste management round out the list of practical ideas.

In the more aspirational category we would include subsidies for research on hydrogen, electricity storage and carbon capture and sequestration. Research on improved agricultural practices also falls in this camp.

Ideas which we are more skeptical about are mass transit, heavy spending on building modernization, changes in local zoning laws to reduce commutes and subsidies for nuclear power. Goals for improvement in industrial processes are so vaguely stated that we would have to label them as aspirational. However, this vagueness may simply reflect the circumstance that the subject is too technical for political manifestos.

Support for workers displaced by climate policy is an unsurprising component of a program from the Democratic party and realistically probably necessary for political enactment. As a measure of the problem we note the following work forces:

Table 15: Employment in 2018

Industry	Work Force	Payroll (B$)
Coal Mining		
...direct	50,770	3.12
...indirect (est)	91,348	5.35
...total	142,118	8.47
Oil & Gas		
...production	141,320	13.65
...oil pipeline	11,800	0.96
...gas pipeline	29,300	2.18
...refining	112,000	8.56
...filling stations	933,650	25.12
...total	1,228,070	50.47

Source: Bureau of Labor Statistics

As can be seen most of the headcount is in gasoline filling stations where average wages are rather low - averaging $25,000 per year. The upstream part of the industry is much less labor intensive but wages are in the $70,000-$90,000 so half of total payroll is in upstream activities.

As with any political program, in the Biden plan there is much attention to political hobby horses and enthusiasm for spreading wealth around. We expect the winnowing process of legislation to edit out a good deal of this persiflage. Overall, however, we feel the program is realistic and impressively comprehensive.

Transition away from the hydrocarbon economy definitely has firms and labor forces which are on the wrong side of history. Labor forces routinely must deal with technology transitions and the general approach is to drop opposition to change in return for job buyouts. The combination of a Democratic president and a hung Congress represents a near optimal situation for negotiating job buyouts. Accordingly, we expect labor to support Biden's climate plan after token resistance. For firms it is a much more novel situation to find the government sun setting whole industries. Firms are also handicapped by the failure of their usual advocates – the Republican party – to have seriously prepared for the current negotiation. Accordingly, we think the business community is at something of a disadvantage in fruitfully engaging with the Biden plan.

The final question is how quickly the transition will occur. Transitioning technologies generally incurs certain costs such as write down of old capital and the costs of redeploying the labor force. But there are also potential gains in terms of productivity. Where productivity gains are compelling, the transition may happen relatively quickly in response to economic forces. Where productivity gains are minor and transition costs high the transition will occur only under government push and at the the pace government sets. Given our overall forecast of fairly slow economic growth, we do not expect the government to raise transition costs by insisting on a fast pace. We expect the basic approach to be one of of keeping current plant for its economic life and then replacing it with new plant based on carbon benign technologies. As discussed earlier, we expect government interventions to be in the form of mandates, excise taxes, specific subsidies, standards setting, tax reform and infrastructure projects rather than a simple grand idea like a carbon tax.