The challenge of getting renewable energy sources into the electric grid

[Updated near the end, on 21 June 2018, after the show of 19 June 2018]

The prime renewable sources for us in New Mexico are solar electric power (photovoltaics) and wind power. Hydropower is clearly out for us. Geothermal energy is a possible source, but in a very real sense it is mined, not replenished in our lifetimes. Nuclear power is not renewable but, in the case of thorium reactors, nearly limitless and free or greenhouse gas emissions for most of its life cycle (GHGs are emitted in mining and in making the power plants, as they are even for solar power plants). Lastly, I execrate biofuels for their enormous use of land and water, with attendant effects that include displacement of food crops and wild fauna and flora. Don't get me started! .... at least, not in this segment of the show.

We're progressing slowly in putting solar and wind power on the electric grid. There are three major reasons for this. Two are economic or political; the third is intrinsic.

Let me forewarn you that I am not an apologist for the fossil-fuel industries nor for the foot-draggers who say we plenty of time to address climate change – we most assuredly do not, and, in fact, we have permanently lost ground already as losses accrue in crop productivity, biodiversity, and various measures of health (heat stress, the spread of insect vectors of disease, to name two).

Rather, **I'm looking to set the scene in full.** Changing to renewable energy resources is (1) an **absolute necessity** to avert greater problems from climate change and pollution and (2) **life-changing for all of us**. That is, our lifestyles will change. Even the availability of open space is affected. Solar energy is very diffuse, taking vast land areas to create the same power as oil wells and coal mines that cover far less area. The era of small-footprint energy technologies is over and we have to live with it. There are economic costs to the changeover, and not just the building of new pieces – solar panels, turbines, transmission lines. Renewables will need battery or other storage that is costly, with costs supported by a well-merited carbon tax. More on this, shortly.

One reason for the difficulty of changeover to renewables : Replacing infrastructure for a major human activity takes time and money. When we humans switched from wood to coal (and whale oil), it took about 60 years...and the same lag when we switched from coal to oil and gas. The technologies have/had instrinsic differences in how the fuels were harvested, transported, converted, and financed. There's a huge amount of detail, well described in the book, *Energies: An Illustrated Guide to the Biosphere and Civilization*, by that polymath, Vaclav Smil. It's a most readable source among many others.

Solution: Non-market motivations to speed up the change. A carbon tax is one part of the solution, which I'll discuss later.

Likelihood: To do this in timely fashion, in the US, with its history (not that uncommon) of motivation only by crises when it's too late to avoid major damage: low. A national energy policy would be needed, and the US has never had one in any form, to the detriment of all and the dismay of some. The likelihood of an energy policy not in the form of business-as-usual is still small.

A second reason: Entrenched interests. This is not to be regarded solely pejoratively. Sure, Exxon Mobil is a heavy, still spreading disinformation about climate change as driven by fossil fuel use (and agriculture, I note). Yet there are real economic burdens to bear, should we collectively switch quickly from fossil fuels to renewables. There are effects on the labor force and on investors (though many shifters of technology, as I may call them, took no heed of such effects – e.g., Silicon Valley's email, social media, and online banking displaced many people and crashed a variety of erstwhile competing businesses). Just as tangible, or more so, are the big mining machines, power plants, sea and land transport systems – these become **stranded investments**, losing much or all of their value in a changeover. Consider a coal-fired power plant with a design (and actual) lifetime of 40 years. Shutting it down after, say, 16 years to replace it with a solar power plant or equivalent dispenses with the 24 years' remaining potential use...and not just the use, but the energy that went into making it. I call this the capital energy. I found a reference that analyzed the energy that went into making a coal-fired power plant. The author found that fully ¼ of the lifetime energy use was in building the plant! Here's the math: we spend energy X in building a plant and run it for only 40% of its full life, processing usefully only 40% of the expected 3X in energy. The return on energy is 1.2X – X = 0.2X, rather appalling. Were the plant to work its full life, the return would be 3X – X =2X, or 10 times greater.

Solution: political will, including buy-back with public funds.

Likelihood: To do this in timely fashion, in the US, with its history (not that uncommon) of motivation only by crises when it's too late to avoid major damage: very low.

Reason 2.5, along similar lines: Giving up a massive set of technologies is giving up a great deal of intellectual investment and a great deal of assured methods of operation. We (again, collectively) know how to run fossil-fueled power plants, in all their complexity, to meet very stringent demands on reliability and safety (well, cavalierly on the part of some interested parties, ignoring some very big health effects from pollution by particulates, mercury, etc. from coal-fired plants; I went into this in earlier shows). The amount of design work is mind-boggling – mechanical engineering of the moving parts, civil engineering of siting the plants, electrical engineering in handling the generation, transmission, and distribution, chemical engineering for understanding combustion and for creating pollution controls, financial schemas to finance the construction of the plants and to enable incredibly complex trades among utilities that keep power on despite big and often fast changes in consumer demand.

Solution: Ongoing; there are vast numbers of engineers, scientists, technicians, planners, and even politicians training for this.

Likelihood: High.

Now to the third major reason: Renewable energy sources have often strikingly different properties from fossil fuels; they are not a turnkey/plug-n-play solution, by any stretch of the imagination, and the challenges become very large when the renewables exceed a modest percentage of total power production. Simple example: a fossil-fueled plant can and commonly does provide power day and night, tightly matching output to consumer demand (including industry) that varies several-fold in a day. Solar panels can't run at night. Wind power is at the mercy of the vicissitudes of local weather. We demand power, not energy, as good friend Clay Doyle of El Paso Electric notes. We won't accept having 200 volts at 1 AM and 50 volts at noon, with us on our own devices to store the energy. Utilities are regulated and must pay hefty penalties if they let voltages or line frequencies droop or rise outside stringent limits. When we want 20% of our power to be renewables, as in New Mexico, utilities can keep fossil-fueled generators running to cover the times that clouds pass over solar panels or the wind dies. There is a significant price to cover the shortfalls of renewables. At El Paso Electric, they use gas turbine engines that can turn on in 10 minutes in such events; the standard generators that recover exhaust heat to run steam turbines can't ramp up or down fast, certainly without damage. EPE has to run generators at 38% thermal efficiency instead of 48% efficiency of standard plants for these events. More fuel gets used to support renewables.

So, one big difference between renewables and fossil fuels is the pattern of availability in time, as just noted. There is also the pattern of availability in space. Solar power in the US is abundant in lightly populated areas, such as the arid lands of the West. Wind power is most abundant in the upper Great Plains, also lightly populated for good reason (think of North Dakota's weather; think also of Wyoming's wind – a weathervane there is an anvil on an anchor chain; when the chain is straight out horizontally, it's breezy; when the anvil is gone, it's windy). The disconnect (literally) between geographic locations of producing renewable energy and of consuming it in cities is a problem. Building transmission lines is neither cheap nor politically easy. Remember the controversy over the Sun Zia transmission line for taking wind power across (and out of) New Mexico.

A bit of electrical engineering: A fair proportion of our home energy use involved electric motors; ditto, in industry. Well, electric motors have an interesting behavior. When they start up, they draw huge electrical currents. Even in constant-speed running, there is an offset in time between the peak current draw and the peak voltage as the cycles of power progress, 60 times a second here in the US. One way to express this is that **electric motors need a good measure of what we call reactive power** – a virtual amount of power rather cross-wise to in-phase power. Solar panels do not have reactive power. If you try living off the grid with solar panels, you can't start motors of any decent size. I just did a test with an upright freezer in our home. The actual power it uses in running steadily is 123 watts; the volt-amperes (average or root-mean square amperes time average voltage) are 234. On start-up, for a half-second or so, it draws 1134 VA! There are some ways to generate reactive power from non-reactive sources such as solar panels, but they involve some major electrical components such as capacitors and inductors.

The big challenge is storing renewable energy so that we can have reliable energy delivery, or power. What does it take to create the technology, and how much does it cost? I'm mainly talking batteries, though there are other storage technologies. The latter include: storing energy as heat in molten salt and using it later to generate steam to drive turbines; pumping water uphill and letting it run back down through water turbines (water? What water? This is New Mexico!); pumping air into a vast cavern and then letting it run out through air turbines (pretty wasteful, given the loss of heat value in what we call diabatic cooling).

Solution to the storage problem: Technological development...but needing economic incentives in the interim before batteries become truly cost-effective (at least in comparison with fossil fuels with some of their unobvious subsidies).

Likelihood: High, for the technological development. Still low for the political and economic will to bridge the time between fairly good battery storage and truly cost-effective batteries, with part of the solution being a carbon tax on fossil-fuel use.

It's being done in California. Will enough of the US follow, in time?

Now for some nitty-gritty details about batteries:

Batteries. How much energy do we need to store? How much does it cost per unit of energy (say, in joules)? What about having to provide that energy very fast, which is typically hard on batteries? Let's start with measures of energy storage in batteries and their cost. The most egregious case of high cost per unit energy, for the sake of convenience in use, is the ordinary alkaline battery or its cousins the nickely-cadmium, nickel metal hydride, or lithium ion battery for hone consumption. Let's look at an alkaline battery with a useful voltage of 1.5V. A AAA battery, nice and small to use in, say, a TV remote, has a storage of 900 milliampere hours; that is, it can discharge a 1 milliampere for 900 h, or faster, at 50 mA for 18 h (but not too much faster, or it dies fast). The energy stored is closely the average voltage multiplied by the current storage, or about 1.3 watt-hours. This battery might cost, at wholesale, \$0.20 to \$0.50 (useless crud to good). We'll calculate the price per kilowatt hour (1.3 Wh is 1.3 thousandths of a kWh), which is the unit used for line power into your home. It comes out to at least \$0.20/0.0013 kWh, or \$154 per kWh. For power from EPE, you pay about \$0.11 per kWh, or less than one-thousandth as much. So, consumer batteries are not the answer, nor would we ever expect them to be. What about industrial lithium-ion batteries, used in Priuses, Teslas, and at least one Google data center.. They cost about\$140 per kWh...but they can charge and recharge over perhaps 500 cycles. That makes the average cost of power delivered about \$0.28 per kWh. Still high, compared to line power.

Many labs are working hard to bring down the cost of battery storage. One national laboratory with a major focus on this is Argonne National Lab. It's where my friend, Al Wagner, who was on the show in February, works. In 2015, the chief of the division working on batteries., George Crabtree said batteries are still 5 to 10 times too expensive for electric utilities to use economically. Note that there are a number of competing battery technologies, using variously lithium, air, graphite, aluminum, sulfur, zinc, vanadium... and solid, liquid, and flowing liquid electrolytes. I won't go into detail here; the reading is fascinating.

Let's look at the tradeoffs. I'll use a real simplification, not delving into the 5 pages of notes I made on the nuts-and-bolts that factor in amortization rates, finance, spot markets, transmission line costs, the need for two tiers of batteries (high power for making up sudden outages, high energy efficiency for base load), and more.

First simple method of accounting, based on energy, not power. Consider an electric utility having to run 100% renewables. Assume that the cost of renewable energy comes down to a fraction, *f*, of fossil energy (skip for now the consideration of power delivery vs. total energy). Some projections even have *f*= 0.3, or 30% of fossil energy. There is the proper question of, Are all costs being properly folded in? There's the capital costs of building the facility, the cost of fuel (if any), and the cost of maintenance and replacement (a big deal for batteries, which do NOT last 250,000 hours of operation or 30+ years as does a steam turbine). There's also the amortization and financing plan, properly weighting current and future costs. Let me assume that all the costs have been factored in. One particular concern for renewable power is the capacity factor. A solar power plant has, at best, an annual average power output that is only 25% of its peak power ("nameplate" rating), because night and winter both intervene. The cost of putting up enough solar panels to meet a designed effort in winter is about twice as high as that for meeting the summer demand...not relying on winter wind power as a compensation.

Let's define:

- The costs per unit energy generated, for fossil-fuel plants, C_{ff}, and for a renewable-supplied plant, C_{re}.
    - Let's scale all to the fossil-fuel case and set C_{re} as a fraction, *r*, of C_{ff}. As above, an optimistic estimate is $r = 0.3$.
- The fraction, *f*, of total power generated by the plant using renewables that has to be stored, on average – e.g., for nighttime use from a solar-powered plant. Of course, no utility is likely to go purely solar, with its very high demand for storage. Wind power at a location often peaks later in the day and into the early night, helping to level the load. I would estimate $f = 0.5$ or more, for a plant using only renewables.
- The net efficiency, η, (eta, I like eta) of storing energy in a battery and then getting it out. There are inefficiencies in driving a chemical reaction in a battery or any other device (e.g., overvoltage). Efficiencies are as low as 55% or 0.55 for electrolyzing water into hydrogen and

oxygen. There are inefficiencies in running the reverse chemical reaction. A very optimistic estimate for utility-scale high-power battery storage may be 50%, or 0.5. We can look at how sensitive to η is the final cost comparison – as also how sensitive it is to f or r.

- The relative cost, s, for batteries compared to real-time generators, per unit of power stored. Here's a quick-and-dirty estimate. Lithium-ion batteries at industrial scale cost about \$140 per kWh stored. They can cycle n times before wearing out; today's batteries have n about 500, but let's be optimistic and set n = 1,000. That makes the cost \$140/1000 per kWh, or \$0.14/kWh – that's comparable to old coal-fired power at the retail level, or as much as 3x wholesale cost for modern plants using natural gas. So, set s = 3.

The cost of supplying a unit of energy, such as a joule or a kWh, is:

For a fossil-fueled plant, our reference case: C_{ff}

For a plant using renewables:

Cost = cost of generation + cost of storing and re-releasing energy

The amount of energy generated = energy never stored + energy needing to be stored and this must equal the amount that a fossil-fuel plant provides, not needing storage

The energy needing to be stored is larger than the amount delivered, by a factor 1/ η

Thus, the cost of total energy generation is

$$(1-f)C_{re}+\frac{f}{\eta}C_{re}$$

Now add the cost of storing a fraction f of the total energy finally deliver, which is the relative battery cost, s multiplied by f/η:

$$s\frac{f}{\eta}C_{re}$$

We then have a total cost

$$\begin{aligned}&(1-f)C_{re}+\frac{f}{\eta}(1+s)C_{re}\\&\to C_{re}\left(1-f+\frac{sf}{\eta}\right)\\&\to C_{ff}r\left(1-f+\frac{sf}{\eta}\right)\end{aligned}$$

The whole factor after C_{cc} is the final relative cost, including battery storage. For the parameter values I estimated, this is

$$\begin{aligned}&0.3\left(1-0.5+\frac{3*0.5}{0.5}\right)\\&=0.3*3.5\\&=1.05\end{aligned}$$

That's looking good for renewables, if all these parameter values are realistic. They are not yet so, for current batteries and, say, current solar panels.

Second, a "simple" method based on power, not energy, from estimates of technology costs provided by the US Energy information Agency in 2018: I examine their publication "Cost and performance characteristics of new generating technologies, annual energy outlook 2018." There's an interesting note, that coal-fired plants with carbon-capture technology, are priced out the market, costing 50% to 600% more than any other likely technology (admitting that some of the others have no carbon capture). In other publications by other groups, non-governmental, it's noted that coal-fired plants are being priced out of the market anyway; there is strong competition for construction materials and for engineering design services that are greatly inflating the cost of new coal-fired power plants. MAGA won't help them.

The EIA publication has entries for:

- Base overnight cost, which is construction. Call it C_c, "c" for "construction."
- An inflator for technological optimism, ranging from 1.00 to 1.25. Anyone who has seen cost overruns on big projects would laugh at this low range, when 2 to 10 is more common – witness the ITER project for nuclear fusion, the James Webb space telescope, the ill-fated US superconducting supercollider; the only project of note that I can recall coming in at or below budget was the Eiffel Tower. I'll ignore this factor for now.
- Variable operating and maintenance (O & M) cost, which is fuel, replacing battery storage, anything that a given technology needs – as a running cost, *proportional to t*he amount of energy generated. Call it C_{vr}, for "running" costs.
- Fixed O & M cost, as a cost per year per unit capacity, independent of the energy generation – the cost of having the plant exist, including, I imagine, finance costs. Call it C_f, for "fixed" costs.
- Battery storage cost, per unit of *power* capacity, not energy. It's the cost of having backup, per unit power. I assume this includes the cost of replacing batteries perhaps 6 to 10 times over the 40-year life of a plant! It has three parts. The first is construction; call it C_{bc}. The second is the variable cost (presumably the cost or servicing and replacing batteries); call it C_{bv}. The third is the fixed cost for having batteries hanging around; call it C_{bf}.

Compare a modern technology, the conventional combustion turbine or CCT, with a solar photovoltaic plant with fixed tilt (not tracking the sun), or SPV.

Take a standard plant size, with 1000 MW output.
Take a plant lifetime as 40 y.
Take a battery storage *power* capacity as 600 MW, or 60% of final capacity.

For the CCT, the total cost over 40 y is

$$C_c + 1000MW*40y*C_{vr} + 1000MW*40y*C_f$$

With C_c = \$1.054 B (billion), C_{vr} = \$3.54 per MWh or \$27,900 per MW-year at 90% run time (duty factor), and C_f = \$17,670 per MW-year, we have a total cost over 40 years of

$$\begin{aligned} &\$1.054x10^9 + 2.79x10^4 * 1000 * 40 + 1.767 * 10^4 * 1000 * 40 \\ &= \$1.054B + 1.116B + 0.707B \\ &= \$2.877B,\ \text{B = billion} \end{aligned}$$

Now do the solar power plant with battery storage. The EIA has C_c =\$1.763 B, C_{vr} = 0, C_f = \$22,020 per MW-year, C_{bc} = \$2.067 B for a 1000 MW capacity (move this down to \$1.240 B for a 600 MW capacity), C_{bv} = \$7.12 per MW-h or \$56,134 per MW-year, and C_{bf} = \$35,600 per MW-year. We get the total cost over 40 years as

$$\begin{aligned} &\$1.240B + 5.6134x104 * 600 * 40 + 3.56x104 * 600 * 40 \\ &= \$1.240\text{B}+1.347\text{B}+0.854\text{B} \\ &=\$3.441\text{B} \end{aligned}$$

This is higher than the modern CCT plant by about 20%.

I didn't do the same calculations for wind power, for which the costs differ radically for onshore and offshore locations. You can find the same EIA publication and do this calculation.

Net: renewable power appears to be in the ballpark of conventional fossil-fuel power for its total cost, with a higher up-front cost (a possible deterrent for utilities having make a "rate case," specifying a high capital investment). Realistic costs are higher for renewables, so that a "pure" market basis makes them uncompetitive. However, climate change costs – net damages – have to be contained. One route is by legislative mandates to utilities, as has been done. Utilities are allowed to cover the costs. To bring every industry and other activity into the game, a fair way is to enact a carbon tax.

Let's estimate what level of tax would be needed, as dollars per ton of carbon. As an order of magnitude, let's say that a power plant using renewables costs $1B more over 40 years than a fossil-fueled one. What would be the climate tax, as we may call it? I'll take a natural-gas-fired plant. The heat value or enthalpy of methane reacting with oxygen in the air is about 40 kilojoules per gram. The heat input rate to provide 900 MW of power (1000 MW plant at 90% duty cycle) is 2.5 times 900 MW, given an efficiency of about 40% for converting heat to electric power. (The plant may have more efficient generators, such as the 48% for combined cycle generators at El Paso Electric, or less-efficient peaking generators operating at 38%.) That's 2250 MW as heat, or 2.25×10^9 joules per second. The consumption of methane is then 2.25×10^9 J s^{-1}/4×10^4 J g^{-1}, which is 5.6×10^4 g per second (I'm keeping only 2 or 2-1/2 significant figures). Run that over 1 year, 3.1×10^7 seconds and you get 1.74×10^{12}g, or 1.7 million metric tonnes. Of that, ¾ is carbon, or 1.30 million metric tonnes. A carbon tax at $770 per ton C would cover that. It can also be phrased as $210 per tonne of CO_2.

Added 21 June 18: Steve Fischmann, consumer activist and candidate for the New Mexico Public Regulation Commission, sent me two links about projected costs of wind and solar power for utilities. On the site *Utility Dive*, this was reported for bids for new generating facilities for the Colorado public utility, Xcel Energy: "In January, the utility revealed the results of a resource solicitation, returning a median price bid for wind-plus-storage projects of $21/MWh and a median bid for solar-plus storage of $36/MWh." These rates, if they reflect actual delivered energy costs, are about 1/3 those of fossil-fueled plants. They are much lower than the optimistic estimates of the US Energy Information Agency. They also are not (yet?) reflected in Xcel's own information at https://www.xcelenergy.com/low-cost-clean-energy, where customers can opt to pay more for wind energy.

Also added 21 June 18: A complementary strategy to reduce greenhouse gases in the atmosphere is to suck CO_2 out of the air with dedicated facilities. This has always been projected as rather expensive ($600 per tonne of CO_2: see go.nature.com/2xuauq7), almost a desperation measure (which it may well turn out to be!). Comes a new report in the 14 June 18 issue of the international journal, *Nature*, on p. 173. Carbon Engineering in Calgary, Alberta, Canada reports fine performance of their pilot plant using potassium hydroxide to react with CO_2 in air, regenerating the KOH after several steps and creating a stream of pressurized CO_2. That CO_2 could be injected into basalt rocks for effectively permanent sequestration or, in Carbon Engineering's plan, using it to synthesize liquid fuels (I ask, With what energy source for the chemical reduction?). They estimate a cost of $94 per tonne of CO_2! If I may exercise my experience with cost overruns in past large projects, we might inflate this estimate by a factor of 2 to 3, which still puts it in the ballpark of the carbon tax I noted above.

That's my assessment of the current status of progress toward renewable electric power. There are other areas to delve into. Vehicular transportation uses mostly liquid fuels. Electric vehicles are coming online for individuals; heavy trucks are another matter. Remember corporate raider T. Boone Pickens projection that cars and light trucks might use electricity but heavy trucks would use natural gas, so, not a completely carbon-free transportation system.

We can also delve into heating for homes, commercial buildings, and industrial processes. Standard fuel-burning furnaces can hit 90% efficiency but are carbon-intensive. Electricity is quite inefficient in delivering heat, with about 60% lost at the power plant for ordinary resistive heating. Heat pumps are much better; they can transfer 3 to 5 units of heat per unit of electrical work input, so they would have on efficiency of 0.40 * (3 to 5), or 120% to 200%. They certainly cost more up-front than resistive heating systems, which deters people. They also are less efficient if heat is extracted from air rather than moist soil (don't buy into ground-sourced heat pumps in Las Cruces!).

We don't have to have all our current carbon-based activities shifted to zero-carbon sources. There are carbon-capture activities – growing and burying trees, adsorbing CO_2 from the air and injecting it into basalt rock formations, etc. These are clearly disruptive of land/water/fertilizer use, or just expensive, or bearing other collateral costs. We can use all our "climate wedges," as Robert Socolow and Stephen Pacala called them; there's no silver bullet that does it all, certainly not just the changeover of electric utilities.

In summary, there are a number of challenges in going to a more climate-safe energy economy. It will take technological progress, but, more so, political will and economic rearrangements. There will be collateral effects, such as greater land use than for fossil fuel power. I hope that my layout of the issues is useful in the discussion. Thanks for reading (or hearing, if you're listening to my show on KTAL LP FM, 101.5 in Las Cruces, NM).