Blue Books

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Global

Power

13 September 2016

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Gradual greening

Power density and the hydrocarbon habit

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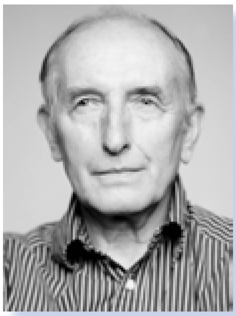


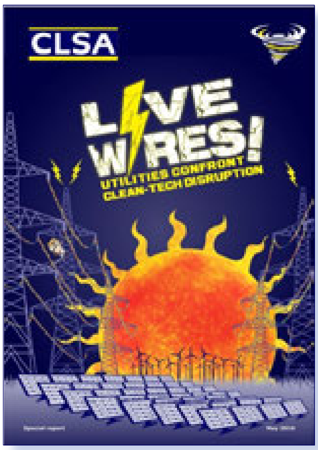
Vaclav Smil

Vaclav Smil does interdisciplinary research in the fields of energy, environmental and population change, food production and nutrition, technical innovation, risk assessment and public policy. He has published or has in press 40 books and nearly 500 papers on these topics. He is a Distinguished Professor Emeritus at the University of Manitoba and a Fellow of the Royal Society of Canada (Science Academy).

In 2010, he was named by *Foreign Policy* as one of the top 100 global thinkers. In 2013 he was appointed as a Member of the Order of Canada and in 2015 he received the OPEC Award for Research. He has worked as a consultant for many US, EU and international institutions, has been an invited speaker in more than 400 conferences and workshops in the USA, Canada, Europe, Asia and Africa, and has lectured at many universities in North America, Europe and East Asia.

Foreword

Bill Gates has said "There is no author whose books I look forward to more than Vaclav Smil". He recommends his work to anyone interested in energy issues - not to cheer them up but to help them have a stronger framework for evaluating energy promises. This is sorely needed today given many ultra-bullish predictions being made about a rapid transition to a carbon-free world.



We countered some such claims - like Elon Musk and Tony Seba's that electricity customers can go off-grid using solar panels and batteries - in *Live wires!* That report approached the issue through bottom-up analysis - for instance how many batteries and solar panels would be required for an average household to go off-grid and how much it would cost.

In this CLSA U Blue Book, Professor Smil approaches the issue from a top-down perspective. He takes us through a history of failed forecasts - by GE, Al Gore and Google among others - about rapid transitions to non-carbon energy. Despite such claims and vigorous growth in modern renewables, their share in the global energy mix has increased from 0.4% in 1990 to just 3.3% in 2015.

So what makes energy transition an inherently protracted affair? As evident from examples of gas turbines, nuclear fission and LNG tankers, the timespan from the first trials of new energy technologies to their widespread commercial acceptance is measured in decades and the quest for a higher market share has been increasingly daunting due to the growing scale of overall demand. Moreover, we presently don't have any viable alternatives (products or manufacturing processes) for some of the basic building blocks of modern civilisation - steel, ammonia, cement, plastics - whose production is heavily dependent on fossil fuels.

Another factor is power density. Downtowns of big cities and industrial enterprises use energy at the rate of hundreds to thousands of Watts per square metre. Very low power density of renewable-energy conversions and intermittency of wind and solar power would require massive changes in the way we collect and distribute our energy.

So how can we improve the odds of success to limit global temperature rise to under 2°C? Some big technical breakthroughs - like in energy storage - will help but that would require a massive increase in our commitment to energy R&D. The benefits of reduced energy consumption in affluent societies - through having smaller houses and cars and lower meat consumption - would be greater than replacing a large part of today's mix of energy sources by the same quantity of non-carbon energies. The scale and the complexity of these challenges make any rapid mass-scale shifts impossible.

Rajesh Panjwani
Head of Power Research

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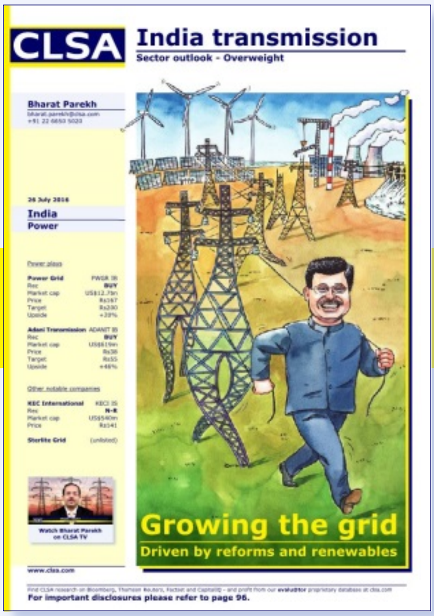
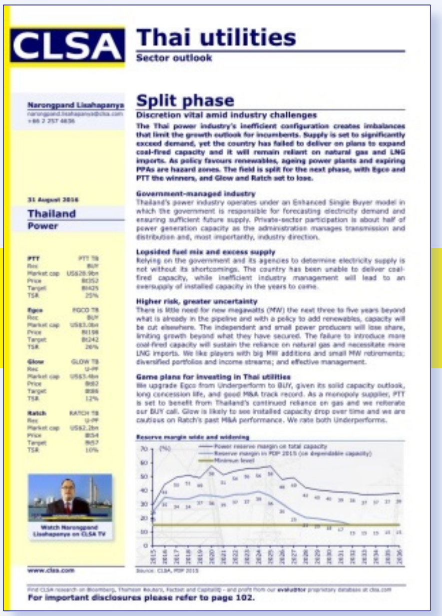
Power-intensive research





Gradual greening

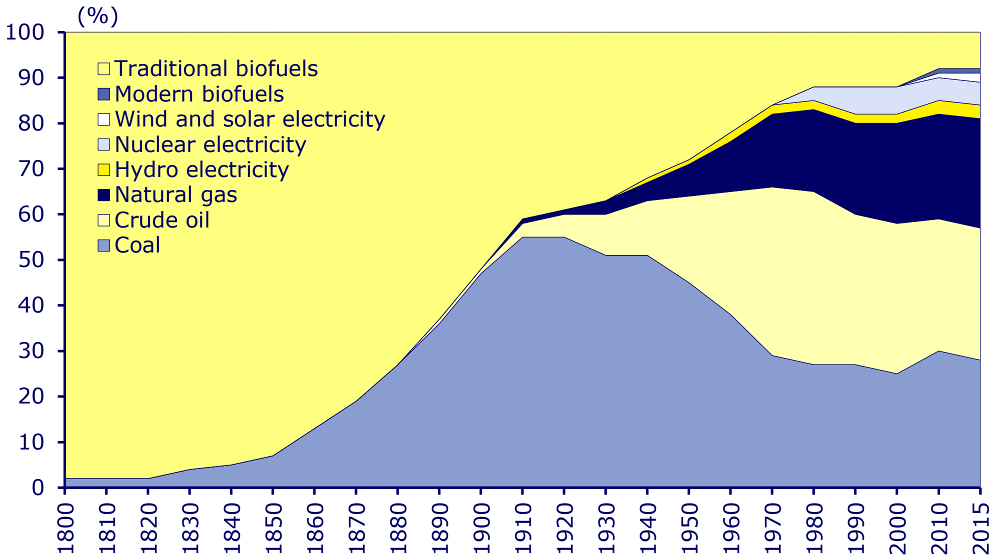
Claims of a rapid transition to a zero-carbon society are plain nonsense

Claims of a rapid transition to a zero-carbon society are plain nonsense. Given the extent and pervasiveness of our dependence on coal and other hydrocarbons, even a greatly accelerated shift towards renewables would not be able to relegate fossil fuels to minority contributors to the global energy supply anytime soon, certainly not by 2050. Many of today's essential items cannot be made without fossil fuels and low power density of renewables would require reshaping the entire energy infrastructure. Lower energy consumption by affluent societies and big technical breakthroughs will help but that requires massive increase in energy R&D and lots of patience as energy innovations take decades to become mass-scale commercial realities.

Fossil fuels account for 86% of global primary energy consumption

Modern civilisation has been created primarily by the combustion of fossil fuels marked by the sequential rise of coal, crude oil and natural gas. Despite vigorous growth in solar and wind power, the share of fossil fuels in primary energy had declined to 86% in 2015 from 87% in 2000. Many people are now talking about a zero-carbon society 15-20 years from now. Unrealistic forecasts of energy supply soon-to-be-dominated by renewable energies are nothing new and a brief review of some well-publicised past claims - by the Carter Administration, Al Gore, Google, T Boon Pickens etc - shows that they have consistently exaggerated the pace of unfolding energy transitions.

Evolution of global primary energy supply



Source: Smil, V. 2017. Energy Transitions: Global and National Perspectives. Santa Barbara. CA: Praeger

Making of steel, cement, plastics, ammonia needs fossil fuels

Scenarios charting a rapid shift from fossil fuels to renewables ignore the indispensable uses of coal and hydrocarbons as critical raw materials or energisers (or both) of several major industrial processes that produce materials - for instance steel, cement, plastics, ammonia - whose mass-scale consumption defines modern economies and that cannot be made on such large scales without fossil carbon by any readily available commercial alternatives. During the next five decades, three-quarters of the global population increase will take place in Africa and India where per-capita consumption of these materials is a fraction of the developed world and will continue to grow for decades. Even manufacturing of wind turbines, solar panels and power transmission lines is not possible without fossil fuels.

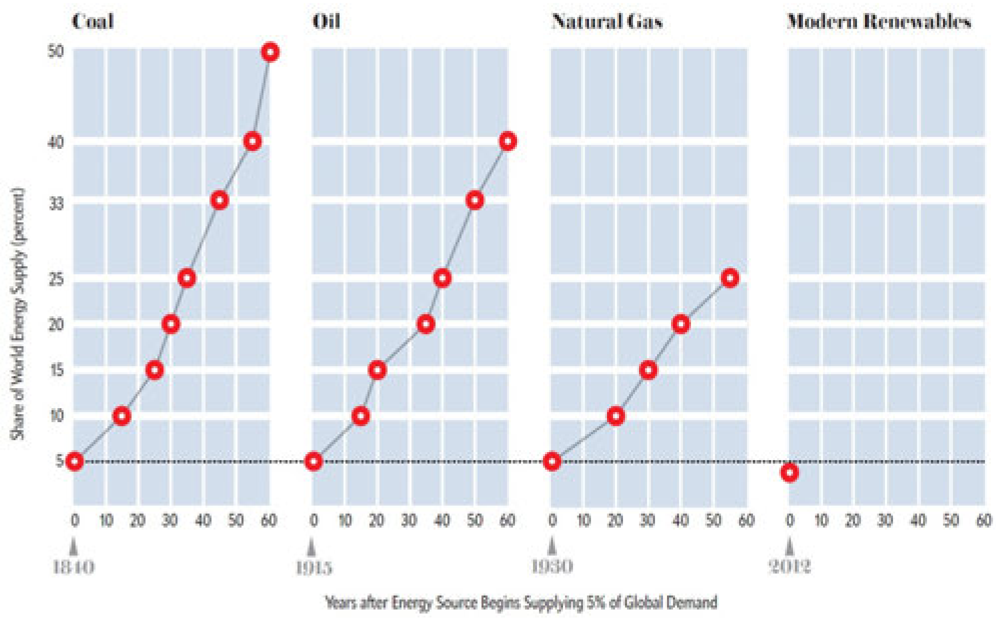
Power density of renewables is orders of magnitude lower than fossil fuels

Extraction of fossil fuels and thermal power generation proceed mostly with power densities of hundreds to thousands of Watts/m^2. Compared to that, wind, solar and bio-fuels produce energy at 0.1-20W/m^2 - a tiny fraction of the power density of energy use in urban areas, industry and high-rise buildings of 10-9,000W/m^2. Mass adoption of renewables would require reshaping the energy infrastructures from a system dominated by global diffusion of concentrated energies to a system that would harness renewable flows over extensive areas and concentrate them in the increasingly more populous consumption centres. Either large reserve capacities or unprecedented long-distance interconnections and vast electricity storage would be needed.

Energy innovations take many decades to become commercial realities

A snapshot of kittens can go globally "viral" in a matter of hours - but decades must elapse before fundamental energy innovations are transformed from ideas or prototypes to mass-scale commercial realities. The first use of gas turbines and demonstration of nuclear fission was in 1939 but four decades elapsed before these could capture 10% of US/world electricity consumption. LNG trade moved 10% of all exported natural gas only a century after the LNG tanker was patented. Once it had hit 5% share of the energy mix, global coal extraction required 35 years to reach the 25% mark, crude oil production needed 40 years to get to that level and natural gas extraction took 55 years.

Global share in primary energy of various fuels over time



Source: Vaclav Smil, Scientific American

The complexity of this challenge makes any rapid mass-scale shifts impossible

We should accept the fact that there is no single, simple, rapid way to transform our current global energy system and that it will require a combination of using less (in all affluent countries, as a result of more rational pricing, better design and dietary changes), using more but much more efficiently (in all modernising low-energy economies), and deploying new technical solutions on unprecedented scales (to be helped by much increased R&D spending across the entire spectrum of energy harnessing and conversion). Such efforts are inherently incremental and their progress is gradual: civilisation without fossil carbon may be highly desirable but the accomplishment will require a multigenerational commitment.

Fossil-fuelled civilisation

Fossil fuels will dominate world's energy use for decades to come

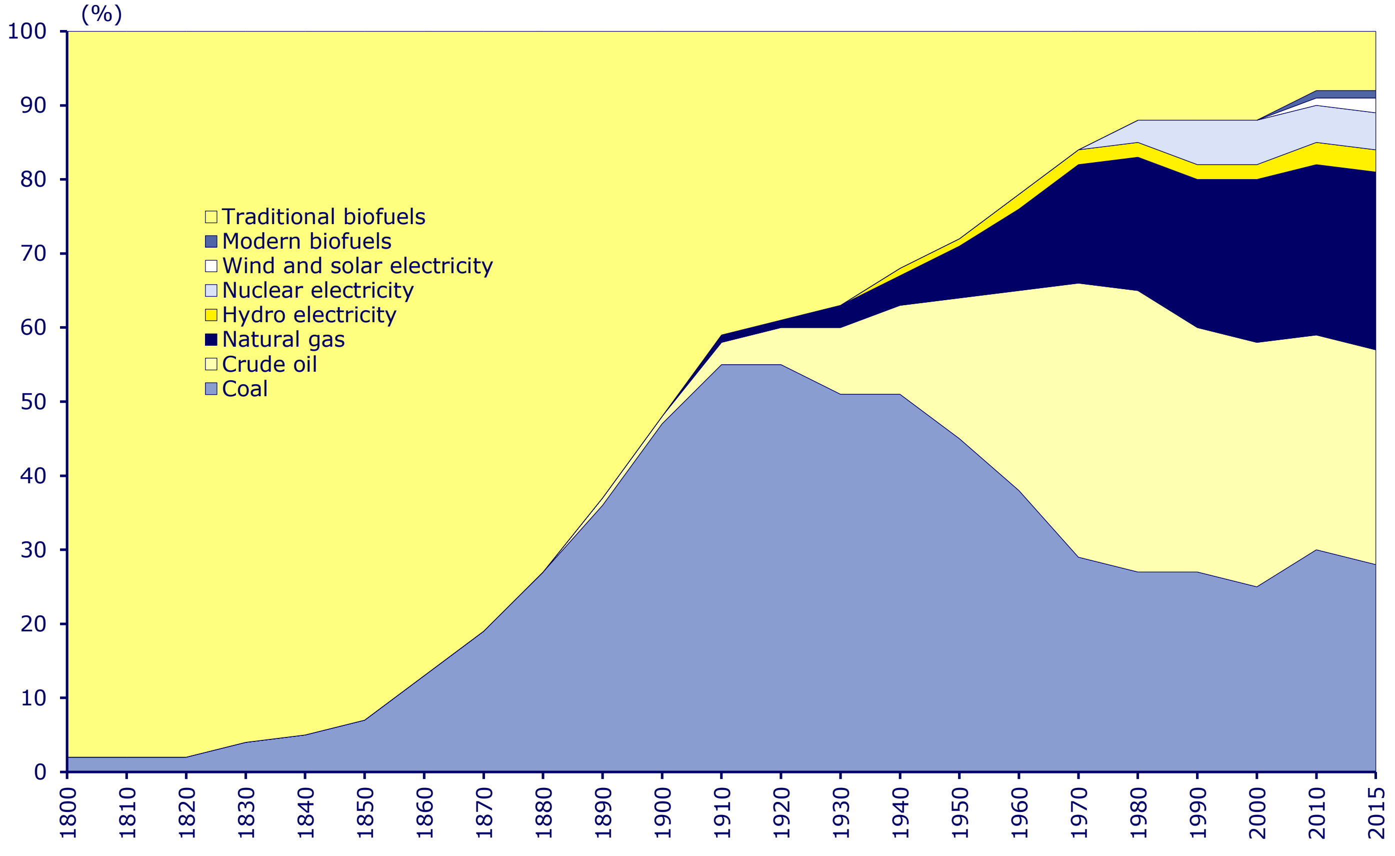
Modern civilisation has been created primarily by the combustion of fossil fuels marked by the sequential rise of coal, crude oil and natural gas. In 2015 these fuels - converted to heat, kinetic energy and electricity - supplied 86% of the world's primary energy consumption and their combustion will continue to dominate worldwide energy use for decades to come.

Share of fossil fuels in primary energy down from 87% in 2000 . . .

At the beginning of the 20th Century, global consumption of fossil fuels, dominated by coal, surpassed the energy contributed by traditional biofuels (fuelwood, charcoal and crop residues). By the century's end, fossil-fuel extraction expanded more than 15-fold, it reached an equivalent of about 8 billion tonnes of crude oil, and it contributed 80% of all energy (including traditional biofuels used in Asia, Africa and Latin America) and 87% of all primary commercial energy.

Figure 1

Evolution of global primary energy supply



Source: Smil, V. 2017. Energy Transitions: Global and National Perspectives. Santa Barbara. CA: Praeger

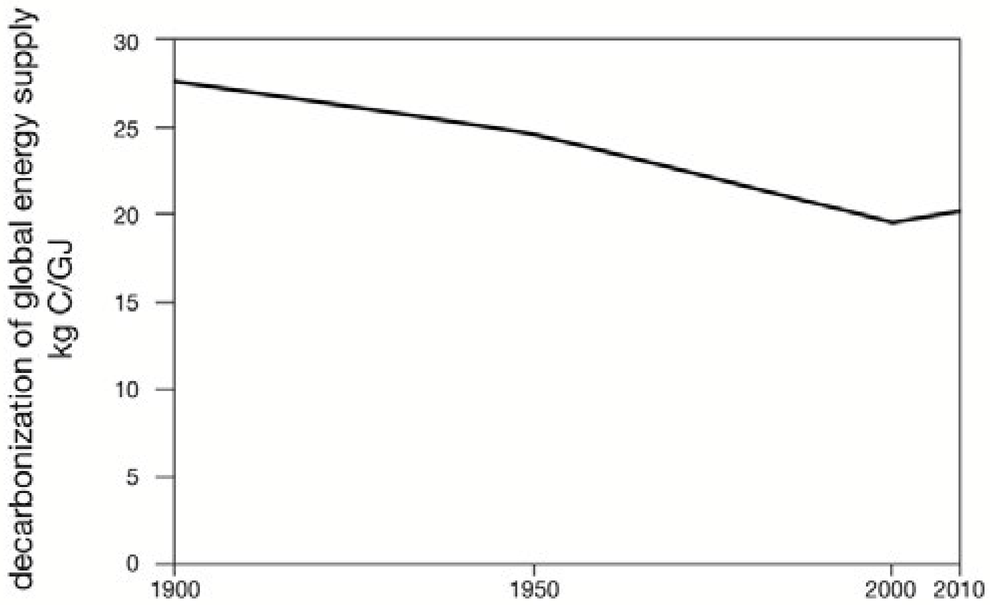
. . . to 86% in 2015. No rapid retreat from renewables

By 2015, the latter share declined only marginally to 86%: there has been no rapid retreat from a fossil fuel-based economy during the first 15 years of the 21st Century and the combination of steadily growing global demand for crude oil and natural gas and of China's (and India's) huge expansion of coal-mining resulted in unprecedented absolute increase of fossil-fuel extraction by about 3.1 billion tonnes (from 8.2 billion in 2000 to 11.3 billion in 2015). As a result, gradual decarbonisation of the primary global energy supply has been temporarily reversed.

Energy transitions lowered the average carbon content of the world's primary energy supply by about 30% during the 20th Century

Figure 2

Decarbonisation of global energy supply



Source: Smil, V. 2017. Energy Transitions: Global and National Perspectives. Santa Barbara. CA: Praeger.

We are now, more than ever before, a primarily fossil-fuelled civilisation

We are now even more what we have been ever since the beginning of the 20th Century when the energy content of coal and hydrocarbons surpassed that of traditional biofuels: a fossil-fuelled civilisation whose accomplishments and benefits, and whose high quality of life have been overwhelmingly energised by burning carbon that was first photo-synthetically captured and deposited between millions and hundreds of millions of years ago.

Global warming concerns should bring the end of fossil fuels long before exhaustion of reserves

Obviously, this extraction of finite fuel deposits cannot continue indefinitely, and concerns about global warming should bring its end long before any actual exhaustion of known reserves - but given the extent and the pervasiveness of our dependence on fossil fuels even a greatly accelerated shift toward renewable energies would not be able to relegate coal and hydrocarbons to minority contributors to the global primary energy supply anytime soon, certainly not by 2050.

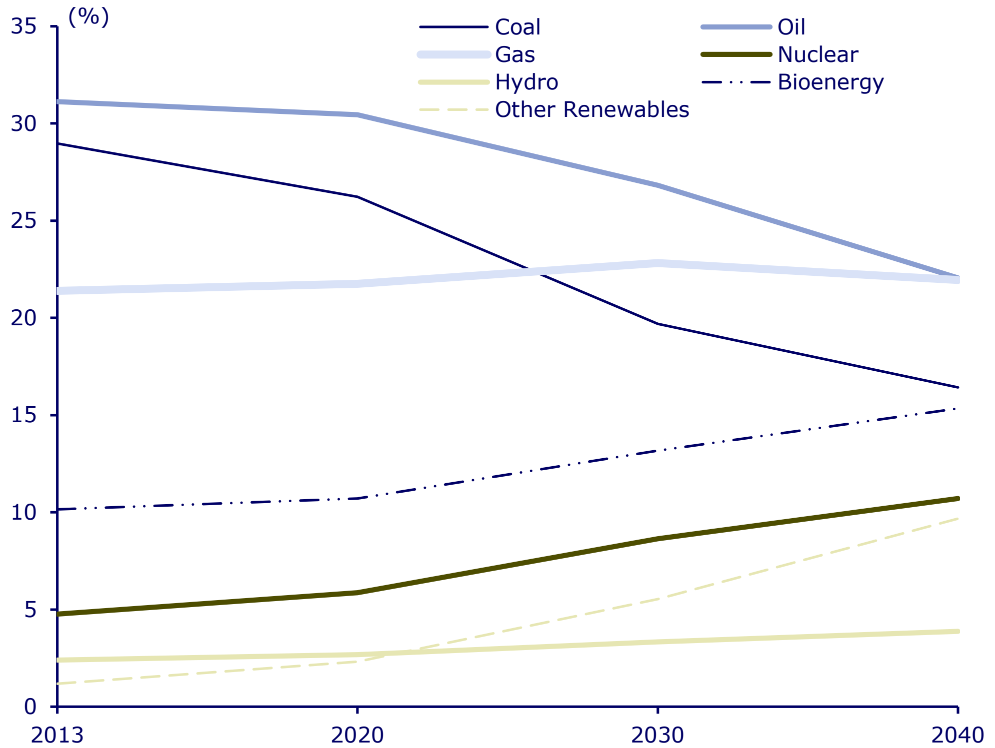
However coal and hydrocarbons are unlikely to be minority contributors to primary energy supply anytime soon

Long-range forecasts are notoriously unreliable but even the most optimistic scenarios published by the International Energy Agency - consistent with keeping the increase of CO_2 concentration to no more than 450ppm (it had surpassed 400ppm in 2015) and the average tropospheric temperature increase to no more than 2^0C (so far up by 0.8^0C since 1880) - puts the share of fossil fuels in the global energy consumption at 60% in 2040, with all renewables (including hydro and both traditional and modern biomass fuels) supplying 29% and new renewables (wind, solar and modern biofuels) accounting for 15%. Other IEA scenarios and long-range forecasts prepared by the US Department of Energy, Opec and ExxonMobil put the shares of fossil fuels at between 75-79% in 2040.

IEA's 450ppm scenario depicts pathway to limiting global warming to 2°C

Figure 3

Share of various energy sources in global energy mix - IEA forecast 450ppm scenario



Source: World Energy Outlook 2015

Failed forecasts of transitions to renewable energy

Men believe what they want to believe.

Publius Terentius Afer, a playwright in the Roman Republic

People talking about zero-carbon society 15-20 years from now

Apparently ignorant of the dominant role of fossil fuels, many people are now talking about a zero-carbon society 15-20 years from now - but unrealistic forecasts of energy supply soon-to-be-dominated by renewable energies are nothing new and a brief review of some well-publicised past claims shows that they have consistently exaggerated the pace of unfolding energy transitions.

End of fossil fuels by 2050 is plain nonsense

On 11 December 2015, a day before the Paris climate summit ended, a group of children dressed in white T-shirts printed with 'I♥100% Clean' stood outside the meeting hall holding large cut-out letters proclaiming "ADIEU FOSSIL FUELS". "If we can move to 100% clean energy by 2050, it means this generation standing behind me really will see the end of fossil fuels," said the group's smiling organiser. After the meeting's end, I stopped counting the headlines that repeated the claim that "This marks the end of the era of fossil fuels." That is plain nonsense, and even saying that the Paris agreement is the "beginning of the end" must be qualified by noting that it will be a very protracted *adieu*. This is not the first time we have been assured that fossil fuels will be soon gone or relegated to a marginal role.

Children outside the meeting hall at Paris climate summit in December 2015

Figure 4

ADIEU FOSSIL FUELS!

Source: Avaaz; Facebook.com

One of the many forecasts about farewell to fossil fuels in the near term

Figure 5

The headline of an article in *Conservation Magazine* in April 2016

WE CAN BID ADIEU TO FOSSIL FUELS WITHIN A DECADE

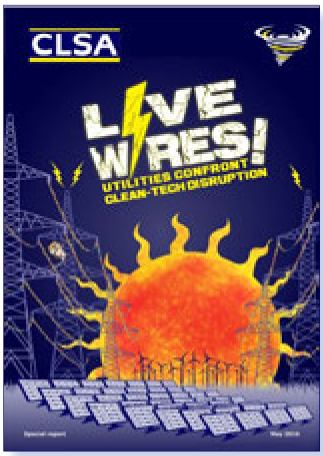
April 21, 2016 | Conservation This Week | 0 Comments

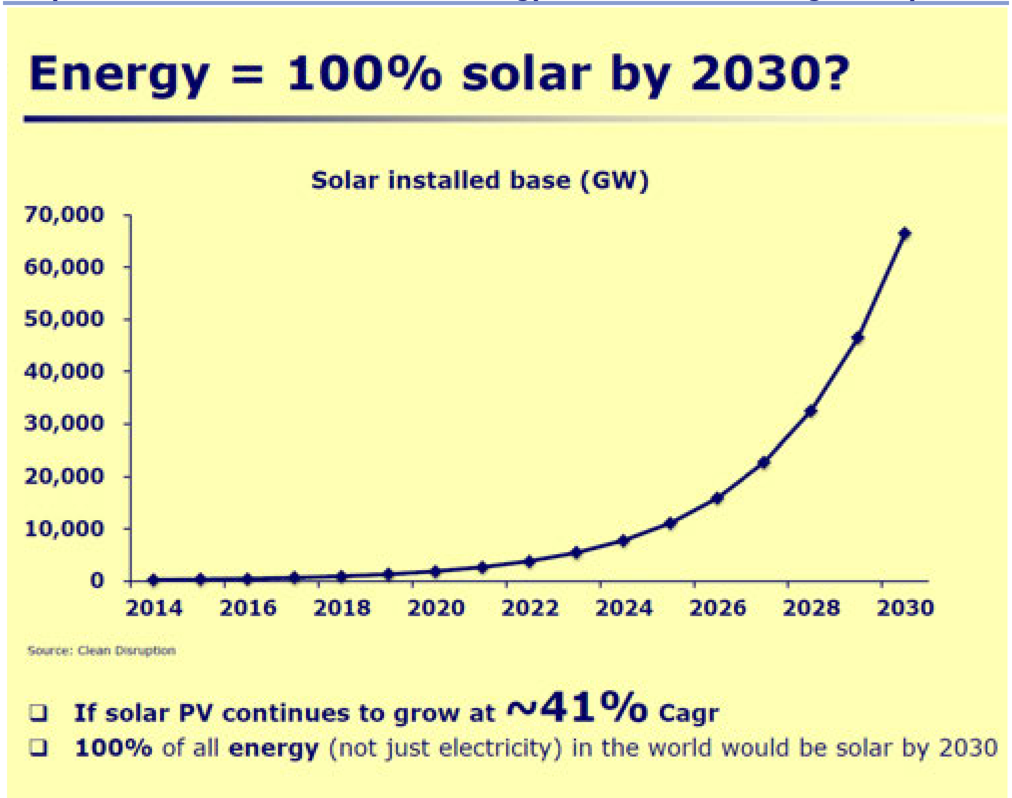
Source: conservationmagazine.org

Figure 6

Tony Seba claims that 100% of world's energy needs can be met using solar by 2030

We countered Tony Seba's claim of 100% energy from solar by 2030 in *Live Wires*





Source: Tony Seba

Oil shock triggered forecasts of green futures in 1970s

Some forecasts in the 1970s put share of renewable energy in the US at 20-49% by the early 2000s

Forecasts of green futures began in the late-1970s in the aftermath of Opec's first round (1973-74) of oil-price rises and the US and Sweden's experiences demonstrate how consistently wrong they have been. In 1976, American energy expert Amory Lovins put the share of US energy originating from decentralised renewables at 33% in the year 2000. Other forecasts for the year 2000 were in 1977 by InterTechnology Corporation (solar energy providing 36% of America's industrial process heat) and in 1978 by the Carter administration (solar accounting for 20% of all US energy), and in 1980 Danish energy expert Bent Sørensen put the share of America's renewable energy at 49% in 2005. But even by 2015 the actual share of all renewables was just 10%, with half of that coming from biomass and less than 2.5% from wind and solar.

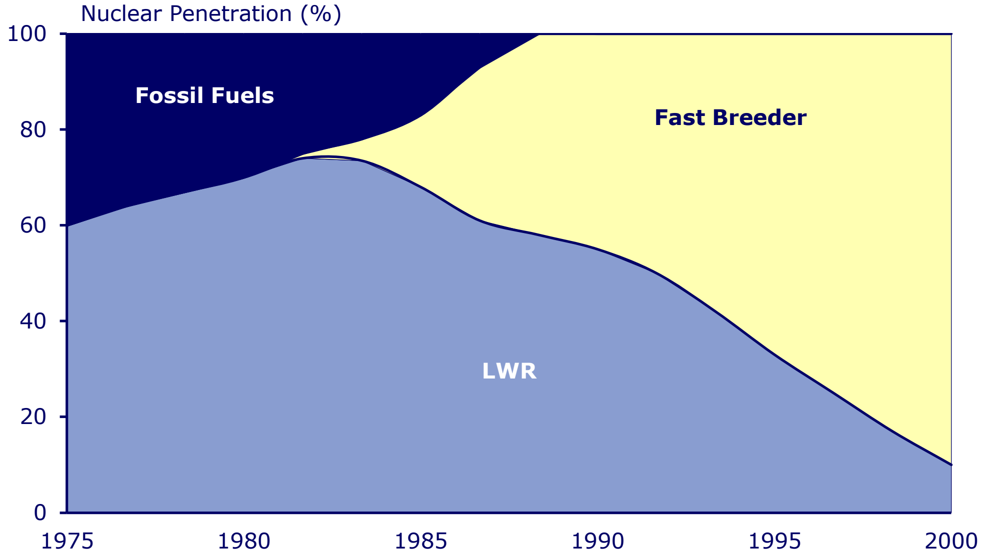
In 1971 a GE study expected all of US electricity to come from nuclear power by 1990

In 1971, before these aggressive forecasts about renewable energy were being made, General Electric published its study about the future of nuclear power. That was the time of rapidly rising nuclear power plant orders and hence GE envisaged that by 1975 fossil plants would be already down to 40% of the US electricity generation as light water reactors take aggressively over, and then fast breeders would be commercially introduced in 1982 and account for some 90% of the total power capacity by the year 2000. That turned out to be one of the classic miscalculations by the world's leading energy engineering company: in 2015 the US did not have a single commercial breeder reactor and the share contributed by nuclear generation was declining.

GE expected all of the US electricity to come from nuclear energy by 1990

Figure 7

GE's forecasts of nuclear-power penetration



Source: *Murphy, P.M. 1971. Incentives for the development of the fast breeder reactor. Stamford, CT: General Electric.*, Vaclav Smil

In 2008 T. Boon Pickens planned to replace gas turbines with wind turbines

More recent goals and transformative plans have not done any better. In 2008 T. Boone Pickens, a Texas oilman and a former corporate raider, revealed his 10-year energy plan for America: Great Plains filled with wind turbines would displace natural gas-based generation and the freed fuel would be used to power natural-gas vehicles while the substitution would create new massive domestic industries, revive the Great Plains, cut US oil imports by more than one-third and lower trade deficit.

The plan was soon dropped given unrealistic investments needed

The plan would have required more than 100,000 wind turbines, at least 65,000km of new transmission lines, and conversions of tens of millions of cars to natural-gas fuel, at a cost of at least US$1.2tn in private investment. But within months of revealing the plan Pickens admitted that the lack of transmission links makes the 10-year deadline impossible, then he switched his natural-gas proposal replacement from passenger cars to less numerous trucks, by July 2009 he claimed that tough financing would delay the start by year or two, but that pretence was dropped soon, and there will never be any massive wind-for-natural gas cars switch.

CLSA comment

Pickens was dropped from Forbes 400 list of richest people in 2013 as his net worth fell below US$1bn that year for the first time since 2005 - mainly due to his investments in the wind business. In an interview on Iowa Public Television Pickens said "I am an expert on the wind (business). Do you know how you get to be an expert? Lose 200 million dollars. That is what I lost in the wind business."

Al Gore proposed 100% electricity from renewables in 10 years

In 2008 Al Gore wanted 100% electricity from renewables in 10 years

An even more ambitious energy transition plan was also revealed in 2008 when the former vice-president Al Gore proposed "a strategic initiative designed to free us from the crises that are holding us down and to regain control of our own destiny" by producing "100 percent of our electricity from renewable energy and truly clean carbon-free sources within 10 years," a goal he claimed to be "achievable, affordable and transformative."

Numerous predictions of a rapid transition away from fossil fuels have fallen flat

Figure 8

History of failed forecasts about transitions to non-carbon energy

Year of forecast	Forecaster	Forecast	By year
1971	GE	100% US electricity from nuclear generation	1990
1976	Amory Lovins	33% of all US energy from renewables	2000
1977	InterTechnology Corporation	36% of US industrial process heat from solar power	2000
1978	Carter Administration	20% of all US energy from solar	2000
1978	Johansson and Steen	50% of Swedish energy from biomass	2015
1980	Sørensen	49% of US energy from renewables	2005
2006	Swedish Government	Create 1st oil-free economy	2020
2007	German Government	CO_2 emissions 40% below 1990 levels	2020
2008	Google	Cut US fossil fuel based capacity by 88%	2030
2008	Al Gore	100% of US electricity from renewables is "*achievable, affordable and transformative*"	2018
2008	T. Boone Pickens	To replace natural gas fired power generation in the US with wind generation and to use the saved gas in cars and wean US off oil imports	2018

Source: Vaclav Smil, CLSA

In 2016 the US still gets 68% of its electricity from fossil fuels, down from 71% in 2008

In fact, Gore's goal was widely unrealistic. In 2008, the US generated only about 6% of electricity from hydro stations and just 2.3% came from "new" renewables, that is wind, geothermal and solar and eliminating carbon-based electricity would have required replacing 71% of the 2008 generation originating in the combustion of fossil fuels. Since 2008 there has been a major shift in the composition of the US electricity generation (more gas, less coal) but in 2016 (the latest data available) the country still derived 68% of its electricity from fossil fuels.

Google wanted to cut American fossil fuel based capacity by 88% by 2030

Google (now Alphabet, and the would-be master of the new electronic universe) has not fared any better with it relatively less ambitious transformative plan. In 2008 the company's *Clean Energy 2030* plan called for "weaning the US of coal and oil for electricity generation by 2030 (with some remaining use of natural gas as well as nuclear), and cutting oil use for cars by 44%". This was to be done by cutting the country's fossil-fuel based electricity generation by 88%, by keeping the overall demand for electricity flat, and by raising the sales of hybrid cars and pure electric vehicles to 90% of all new sales by 2030.

"We can put a big dent in climate change"

Figure 9

A screen shot of Google's now abandoned Clean energy plan 2030

Google

Official Blog

Insights from Googlers into our products, technology, and the Google culture

Clean energy 2030

October 1, 2008

Right now the U.S. has a very real opportunity to transform our economy from one running on fossil fuels to one largely based on clean energy. We are developing the technologies and know-how to accomplish this. We can build whole new industries and create millions of new jobs. We can reduce energy costs, both at the gas pump and at home. We can improve our national security. And we can put a big dent in climate change. With strong leadership we could be moving forward on an aggressive but realistic timeline and an approach that balances costs with real economic gains.

Source: Google

Google later abandoned its plan - "we now know that to be a false hope"

Google noted that such rapid build-ups of new electricity generating capacity have precedents in US history (expansion of natural gas-fired capacity between 1998 and 2006, and of nuclear capacity between 1972 and 1987) - but both of these rapid gains came from installations of much larger generating units (with most nuclear turbo-generators rated between 400-800MW) that can be located with much greater flexibility (gas turbines even inside urban areas) than wind and solar devices with their specific location constraints. In any case, just three years and one month after launching the plan Google abandoned it entirely, admitting that "We felt that with steady improvements to today's renewable energy technologies, our society could stave off catastrophic climate change. We now know that to be a false hope." See Appendix 1 for Google's detailed explanation of its rapid energy transition failure. Also see Appendix 2 for a lesson from Bill Gates on energy and climate change. That lesson should make it amply clear why Google had to abandon its plan.

Sweden targets to make country oil-free by 2020 . . .

In Sweden Johansson and Steen forecast in 1978 that by 2015 half of the country's primary energy supply coming from biomass plantations covering 6-7% of the nation's territory, and in 1980 a plan for solar Sweden envisaged electricity, methanol, wood and heated water as the only energy sources. By 2015 there were no extensive tree plantations (willow planting programme was abandoned in 1996) and fossil fuels supplied 32% of all energy. In 2006 the Swedish government promised to make the country the world's first oil-free economy by 2020, and to do so without any help from nuclear generation. But in June 2016 Sweden abolished the nuclear capacity tax in order to make large investments, needed to extend the lifetime of nuclear reactors, possible, and the upgraded reactors at Forsmark and Ringhals stations should be able to operate until the mid-2040s.

. . . an impossible goal. "Oil free" only applies to heating for buildings

And while Sweden's oil consumption declined by about 18% between 2005 and 2015, it still accounts for 27% of all primary supply and nuclear electricity for 24%: in order to be free of oil and without any nuclear generation Sweden would have to convert 51% of its primary energy supply to renewable energies in just five years, clearly an impossible goal. But a closer reading of the "oil-free" plan shows that it was meant to apply only to heating of residential and commercial buildings: by 2020 "in principle no oil should be used" by those sectors, with biofuels and renewable electricity filling the need. Driving Volvos and flying to Thailand are thus two great Swedish pastimes that would be exempt in the country's not-quite-oil-free economy!

Germany's *Energiewende* has led to only a 5.4% drop in CO_2 emissions from electricity generation between 2004 and 2014

But has not Germany, with its Energiewende (German for energy transition), met and surpassed its forecast targets? The principal goal of the programme is to accelerate the decarbonisation of Germany's energy supply - but between 2004 and 2014 the country's CO_2 emissions from electricity generation declined by 5.4% while during the same period emissions from American electricity-generating plants decreased more than twice as fast, by 12.9%! And the official German target of reducing 2020 CO_2 emissions at least 40% below the 1990 level looks increasingly unrealistic: by 2014 they were 24% lower, there was no reduction between 2009 and 2014, and in order to achieve the 2020 goal the average pre-2015 annual reduction rate would have to be nearly three times higher!

Indispensable fossil fuels

In a civilisation deriving 86% of its primary commercial energy from fossil (that was the global average in 2015) there are no major industrial products made without conversion of coal or hydrocarbons, and for several of them - most notably for steel, ammonia and plastics - there are no readily available alternatives capable to cover large shares of respective global needs.

Coal and hydrocarbons are indispensable in manufacturing steel, ammonia and plastics

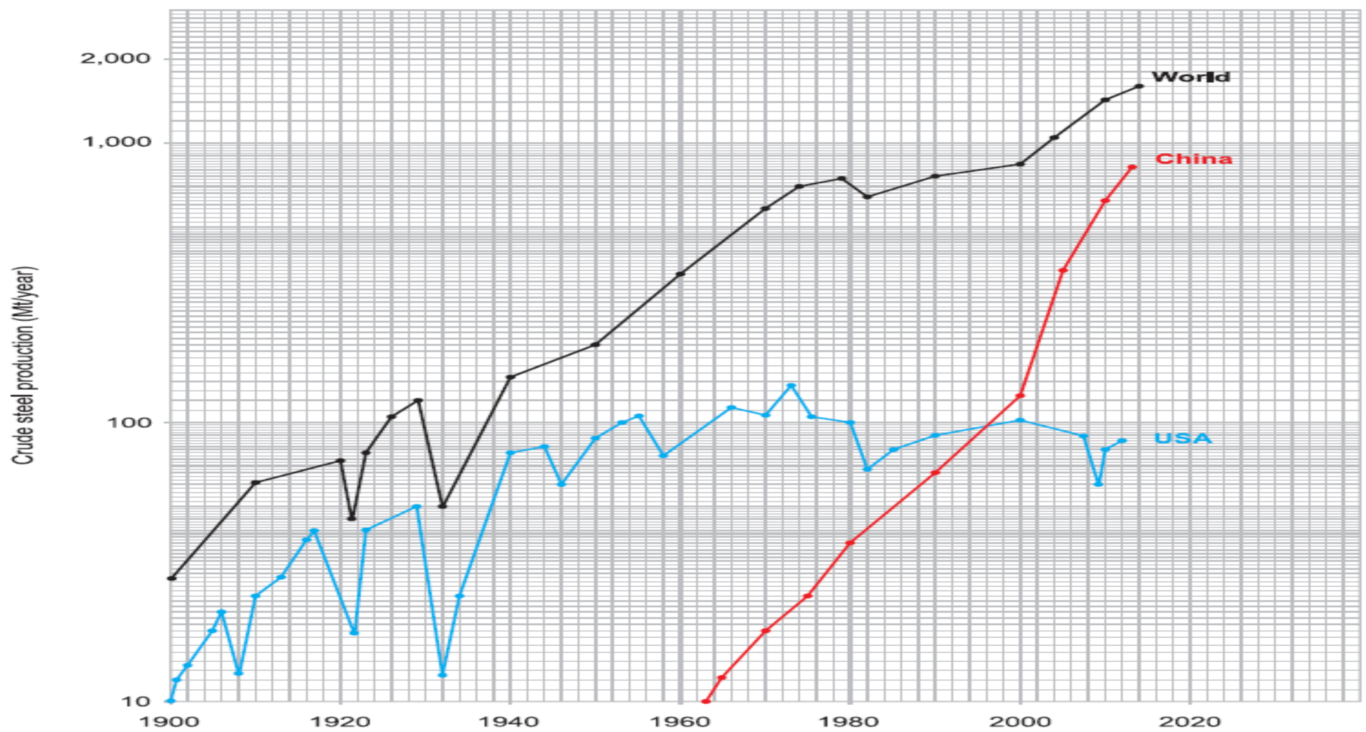
I find it incredible that scenarios charting a rapid shift from fossil fuels to renewables ignore the indispensable uses of coal and hydrocarbons as critical raw materials or energisers (or both) of several major industrial processes that produce materials whose mass-scale consumption defines modern economies and that cannot be made on such large scales without fossil carbon by any readily available commercial alternatives. Materials in this category include steel, the leading metal in modern infrastructures and the dominant component of countless industrial products; ammonia, without whose synthesis it would be impossible to feed about 40% of the world's population; and plastics whose widespread applications have transformed so many industrial and consumer products.

About two-thirds of the world's steel is made in blast furnaces charged with coke

None of the modern energy-intensive materials is more important, and more ubiquitous than steel, the leading metal required in construction and transportation and by industries and households. About a third of all steel is made by recycling the metal in electric arc furnaces and, of course, that process could run on renewable electricity. Most of the steel (slightly more than a billion tonnes in 2015) is made by the reduction of iron ores. Iron ores are extracted in large surface mines, shipped (now commonly overseas) in large bulk carriers, then sintered or pelletised to be smelted in blast furnaces that are charged with coke, made by pyrolysis (destructive distillation) of coking coal, and that also receives infusions of powdered coal and natural gas. Resulting cast (pig) iron is decarburised in basic oxygen furnaces and continuous casting is used to make many semi-finished products (beams, billets, sheets).

Figure 10

Global steel production, 1900-2015



Source: Smil, V. 2016. *Still the Iron Age: Iron and Steel in the Modern World*. Oxford: Elsevier.

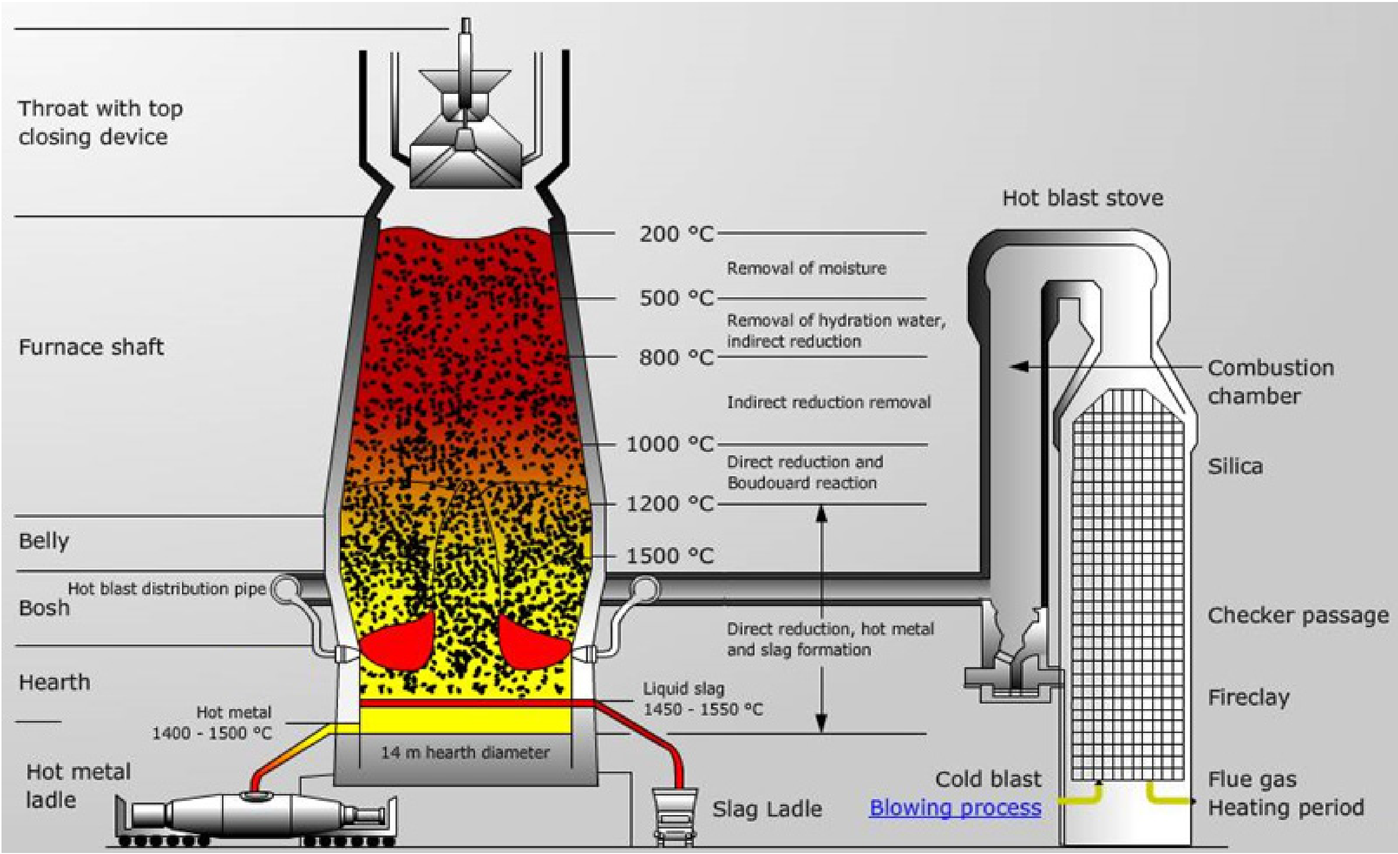
There is no mass-scale non-carbon alternative to coke in pig iron production

No mass-scale carbon-free alternative for steel production

Basic oxygen furnaces, now energised by electricity generated mostly from the combustion of fossil fuel, can be powered by renewably generated electricity but primary ironmaking requires a reductant that is supplied by metallurgical coke. Coke's oxidation produces the reducing gas and energises the smelting process by generating high temperature required to liquefy the metal, and its strong and porous structure creates permeability that enables the furnace to run as a counter-current reactor. Production of metallurgical coke required about a billion tonnes of coal in 2015 and no mass-scale non-carbon alternative is available.

Figure 11

Cross-section of a typical modern large blast furnace



Source: en.informatiitehnice.com

Figure 12

Material balance in iron making

Inputs	Hot metal (kg/tonne)
Iron ore (sinter, pellets)	1,500
Coke	400
Coal (75% C)	200
Total carbon	**550**

Source: Vaclav Smil, CLSA

Charcoal based smelting cannot be expanded to cover global demand

Direct reduction of iron produces less than 5% of today's global output but it, too, requires fossil carbon (from natural gas, petroleum coke), and the option of using non-fossil carbon (charcoal) would entail enormous environmental costs and require a profound transformation of the industry. Charcoal-based

smelting, still done to some extent in Brazil, cannot be readily expanded to cover the global demand. Charcoal is an excellent reductant but it is too fragile to support heavy ore and flux burdens charged into modern blast furnaces and that is why charcoal-fuelled furnaces have internal volumes an order of magnitude smaller than those of modern coke-fuelled units (typically just 350m^3 compared to as much as 5,000m^3).

It would need 3bn tonnes of wood a year - creation of a new industry!

Immediate transition from coke to charcoal would thus require closure of tall modern furnaces, mass-scale construction of smaller units and inevitably higher capital and production costs - and an enormous increase in charcoal production. Even with high-yielding eucalyptus clones (annual harvests of 20-25t/ha) and with efficient (35-40%) continuous charcoaling retorts today's annual pig iron output would require wood from about 125-150 million hectares. A new industry would have to produce more than 3 billion tonnes of wood a year, or about as much as the global output of all wood currently harvested for lumber and pulp.

Best non-carbon alternative is hydrogen reduction- not economically attractive before 2050

Even when ignoring enormous environmental implications of doubling the current wood harvests, such an industry could not be developed in a decade or two. The best long-term possibility for replacing coke-based smelting in blast furnaces might be the suspension reduction of iron-ore concentrates that would reduce fine iron oxide concentrates sprayed into the furnace chamber by natural gas, syngas, hydrogen, or their combination. Hydrogen use would cut CO_2 emissions by 96% compared to traditional ironmaking - but hydrogen reduction and electrolysis are unlikely to be economically attractive before 2050.

Manufacturing of cement, ammonia and plastics also need fossil fuels

Cement production consumes equivalent of over 500 million tonnes of coal

And production of cement, now surpassing 4 billion tonnes a year, is a highly energy-intensive process now fuelled mostly by coal and petroleum coke, with no alternatives readily available on the needed massive scale (annual output of 4.2 billion tonnes, about the same mass as crude oil, now consumes an equivalent of more than 500 million tons of coal).

Transition to non-carbon alternatives is not possible in a decade or two

Most of the CO_2 during cement production is not released during combustion but during the calcination from heated $CaCO_3$. Several processes have been proposed to reduce or to eliminate these emissions but as of 2016 none of these new techniques has become commercially available and given the industry's global size it is, once again, obvious that any transition to non-carbon alternatives cannot be accomplished in a decade or two.

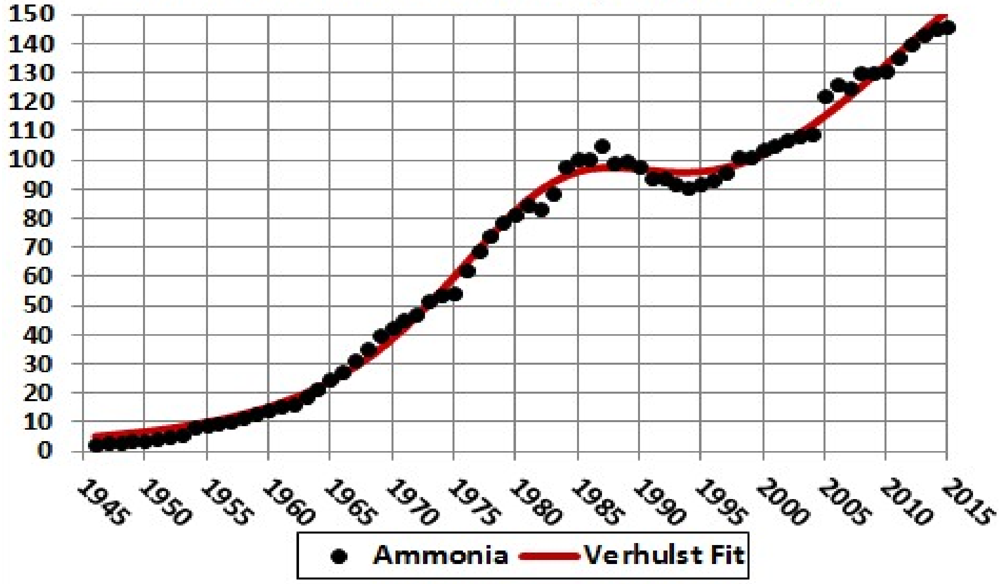
Synthesis of ammonia relies heavily on methane

Similarly, no rapid shift can be expected for the synthesis of ammonia, the first step in producing all modern nitrogenous fertilisers. The Haber-Bosch process, invented in 1909 and commercially introduced in 1913, still dominates the production (now annually at about 175 million tonnes of NH_3) and it relies on methane, both as a feedstock (to yield hydrogen) and as a fuel for energy-intensive synthesis. A long-established and more expensive alternative relies on high-temperature electric arc to oxidise atmospheric nitrogen and then to convert the resulting NO to NO_2 and HNO_3, but it requires uninterrupted supply of very cheap electricity and Norsk Hydro was the only company to use it between 1911 and 1991.

It would be impossible to feed about 40% of the world's population without ammonia synthesis

Figure 13

World ammonia production (million tonnes)



Source: www.roperld.com

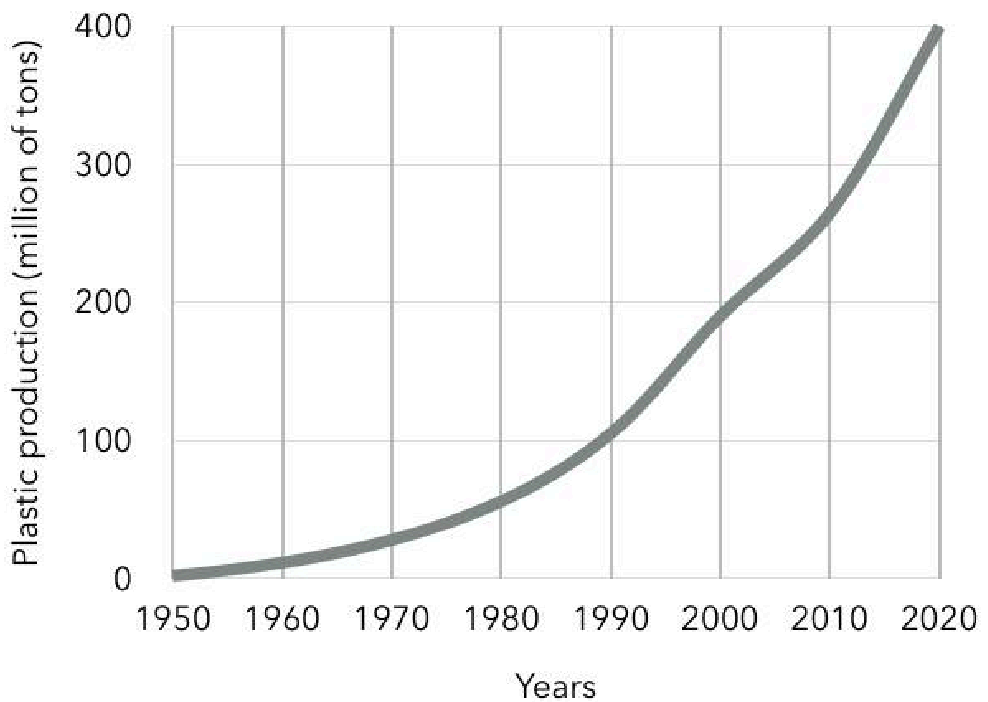
Production of plastics requires hydrocarbons for feedstocks and energy

And production of about 300 million tonnes of plastics (all of them energy-intensive materials) relies on liquid and gaseous hydrocarbons (mostly methane, naphtha and ethane) for its feedstocks and energy. Alternatives based on cellulose, starches and ethanol are already available but none is ready to be deployed rapidly on mass (million tonnes) scales - even if sourcing of newly required raw materials would not have any environmental implications.

Widespread applications of plastics have transformed many industrial and consumer products

Figure 14

World plastics production

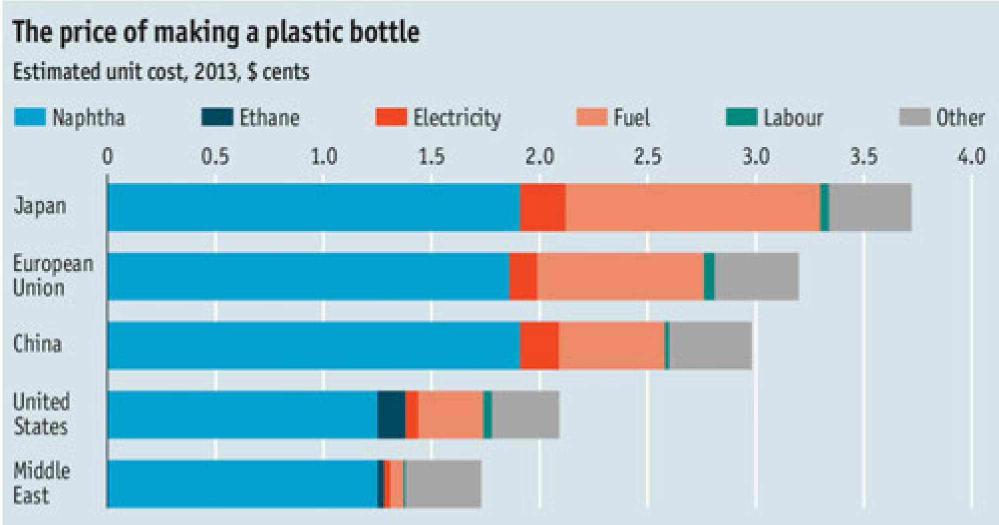


Source: plasticeurope.org

The cost of making a plastic bottle comprises almost entirely of fossil fuels

Figure 15

Fossil fuel use dominates production of plastic bottles



Source: IEA World Energy Outlook 2014

Production of steel, cement, ammonia and plastics emitted more than 7 billion tonnes of CO_2 in 2015

When assuming approximate emissions factors of 0.3tonne of carbon per tonne (t C/t) of cement, 0.4t C/t of steel, 0.8t C/t of plastics and 1.25t C/t of ammonia then in 2015 the production of these key fossil fuel-dependent materials emitted about 2 billion tonnes of carbon: that is 7.3 billion tonnes of CO_2, or nearly 20% of the total anthropogenic released in 2015 from combustion of fossil fuels and land-use changes. Specific carbon emissions (t C/t of the final product) will be declining due to steady gains in efficiency (typically by 1-2%/year) but growing demand for those key industrial commodities will negate most (or all) of these gains. Per-capita demand for those key materials may be largely saturated in Europe, North America and even in China, and with low (or no) population growth in those regions this may result in prolonged stagnating production.

This demand will come from India and Africa

But during the next five decades, three-quarters of the global population increase will take place in Africa and India where both the basic steel- and concrete-intensive housing, transportation and industrial infrastructures as well as average per-capita consumption of food (reflecting the typical use of fertilisers) and disposable incomes (whose rise leads to higher purchases of finished products) remain a fraction of China's new means: India's annual per-capita steel use is just 50 kilograms compared to China's 500 kilograms, a tenfold difference! There can be no doubt that materials whose production is based on conversions of fossil carbon will have to be deployed on mass scale in order to lift those 2.5 billion people from current living conditions.

Power density and intermittency

> Smil opened my eyes to the challenges of many of the new energy technologies by showing their limited energy density. If you compare renewable energy technologies with current power plants fuelled by fossil fuels, they are 10 to 100 times less power-dense. This doesn't mean renewables won't succeed, but there are a lot of variables to consider, such as weather conditions that affect the predictability of energy generation and the lifespan of equipment.
>
> Bill Gates

Lower power density of renewables is a significant constraint

Power density measures the rate of energy production or use (that is power, W = J/s) per unit of horizontal surface (W/m^2). This rate can be used to evaluate every kind of energy extraction and conversion and it determines key spatial characteristics of energy systems. Power densities of harnessing renewable energy flows are, in general, significantly lower than the power densities of fossil fuel-based systems. Many uncritical proponents of renewable conversions are either unaware of this fact or they dismiss it as being of marginal importance. But just the opposite is true.

Power density of solar PV is now mostly between 3-11W/m^2

Solar radiation can be converted to heat with relatively high power densities (annual means of 40-100W/m^2, global mean for solar water heaters is nearly 60W/m^2) while the rates for photovoltaic generation in large solar parks range between 3-7W/m^2 in less sunny locations and 7-11W/m^2 in sunny regions. These rates refer to annual means, not to peak power (80-150W/m^2 of a module) during brief noon-time periods, and include the entire area claimed by a solar installation, not just the module surfaces.

That of wind power is 1W/m^2 and that for biofuels is 0.1-0.5 W/m^2

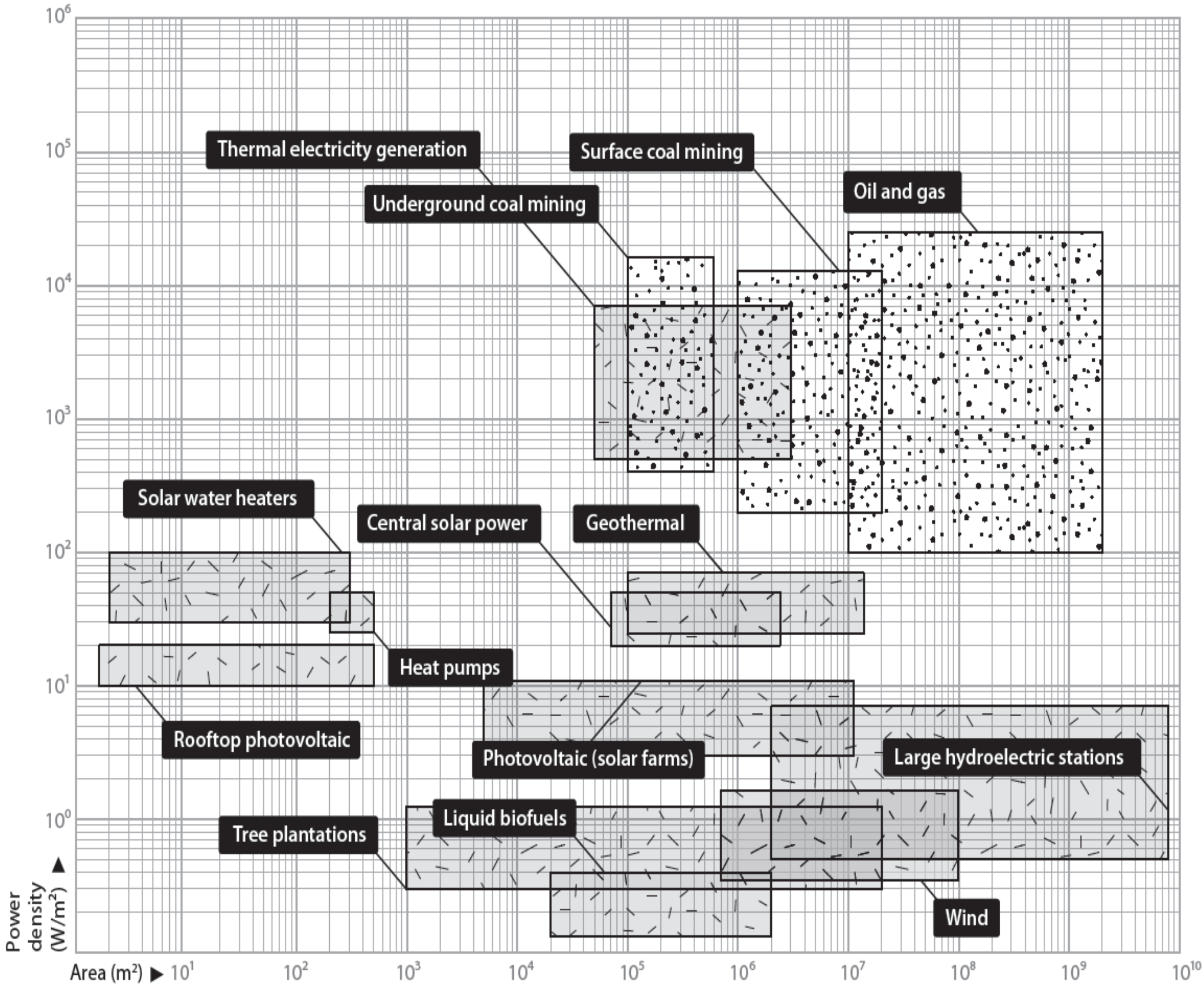
Electricity generation by wind turbines requires adequate spacing of the machines and with typical capacity factors of 15-25% in Europe and 30-35% in the US average operating power densities of large wind farms are no higher than about 1W/m^2. And because of inherently low efficiency of photosynthesis even exceptionally high biomass harvests have power densities just above 1W/m^2 and conversions to useful energies (ethanol, biodiesel, biogas or electricity) reduce that to just 0.1-0.5W/m^2.

Extraction of fossil fuels proceeds with hundreds or thousands W/m^2

Extraction of fossil fuels proceeds mostly with power densities of hundreds to thousands of W/m^2, and electricity generation in thermal stations (coal- and gas-fired or nuclear) has a similar range of power densities. Consequently, fossil-fuelled economies energised by burning ancient carbon extract fuels with high power densities, produce concentrated energy flows and then diffuse them by using pipelines, railways and high-voltage transmission lines to final users. In contrast, economies based on renewable energy conversions will have to harness low power-density flows over large areas and then concentrate their use for consumption in cities which already house more than half of humanity and where some 70% of the world population will live by 2050.

Figure 16

Power density of various sources of energy (log scale)



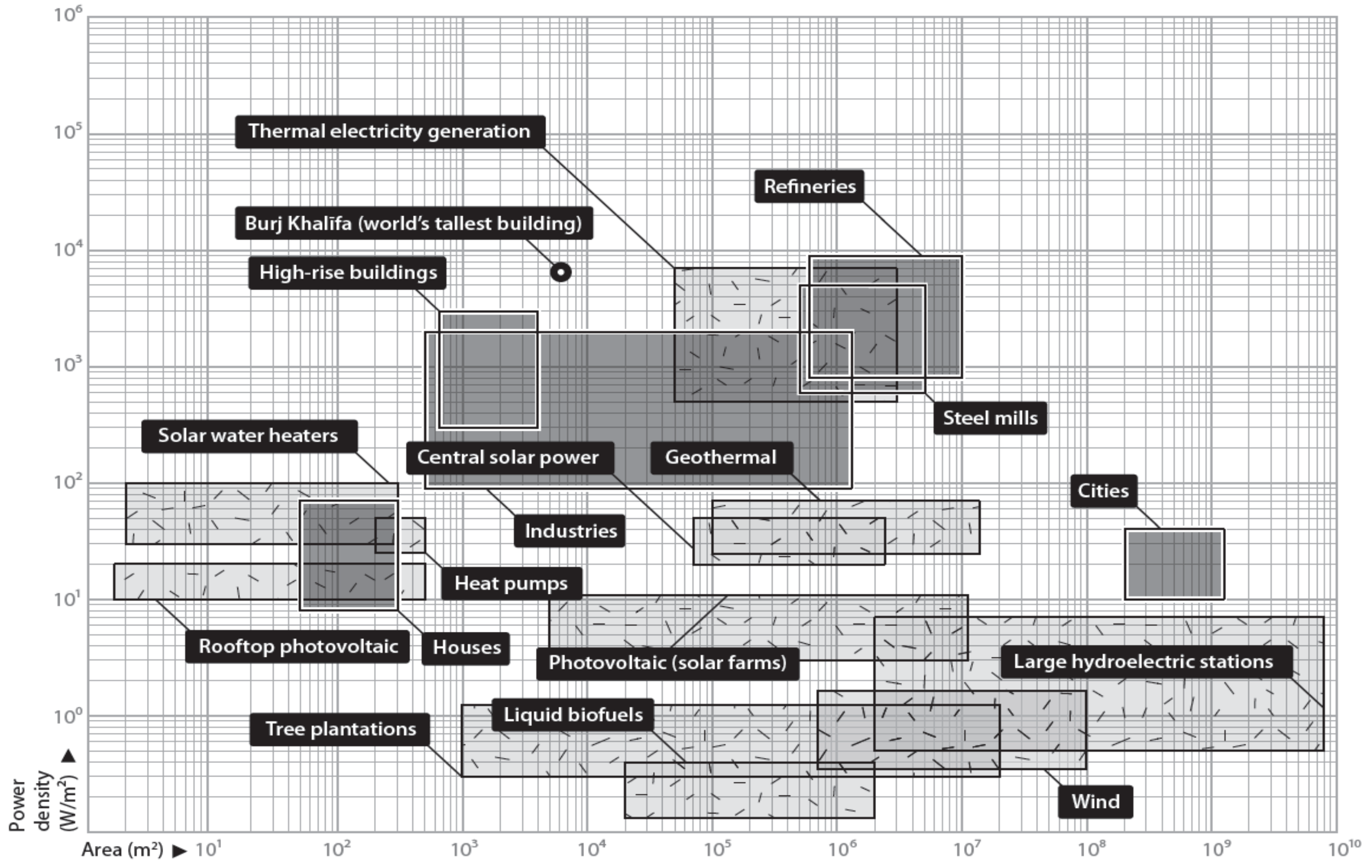
Source: Smil, V. 2015. Power Density: A Key to Understanding Energy Sources and Uses. Cambridge, MA: MIT Press.

Urban areas consume energy at 10-50W/m^2 and downtowns at 500-1,000W/m^2

And energy in modern societies is consumed with power densities ranging from 10-50W/m^2 in urban areas to 500-1,000W/m^2 in downtowns of large cities and in many industrial enterprises. This mismatch between the inherently low power densities of renewable energy flows and relatively high power densities of modern final energy uses means that a purely renewable system would require a profound spatial restructuring with major environmental and socio-economic consequences. In order to energise the existing residential, industrial and transportation infrastructures inherited from the fossil-fuelled era, civilisation energised by renewables would have to concentrate diffused flows to bridge power density gaps commonly of two orders of magnitude (biofuels at 0.5W/m^2 to heating at 50W/m^2) and up to three orders of magnitude (wind-generated electricity at 1W/m^2 energising a downtown area at 1,000W/m^2).

Figure 17

Power densities of various energy uses and those of renewable energy sources (log scale)



Source: Smil, V. 2015. Power Density: A Key to Understanding Energy Sources and Uses. Cambridge, MA: MIT Press.

Power density of energy production by renewables is orders of magnitude lower than that by fossil fuels

Figure 18

Range of power densities for various energy sources and uses

	Range of power density (W/m²)	
	Lower end	Upper end
Energy Source		
Liquid bio-fuels	0.2	0.5
Wood from tree plantations	0.5	1.2
Wind farms	0.3	3
Large hydroelectric stations	0.4	6
Photovoltaic (solar farms)	3	11
Rooftop photovoltaic	10	20
Heat pumps	25	50
Solar radiation (annual mean received at the surface)	100	250
Solar water heaters	30	100
Geothermal	25	100
Thermal electricity generation	500	7,000
Surface coal mining	200	10,000
Underground coal mining	400	12,000
Oil and gas	1,000	25,000
Energy Use		
Cities	10	40
Houses	8	70
Industries	90	2,000
High rise buildings	300	3,000
Steel mills	600	5,000
Burj Khalifa (world's tallest building)		7,000
Refineries	800	9,000

Source: Smil, V. 2015. Power Density: A Key to Understanding Energy Sources and Uses. Cambridge, MA: MIT Press.

Fundamental reshaping of energy infrastructure

Fundamental reshaping of energy infrastructures needed for mass renewables adoption

Mass adoption of renewable energies would thus necessitate a fundamental reshaping of modern energy infrastructures, from a system dominated by global diffusion of concentrated energies from a relatively limited number of extraction/conversion nodes to a system that would harness renewable flows over extensive areas and concentrate them in the increasingly more populous consumption centres.

Infrastructural reorganisation challenges should not be underestimated

Challenges of this massive infrastructural reorganisation should not be underestimated, and they would be especially large in order to produce liquid biofuels for global transportation. As already noted, ethanol and biodiesel output is now equal to just 70 million tonnes of crude oil and even a ten-fold expansion of their output would supply just a third of the current demand, assuming it could ignore many attendant economic and environmental problems.

Converting food crops to biofuel is unthinkable in many crowded countries

Only a handful of countries have enough farmland do replicate what the US and Brazil have done with corn and sugar cane, but even after diverting a third of its largest crop to ethanol the US has displaced less than 10% of its gasoline - and it may not have reduced overall CO_2 emissions. In fact, cultivation of previously untilled land may completely offset any carbon gains attributable to ethanol use or it may result in as much as doubling of greenhouse gas emissions for a period of more than 30 years. In any case, farmland diversions from food crops to biofuel crops are unthinkable on similar scales in densely populated, land-short China, India, Indonesia, Bangladesh and Pakistan, and in many African countries they could be achieved only with further large-scale deforestation.

Ethanol derived from inedible plant matter has challenging scaling task

Ligno-cellulosic ethanol, derived from logging waste and crop residues (indigestible by humans), is a more rational choice but its commercial production has just started. The world's first two large plants began full-scale operation in 2015 (in Iowa using corn stover, in Brazil using cane bagasse) and their combined annual capacity will be about 150 million litres or a mere 0.005% of current global demand for transportation fuels. Again, just to raise that to 10% of the overall supply (a 2,000-fold expansion) entails an enormously challenging scaling task and also (with rising production) serious concerns about raw material supply and environmental impacts.

600m hectares of soybean plantation needed to produce jet fuel

To replace jet fuel with palm oil would need over 3.5 times the area of current palm plantations

Worldwide demand for aviation kerosene (jet fuel) reached about 270 million tonnes, or about 360GW, and the International Civil Aviation Organization expects it to reach 1TW by 2050. Power densities of biojet fuel derived from soybeans is just 0.06W/m^2 and 0.65W/m^2 for palm oil-based fuel. Even the latter alternative would require about 57 million hectares of palm-oil plantations, 3.5 times their global 2010 area, inevitably leading to a further increase in tropical deforestation that has accompanied the crop's recent expansion.

To replace it with soybeans would require 5.5 times the current global area planted to soybeans

Basing the fuel on soybeans would need about 600 million hectares of soybeans dedicated to biojet fuel at the 2015 level of consumption, about 5.5 times the 2015 global total, obviously a highly unlikely (if not impossible) extension (60% of all soybeans are now produced in just four countries, USA, Brazil, Argentina and China).

Area equal to half of China's territory would need to be in jatropha plantations by 2050

Turning to crops grown on marginal, non-arable land, could provide only a partial solution: much touted jatropha (*Jatropha curcas*, a hardy oilseed-bearing shrub or a small tree able to grow on arid soils) would not produce more than 0.2W/m^2

and hence the world would need 180 million hectares of it to satisfy current jet-fuel demand, and 500 million hectares in 2050, an area equal to slightly more than half of China's territory. Even if genetically improved cultivars were to double the yield the likely jet-fuel demand in 2050 would still call for covering roughly an Argentina- or Kazakhstan-size area with jatropha.

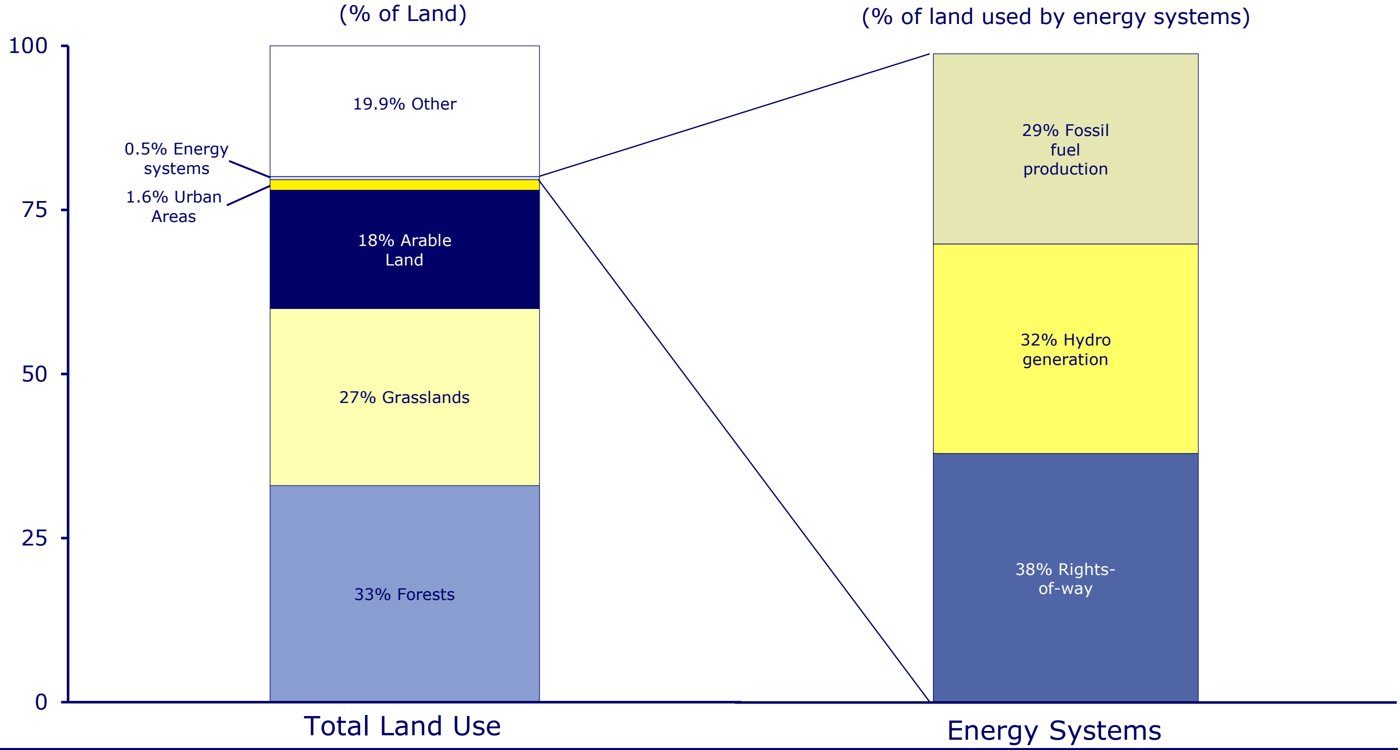
Current energy systems only occupy 0.5% of US land

Power density matters, especially for bioenergy

I have compared itemised calculations of the spatial extent of the existing fossil-nuclear-hydro energy system that now energises the US with its replacements by renewables. The current system claims about 55,000 square kilometres, roughly 0.5% of the US territory and an equivalent of half of Virginia), of which slightly more than half are right-of-way corridors. In contrast, replacing all transportation fuels (that is gasoline, kerosene and diesel) by biofuels would require - even when assuming that half of the total would come from cellulosic ethanol and the rest from crop-based ethanol and biodiesel - nearly 4,000,000km^2 or 40% of US territory. Mass-scale electrification of transport could cut this total considerably but even 80% reduction would still demand (depending on yields) 5-6 times more land for biofuels than the total area occupied by today's entire energy system: power density matters, particularly with bioenergy!

Figure 19

Comparison of US land-use categories in 2010



Source: Smil, V. 2015. Power Density: A Key to Understanding Energy Sources and Uses. Cambridge, MA: MIT Press

Problems with intermittent electricity generation

Rising share of wind and solar will require massive investments to deal with intermittency

Inherent intermittency of solar radiation and wind frequencies and speeds poses challenges for modern societies that require assured and reliable electricity supply. Low shares of intermittent generation can be easily accommodated in large modern interconnected systems, but rising shares of wind and solar will require either large reserve capacities or unprecedented extent of long-distance interconnections and electricity storage.

Wind and solar now supply significant shares of electricity in some countries

Advances in photovoltaic electricity generation (gradually rising conversion efficiencies of PV panels, their lower unit costs) and in wind-turbine performance (larger machines, now up to 8MW, wider operating ranges, improving capacity factors) combined with subsidies, preferential access to the market and mandated shares of electricity from renewables drive rapid gains in intermittent electricity generation. As already noted, wind and solar, still marginal globally, now supply significant shares of electricity in a number of European and Asian countries but the further development of these resources will be increasingly constrained by their intermittency.

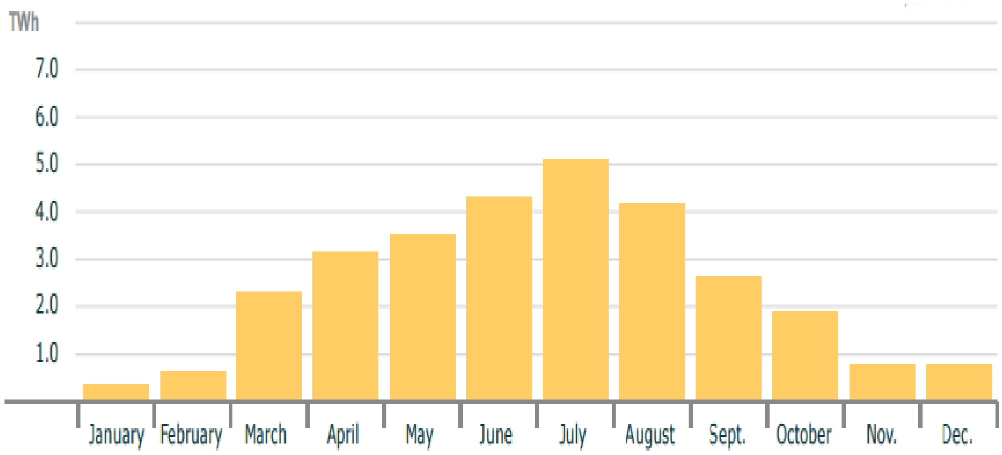
As those shares will rise we will need better ways to deal with large seasonal variations of solar and wind flows

For instance let's look at Fraunhofer ISE data and monthly generation of solar power in Germany. The maximum generation in 2013 was in July at 5.1TWh and the lowest generation was in December at 0.35TWh: generation in July was around 14.5 times that in December.

Solar generation in July is 14.5 times that in January

Figure 20

Monthly solar power generation in Germany in 2013



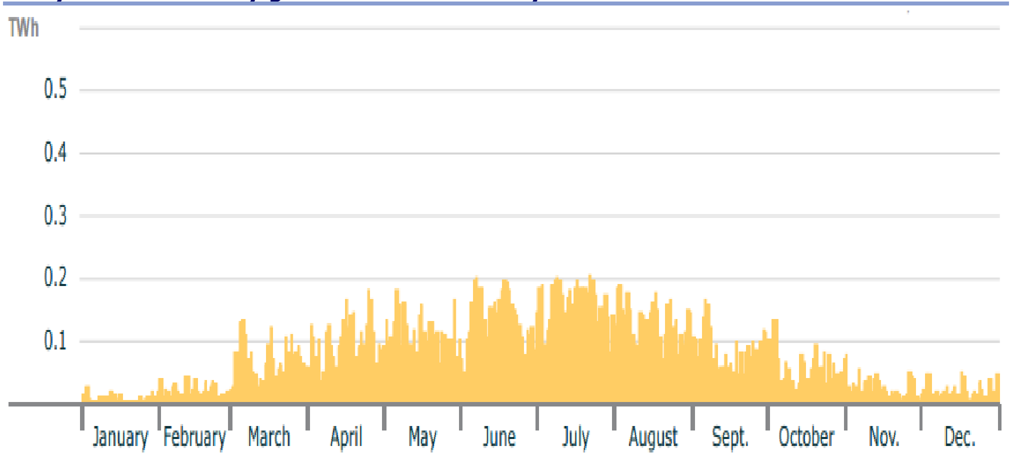
Source: Fraunhofer ISE

Max daily generation during the year is 100x minimum daily generation

As one would expect, the variations in daily solar power generation are even starker with maximum daily generation during the year being 100 times the minimum daily generation. These are variations in generation levels for the country as a whole. Obviously variation in individual solar panels would be far more pronounced.

Figure 21

Daily solar electricity generation in Germany

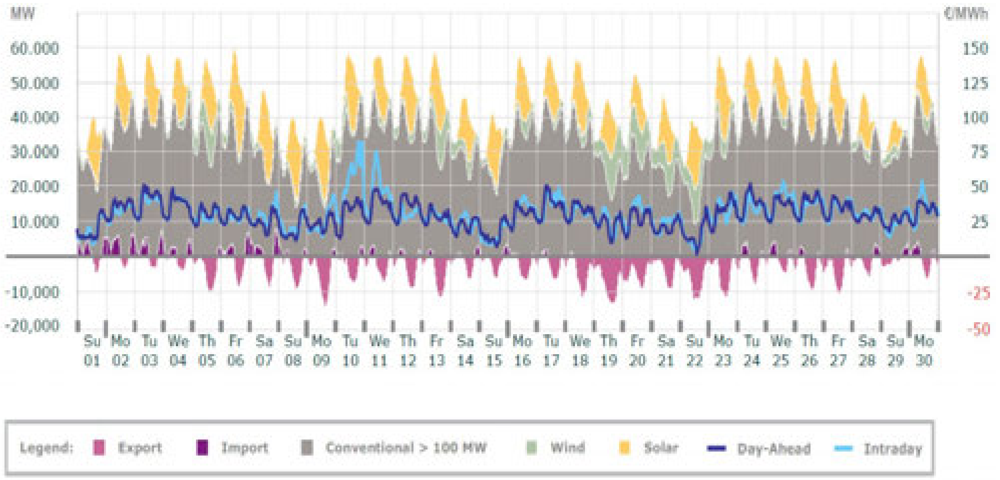


Source: Fraunhofer ISE

Solar has significant contribution to daily generation in June

Figure 22

Daily electricity generation and prices in Germany in June 2014

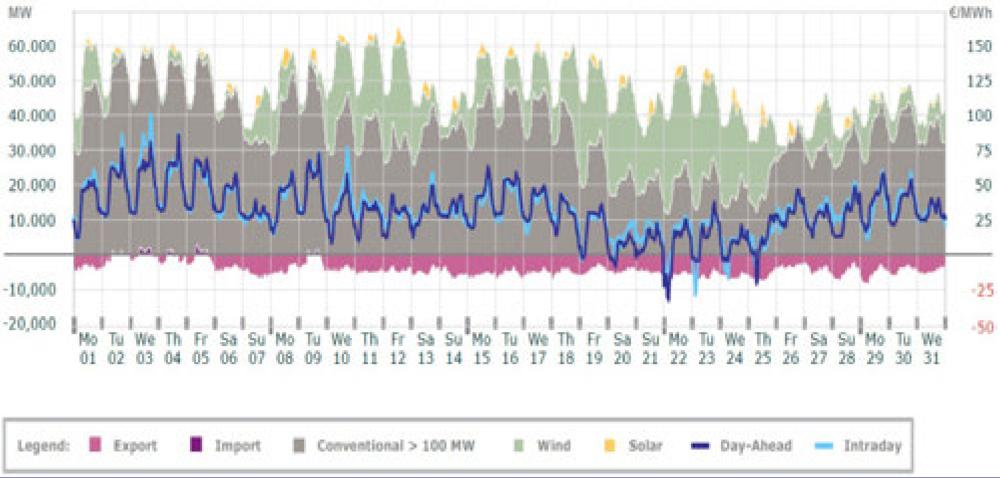


Source: Fraunhofer ISE

But hardly contributes anything in December

Figure 23

Daily electricity generation and prices in Germany in December 2014

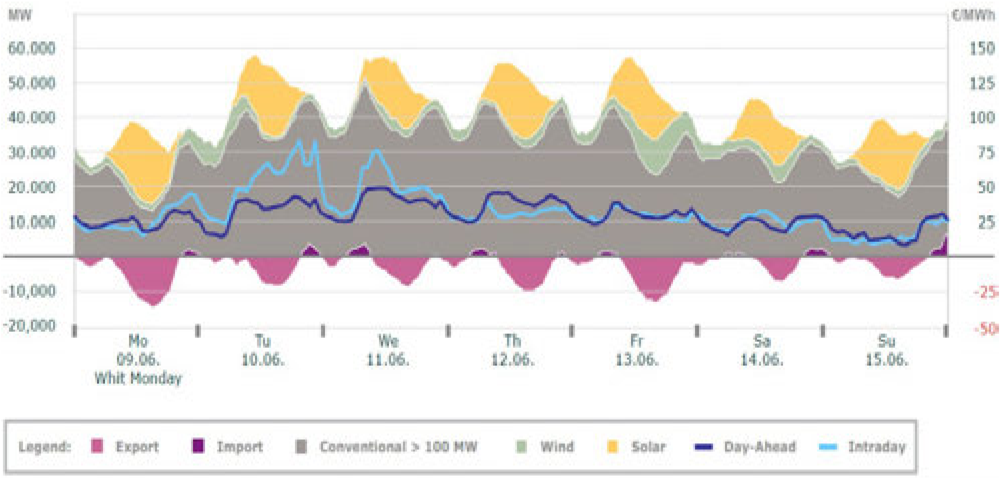


Source: Fraunhofer ISE

Solar is a large contributor to power generation in week 24 . . .

Figure 24

Daily electricity generation breakdown in week 24 in Germany (2014)

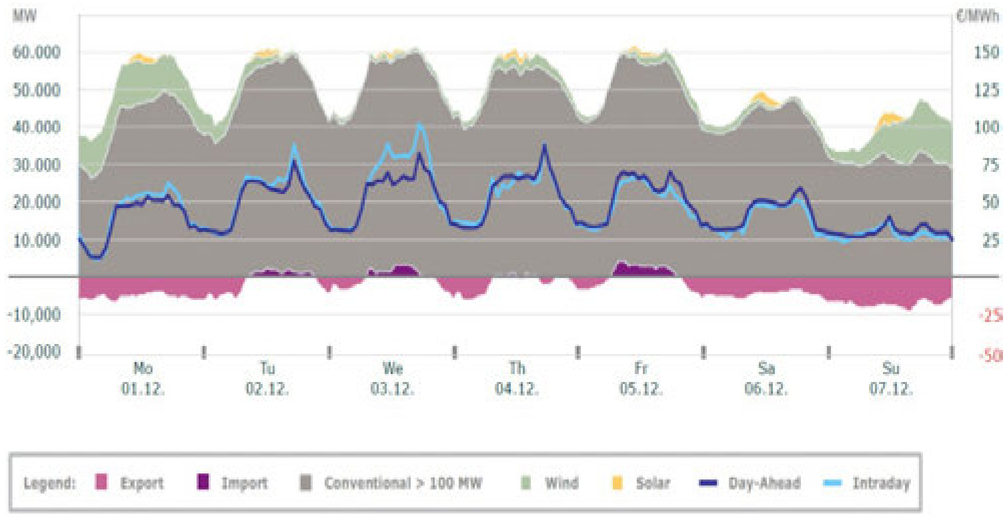


Source: Fraunhofer ISE

. . . but contributes almost nothing in week 49

Figure 25

Daily electricity generation breakdown in week 49 in Germany (2014)



Source: Fraunhofer ISE

Media headlines -"Fossil Fuels Just Lost the Race Against Renewables"

Remarkably, this reality (as well as the fact that PV modules have inherently low capacity factors) is not even hinted at in glowing media reports which are preoccupied with the totals of installed capacity, not with actual electricity generation. This Bloomberg News headline from April 2015 is typical: *Fossil Fuels Just Lost the Race Against Renewables* - because the world is now installing annually more renewable generating capacity than fossil-fuelled capacity, and as the price of solar electricity will continue to plummet (a favourite media term) it will become the unequalled leader.

Sharp price declines not uncommon in early stages of technical developments

Sharp price declines not uncommon in early stages of technologies

About the plummeting prices: the median reported installed prices of US PV modules had an exponential decline rate of about 7% between 1998 and 2014, but people who write without any understanding of history do not appreciate that such vigorous price decreases are not uncommon in early stages of technical developments when innovation and economies of scale combine to produce significant savings.

In early decades of US electrification prices were falling at over 5% a year

For example, the average US electricity price was declining exponentially by more than 5% a year between 1902 (the first year when nationwide price information is available) and 1920, and the rate would have been higher if we had data for the 1890s. But with thermal generation we were developing a source that was constantly and instantly available which is not the case with solar PV: its declining price does nothing to raise its average capacity factors which remain very low in Germany (less than 11%) and much higher in the USA (28.7% in 2015) but with a large difference between monthly means of just 19% in December and 35% in July.

There are no imminent technical breakthroughs in GW-scale electricity storage

Intermittency of PV (and its seasonal fluctuations) and wind generation would matter much less if we had an inexpensive, readily available large-scale storage of electricity, with individual installations having capacities of hundreds of MW to a few GW. Although the performances of solid state batteries, flow batteries and electrochemical capacitors have been improving, there has been no breakthrough at the top of the scale where pumped hydro storage (a simple solution whose origins go back to the 1890s) remains the only practical and relatively affordable option. The largest pumped storage installations now have capacities of 2-3 GW, but even the most efficient units operate with net electricity loss of about 25%.

High share of renewables require large reserve capacities

Intermittent generation requires reserve capacities and high-voltage connections

As a result, integration of higher shares of intermittent generation requires the availability of on-call reserve capacities and extensive high-voltage interconnections. Interconnections make it easy to support high shares of intermittent generation in small economies that can rely on sufficient and reliable transfers from neighbours with diversified generation: Denmark's exceptionally high reliance on wind would be impossible if it were an isolated island rather than a small economy linked to Sweden and Germany. This option is not available for economies without integrated national grids (USA, Canada) or with inadequate interconnections (India and, surprisingly, even Japan).

Intermittency reduces the importance of wind and PV contributions and raises costs

During the past five years many studies have concluded that intermittency greatly reduces the importance of wind and solar contributions and raises levelised cost (above all due to necessity of back-up thermal capacity and storage) in all simulations of future grids with high shares of wind and solar: integration costs in such systems can be up to half of total generation costs. Many studies, including those by Apt and Jaramillo and by the Clean Air Task Force, showed that, even with future cost declines, any largely renewable system will be expensive. The need for adequate back-up would almost double the standard cost in Germany and in California, due to higher capacity factors, the cost would be somewhat lower.

CLSA Comment

Household electricity prices in Germany are up 65% in last decade

The rising share of renewables in electricity generation has raised the price of electricity for households in Germany by 65% over the last decade and Germany now has the second-higher power prices in the European Union. The only country with higher price than Germany is Denmark which has an even higher share of renewables. As can be seen from the chart below the biggest component in electricity prices in Denmark and Germany is not generation cost or transmission & distribution costs. The biggest component is "taxes and levies" which accounts for 69% of the total costs in Denmark and 52% of the cost in Germany. A large part of these taxes and levies are used for subsidising renewables energy. T&D cost are also higher than what they otherwise would have been.

Figure 26

Household electricity prices in Germany and EU

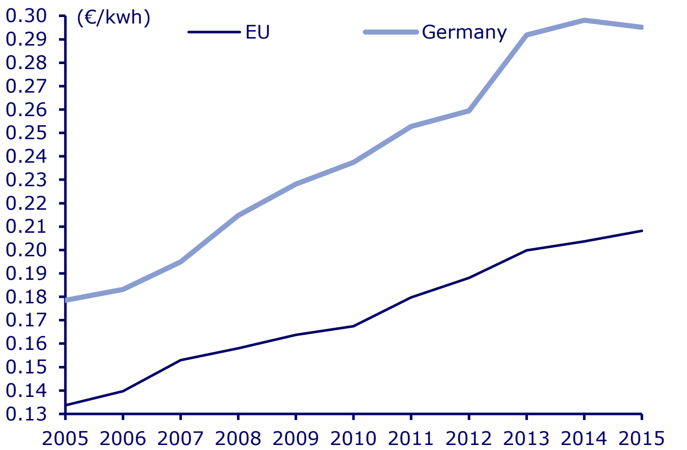
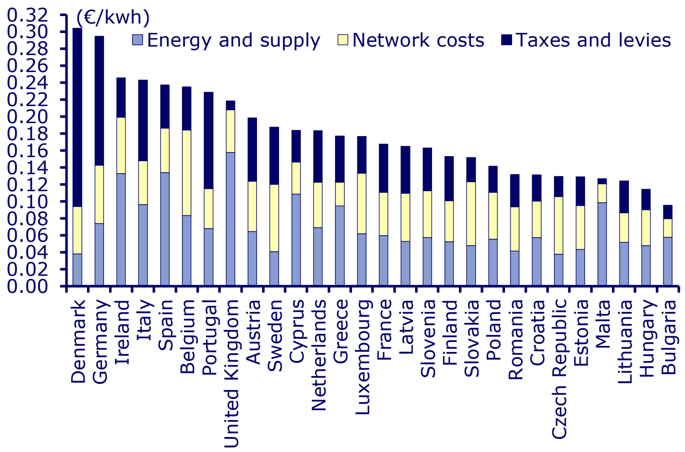


Figure 27

Break-up of household electricity prices in EU countries



Source: Eurostats

Germany's need for thermal power capacity has not fallen with *Energiewende*

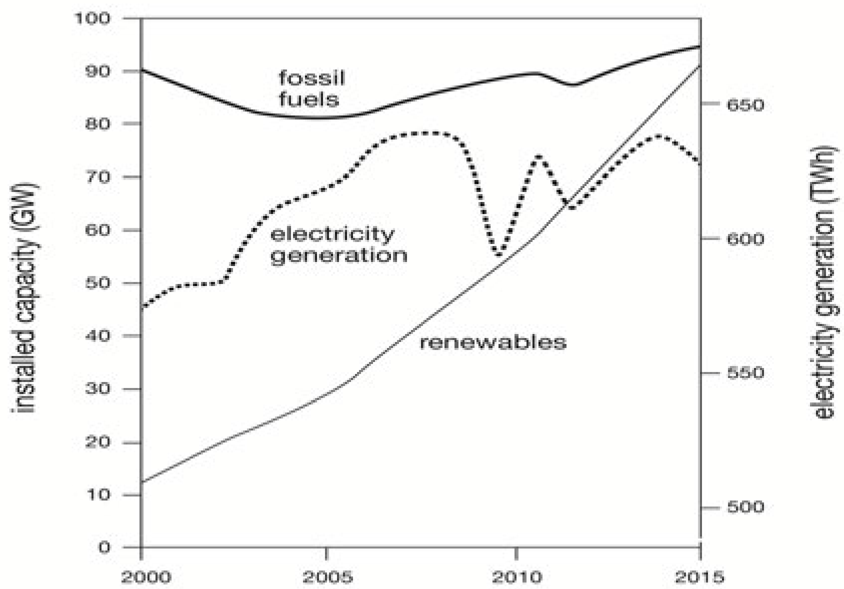
Daily and seasonal fluctuations of electricity demand and availability of solar radiation and wind power mean that by 2050 a German system that would be deriving 80% of its electricity from renewables would have annual surpluses of 47 terawatt-hours higher than the load but deficits of 107 terawatt-hours.

Obviously, electricity storage would not eliminate the need for substantial back-up capacities because surpluses would be less than half of deficits. Germany's need for thermal power capacity thus does not fall with *Energiewende* - and this surprising conclusion is fully supported by German statistics. Germany had 84.2GW of fossil-fuelled capacity in 2000 (mostly fuelled by coal), and by 2014 that total actually rose by about 4% to 87.5GW. During the same time, capacity of intermittent generation rose from just 6.2GW to 84.8GW. Additions of intermittent renewables had thus almost perfectly matched the total installed in fossil-fuelled generators! Due to the concurrent halving of nuclear capacity Germany expanded installed generating power by 62% in 15 years - in order to produce less than 9% more of electricity: such development cannot come cheap.

Despite massive rise in renewable capacity Germany's fossil fuel-fired capacity has not declined

Figure 28

Germany's installed capacity of fossil fuels and renewables and electricity generation



Source: Smil, V. 2017. Energy Transitions; Plotted from data in BWE (2016) and Fraunhofer ISE (2016).

Electricity generated from new renewables up nearly 22 times from 1.19% to 26%

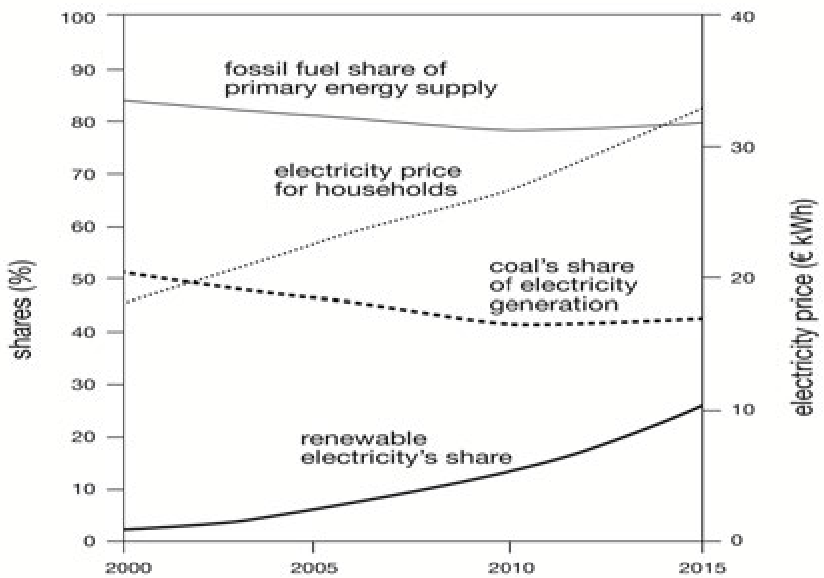
Electricity generated from coal down 16% from 50.5% to 42.2%

Share of fossil fuels in primary energy supply down just by 5% from 83.7% to 79.4%

Cost of household electricity up nearly 80%

Figure 29

***Energiewende* 2000-2015 in four revealing lines**



Source: Smil, V. 2017. Energy Transitions; Plotted from data in BWE (2016)

CLSA comment

As can be seen from the tables below, while Germany's generation capacity has gone up by 62% during 2000-14 the share of renewable generation has gone up from 2% to 19%. Meanwhile, the share of generation from fossil fuels has come down from 61% to 52% during the same period. Also as discussed earlier household electricity prices in Germany have doubled over the past 10 years to fund the higher share of renewables.

Figure 30

Germany's power capacity by source

(GW)	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Coal	32	31	30	30	32	29	29	29	30	29	30	30	30	29	34
Lignite	22	22	22	22	22	22	22	23	22	22	23	25	24	23	23
Oil	8	8	5	5	6	5	5	5	5	5	6	6	4	3	3
Gas	22	23	20	20	19	21	21	21	23	23	24	24	26	27	27
Nuclear	24	24	24	22	21	21	21	21	22	22	22	13	13	13	13
Hydro	9	9	9	9	10	10	10	10	10	10	10	11	10	10	10
Wind	6	9	12	15	17	18	21	22	24	26	27	29	31	34	39
Photovoltaic	0	0	0	0	1	2	3	4	6	10	18	25	33	36	38
Biomass	1	1	1	1	2	2	3	3	4	5	5	6	6	7	7
Other	2	3	4	4	4	5	5	5	6	6	6	6	7	8	8
Total	**125**	**128**	**127**	**129**	**135**	**137**	**140**	**145**	**151**	**158**	**171**	**175**	**185**	**190**	**203**

Figure 31

Germany's power generation by source

(TWh)	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Hard Coal	143	138	135	146	141	134	138	142	125	108	117	112	116	127	119	118
Lignite	148	155	158	158	158	154	151	155	151	146	146	150	161	161	156	155
Mineral Oil	6	6	9	10	11	12	11	10	10	10	9	7	8	7	6	5
Natural gas	49	56	56	63	63	73	75	78	89	81	89	86	76	68	61	60
Nuclear	170	171	165	165	167	163	167	141	149	135	141	108	99	97	97	92
Wind	10	11	16	19	26	27	31	40	41	39	38	49	51	52	57	88
Hydro	29	28	28	23	26	26	27	28	26	25	27	24	28	29	25	25
Other fuels	22	22	20	24	26	33	40	47	51	53	66	77	91	98	107	109
- Biomass	2	3	5	7	8	11	15	20	23	26	30	33	40	41	43	44
- PV		0	0	0	1	1	2	3	4	7	12	20	26	31	36	38
- Waste	2	2	2	2	2	3	4	5	5	4	5	5	5	5	6	6
- Other	18	17	13	15	15	17	19	20	19	16	20	20	20	20	21	20
Total	**577**	**586**	**587**	**609**	**617**	**623**	**640**	**641**	**641**	**596**	**633**	**613**	**630**	**639**	**628**	**652**

Figure 32

Shares of Germany's electricity generation

(%)	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Hard Coal	25	24	23	24	23	22	22	22	19	18	18	18	18	20	19	18
Lignite	26	26	27	26	26	25	24	24	24	24	23	24	26	25	25	24
Mineral Oil	1	1	1	2	2	2	2	2	2	2	1	1	1	1	1	1
Natural gas	9	9	10	10	10	12	12	12	14	14	14	14	12	11	10	9
Nuclear	29	29	28	27	27	26	26	22	23	23	22	18	16	15	15	14
Wind	2	2	3	3	4	4	5	6	6	6	6	8	8	8	9	13
Hydro	5	5	5	4	4	4	4	4	4	4	4	4	4	5	4	4
Others	4	4	3	4	4	5	6	7	8	9	10	13	14	15	17	17
- Biomass	0	1	1	1	1	2	2	3	4	4	5	5	6	6	7	7
- PV	-	0	0	0	0	0	0	0	1	1	2	3	4	5	6	6
- Waste	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1
- Other	3	3	2	2	2	3	3	3	3	3	3	3	3	3	3	3
Total	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Source: BWE 2016

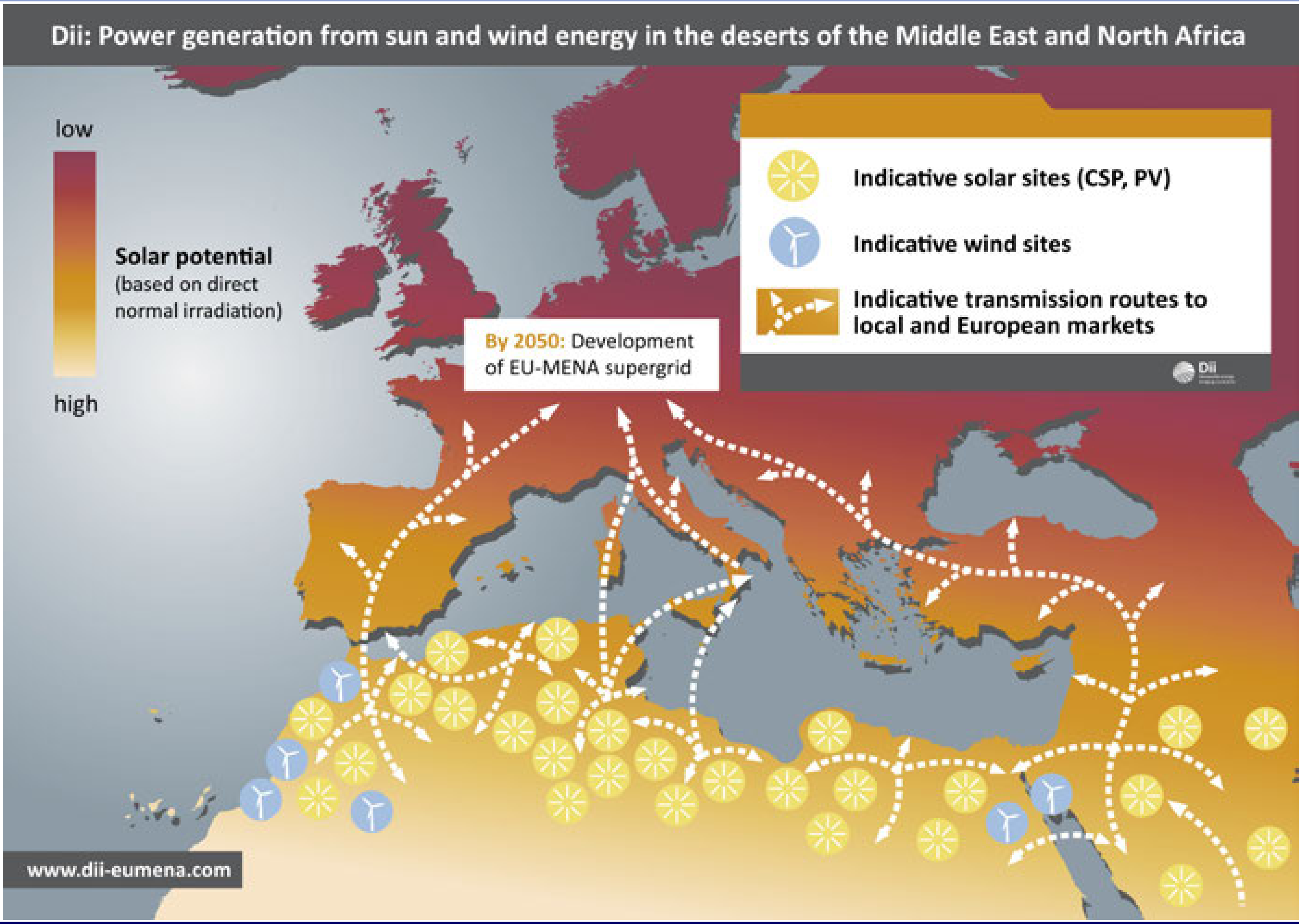
Transmission lines spanning 4-5 time zones to reduce intermittency

Transmission lines would have to span several time zones to counter solar intermittency

Intermittency problems could be lessened in the future by new long-distance high-voltage connections, but for solar generation these would have to span at least four or five time zones to make a substantial difference. Such options are often unavailable: the planned (and now abandoned) DESERTEC project that was to bring export solar electricity from the Sahara to Europe, would have operated within the same two time zones, offering peak power in Algeria at the same time the solar flux would be peaking in Italy or Germany, and there is, of course, no land to locate large solar capacities three or four time zones west of Europe.

Figure 33

The proposed (now abandoned) DESERTEC project



Source: DESERTEC.ORG

US lacks high-capacity transmission lines to trade electricity across the continent

In contrast, large-scale solar farms in California could contribute at 3pm to the East Coast peak at 6pm - but the US lacks mass-capacity longitudinal high-voltage links to trade electricity across the continent. Similar grid constraints apply to exporting electricity from windy Great Plains to the coasts.

Intermittent electricity cannot be readily used for heating and cooling

Peak space-heating needs are mostly after the sunset

And intermittent electricity could not be readily used (even when assuming its very low future costs and leaving the cost of replacing furnaces by heaters aside) for space heating required by more than half a billion people in the northern hemisphere's temperate and sub-Arctic climates: peak heating needs are mostly after sunset with the coldest spells produced by high-pressure cells and the absence of winds. Theoretically, we could turn to geothermal heating and to seasonal storage of solar heat underground - but (even when leaving aside the practicality of retrofitting tens of millions of units of existing housing stock or re-engineering downtowns of megacities) capital and infrastructural needs would make that a transition taking several decades.

Unprecedented electricity demand at night hours for air-conditioning by 2050

But perhaps the greatest challenge created by the intermittency of solar and wind conversions arises from supplying the air-conditioning needs of tropical and subtropical countries in Asia, Africa and Latin America. By 2050 most people inhabiting those three continents will live in large cities in high-rise apartment blocks and air conditioning is one of the first possessions acquired as incomes rise. With the summers getting demonstrably hotter there will be unprecedented increase of electricity demand to night hours as people will run their ACs in order be able to sleep during the spells of 40^0C+ and near-100% humidity weather.

Slow pace of energy transitions

> If we use our fuel to get our power, we are living on our capital and exhausting it rapidly. This method is barbarous and wantonly wasteful, and will have to be stopped in the interest of coming generations. The heat of the sun's rays represents an immense amount of energy vastly in excess of waterpower . . . The sun's energy controlled to create lakes and rivers for motive purposes and transformation of arid deserts into fertile land . . .
>
> Nikola Tesla, 1915

Solar power has taken off only since 1990s

Abundance of solar energy is obvious but (leaving, obviously, food, fibres and wood aside) until recently we were harnessing it on a large scale only via hydroelectricity generation. Its direct (PV) and indirect conversions have taken-off only since the 1990s but in some countries they have gained substantial shares of electricity generation. Transitions in terms of total primary energy are a different matter.

Small economies can shift energy mix rapidly but global shifts are protracted affairs

Small economies can shift their primary energy bases rather rapidly but fuel transitions on the global level, as well in large populous nations, are inherently protracted affairs. Moreover, there is no sign that the overall pace of these transitions has been accelerating: actually the opposite is true as natural gas has been displacing coal and oil at a slower pace than crude oil was displacing coal and traditional biofuels. Several fundamental considerations explain this reality.

In some small economies energy transitions from coal to oil and natural gas have been rapid

In the past many small economies with few domestic energy resources that derived most of its consumption from imports of coal switched fairly rapidly to imported crude oil: energy supply in Ecuador, Haiti, Nicaragua and Cuba became dominated by oil more than half a century before such transitions was accomplished in Europe. And even some large modern economies made a fast substitution by tapping new fuel supplies, as did the Netherlands after 1965. The super-giant Groningen field was discovered in 1959 and at the time coal supplied about 55% of all primary energy, crude oil 43% and natural gas less than 2%. In December 1965 the Dutch government decided to phase out all of the coal mining within 10 years and the last two operating Limburg mines shut down in December 1974. Groningen's rapid development and the closure of all coal mines doubled the share of natural gas from 5% to 10% of total energy consumption in a single year, it took three years to reach 25% and six years to get to 50%.

Shifts in energy supply in large nations proceed incrementally

In contrast, shifts in primary energy supply in large nations and at the global level proceed incrementally and as a result no energy resource has been completely eliminated in 25-50 years. My studies of these fundamental shifts show that after a new energy resource provides 5% of the total supply (that is once it begins to matter in the overall market) it still takes decades before it reaches progressively higher thresholds.

35-55 years needed for coal, oil and gas to reach 25% share

Coal, oil and natural gas required 35, 40 and 55 years to go from 5% share to 25% share

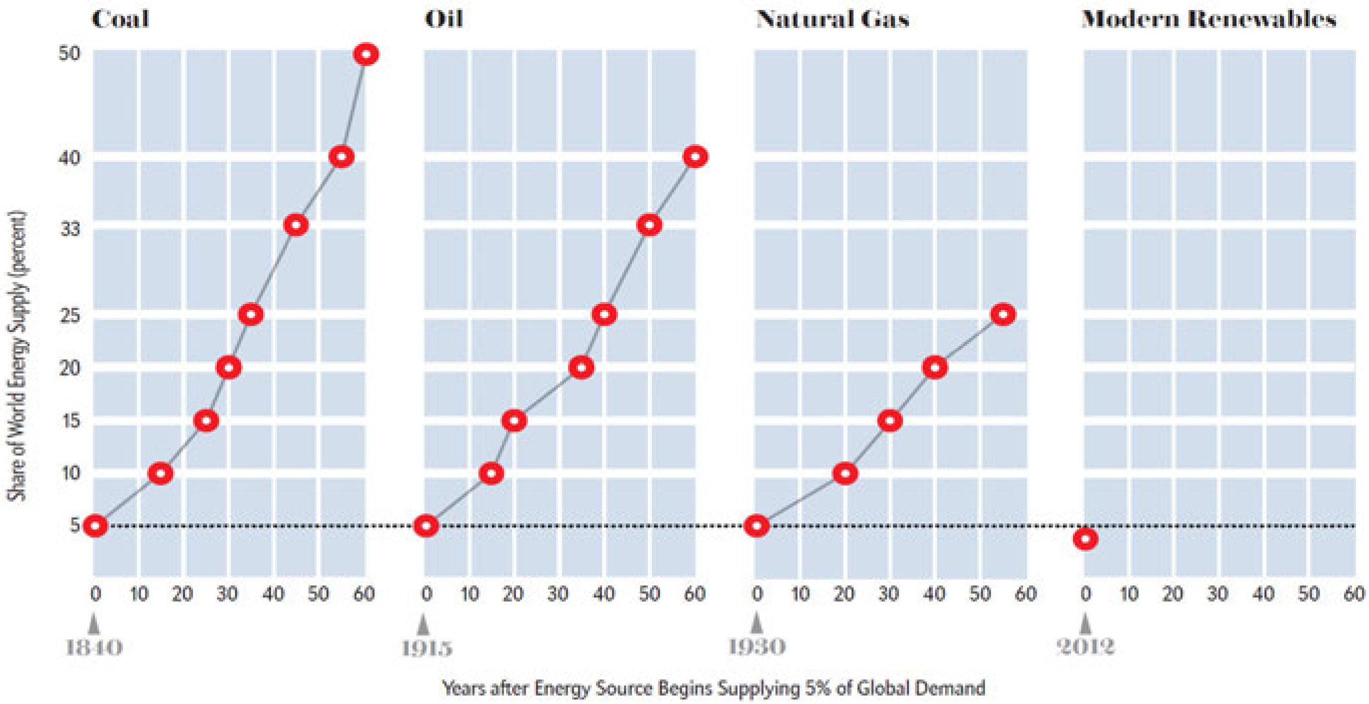
Global coal extraction required 35 years to reach the 25% mark, crude oil production needed 40 years to get to that level and natural gas extraction did it in 55 years. National trajectories differ, but there are no sudden jumps. Once coal began to supply at least 5% of all primary energy it took only 30 years to claim 50% of the supply in Asia's two late-start modernisers (Japan and China), but 55 years in the USA and Sweden. The span was about 70 years for Russia/USSR, and coal's rise from 5% to 50% took more than a century in France and even longer in the UK.

Transition to natural gas has been slower than transition from coal to oil

Oil supply surpassed coal's share only in 1951 in the USA, and in 1974 in the USSR and China still remains highly dependent on coal (64% of all primary consumption in 2015). The transition to natural gas has been significantly slower than the switch from coal to crude oil.

Figure 34

Global share in primary energy of various fuels over time



Source: Vaclav Smil, Scientific American

Extensive and expensive infrastructure needed for transitions

Slowed by rising aggregate supply and infrastructure needs

This has been due not only to the intervening rise in aggregate supply (requiring larger inputs to achieve the same shares) but also due to the need to put in place extensive and expensive infrastructures. Natural gas now supplies more energy than crude oil in about 20 countries including Russia, Qatar, Iran, Nigeria, Brunei, Trinidad, UAE, Malaysia, Egypt and Bolivia.

Energy transition needs combination of technical capabilities and economic advantages (or subsidies)

Gradual progress of fuel transitions has been dictated by a combination of technical and economic imperatives and also by the sheer magnitude of modern energy uses. Many decades were needed to:

- raise labour productivity in coal mining by deploying coal cutting and loading machinery and by shifting more extraction from deep to surface mines;
- develop new drilling techniques (drilling of oil and gas wells was dominated by percussion method, an ancient Chinese invention, until after WWI);
- increase capacities of coal-fired turbo-generators or crude oil tankers (both of these techniques stagnated between the two world wars);
- and build infrastructures needed to move (railroads, oil and gas pipelines, tankers and their terminals), process (coal preparation and coking facilities, refineries) and use (industrial boilers, furnaces, power plants, internal combustion engines) solid, liquid and gaseous fossil fuels.

High capital costs of extraction, transportation and conversion activities

High capital cost of these extractive, transportation and conversion activities has promoted their longevity while technical innovation enabled continued extraction and conversion of resources that were previously classified as uneconomical. The recent rise of hydraulic fracturing in the USA has been a perfect illustration of these trends. Its key components, horizontal drilling and high-pressure fracturing, are old practices dating, respectively, to before WWII and to the late-1940s, and experiments with their combined deployment began during the 1980s, but only when the production cost declined sufficiently (while oil and gas cost had increased) the option became

economical and led to a rapid increase of US hydrocarbon production. Similarly, the first commercial LNG shipment took place in 1964 but it was only in 2015 when liquefied gas accounted for 25% of all traded natural gas.

Decades between first trials of new techniques and their widespread commercial acceptance

Quest for higher market share made difficult by rising energy use

Time spans from the first trials of new techniques and their widespread commercial acceptance are thus commonly measured in decades, and the quest for a higher market share has been increasingly daunting due to the growing scale of overall demand. For example, replacing 10% of the global coal output by natural gas would have needed additional 160bn m^3 in 1970 -- but more than 400bn m^3 in 2015, and the US wind turbines could have captured 10% of electricity generation with 230TWh in 1980 - but the total rose to 430TWh by 2015 (when actual wind generation was about 190TWh).

Each primary fuel currently dominates specific markets . . .

. . . making it impossible for a single energy source to account for more than 50% of primary energy consumption

Moreover, segmentation of modern energy demand - coal now has just two large markets, for electricity generation and coke; refined oil products dominate transportation uses and supply feedstocks for chemical syntheses; and natural gas is used mostly for industrial and household heat, electricity generation and as a petrochemical feedstock - makes it impossible for a single energy source to account for more than 50% of overall primary energy consumption as coal did during the first half of the 20th Century. That explains why the consumption shares of fossil fuels have remained remarkably stable during the past generation even as the total demand (including traditional biofuels) rose by 50%: shares of coal, oil and natural gas were, respectively, 28%, 39% and 22% in 1990, little changed in 2015 at 29%, 33% and 24%.

Figure 35

Global energy mix - 1990

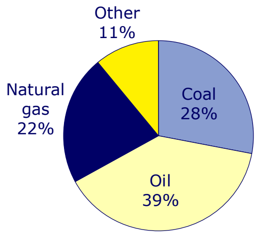
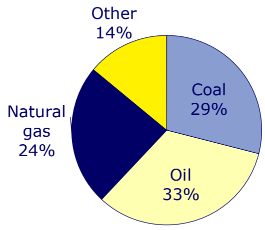


Figure 36

Global energy mix - 2015



Source: Vaclav Smil

After 25 years of vigorous development renewables remain marginal contributors

Ascending renewables: Just facts

The 20th-Century energy transitions changed the mix of fossil fuels whose combustion created modern societies, but the new global energy transition has been largely a shift in electricity generation and, to a much lesser extent, production of liquid biofuels. Contrary to common beliefs, after a quarter century of vigorous development renewable conversions remain marginal contributors to the global primary energy supply.

Primary electricity generation now contributes about third of the total

Primary electricity generation (not based on the combustion of fossil fuels) began its slow market penetration during the 1880s with the construction of first small hydro stations. Hydro generation rose to unprecedented heights during the 1930s with large-scale projects in the USA and the USSR, and dam building had its largest expansion during the second half of the 20th Century. Commercial nuclear generation began in 1956 and experienced its fastest expansion between 1970 and 1990. Modern wind turbines were first used in large numbers in California during the 1980s, but European countries led the post-1990 expansion of wind-powered generation. Solar photovoltaics were quite negligible until the beginning of the 21st Century. Geothermal electricity remains a relatively small contributor. In 2015 primary electricity, dominated by hydro and nuclear, contributed nearly a third of the total global generation.

Figure 37

Share of modern renewables in primary energy supply using different energy conversion rates[1]

	Electricity/ energy units	Converting 1kWh of renewable generation to 3.6MJ energy		Converting 1kWh of renewable generation to 9.5MJ energy	
		1995	**2015**	**1995**	**2015**
Fossil fuels (energy)	Mtoe	7,464	11,306	7,464	11,306
Hydro power (electricity)	TWh	2,479	3,946	2,479	3,946
Hydro power (energy)	Mtoe	213	338	562	892
Nuclear power (electricity)[2]	TWh	2,324	2,577	2,324	2,577
Nuclear power (energy)	Mtoe	526	583	526	583
Solar power (electricity)	TWh	0.6	253	0.6	253
Solar power (energy)	Mtoe	0.05	22	0.13	57
Wind power (electricity)	TWh	8	841	8	841
Wind power (energy)	Mtoe	0.7	72	1.9	190
Geothermal and bio-waste (electricity)	TWh	151	518	151	518
Geothermal and bio-waste (energy)	Mtoe	13	44	34	117
Biofuels (energy)	Mtoe	9	75	9	75
Total Primary energy supply	**Mtoe**	**8,226**	**12,440**	**8,597**	**13,221**
Energy supply by new renewables[3]	**Mtoe**	**23**	**213**	**45**	**439**
Share of modern renewables (%)		**0.28**	**1.71**	**0.52**	**3.32**
Share of wind (%)		0.01	0.58	0.02	1.44
Share of solar (%)		0.00	0.17	0.00	0.43
Share of biofuels (%)		0.11	0.60	0.11	0.57
Share of geothermal and bio-waste (%)		0.16	0.36	0.40	0.89

[1] As discussed in this report the choice of conversion rates from electricity to energy is the most important reason (besides some uncertain conversions of fuel output to energy equivalents) for having different shares of renewables in the total supply depending on the data source, that is using UN, IEA, US EIA or BP statistics. [2] Nuclear energy has been converted at 9.5MJ per kWh in both the scenarios. [3] New renewables include solar, wind, biofuels, geothermal power and bio-waste energy. Source: BP, Vaclav Smil, CLSA

This report converts 1kWh of hydro, solar and wind electricity as 3.6MJ and 1kWh of nuclear electricity as 10.9MJ nuclear

There are two ways of converting primary electricity to a common energy equivalent. The first one is to use electricity's thermal equivalent with 1kWh equal to 3.6MJ. The second one is by calculating the equivalent amount of fossil fuel required to generate the same amount of electricity in a thermal power station, assuming average conversion efficiency between 33-38%: 1kWh is then equal to 9.5-10.9MJ. National and international statistics have approached this choice in different ways: United Nations and the International Energy Agency use a hybrid solution: thermal equivalent for hydroelectricity and also for solar and wind, but for nuclear electricity they assume 33% efficiency (1kWh=10.9MJ). In my work I follow this hybrid solution but I assume higher average efficiency (about 38%) when converting recent nuclear electricity generation. The US Energy Information Administration uses an annually adjusted conversion factor for nuclear electricity (11MJ/kWh in 2015), and it applies the average fossil-fuels heat rate to convert electricity generated by all renewable conversions (average of 10MJ/kWh in 2015) in order to approximate the amount of fossil fuels that have been replaced by these non-fossil sources. And British Petroleum's *Review of World Energy* converts all primary electricity at 9.5MJ/kWh.

In 2015 wind and solar contributed 1.8% of the world's primary energy

Obviously, these choices will convert the same amount of primary electricity to substantially different amounts, and hence shares, of primary energy and for proper comparisons it is necessary to specify the conversion. In 2015 PV generation reached 1% of the total electricity and even when converted at the high rate of 9.5-10MJ/kWh it added up to only about 0.4% of the world's 2015 primary energy consumption. Shares for wind-generated electricity were 3.5% of the total and maximum of 1.4% of primary energy in 2015. Combined solar and wind generation thus produced about 4.5% of the world's electricity in 2015, but at most only 1.8% of all primary energy, still far below the 5% share, the level at which an energy source becomes a significant component of the overall supply.

Share of renewables in energy is growing at a slower pace than fossil fuels in their early days

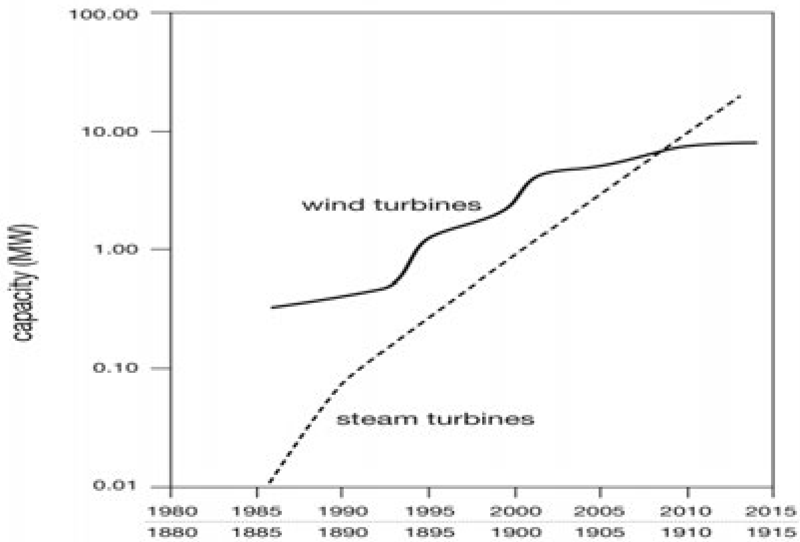
And after adding geothermal electricity and energy supplied by modern biofuels (ethanol, biodiesel) and biomass waste, the share of new renewables in total energy supply had increased (using the maximum conversion alternative for wind and solar generation) from about 0.5% in 1995 to about 3.3% in 2015, growing at an average annual exponential rate of 9.7%. That pace is actually comparable to the growth of other energy sources during their early stages of expansion when our technical capabilities were much

weaker. Coal was increasing market share at more than 5%/year between 1850 and 1870; crude oil growth averaged more than 9%/year during 1880-1900, and natural gas was increasing its global market share by 7%/year between 1920 and 1940. And it must be also remembered that the early expansion of fossil fuel production required the development of new expensive infrastructures for their transport and use, while most of today's renewably generated electricity can be readily sold through the existing grid and liquid biofuels use the existing network of filling stations.

In its early days, growth rate of steam turbine capacities was as fast, or faster, than growth of modern wind turbines

Figure 38

Growth of wind turbines (1986-2014) and steam turbines (1885-1913)



Source: Plotted from data in Smith (1987), UpWind (2011), MHI Vestas Wind Offshore (2016) and Smil (2005)

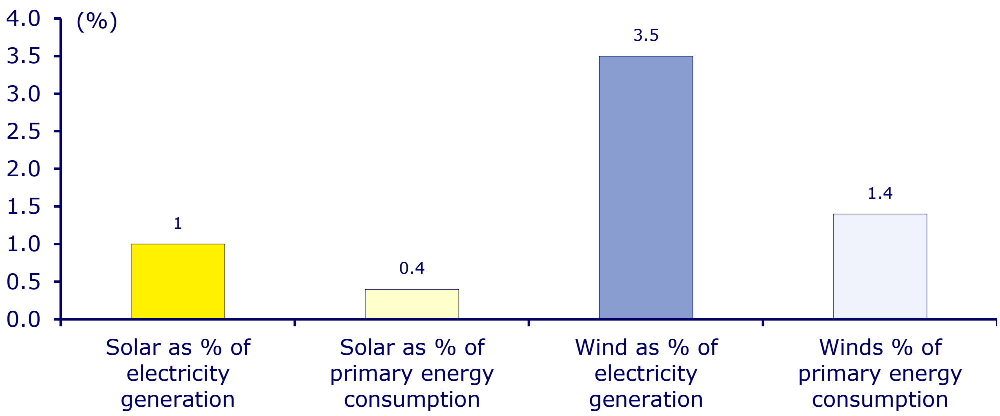
In its first 25 years nuclear generation grew at similar rates as solar and wind in last 25 years

And how about if we leave aside the conversions to primary energy and assess the expansion of new renewable electricity simply in terms of actual generation? Global output of solar PV went from 0.5TWh in 1990 to 253TWh in 2015, wind generation rose from 3.6 to 841.2TWh during the same period. This means that solar generation has been expanding by an average annual exponential rate of about 25% while wind generation has been rising at nearly 22% per year. These have been fast rates but nuclear electricity generation grew at a comparable annual rate (22.6%) during the first 25 years of its commercial expansion between 1960 and 1985. Worldwide, combined solar and wind generation produced 4.5% of electricity in 2015, compared to 16.4% from hydro and 10.7% from nuclear.

Solar and wind power contribute 1.8% to global primary energy supply

Figure 39

Share of solar and wind power in global electricity and energy mix in 2015



Source: Vaclav Smil, CLSA

Most of PV and wind capacity is concentrated in a small number of countries

And while scores of nations now have some PV installations or wind turbines, so far both of these conversions have been disproportionately concentrated in a small number of countries. In 2015 three-fifths of all wind electricity originated in just four countries (USA, China, Germany and Spain) and the same high share of solar electricity came from just five nations (Germany, Italy, China, Spain and Japan). As for the national shares of PV generation in total electricity output, in 2015 they ranged from 8.9% in Italy and 5.9% in Germany to 3% in Japan, 0.9% in the USA and 0.7% in China. The highest shares for wind-generated electricity were in Denmark (50%), Portugal (22%), Spain (18%) and Germany (nearly 14%), with the USA at 4.5% and China and India at 3.2%. This means that both globally, as well as in the USS and in China, the combined share of solar and wind is still smaller than the contribution by hydroelectricity: in the USA 5.4% vs 5.9%, in China 3.9% vs 19.4%.

Bio-fuels growing at a slower rate and concentrated in USA and Brazil

The other fast-rising sources of new renewables have been biofuels, ethanol fermented mostly from corn and sugar cane, and biodiesel derived from various oil crops. Worldwide output of these fuels has been growing at less than half the rate of solar or wind expansion (at about 9.5%/year since 1990) and nearly two-thirds of the total is ethanol from just two countries, the USA (about 40% of the total) and Brazil (about 25%). In 2015 the combined production of these two fuels reached an equivalent of about 75 million tonnes of crude oil, which is only about 3% of the world's demand for liquid transportation fuels.

No unusually rapid transition to renewables

Transition to renewables to happen at the same pace as transition to coal

As already noted, no forecast of global energy transitions puts the share of new renewables (wind, solar and modern biofuels) higher than 15% by 2040. Even when assuming that the new renewables (at 3.3% of global primary energy in 2015) will reach 5% of the total supply by 2020 on their way to 15% by 2040, that rate of growth would be very much in line with the pace of previous substitutions, implying that new renewables would take about 35 years to go from 5% to 25% of the global supply, or the same speed with which coal was replacing wood after 1840, and just a bit faster than crude oil was displacing coal after 1915: no unusually rapid energy transition has been underway!

Four factors will be the key determinants of the future shift to new renewables:

Four key factors: scale of demand; availability of renewable energy; intermittent generation; low power densities of renewables

- The already noted overall scale of the replacement demand (at today's rate the future non-carbon world would have to find substitutes for more than 11bn tonnes of oil equivalent a year, power of 15 terawatt!);
- Availability of renewable energy resources (only solar flux is large enough to provide many times more energy than is currently needed worldwide, all other renewable energy flows are relatively much more limited);
- Intermittent generation of solar and wind electricity; and
- Generally low power densities of renewable energies.

New renewables and fossil fuels

Today no new conversions of renewables can be done without fossil-fuel inputs

Hydro electricity, still the most important form of renewable energy production, requires substantial inputs of fossil fuels for steel and concrete required to build large dams, turbo-generators and high-voltage transmission lines. No new conversions of renewable energies can be done without fossil-fuel inputs, wind-powered generation is particularly dependent on coal and hydrocarbons. But the production of solar photovoltaic modules also relies on fossil fuels.

All renewable conversions will, for decades, continue to rely on fossil fuels

The term non-carbon energies is a misnomer because all renewable conversions depend on large amounts of raw materials that are, and for decades will continue to be, produced solely or predominantly by burning fossil fuels.

A 5MW wind turbine needs 900 tonnes of steel whose production requires 25GJ/tonne

World Steel Association data show that a 5-megawatt wind turbine requires 150 tonnes of steel for its reinforced concrete foundations, 250 metric tonnes for the rotor hubs and nacelles (housing the gearbox and generator), and 500 tonnes for the towers. Typical energy cost of steel used in wind turbines is about 25 gigajoules per tonne.

Wind farms also rely heavily on plastics and fibreglass

Turbines have three 60-metre-long 15-tonne airfoils; their light cores made of balsa wood or of styrene acrylonitrile, polyvinyl chloride and polyethylene terephthalate foam are covered by glass-fibre-reinforced epoxy or polyester resins. Glass is made in furnaces fired by natural gas and the production of resins is based on ethylene derived from naphtha cracking in refineries, from liquefied petroleum gas or from ethane separated from natural gas. Energy cost of fibre-reinforced composites is around 170 gigajoules per tonne, and the entire assembly must be waterproofed with ethylene-based resins.

Substantial use of coal and oil would be needed to get a high proportion of electricity from wind power

My conservative calculations show that if wind farms were to generate a quarter of the global electricity by the year 2030 their construction during the next 14 years would require nearly half a billion tonnes of steel (equivalent to nearly a third of annual output in 2015) and nearly 100 million tonnes of plastics (almost equal to annual output of all plastic varieties). Altogether, production of these materials would consume an equivalent of more than 600 million tonnes of coal and 90 million tonnes of crude oil. And more coke would be needed for steel in transformers, more liquids derived from oil would be needed to transport the massive blades and towers to their sites and to excavate their foundations by using heavy diesel-fuelled machinery, and turbine gearboxes would have to be filled, and refilled, with lubricating oil and fossil fuels would be required to produce millions of tonnes of cement poured into turbine tower foundations.

PV modules and plants also need carbon and steel

Silicon, be it for microchips or PV cells, is produced on a commercial scale by the carbothermic reduction of quartz (SiO_2) in arc furnaces lined with carbon and equipped with three suspended pre-baked carbon electrodes. Liquid silicon is produced by passing high current through mixtures of quartz and reducing agents, most commonly coal, petroleum coke or charcoal. Large solar farms are also substantial consumers of special structural steel that must have high corrosion resistance because module frames and ground-mounted structures should last, without maintenance, for the duration of the project. And the continued expansion of both wind and PV farms would require extensive additions of new high-voltage lines, and hence more steel and cement to connect new generation facilities installed in optimum location with distant load centres.

Production of biofuels is dependent on fossil fuels for harvesting, fertilisers, transport and processing

Production of biofuels is also highly dependent on fossil energies. Steel is needed for field machinery (tractors, harvesters) and for irrigation pumps and fossil energies provide fuel and feedstock to synthesize ammonia (high-yielding biofuels require fertilisation). And the production of most pesticides (whose applications are needed to ensure high yields in monocultural biomass plantations) starts with ethylene and propylene that are derived by catalytic cracking of crude oils or from natural gas. More steel is needed for trucks to transport the harvested biomass to conversion points, and for fermentation plants (stainless steel tanks, piping, storage tanks).

In foreseeable future renewable energy systems will continue to depend on fossil fuels

And while it is true that an efficient large turbine operating with a high capacity factor would generate in a single year more energy than it took to produce its constituent materials, all of it comes as intermittently produced electricity while the production of requisite materials will need specific fossil fuels (coke, petroleum coke, naphtha, natural gas). Future energy systems would totally sever their dependence on fossil fuels only when all energies required to produce the materials for wind turbines, photovoltaic panels, ethanol or biodiesel industry would come from renewable energy conversions - and I would not even venture a guess how remote such a reality might be.

Electric vehicles

Critical appraisal of EV market not as positive as media suggests

Mass media, as well as some organisations, have been uncritical promoters of electric vehicles in general and of Tesla cars in particular, creating an uninformed impression that such cars will soon dominate the automotive market. Critical appraisal of actual sales, their likely prospects and environmental impacts of electric vehicles offer a corrective perspective.

Large gaps between projections and reality

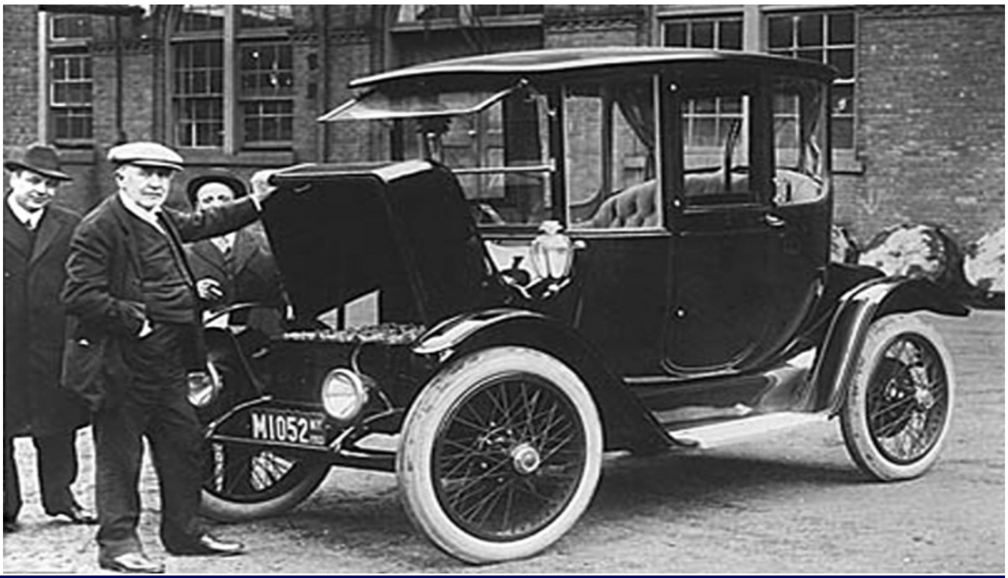
2015 US EV market share of 0.6% of car sales was well below forecasts of 2-6%

In the second section of this report, I reviewed large gaps between overly enthusiastic green energy forecasts and actual realities. Such gaps are similarly large as far the projections of electric car sales are concerned. Between 2009 and 2011 eight different forecasts put the US shares of electric car sales (including plug-in hybrids) at between nearly 2% an 6% in 2015 and 3-11% in 2020 - while actual electric vehicles and their closest kin, plug-in electric hybrid vehicles, claimed just 0.6% of the market in 2015, or as much as an order of magnitude below the forecast levels. Global stock of electric vehicles reached 1.26 million units in 2015 or 0.1% of vehicles on the road. But that has not changed many bold forecasts with imminent visions of rapid take-off. But the latest International Energy Agency report on electric vehicles makes it clear than even annual sales growth of 60% in the 14 largest national markets would bring the stock of electric vehicles to no more than 3% in 2020: a long road to market dominance lies ahead.

Electric cars was one of Edison's pet projects and he spent many years of his life on it

Figure 40

1905, Thomas Edison with his favourite vehicle: he saw no future for gas-fuelled cars



Source: pbs.org

Figure 41

2015, Tesla S US$72,700; 50,580 sold = 0.28% of all US light vehicle sales

Enthusiastic forecasts of EV sales have so far proved wrong

Source: Tesla

Global cumulative sales of electric and plug-in hybrids less than 0.1% of passenger cars in service

Although global cumulative sales of electrics and plug-in hybrids surpassed one million units by the end of 2015, that total was less than 0.1% of about 1.25 billion passenger cars in service. Perhaps the most notable example of exaggerated expectations is Tesla's promise to produce 500,000 affordable Model 3 EVs by 2018.

Tesla repeatedly missed its targets and the Model S has worse than average overall problem rate

The company has repeatedly missed its previous production targets. Moreover, media besotted by Musk's manipulative tweets have ignored a telling judgment: Tesla cars were judged as having a "worse-than-average overall problem rate" by *Consumer's Reports*, America's premier ratings source of product quality.

Often electricity used in EVs is generated using fossil fuels

Electric vehicles offer carbon-free transport only where power supply is hydroelectric

The most fundamental misunderstanding regarding EVs is the uncritical use of the term 'electric' with its implication of no-carbon greenness, the label which makes them instantly superior to gasoline-fuelled internal combustion engines, and hence a key ingredient of the global strategy to keep the rise of average tropospheric temperatures to less than 2^0C. But that is inarguably true only in those instances where all electricity comes from water power: in Norway, Quebec, Manitoba or Nepal. To a very large extent it is true in Canada and France, where about 80% of all electricity come from either hydro or nuclear generation. Although construction of both hydro and nuclear plants required fossil fuels, EVs in those countries are powered by electricity whose generation does not directly produce greenhouse gasses - although large reservoirs are major sources of both carbon dioxide and methane, making even this source far from greenhouse gas-free!

In most of the world EVs use electricity generated from fossil fuels

But EVs operating in many other countries just translocate the greenhouse gas generation from where the cars are driven to where electricity is generated. An EV operating in China's northern provinces or in many Indian states where 90% of all electricity is generated by coal combustion, will (everything else being equal) emit only 25% less greenhouse gasses than a car with a gasoline-fuelled internal combustion engine. And electric vehicles are not the most effective choice to reduce CO_2 emissions also in such populous countries as Turkey, Indonesia, Thailand, Mexico and Japan in Asia,

Poland and the Netherlands in the EU, and in such US states as Missouri, Texas and Florida, where fossil fuels generate more than three-quarters of all electricity.

Switching to EVs in countries relying on electricity from coal may not be the best choice

In all those instances switching to electric vehicles would mostly amount just to transferring CO_2 emissions from urban areas to the regions with the largest concentrations of coal-fired electricity generating plants (which, in some instances, are fairly close to large cities). That might improve urban air quality (because internal combustion also generates nitrogen oxides, CO and volatile organic compounds, the precursors of photochemical smog) but it will do very little to reduce the overall carbon emissions. Where coal-generated electricity dominates the supply hybrid vehicles, rather than electric vehicles, would be the best choice to cut CO_2 emissions.

In Missouri EVs will lower emissions by 27% but hybrids would lower them by 45%

For example, a US study showed that in Missouri (80% of electricity from fossil fuels) electric vehicles would cut the emissions by 27% but hybrids would lower them by 45%. And hybrids have already a much larger share of new car market: in 2015 they accounted for nearly 3% of global car sales and by 2020 that share may approach 8%.

Owning Toyota Prius or Ford Fusion would be a better choice than Tesla

Unless you live in Norway or in Manitoba you have no compelling case for owning a pure electric vehicle and buying such hybrids as the Ford Fusion or Toyota Prius would be a far better choice than spending money on a poor-quality Tesla. Even more fundamentally, considerable energy savings (and hence emission cuts) could be achieved by building lighter cars by reversing the post-1990 trend toward ever-heavier vehicles (the US mean is now about 1.7 tonnes, the European average is about 1.4 tonnes, 25-50% above the mean of the early 1980s.

Hybrids would be a better choice than pure electric vehicle

Figure 42

Ford Fusion

Source: Ford

How to reduce reliance on fossil fuels

We shall need a substantially new way of thinking if humanity is to survive.

Albert Einstein, 1954

Could this be beyond our capabilities?

How to reduce our reliance on fossil fuels and raise the share of renewables in order to limit the extent of global warming while maintaining affordable supply of fuels and electricity in affluent nations and assuring substantial expansion of energy use for billions of people in low-income countries? We must concede that to do this all within a few decades might be beyond our capabilities.

Even if all Paris pledges are fulfilled global temperatures would rise above 2^{0}C

Enormous benefits of fossil fuel would have to end due to an eventual exhaustion of their economically recoverable resources - even if their combustion would not drive the rise in global temperatures. The concern about global warming is already the key factor motivating the transition to a non-carbon world but it will be a long and difficult shift and there is no guarantee of a timely success: even the fulfilment of all emission reduction pledged in Paris in 2015 would lead to roughly 50% rise of CO_2 emissions above the 2014 level and to global temperature increase higher than 2^{0}C. How can we improve the odds of success? A few major technical advances would help, none more urgent than new and better ways to store electricity.

No indications of any imminent breakthrough in large-scale commercial electricity storage

That would be the most consequential help to accelerate further advance of intermittent renewables. But a combination of the falling cost of PV cells and of better batteries will not bring an early demise of all fossil-fuelled generation (recall that, so far, there has been no decline in coal-fired capacity even in Germany with its extraordinary push toward renewables). Module prices have been dropping steadily but typical field efficiencies of commonly deployed cells have been rising very slowly and the same has been true about the scale of better storage: elimination of coal- and gas-based generation is predicated on an inexpensive and flexible storage on a gigawatt scale (far beyond a better battery) and there are no indications of an early breakthrough in that regard.

Cars are an easier challenge compared to heavy diesel engines powering trucks, ships

We also need better ways to power all means of transportation. Cars are actually an easier challenge compared to finding a replacement for heavy diesel engines that power trucks, construction machinery, giant container ships and bulk cargo carriers.

Flights without highly efficient kerosene-powered gas turbines is an even bigger problem

Flight without highly efficient kerosene-powered gas turbines is an even greater challenge and no early breakthroughs are on the commercial horizon: incremental improvements will continue, but (especially given the scale of their current deployment) both diesel engines and gas turbines will be with us for decades to come.

Infatuation with rapid technical innovation as the solution is bound to disappoint

And so will some key industrial processes that are energised by fossil fuels and that have no ready alternatives. In any case, recent infatuation with technical innovation as a rapid solution of all problems is bound to lead to disappointments.

Decades must elapse before fundamental energy innovations . . .

History of technical advances shows that even successful innovations take a long time to make their mark in all cases that require mass-scale diffusion of fundamental techniques, be they new processes in metallurgy, new prime movers in transportation or new ways of energy conversions.

. . . are transformed from ideas or prototypes to mass-scale commercial realities

A snapshot of kittens can now go globally "viral" in a matter of hours - but decades must elapse before fundamental energy innovations are transformed from ideas or prototypes to mass-scale commercial realities: today's breakthroughs in mass-scale energy conversion and use would not be tomorrow's runaway commercial successes. Examples abound.

Figure 43

Time taken for energy technology adoption

Energy source / technology	Timespan from early stages to mass-scale commercial reality
Gas turbines	112 years from the concept to first poorly working machine
	36 years from first working machine to first commercial installation
	30 years from first commercial installation to the first (US) wave of widespread adoption
	20 years from start of widespread adoption to orders for gas turbines surpassing orders for steam turbines
	86 years from the first commercial machine to being converter of choice (but still competing with other machines)
LNG Transportation	43 years from breakthrough in liquefaction of gases to air liquefaction patent
	44 years from first LNG shipping patent to first trial LNG delivery
	46 years between first commercial delivery and LNG accounting for around 10% of all natural trade
Hydraulic fracturing to produce hydrocarbons	60 years between introduction and widespread use
Air conditioning	70 years between invention and half of US households using it
Coal extraction	35 years between reaching 5% of global primary energy supply to 25% share
Oil Extraction	40 years between reaching 5% of global primary energy supply to 25% share
Natural Gas Extraction	55 years between reaching 5% of global primary energy supply to 25% share

Source: Vaclav Smil, CLSA

It took four decades for gas turbines to generate 10% share of US electricity

The first use of gas turbine in electricity generation was in 1939 but new machines began to generate more than 10% of US electricity only four decades later. And four decades had also elapsed between demonstrating nuclear fission (1939) and the time the nuclear plants generated 10% of the world's electricity.

The table below traces the development of stationary gas turbines for electricity generation (gas turbines as jet engines propelled the first test flight in 1939, the first, ill-fated commercial airliner in 1952, Boeing 707 in 1958 etc.)

Figure 44

History of stationary gas turbine for electricity generation

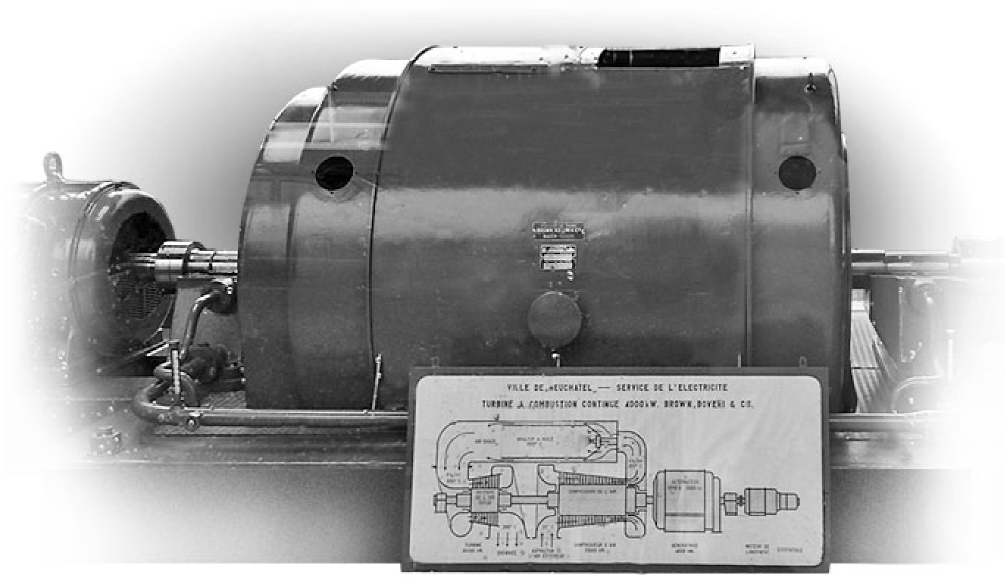
Year	Event
1791	John Barber patent for turbine engine (impossible to build at that time as there were no suitable materials)
1882	Aegidius Elling (Norway) begins to build his simpler, six-stage centrifugal compressor machine that eventually produced small amount of power in 1903
1895	Sanford Moss (US) made his first design proposal in 1895 and builds a laboratory prototype at GE by 1907
1899	Charles G. Curtis received his patent for a gas turbine engine (US 635,919)
1903	Société des Turbo-moteurs (Auguste Rateau, Charles Lemale and Rene Armengaud) designed and built several machines, the best one with the efficiency of less than 3%
1908	Swiss company Brown Boveri completed its first prototype based on the designs of Hans Holzwarth
1917	Sanford Moss sets up a turbine research department at GE's steam turbine factory in Lynn, Massachusetts
1921	Maxime Guillaume filed a French patent application for a turbojet engine (*propulseur par réaction sur l'air*), another theoretical exercise
1928	Holzwarth's small gas turbine made by Brown Boveri installed in a German steel mill
1939	The first stationary gas turbine with utility-scale capacity by Brown Boveri for the municipal electricity-generating station in Neuchâtel. Its rated capacity was 15.4MW but because its compressor consumed almost 75% of the generated power and because all exhaust heat was vented the actually available capacity was no higher than 4MW, resulting in a poor efficiency of just over 17%
1949	Westinghouse and GE introduced their first gas turbines for electricity generation (with capacities of less than 1.5MW)
1959	Aggregate capacity of American gas turbines was just 240MW, less than a single large machine delivers today
1960	Largest turbine capacity reaches 20MW
1965	Northeastern blackout (November 9) promotes the use of rapidly deployable gas turbines
1968	Turbines with total capacity of 8GW installed between 1965 and 1968
1970s	Combined cycle generation begins
1975	Total US gas turbine capacity reaches nearly 45GW
1976	Largest gas turbines reach 100MW capacity and 32% efficiency
1988	Largest turbine reaches 200MW capacity
1990	Worldwide orders for gas turbines surpass the orders for steam turbines
2007	Siemens introduces the world's largest machine, SGT5-8000H rated at 340MW and 530MW in combined-cycle plant with efficiency of 60%
2011	GE introduces 9HA 01 rated at 397MW
2015	Siemens SGT5-8000H now at 400MW simple and 600MW (gross) combined cycle
2015	US has added nearly 80GW gas turbine capacity since 2005
2016	GE 9HA 02 rated at 519MW in simple cycle and 592MW (net) in combined cycle, 61.4% efficient

Source: Smil, V. 2014. *Natural Gas: Fuel for the 21st Century*. Cambridge. MA: MIT Press; Hunt, R.J. 2011. *The History of the Industrial Gas Turbine*. IDGTE Paper 582; US Energy Information Aadministration. 2016. Electricity Statistics.

World's first successful electricity generating turbine to go into commercial operation

Figure 45

Neuchatel gas turbine, 1939: 4MW capacity, 17% efficiency



GE's modern gas turbine with over 41% efficiency in single cycle and over 61% in combined cycle

Figure 46

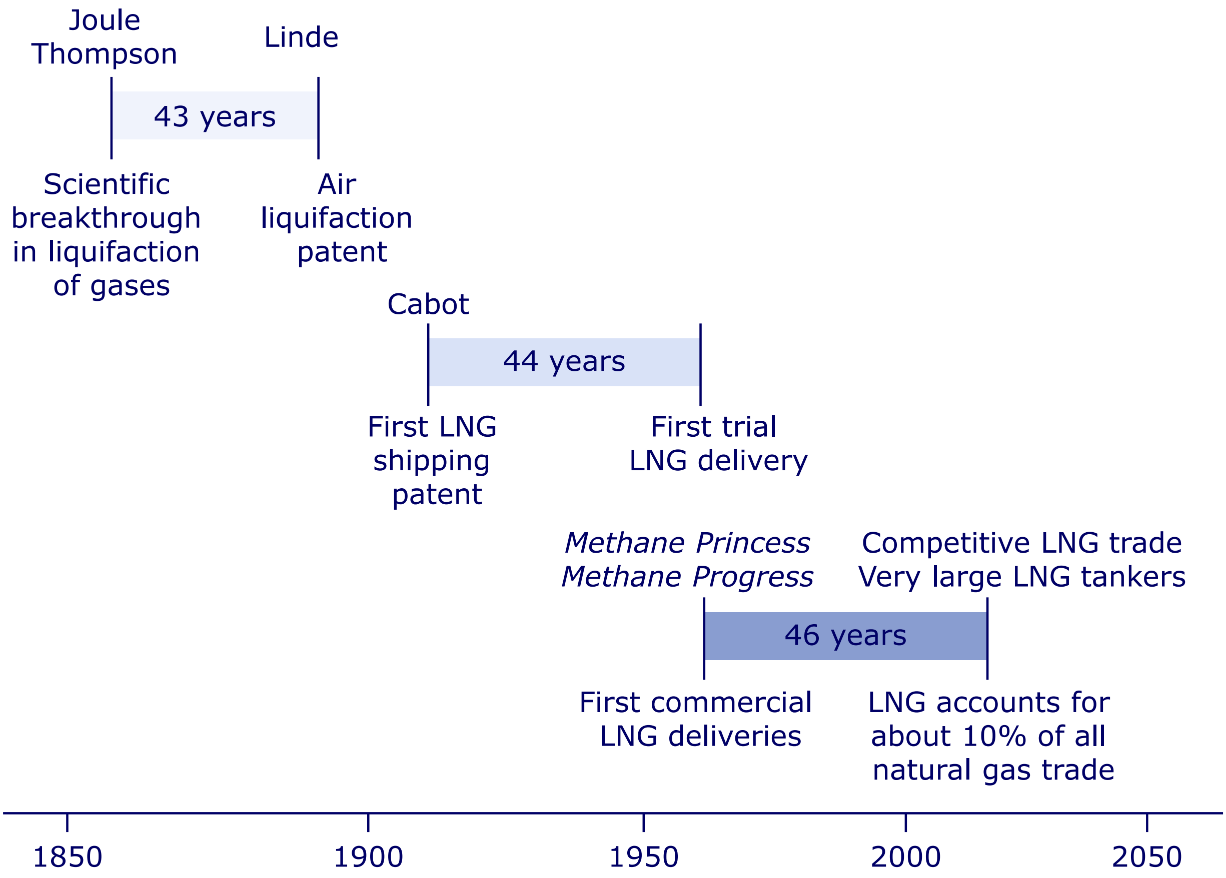
GE's 7HA gas turbine, 2014: 227-335MW single cycle capacity, >61% combined cycle efficiency

Source: ASME

This timeline of another key modern energy technique, LNG transportation, provides a similar example of prolonged development spanning generations:

Figure 47

Timeline of the development of LNG transportation



Source: Smil, V. 2014. Natural Gas: Fuel for the 21st Century. Chichester: Wiley

Figure 48

1853, William Thomson (Lord Kelvin): Gas cools as it expands when forced through a nozzle

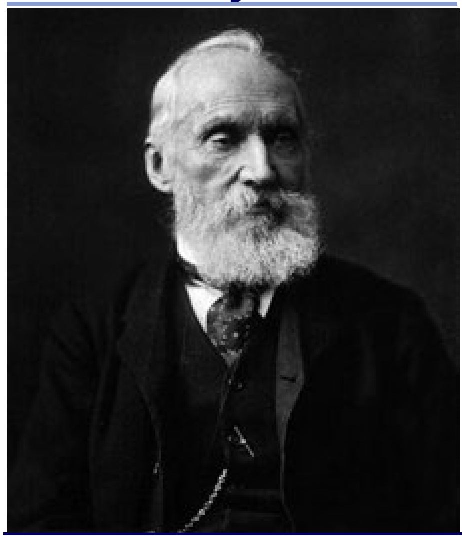


Figure 49

1895, Carl von Linde: Commercial air liquefaction

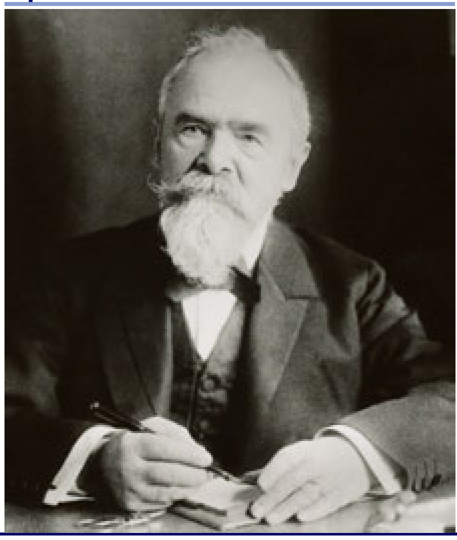
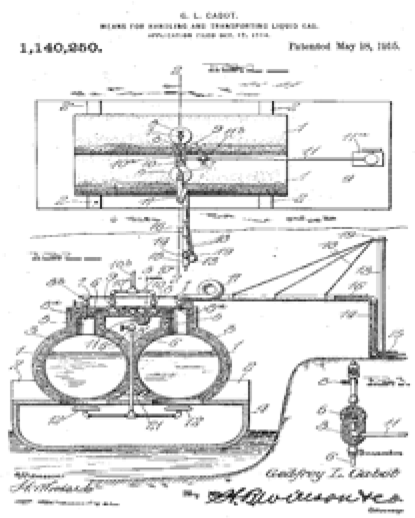


Figure 50

1915, Godfrey L. Cabot: First patent for handling and transporting liquid gas



Source: www.deutsches-stiftungszentrum.de; www.google.com/patents/US1140250

Figure 51

1964, *Methane Princess*, 71,500m³

Source: www.maritime-connector.com

Figure 52

2008, Qatar *Mozah*, 266,000m³

Source: www.helderline.nl

Successful energy innovations take decades for mass-scale diffusion

Energy production and conversion processes take decades from the initial concept to significant market shares

Many additional examples could be used to illustrate these realities. Hydraulic fracturing to produce hydrocarbons was introduced during the late-1940s but the technique took off, in combination with horizontal drilling and just in North America, only six decades later. Air conditioning, now a major user of electricity, was invented in 1902 but half of the US households owned it only 70 years later. The idea of a LNG tanker was patented in 1915 but only a century later did LNG trade move 10% of all exported natural gas. Curious readers should check the history of fuel cells or fast breeder reactors to see some truly disheartening examples of innovations that have not conquered when they were supposed to do so.

But the very fact of inherently gradual rise of fundamental energy innovations means that we should see a substantial increase of worldwide investment in energy research that has, so far, received too little attention compared to many other, less urgent investments. As Bill Gates put it in his call for energy miracles:

Neither the private nor the US government is making necessary investments in energy R&D

> I often talk about the miracle of vaccines: With just a few doses, they protect children from deadly diseases forever. When it comes to clean energy, we need breakthroughs that are just as miraculous. Just like vaccines, clean-energy miracles don't just happen by chance. We have to make them happen, through long-term investments in research and development. Unfortunately, right now neither the private sector nor the US government is making anywhere near the scale of investment it takes to produce these breakthroughs.

Please see Appendix 2 for Bill Gates' view on energy and climate change.

Affluent societies should aim at halving energy use in the long run

High-income countries must consumer less and face price increases

And we need different approaches in high-income and low-income countries: consuming much less in the first case, much more in the other. Rationally managed affluent societies could easily maintain their quality of life while consuming 25-30% less energy than they do today, and in the long run we should aim at halving the current rates. Benefits of reduced energy consumption would be larger than replacing a large part of today's mix of energy sources by the same quantity of non-carbon energies whose development still requires not insignificant carbon inputs and whose operation is not without environmental impacts.

Relative dematerialisation is one of the most effective ways to reduce energy use

One of the most effective approaches to lowered energy use in affluent countries is by rational design that would bring substantial reduction of material used in construction and manufacturing and hence lower the overall energy intensity of modern economies. This would reverse the current trends that have been best exemplified by two inherently energy-wasting developments: houses getting larger and equipped with larger numbers of energy-consuming items, and passenger cars getting heavier. And a further step in this desirable direction would be not only to lighten the material burden but to introduce longer-lasting designs: jetliners operate routinely for 20-25 years and there is no reason why cars could not be equally long-lived.

Eating less meat would make a big difference

Reducing meat intake would help reduce energy input and GHG emissions

And curiously overlooked but very large energy-saving opportunities would come from moving toward more rational diets. Eating less meat would make the greatest difference because the production of feed crops and animal husbandry are major sources of not only CO_2 but also of nitrous oxide and methane, two greenhouse gases with significantly higher short-term global warming potential than CO_2. Reducing very high Western (and now also Japanese and Chinese) meat intakes by 25-30% and keeping them at such lower levels would not compromise the quality of existing diets but it would help to reduce both energy inputs and greenhouse gas emissions. And there are other opportunities in the food sector, ranging from much less wasteful food packaging to reduced intercontinental trade in perishable foods (do we really need everything available all the time?).

Rational use of energy is impossible with current low pricing

Be it houses, cars or meat, "less is more" is the most desirable long-term strategy for tackling the rising levels of atmospheric CO_2 in the world of excessive consumption. But in order to succeed in this quest affluent consumers must start paying more for energy. That is a conclusion nobody wants to hear, but in the US energy spending is now near a historically low level of only 5% of disposable income for an average household, even in Japan, almost completely dependent on imports, the share is just 10%: truly rational use of energy is impossible with such pricing (which, of course, ignores nearly all environmental externalities). The same is true for food: in the US average family now pays less than 10% of its disposable income for its nutrition.

Around 15% of high-income humanity claims nearly half of all energy use

Without paying more there is also little chance to reduce the great consumption disparity whereby 15% of high-income humanity claims nearly half of all energy use. That is also why Africa, large parts of Asia and parts of Latin America need substantial gains in per-capita energy use, but in order to make those gains as compatible with the goal of restrained carbon emissions those gains should come from deploying the most efficient alternatives. Unfortunately, that has not been the case in China with its energy waste, excess capacities and ostentatious consumption, and it is even less so the case with India's slower rise and with Africa's chaotic development.

Quest for any early shift to non-carbon future may not succeed

We may not succeed with our efforts and will have to face further challenges

Being realistic also means to concede that the quest for an early shift to a non-carbon future based on massive deployment of intermittent electricity generation and large-scale cultivation of biofuels may not succeed even if we were to surpass our best current expectations. Even an early and total elimination of carbon emissions might not suffice: some models show that future cuts of atmospheric CO_2 concentration ("negative CO_2 emissions") would be needed to keep the warming below 2°C and that would be possible only with mass-scale sequestration and storage of carbon, yet another technical, economic and social challenge of an immense magnitude.

Geoengineering may face unprecedented and unintended consequences

If we're unable to do that then the only option would be some sort of planetary geoengineering by deliberately changing the planet's radiation balance. There is no shortage of proposals to pursue both of these radical strategies, and in the case of carbon sequestration we already have a number of actually operating small-scale projects - but raising carbon sequestration efforts to the level of an effective solution would require removing at least several billion tonnes of the gas every year, and geoengineering schemes face many unprecedented problems of international governance and risk assessment, to say nothing about unintended consequences.

The scale and complexity of the problem makes any rapid shifts impossible

We should accept the fact that there is no single, simple, rapid way to transform our current global energy system and that it will require a combination of using less (in all affluent countries, as a result of more rational pricing, better design and dietary changes), using more but much more efficiently (in all modernising low-energy economies), and deploying new technical solutions on unprecedented scales (to be helped by much increased R&D spending across the entire spectrum of energy harnessing and conversion). Such efforts are inherently incremental and their progress is gradual: the scale and the complexity of this challenge makes any rapid mass-scale shifts impossible: civilisation without fossil carbon may be highly desirable but the accomplishment will require a multigenerational commitment.

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Appendix 1: Why Google gave up on RE<C?

The following article was posted on IEEE Spectrum in October 2014 by Ross Koningstein and David Fork, who are engineers at Google, who worked together on the bold renewable energy initiative known as RE<C.

What it would really take to reverse climate change?

Today's renewable energy technologies won't save us. So what will?

By Ross Koningstein and David Fork

Posted 18 Nov 2014 | 20:00 GMT

Google cofounder Larry Page is fond of saying that if you choose a harder problem to tackle, you'll have less competition. This business philosophy has clearly worked out well for the company and led to some remarkably successful "moon shot" projects: a translation engine that knows 80 languages, self-driving cars, and the wearable computer system Google Glass, to name just a few.

Starting in 2007, Google committed significant resources to tackle the world's climate and energy problems. A few of these efforts proved very successful: Google deployed some of the most energy-efficient data centres in the world, purchased large amounts of renewable energy, and offset what remained of its carbon footprint.

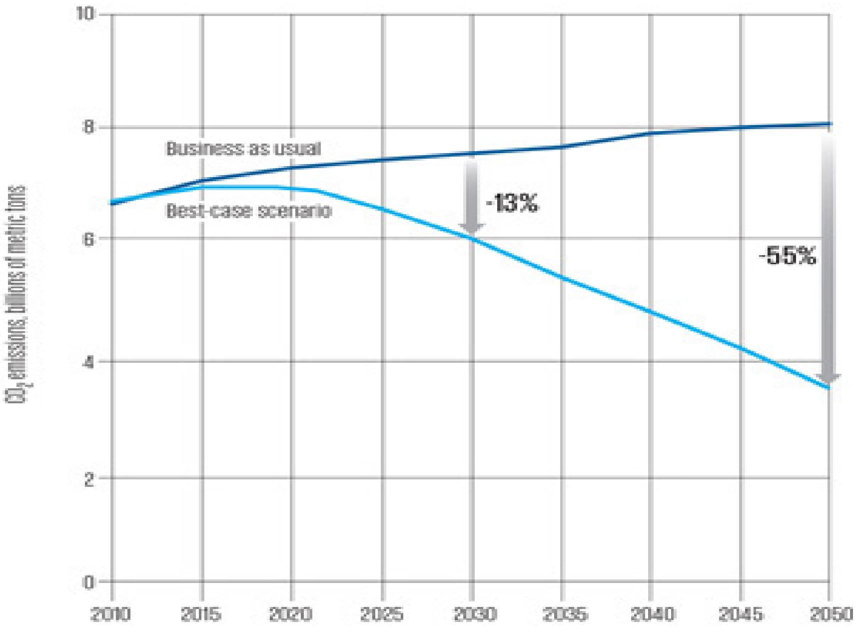
Google's boldest energy move was an effort known as RE<C, which aimed to develop renewable energy sources that would generate electricity more cheaply than coal-fired power plants do. The company announced that Google would help promising technologies mature by investing in start-ups and conducting its own internal R&D. Its aspirational goal: to produce a gigawatt of renewable power more cheaply than a coal-fired plant could, and to achieve this in years, not decades.

Unfortunately, not every Google moon shot leaves Earth's orbit. In 2011, the company decided that RE<C was not on track to meet its target and shut down the initiative. The two of us, who worked as engineers on the internal RE<C projects, were then forced to re-examine our assumptions.

At the start of RE<C, we had shared the attitude of many stalwart environmentalists: We felt that with steady improvements to today's renewable energy technologies, our society could stave off catastrophic climate change. We now know that to be a false hope - but that doesn't mean the planet is doomed.

In the energy innovation study's best-case scenario, rapid advances in renewable energy technology bring down carbon dioxide emissions significantly

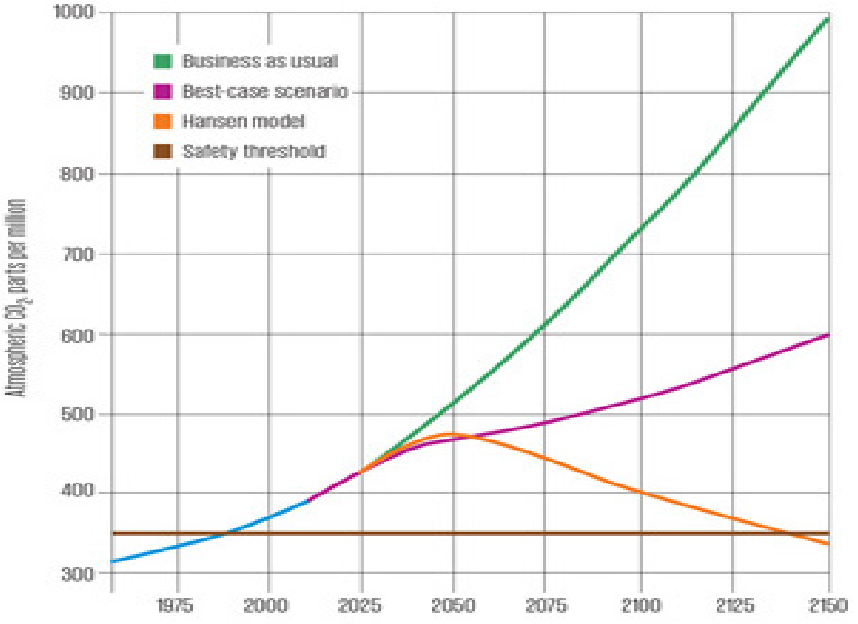
The Climate Conundrum



Sources: "The Impact of Clean Energy Innovation," Google-McKinsey, 2011; "Target Atmospheric CO2: Where Should Humanity Aim?," James Hansen et al., 2008

Yet because CO_2 lingers in the atmosphere for more than a century, reducing emissions means only that less gas is being added to the existing problem. Research by James Hansen shows that reducing global CO_2 levels requires both a drastic cut in emissions and some way of pulling CO_2 from the atmosphere and storing it

The Climate Conundrum



Sources: "The Impact of Clean Energy Innovation," Google-McKinsey, 2011; "Target Atmospheric CO2: Where Should Humanity Aim?," James Hansen et al., 2008

As we reflected on the project, we came to the conclusion that even if Google and others had led the way toward a wholesale adoption of renewable energy, that switch would not have resulted in significant reductions of carbon-dioxide emissions. Trying to combat climate change exclusively with today's renewable energy technologies simply won't work; we need a fundamentally different approach. So we're issuing a call to action. There's hope to avert disaster if our society takes a hard look at the true scale of the problem and uses that reckoning to shape its priorities.

Climate scientists have definitively shown that the buildup of carbon dioxide in the atmosphere poses a looming danger. Whether measured in dollars or human suffering, climate change threatens to take a terrible toll on civilisation over the next century. To radically cut the emission of greenhouse gases, the obvious first target is the energy sector, the largest single source of global emissions.

RE<C invested in large-scale renewable energy projects and investigated a wide range of innovative technologies, such as self-assembling wind turbine towers, drilling systems for geothermal energy, and solar thermal power systems, which capture the sun's energy as heat. For us, designing and building novel energy systems was hard but rewarding work. By 2011, however, it was clear that RE<C would not be able to deliver a technology that could compete economically with coal, and Google officially ended the initiative and shut down the related internal R&D projects. Ultimately, the two of us were given a new challenge. Alfred Spector, Google's vice-president of research, asked us to reflect on the project, examine its underlying assumptions, and learn from its failures.

We had some useful data at our disposal. That same year, Google had completed a study on the impact of clean energy innovation, using the consulting firm McKinsey & Co's low-carbon economics tool. Our study's best-case scenario modelled our most optimistic assumptions about cost reductions in solar power, wind power, energy storage, and electric vehicles. In this scenario, the United States would cut greenhouse gas emissions dramatically: Emissions could be 55% below the business-as-usual projection for 2050.

While a large emissions cut sure sounded good, this scenario still showed substantial use of natural gas in the electricity sector. That's because today's renewable energy sources are limited by suitable geography and their own intermittent power production. Wind farms, for example, make economic sense only in parts of the country with strong and steady winds. The study also showed continued fossil fuel use in transportation, agriculture, and construction. Even if our best-case scenario were achievable, we wondered: Would it really be a climate victory?

A 2008 paper by James Hansen, former director of NASA's Goddard Institute for Space Studies and one of the world's foremost experts on climate change, showed the true gravity of the situation. In it, Hansen set out to determine what level of atmospheric CO_2 society should aim for "if humanity wishes to preserve a planet similar to that on which civilisation developed and to which life on Earth is adapted." His climate models showed that exceeding 350 parts per million CO_2 in the atmosphere would likely have catastrophic effects. We've already blown past that limit. Right now, environmental monitoring shows concentrations around 400ppm. That's particularly problematic because CO_2 remains in the atmosphere for more than a century; even if we shut down every fossil-fuelled power plant today, existing CO_2 will continue to warm the planet.

We decided to combine our energy innovation study's best-case scenario results with Hansen's climate model to see whether a 55% emission cut by 2050 would bring the world back below that 350ppm threshold. Our calculations revealed otherwise. Even if every renewable energy technology advanced as quickly as imagined and they were all applied globally,

atmospheric CO_2 levels wouldn't just remain above 350ppm; they would continue to rise exponentially due to continued fossil fuel use. So our best-case scenario, which was based on our most optimistic forecasts for renewable energy, would still result in severe climate change, with all its dire consequences: shifting climatic zones, freshwater shortages, eroding coasts, and ocean acidification, among others. Our reckoning showed that reversing the trend would require both radical technological advances in cheap zero-carbon energy, as well as a method of extracting CO_2 from the atmosphere and sequestering the carbon.

Those calculations cast our work at Google's RE<C programme in a sobering new light. Suppose for a moment that it had achieved the most extraordinary success possible, and that we had found cheap renewable energy technologies that could gradually replace all the world's coal plants - a situation roughly equivalent to the energy innovation study's best-case scenario. Even if that dream had come to pass, it still wouldn't have solved climate change. This realisation was frankly shocking: Not only had RE<C failed to reach its goal of creating energy cheaper than coal, but that goal had not been ambitious enough to reverse climate change.

That realisation prompted us to reconsider the economics of energy. What's needed, we concluded, are reliable zero-carbon energy sources so cheap that the operators of power plants and industrial facilities alike have an economic rationale for switching over soon - say, within the next 40 years. Let's face it, businesses won't make sacrifices and pay more for clean energy based on altruism alone. Instead, we need solutions that appeal to their profit motives. RE<C's stated goal was to make renewable energy cheaper than coal, but clearly that wouldn't have been sufficient to spur a complete infrastructure changeover. So what price should we be aiming for?

Consider an average US coal or natural gas plant that has been in service for decades; its cost of electricity generation is about 4 to 6 US cents per kilowatt-hour. Now imagine what it would take for the utility company that owns that plant to decide to shutter it and build a replacement plant using a zero-carbon energy source. The owner would have to factor in the capital investment for construction and continued costs of operation and maintenance—and still make a profit while generating electricity for less than US$0.04/kWh to US$0.06/kWh.

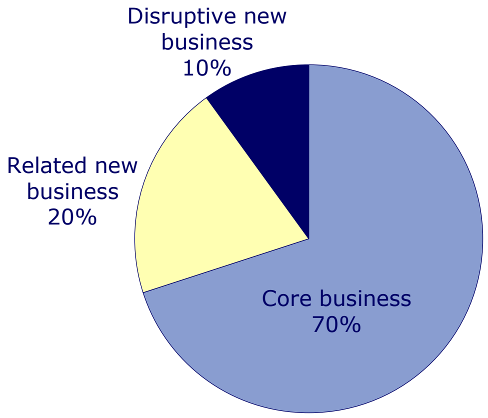
That's a tough target to meet. But that's not the whole story. Although the electricity from a giant coal plant is physically indistinguishable from the electricity from a rooftop solar panel, the value of generated electricity varies. In the marketplace, utility companies pay different prices for electricity, depending on how easily it can be supplied to reliably meet local demand.

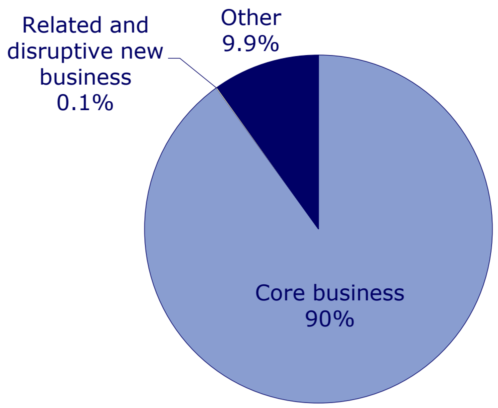
"Dispatchable" power, which can be ramped up and down quickly, fetches the highest market price. Distributed power, generated close to the electricity meter, can also be worth more, as it avoids the costs and losses associated with transmission and distribution. Residential customers in the contiguous United States pay from US$0.09/kWh to US$0.20/kWh, a significant portion of which pays for transmission and distribution costs. And here we see an opportunity for change. A distributed, dispatchable power source could prompt a switchover if it could undercut those end-user prices, selling electricity for less than US$0.09/kWh to US$0.20/kWh in local marketplaces. At such prices, the zero-carbon system would simply be the thrifty choice.

A balanced energy R&D portfolio proposed by the authors would allocate the bulk of resources to proven technologies like hydro, wind, solar photovoltaics, and nuclear; devote 20% of funds to related technologies like thin-film solar PV and next-generation nuclear fission reactors; and keep a pot of money for "crazy" ideas like cheap fusion

Today in the USA the vast bulk of funding for energy R&D goes to established technologies. Essentially no money is allocated to related and potentially disruptive technologies, and about 10% is spent on projects that don't seek to produce economically competitive energy

How to revolutionise R&D





Source: IEEE Spectrum, Google

Unfortunately, most of today's clean generation sources can't provide power that is both distributed and dispatchable. Solar panels, for example, can be put on every rooftop but can't provide power if the sun isn't shining. Yet if we invented a distributed, dispatchable power technology, it could transform the energy marketplace and the roles played by utilities and their customers. Smaller players could generate not only electricity but also profit, buying and selling energy locally from one another at real-time prices. Small operators, with far less infrastructure than a utility company and far more derring-do, might experiment more freely and come up with valuable innovations more quickly.

Similarly, we need competitive energy sources to power industrial facilities, such as fertiliser plants and cement manufacturers. A cement company simply won't try some new technology to heat its kilns unless it's going to save money and boost profits. Across the board, we need solutions that don't require subsidies or government regulations that penalise fossil fuel usage. Of course, anything that makes fossil fuels more expensive, whether it's pollution limits or an outright tax on carbon emissions, helps competing energy technologies locally. But industry can simply move manufacturing (and emissions) somewhere else. So rather than depend on politicians' high ideals to drive change, it's a safer bet to rely on businesses' self-interest: in other words, the bottom line.

In the electricity sector, that bottom line comes down to the difference between the cost of generating electricity and its price. In the USA alone, we're aiming to replace about 1 terawatt of generation infrastructure over the next 40 years. This won't happen without a breakthrough energy technology that has a high profit margin. Subsidies may help at first, but only private-sector involvement, with eager money-making investors, will lead to rapid adoption of a new technology. Each year's profits must be sufficient to keep investors happy while also financing the next year's capital investments. With exponential growth in deployment, businesses could be replacing 30 gigawatts of installed capacity annually by 2040.

While this energy revolution is taking place, another field needs to progress as well. As Hansen has shown, if all power plants and industrial facilities switch over to zero-carbon energy sources right now, we'll still be left with a ruinous amount of CO_2 in the atmosphere. It would take centuries for atmospheric levels to return to normal, which means centuries of warming and instability. To bring levels down below the safety threshold, Hansen's models show that we must not only cease emitting CO_2 as soon as possible but also actively remove the gas from the air and store the carbon in a stable form. Hansen suggests reforestation as a carbon sink. We're all for more trees, and we also exhort scientists and engineers to seek disruptive technologies in carbon storage.

Incremental improvements to existing technologies aren't enough; we need something truly disruptive to reverse climate change. What, then, is the energy technology that can meet the challenging cost targets? How will we remove CO_2 from the air? We don't have the answers. Those technologies haven't been invented yet. However, we have a suggestion for how to foster innovation in the energy sector and allow for those breakthrough inventions.

Consider Google's approach to innovation, which is summed up in the 70-20-10 rule espoused by executive chairman Eric Schmidt. The approach suggests that 70% of employee time be spent working on core business tasks, 20% on side projects related to core business, and the final 10% on strange new ideas that have the potential to be truly disruptive.

Wouldn't it be great if governments and energy companies adopted a similar approach in their technology R&D investments? The result could be energy innovation at Google speed. Adopting the 70-20-10 rubric could lead to a portfolio of projects. The bulk of R&D resources could go to existing energy technologies that industry knows how to build and profitably deploy. These technologies probably won't save us, but they can reduce the scale of the problem that needs fixing. The next 20% could be dedicated to cutting-edge technologies that are on the path to economic viability. Most crucially, the final 10% could be dedicated to ideas that may seem crazy but might have huge impact. Our society needs to fund scientists and engineers to propose and test new ideas, fail quickly, and share what they learn. Today, the energy innovation cycle is measured in decades, in large part because so little money is spent on critical types of R&D.

We're not trying to predict the winning technology here, but its cost needs to be vastly lower than that of fossil energy systems. For one thing, a disruptive electricity generation system probably wouldn't boil water to spin a conventional steam turbine. These processes add capital and operating expenses, and it's hard to imagine how a new energy technology could perform them a lot more cheaply than an existing coal-fired power plant already does.

A disruptive fusion technology, for example, might skip the steam and produce high-energy charged particles that can be converted directly into electricity. For industrial facilities, maybe a cheaply synthesized form of methane could replace conventional natural gas. Or perhaps a technology would change the economic rules of the game by producing not just electricity but also fertiliser, fuel, or desalinated water. In carbon storage, bioengineers might create special-purpose crops to pull CO_2 out of the air and stash the carbon in the soil. There are, no doubt, all manner of unpredictable inventions that are possible, and many ways to bring our CO_2 levels down to Hansen's safety threshold if imagination, science, and engineering run wild.

We're glad that Google tried something ambitious with the RE<C initiative, and we're proud to have been part of the project. But with 20/20 hindsight, we see that it didn't go far enough, and that truly disruptive technologies are what our planet needs. To reverse climate change, our society requires something beyond today's renewable energy technologies. Fortunately, new discoveries are changing the way we think about physics, nanotechnology, and biology all the time. While humanity is currently on a trajectory to severe climate change, this disaster can be averted if researchers aim for goals that seem nearly impossible.

We're hopeful, because sometimes engineers and scientists do achieve the impossible. Consider the space programme, which required outlandish inventions for the rockets that brought astronauts to the moon. MIT engineers constructed the lightweight and compact *Apollo Guidance Computer*, for example, using some of the first integrated circuits, and did this in the vacuum-tube era when computers filled rooms. Their achievements pushed computer science forward and helped create today's wonderful wired world. Now, R&D dollars must go to inventors who are tackling the daunting energy challenge so they can boldly try out their crazy ideas. We can't yet imagine which of these technologies will ultimately work and usher in a new era of prosperity - but the people of this prosperous future won't be able to imagine how we lived without them.

Appendix 2: A lesson in energy and climate change by Bill Gates

Excerpt from the Annual letter of Bill and Melinda Gates Foundation

MORE ENERGY

by Bill.

At some point today, you'll probably do one or all of these things: Flip a switch for light. Take fresh food from a refrigerator. Turn a dial to make your home warmer or cooler. Press a button on your laptop to go online.

You probably won't think twice about any of these actions, but you will actually be doing something extraordinary. You will be using a superpower - your access to energy.

Does that sound ridiculous?

Just imagine, for a minute, life without energy.

You don't have a way to run a laptop, mobile phone, TV, or video games. You don't have lights, heat, air conditioning, or even the internet to read this letter.

About 1.3 billion people – 18% of the world's population - don't need to imagine. That's what life is like for them every day.

You can see this fact for yourself in this photograph of Africa at night taken from space.

Seven out of every 10 of the billion people in sub-Saharan Africa live in dark

Africa at night taken from space

Source: Bill and Melinda Gates Foundation

Africa has made extraordinary progress in recent decades. It is one of the fastest-growing regions of the world with modern cities, hundreds of millions of mobile phone users, growing internet access, and a vibrant middle class.

But as you can see from the areas without lights, that prosperity has not reached everyone. In fact, of the nearly one billion people in sub-Saharan Africa, seven out of every 10 of them live in the dark, without electricity. The majority of them live in rural areas. You would see the same problem in Asia. In India alone, more than 300 million people don't have electricity.

If you could zoom into one of those dark areas in that photograph, you might see a scene like this one. This is a student doing her homework by candlelight.

A young girl studies by candlelight in Tanzania, 2015

Source: Bill and Melinda Gates Foundation

I'm always a little stunned when I see photographs like this. It's been well over a century since Thomas Edison demonstrated how an incandescent light bulb could turn night into day. (I'm lucky enough to own one of his sketches of how he planned to improve his light bulb. It's dated 1885.) And yet, there are parts of the world where people are still waiting to enjoy the benefits of his invention.

If I could have just one wish to help the poorest people, it would be to find a cheap, clean source of energy to power our world.

You might be wondering, "Aren't people just trying to stay healthy and find enough to eat? Isn't that important too?" Yes, of course it is, and our foundation is working hard to help them. But energy makes all those things easier. It means you can run hospitals, light up schools, and use tractors to grow more food.

Think about the history classes you're taking. If I had to sum up history in one sentence it would be: "Life gets better - not for everyone all the time, but for most people most of the time." And the reason is energy. For thousands of years, people burned wood for fuel. Their lives were, by and large, short and hard. But when we started using coal in the 1800s, life started getting better a lot faster. Pretty soon we had lights, refrigerators, skyscrapers, elevators,

air conditioning, cars, planes, and all the other things that make up modern life, from lifesaving medicines and moon landings to fertiliser and Matt Damon movies. (*The Martian* was my favourite movie last year.)

Without access to energy, the poor are stuck in the dark, denied all of these benefits and opportunities that come with power.

So if we really want to help the world's poorest families, we need to find a way to get them cheap, clean energy. Cheap because everyone must be able to afford it. Clean because it must not emit any carbon dioxide - which is driving climate change.

I'm sure you have read about climate change and maybe studied it in school. You might be worried about how it will affect you. The truth is, the people who will be hit the hardest are the world's poorest. Millions of the poorest families work as farmers. Changes in weather often mean that their crops won't grow because of too little rain or too much rain. That sinks them deeper into poverty. That's particularly unfair because they're the least responsible for emitting CO_2, which is causing the problem in the first place.

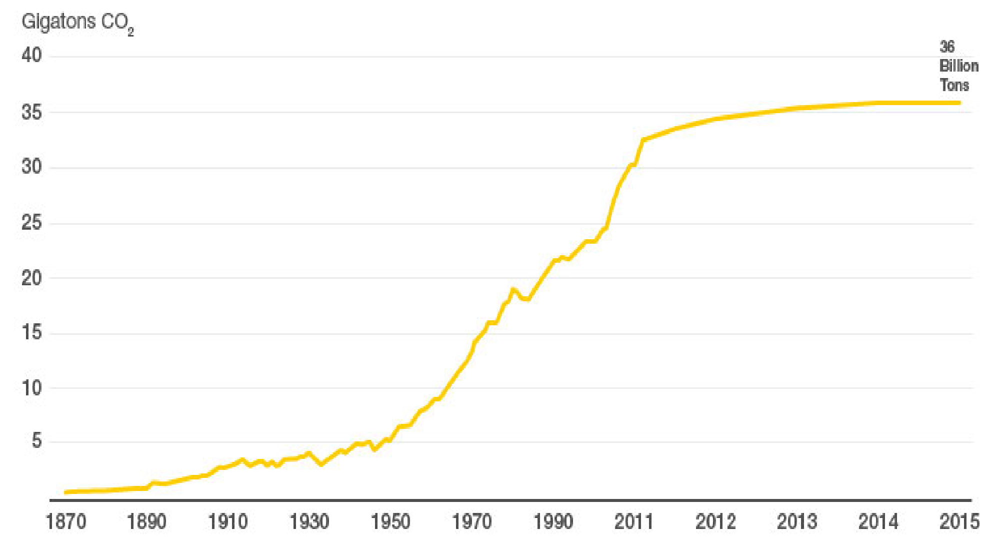
Scientists say that to avoid these dramatic long-term changes to the climate, the world must cut greenhouse gas emissions by up to 80% by 2050, and eliminate them entirely by the end of the century.

When I first heard this I was surprised. Can't we just aim to cut carbon emissions in half? I asked many scientists. But they all agreed that wouldn't be enough. The problem is that CO_2 lingers in the atmosphere for decades. Even if we halted carbon emissions tomorrow, the temperature would still rise because of the carbon that's already been released. No, we need to get all the way down to zero.

That's a huge challenge. In 2015, the world emitted 36 billion tonnes of carbon dioxide to produce energy. This is a mind-boggling number. (It's worth remembering, because it will come in handy. For example, someone may tell you they know how to remove 100 million tonnes of carbon per year. That sounds like a lot, but if you do the math - 100 million divided by 36 billion - you'll see that they're talking about 0.3% of the problem. Every reduction in emissions helps, but we still have to work on the other 99.7%.)

How can we ever reduce a number like 36 billion tonnes to zero?

Global carbon emissions from fossil fuels



Source: International Energy Agency

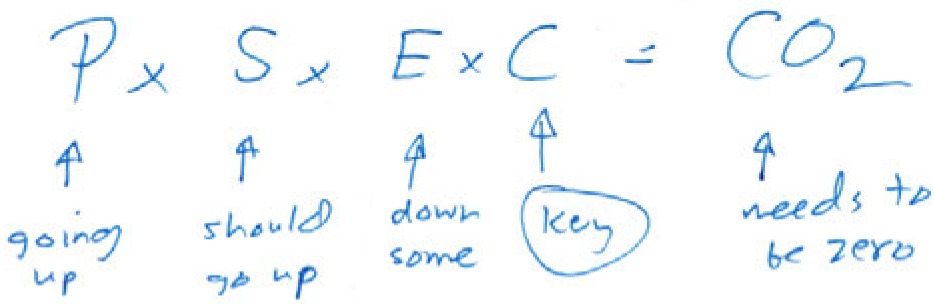
Whenever I'm confronted with a big problem I turn to my favourite subject: math. It's one subject that always came naturally to me, even in middle school when my grades weren't that great. Math cuts out the noise and helps me distil a problem down to its basic elements.

Climate change is an issue that has plenty of noise surrounding it. There are those who deny it is a problem at all. Others exaggerate the immediate risks.

What I needed was an equation that would help me understand how we might get our CO_2 down to zero.

That might look complicated. It's not

Here's what I came up with:



Source: Bill and Melinda Gates Foundation

On the right side you have the total amount of carbon dioxide (CO_2) we put in the atmosphere. This is what we need to get to zero. It's based on the four factors on the left side of the equation: the world's population (P) multiplied by the services (S) used by each person; the energy (E) needed to provide each of those services; and finally, the carbon dioxide (C) produced by that energy.

As you learned in math class, any number multiplied by zero will equal zero. So if we want to get to zero CO_2, then we need to get at least one of the four factors on the left to zero.

Let's go through them, one by one, and see what we get.

The world's population (P) is currently 7 billion and expected to increase to 9 billion by 2050. No chance it'll be zero.

Next, services. This is everything: food, clothing, heat, houses, cars, TV, toothbrushes, Elmo dolls, Taylor Swift albums, etc. This is the number that I was saying earlier needs to go up in poor countries, so people can have lights, refrigerators, and so on. So (S) can't be zero, either.

Let's take a look at (E). That's the energy needed per service. There's some good news here. Fuel-efficient cars, LED light bulbs, and other inventions are making it possible to use energy more efficiently.

Many people, and you may be one of them, are also changing their lifestyles to conserve energy. They're biking and carpooling to save gas, turning down the heat a couple degrees, adding insulation to their homes. All of these efforts help cut down on energy use.

Unfortunately, they don't get us to zero. In fact, most scientists agree that by 2050 we'll be using 50% more energy than we do today.

So none of the first three - population, services and energy - are getting close to zero. That leaves the final factor (C), the amount of carbon emitted per each unit of energy.

The majority of the world's energy, other than hydro and nuclear, is produced by fossil fuels like coal that emit an overwhelming amount of CO_2. But there's some good news here, too. New green technologies are allowing the world to produce more carbon-free energy from solar and wind power. Maybe you live near a wind farm or have seen solar panels near your school.

It's great that these are getting cheaper and more people are using them. We should use more of them where it makes sense, like in places where it's especially sunny or windy. And by installing special new power lines we could make even more use of solar and wind power.

But to stop climate change and make energy affordable for everyone, we're also going to need some new inventions.

Why? Solar and wind power are reliable energy sources so long as the sun is shining and the wind is blowing. But people still need dependable energy on cloudy days, at night-time, and when the air is still. That means power companies often back up these renewable sources with fossil fuels like coal or natural gas, which emit greenhouse gases.

It would help, of course, if we had a great system for storing solar and wind power. But right now, the best storage option is rechargeable batteries, and they are expensive. Lithium-ion batteries like the one inside your laptop are still the gold standard. If you wanted to use one to store enough electricity to run everything in your house for a week, you would need a huge battery - and it would triple your electric bill.

So we need more powerful, more economical solutions.

In short, we need an energy miracle.

When I say "miracle," I don't mean something that's impossible. I've seen miracles happen before. The personal computer. The internet. The polio vaccine. None of them happened by chance. They are the result of research and development and the human capacity to innovate.

In this case, however, time is not on our side. Every day we are releasing more and more CO_2 into our atmosphere and making our climate-change problem even worse. We need a massive amount of research into thousands of new ideas - even ones that might sound a little crazy - if we want to get to zero emissions by the end of this century.

New ways to make solar and wind power available to everyone around the clock could be one solution. Some of the crazier inventions I'm excited about are a possible way to use solar energy to produce fuel, much like plants use sunlight to make food for themselves, and batteries the size of swimming pools with huge storage capacity.

Many of these ideas won't work, but that's okay. Each dead end will teach us something useful and keep us moving forward. As Thomas Edison famously said, "I have not failed 10,000 times. I've successfully found 10,000 ways that will not work."

But to find thousands of ways that won't work, you first need to try thousands of different ideas. That's not happening nearly enough.

Governments have a big role to play in sparking new advances, as they have for other scientific research. US government funding was behind breakthrough cancer treatments and the moon landing. If you're reading this online, you have the government to thank for that too. Research paid for by the US government helped create the internet.

But energy research and the transition to new energy sources take a long time. It took four decades for oil to go from 5% of the world's energy supply to 25%. Today, renewable energy sources like wind and solar account for less than 5% of the world's energy.

So we need to get started now. I recently helped launch an effort by more than two dozen private citizens that will complement government research being done by several countries. It's all aimed at delivering energy miracles.

You may be wondering what you can do to help.

First, it's important for everyone to get educated about this energy challenge. Many young people are already actively involved in climate and energy issues and I'm sure they could use more help. Your generation is one of the most globally minded in history, adept at looking at our world's problems beyond national borders. This will be a valuable asset as we work on global solutions in the decades ahead.

Second, if you're someone with some crazy-sounding ideas to solve our energy challenge, the world needs you. Study extra hard in your math and sciences. You might just have the answer.

The challenge we face is big, perhaps bigger than many people imagine. But so is the opportunity. If the world can find a source of cheap, clean energy, it will do more than halt climate change. It will transform the lives of millions of the poorest families.

I'm so optimistic about the world's ability to make a miracle happen that I'm willing to make a prediction. Within the next 15 years - and especially if young people get involved - I expect the world will discover a clean energy breakthrough that will save our planet and power our world.

I like to think about what an energy miracle like that would mean in a slum I once visited in Nigeria. It was home to tens of thousands of people but there was no electricity. As night fell, no lights flickered on. The only glow came from open fires lit in metal barrels, where people gathered for the evening. There was no other light for kids to study by, no easy way to run a business or power local clinics and hospitals. It was sad to think about all of the potential in this community that was going untapped.

A cheap, clean source of energy would change everything.

Imagine that.

Bill

Companies mentioned

Alphabet (GOOGL US - US$793.22 - BUY)
Brown Boveri (N-R)
DESERTEC (N-R)
ExxonMobil (XOM US - US$87.27 - OUTPERFORM)
General Electric (N-R)
Google (N-R)
InterTechnology Corporation (N-R)
MHI (7011 JP - ¥418 - BUY)
Norsk Hydro (N-R)
Siemens AG (N-R)
Tesla (TSLA US - US$219.99 - UNDERPERFORM)
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Overall rating distribution for CLSA/CLSA Americas only /CA Taiwan only Universe:

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