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INTRODUCTION

Global visions about the energy transition

This journal was born in 2016 with the objective of contributing, from independent scientific knowledge, to the necessary debate about the global, European, and Spanish energy transition. As I mentioned in the introduction to the first issue, global energy systems face several challenges and opportunities in their evolution towards more sustainable and robust systems, and it is essential to reach a political and social consensus that will facilitate the investments and actions required, with a long-term vision. And a fundamental element for this consensus is rigorous and independent analysis from different perspectives.

In the seven issues published along these four years, major international researchers have been covering both general issues about the transition and particular aspects, such as the role of demand or business models, competition or innovation policies, the design of electricity markets, or the aspects associated to a just transition.

In this issue we return to the first topic, presenting the vision of three of the most renowned international experts on global energy transitions. As may be easily seen, these experts do not necessarily share their views, something not really surprising given the difficulty in predicting the future… although it is possible to extract a common message from their analysis, a message that, in my opinion, allows us to move towards this sustainable future desired by all.

In the first paper, **Vaclav Smil**, Distinguished Professor Emeritus at the University of Manitoba, and probably the best known analyst of the evolution of the use of energy throughout history, as shown in his many books, makes use of his ever-present critical spirit and reminds us that the public discourse about energy transitions has focused too much on the electricity sector and on the electrification of transport, has forgotten about the industrial transition, has not accounted enough for the history of past energy transitions, and is, in general, excessively optimistic. In his paper he focuses on what he calls six fundamental realities: there is nothing new about energy transitions, which have taken place since the beginning of civilization; the current transition is unprecedented in terms of the desired speed, of the scale required, and of the use of variable and low-density energy sources; the decarbonization of the global energy supply is not being driven by energy prices or fuel scarcity, or by security of supply; even modest reductions in emissions will be very difficult; global civilization will be dependent on fossil fuels for a long time, and therefore any statement that decarbonization may be achieved in two or three decades is unrealistic and irresponsible; and finally, decarbonization includes some relatively simple transitions, but also others for which we do not have answers currently.

His conclusion, initially negative, is that this transition will share attributes of past ones: it will be gradual, intergenerational, and with different progress rates by region. However, he also ends with a positive note: engaging more strongly in innovation and energy efficiency can speed up this transition.

In the following paper, **Jorge Blázquez** and **Spencer Dale**, lead and chief economists respectively at the BP group, present the main questions and uncertainties related to the energy transition. Blázquez and Dale have a clear view that the energy mix in 2040 will be very different to the current one; that energy demand will continue growing in developing countries; and that we must reduce greenhouse gas emissions as quickly as possible. But this is where certainty ends: neither the speed of this transformation, or the role of the different technologies, or its share among sectors, are clear. Their Evolving Transition scenario tries to identify the key issues affecting the energy transition, in particular how much energy will the world require, how important are plastics for oil demand, how fast can renewable energy grow, and what else do we need to ensure a quick transition toward a decarbonized system.

Their (summarized) answers are: energy demand will grow 30% by 2040, driven by the increased prosperity of developing countries, mostly in Asia, something that clearly makes it more difficult to achieved the required reduction in emissions; growing trade disputes may reduce global GDP growth, and with it energy demand,

and also promote the use of domestic energy sources (including coal); regulations about the use of plastics may affect significantly oil demand; renewables are growing much faster than other energy sources in the past, but may be slowed by the capital intensity required, and may not grow enough to reach climate targets. The consequence of all this is that this scenario is not consistent with the Paris Agreement. Achieving it would require a much more rapid transition, which in turn will require a wide set of measures, combining carbon prices with other more specific policies, including in particular an unprecedented deployment of renewable energy. However, renewables will continue representing only a third of global energy supply (in primary energy terms), so other technologies will be needed to decarbonize the rest of the energy system, in particular hydrogen and carbon capture.

In a clear contrast, **Seb Henbest**, chief economist at Bloomberg New Energy Finance, seems to have a much clearer view, at least in the medium term. Henbest relies on the spectacular advances in the cost of photovoltaic and wind energy and of batteries to preview a future in which, by 2050, renewable power (photovoltaics and wind) will produce 80% of the electricity at the global level, something he calls Phase I of the energy transition. In addition, Henbest remarks that these advances will be more important for the global energy matrix than what is generally shown by primary energy statistics, which don't actually represent the real use of energy (which must be done in terms of final energy). Europe will clearly lead this process, but other regions must speed up renewable energy deployment if they want to achieve this level of penetration before 2050. In the US natural gas is more competitive and hence renewables do not progress that much. In China, India and Southeast Asia cheap coal is the major obstacle. However, a very important point in Henbest's conclusion, shared by the three papers, is that reaching the climate target of 2º C, or even 1.5º C, is impossible if current trends are not changed radically.

Therefore, beyond the different views of the authors, there is a shared central message: achieving the targets included in the Paris Agreement will require additional, substantive measures to speed up the transition. To this extent, the different author's proposals are not opposed but complementary. We will require, as Smil proposes, to step up our efforts on innovation and energy efficiency; also, as mentioned by Blázquez and Dale, to explore the options offered by hydrogen and carbon capture; and above all, as put forward by Henbest, to create a regulatory framework that may mobilize the large investments required to achieve the targets. As I said at the beginning, these complementary proposals should allow us to advance, from a shared position, towards a more sustainable energy model, from a good understanding of the current situation and the potential constraints, but also of the benefits of adopting ambitious but sensible policies.

As has been repeatedly expressed in the recent COP in Madrid, it is time to act, it is the time to move from target setting to political action. It is the moment in which governments and opposing parties must act responsibly and with a long-term vision, creating those efficient and fair regulatory frameworks that promote investments, and also innovation and energy efficiency. I hope that from *Papeles de Energía* we will continue offering independent and rigorous knowledge that informs these regulatory frameworks.

INTRODUCCIÓN

Visiones globales de la transición energética

Esta revista nació en 2016 con el objetivo de contribuir, desde el conocimiento científico independiente, al necesario debate sobre la transición energética global, europea, y española. Como decía en la introducción al primer número, los sistemas energéticos globales se enfrentan a numerosos retos y oportunidades en su evolución hacia sistemas más sostenibles y robustos, y es imprescindible un consenso político y social que permita emprender las inversiones y acciones necesarias con visión de largo plazo. Y una pieza fundamental para este consenso es el análisis riguroso e independiente, desde distintas perspectivas.

En los siete números publicados a lo largo de estos cuatro años, investigadores de primer nivel internacional han cubierto tanto cuestiones generales sobre la transición, como aspectos particulares de la misma, como el papel de la demanda o de los modelos de negocio, las políticas de competencia o de innovación, el diseño de los mercados eléctricos, o los aspectos más sociales asociados a una transición justa.

En este número volvemos de alguna forma al origen, presentando la visión de tres de los mayores expertos en transiciones energéticas globales. Como se puede ver fácilmente, los expertos no coinciden necesariamente en sus apreciaciones, algo por otra parte no sorprendente dado lo complicado que es predecir el futuro… aunque sí es posible extraer un mensaje común de todos sus análisis, un mensaje que, en mi opinión, permite avanzar hacia ese futuro sostenible que todos deseamos.

En primer lugar, **Vaclav Smil**, profesor emérito de la Universidad de Manitoba, y quizá el principal estudioso de la evolución del uso de la energía a lo largo del tiempo, como atestiguan sus valiosísimas publicaciones, apela a su constante espíritu crítico para recordarnos que el discurso público de la transición energética se ha centrado excesivamente en el sector eléctrico y en la electrificación del transporte, se ha olvidado de la transición industrial, no ha tenido en cuenta la historia de transiciones energéticas anteriores, y es, en general, excesivamente optimista. En su artículo se centra en lo que él llama seis realidades fundamentales: no hay nada nuevo acerca de las transiciones energéticas, que llevan teniendo lugar desde el origen de la humanidad; la transición actual no tiene precedentes por su velocidad deseada, por la escala necesaria, y por su utilización de fuentes energéticas variables, con baja densidad energética; la descarbonización del suministro energético global no está siendo impulsada por los precios o la escasez de los fósiles, ni por la seguridad de suministro; incluso reducciones moderadas de las emisiones serán muy difíciles; la civilización global seguirá siendo dependiente de los fósiles por bastante tiempo, y cualquier afirmación de que la descarbonización se puede lograr en dos o tres décadas es irrealista e irresponsable; y finalmente, la descarbonización incluye algunas transiciones relativamente sencillas, pero también otras para las que no tenemos alternativa libre de carbono.

Su conclusión, negativa en principio, es que la transición compartirá atributos de otras anteriores: será gradual, intergeneracional, y con tasas de progreso distintas por país. Sin embargo, termina con una nota optimista: nuestro compromiso con la innovación y con la eficiencia energética puede acelerarla en gran medida.

A continuación, **Jorge Blázquez** y **Spencer Dale**, economista principal y economista en jefe, respectivamente, del grupo BP, presentan las principales preguntas e incertidumbres asociadas a la transición energética. Blázquez y Dale tienen claro que el *mix* energético en 2040 será muy distinto al actual, y que la demanda energética seguirá creciendo en los países en desarrollo, así como que hay que reducir las emisiones de gases de efecto invernadero lo más rápidamente posible. Pero ahí terminan las certidumbres: no están claras ni la velocidad de la transformación, ni el papel de las distintas energías, ni su reparto por sectores. Su escenario de Transición en Evolución trata de identificar las cuestiones clave que afectan a la transición energética, en particular: ¿Cuánta energía necesitará el mundo?; ¿Qué sucederá si se intensifican las guerras comerciales?; ¿Cómo de importantes son los plásticos para la demanda de petróleo?; ¿Cómo de rápido puede crecer la energía renovable?; y ¿Qué más hace falta para asegurar una transición rápida hacia un sistema descarbonizado?

De forma sucinta, sus respuestas a estas preguntas son: La demanda energética crecerá un tercio hasta 2040, alimentada por la mayor prosperidad en países en desarrollo, sobre todo Asia, algo que evidentemente complica la reducción de emisiones necesaria; las crecientes disputas comerciales puede reducir el crecimiento del PIB global, y con ello de la demanda de energía, y también incentivar el uso de fuentes de energía autóctonas (incluido el carbón); las regulaciones sobre el uso de plásticos pueden afectar de forma significativa a la demanda de petróleo; las renovables están penetrando mucho más rápidamente que otras fuentes energéticas en el pasado, pero resultan frenadas por la intensidad de capital necesaria, y no consiguen crecer tanto como para alcanzar los objetivos climáticos. La consecuencia de todo lo anterior es que estos escenarios no son coherentes con el Acuerdo de París. Para lograrlo sería necesaria una transición mucho más rápida, que a su vez requerirá un conjunto amplio de medidas que combinen precios de CO_2 con otras medidas regulatorias más específicas, y en particular un despliegue sin precedentes de las energías renovables. Sin embargo, las renovables seguirán representando únicamente un tercio del suministro global, por lo que seguirá siendo necesario desarrollar otras tecnologías para descarbonizar el resto del sistema energético, en particular hidrógeno y captura de CO_2.

En un claro contraste, **Seb Henbest**, economista jefe de Bloomberg New Energy Finance, parece tener las cosas mucho más claras, al menos a medio plazo. Henbest se apoya en los espectaculares avances en el coste de la energía solar fotovoltaica, la eólica, y las baterías, para anticipar un futuro en el que, hacia 2050, las renovables (solar fotovoltaica y eólica) producirán el 80% de la electricidad a nivel global, algo que él llama la fase I de la transición energética. Además, Henbest hace notar que estos avances serán mucho más importantes en la matriz energética global de lo que generalmente muestran las estadísticas de energía primaria, ya que esta no representa correctamente el uso real de la energía, que debe hacerse en términos de energía final. Europa liderará claramente este proceso, pero otras regiones deberán acelerar el despliegue renovable si quieren lograr esta penetración antes de 2050. En Estados Unidos el gas es más competitivo y, por tanto, las renovables no avanzan tanto. En China, India, y el sureste asiático es el carbón barato el principal obstáculo. Ahora bien: un punto muy importante de la conclusión de Henbest, y en el que como vemos coinciden los tres autores, es que alcanzar un objetivo climático de 2º C, o más aún de 1,5º C, es imposible si no se cambian radicalmente las tendencias actuales.

Por tanto, más allá de las distintas visiones de los autores, hay un mensaje central compartido: alcanzar los objetivos marcados en el Acuerdo de París requerirá acciones adicionales y sustantivas para acelerar la transición. En este sentido, creo que las propuestas de todos los autores no son opuestas sino complementarias. Será necesario, como propone Smil, redoblar los esfuerzos en innovación y eficiencia energética; también, como mencionan Blázquez y Dale, explorar las opciones que pueda ofrecer el hidrógeno y la captura de CO_2; y sobre todo, como plantea Henbest, crear un marco regulatorio que permita movilizar las grandes inversiones necesarias para alcanzar estos objetivos. Como decía al principio, estas propuestas complementarias deberían permitirnos avanzar, desde una posición compartida, hacia un modelo energético más sostenible, entendiendo bien la situación actual y las posibles restricciones, pero también los beneficios de adoptar políticas ambiciosas pero sensatas.

Como se ha repetido insistentemente en la reciente COP celebrada en Madrid, es el momento de actuar, es el momento de pasar del establecimiento de objetivos a la acción política. Es el momento de los gobiernos y de las oposiciones de actuar responsablemente y con visión de largo plazo, creando esos marcos regulatorios eficientes y justos que impulsen la inversión, y también la innovación y la eficiencia energética. Confío en que desde *Papeles de Energía* podamos seguir ofreciendo conocimiento independiente y riguroso que informe estos marcos regulatorios.

Energy Transitions: Fundamentals in Six Points

*Vaclav Smil**

Abstract

The public discourse of the unfolding energy transition has been poorly defined, it has been often misinformed and misleading, almost always ahistorical, and overwhelmingly unrealistic. In this paper I focus on six fundamental realities that must be taken into account: There is nothing new about energy transitions; All energy transitions have many specific attributes, but the one currently underway is truly unprecedented; Decarbonization of the global energy supply is taking place not because of resource shortages and excessive prices, or because of the need to do away with inferior efficiencies and to increase supply reliability; Even moderate reductions of annual global carbon combustion are difficult because our dependence on fossil fuels is enormous and because most of the humanity needs more energy and this requirement cannot be met by a rapid expansion of renewables; Global civilization remains highly dependent on fossil fuels and future demand for coal and hydrocarbons will rise in many middle- and low-income countries; And decarbonization includes energy transitions that are relatively easy to accomplish as well as carbon substitutions for which we currently do not have any commercial non-carbon alternatives. As unique and as unprecedented the unfolding global energy transition may be, it shares the key feature with its predecessors: it will be a gradual, multidecadal, inter-generation process with different and diverging national pathways and rates of progress. Still, our commitment to innovation and to better ways of managing our energy use can make a real difference to its rate of progress.

Keywords: Energy transition, decarbonization.

Four decades ago, the Iranian revolution (Ayatollah Khomeini returned to Tehran on February 1, 1979) led to the second round of crude oil price increases. During the first round, in 1973-1974, the OPEC forced the quintupling of the posted price (from $1.9/barrel in 1972 to $10.41/barrel in 1974), the second round had nearly quadrupled that total (to $35.7/barrel by 1980). Crude oil provided the largest share of primary global energy use, and the concerns were about its supply and price. Producers of coal and natural gas saw the higher

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oil prices as an opportunity to increase their share of the market. Discussions of potential global warming were limited to infrequent papers in academic journals, and the broad consensus saw the acid deposition (commonly called acid rain) as the worst environmental problem both in Europe and in North America (Smil, 1987). And in 1979 the USSR invaded Afghanistan and the Chinese had just began (three years after Mao Zedong's death) to talk about the need for economic reforms.

Four decades later we live in a very different world. OPEC is still around but with greatly reduced influence, mainly because of the US re-emergence as the world's largest oil and gas producer (BP, 2019). Globally, crude oil is still the most important fuel but in 2018 it supplied only about 24% more energy than coal, whose production (mainly because of the surge in China) rose by more than two-thirds since the year 2000. Since 1979, oil prices have fluctuated but in real terms they are much lower than they were four decades ago. USSR had collapsed in 1991 while the post-Mao China rose to become the world's largest (in PPP terms) or the second largest (in exchange rated GDP) economy and the largest exporter of manufactured goods. Concerns about acid rain are a distant history and the new consensus sees global warming, caused by the anthropogenic emissions of greenhouse gases, as by far the greatest threat to modern civilization. These emissions come from many sources, but the combustion of fossil fuels dominates, and that is why the energy transition to non-fossil sources, commonly termed decarbonization, has emerged as one of the most prominent global concerns.

Unfortunately, public discourse of the unfolding energy transition has been poorly defined (focusing disproportionately on the decarbonization of electricity generation or on electrification of road transport), it has been often misinformed and misleading (quoting newly installed capacities of renewable conversions rather than their actual generation shares and neglecting difficult industrial transitions), almost always ahistorical (ignoring the lessons of past energy transitions) and overwhelmingly unrealistic (commonly assuming impossibly rapid rates of adoption of non-carbon conversions). I have addressed all of these shortcomings in my recent writings (Smil, 2010, 2014, 2015, 2016, 2017a, 2017b, 2019) and here I will focus briefly on just six fundamental realities, taking into account the recent composition of primary energy supply and its near-term prospects, and stressing the limits of technical innovations.

1. *There is nothing new about energy transitions.* Economic accomplishments and quality of life always reflect the levels and modes of energy use and energy transitions thus involve not only the changing supply of primary energies (fuels or primary electricity) but also the introduction of new converters (ranging from boilers to electric motors) and new prime movers used to produce useful thermal, electric and mechanical energies required by food and industrial production, in construction and for services and transportation. Without steam engines and, later, steam turbines, the transition from wood to coal would have been limited just to a more efficient generation of heat. Without gas turbines (jet engines) kerosene refined from crude oil would be used just for lighting.

Even during the pre-industrial era, when traditional biomass fuels dominated the supply of heat and animal and human muscles provided most of the kinetic energy, some societies were gradually turning to higher-quality charcoal, adopted better wood-burning stoves, installed significant capacities of mechanical power in water wheels and wind mills, and improved the performance of draft animals by better harnessing and feeding. And the history of the industrial era could be seen as a continuous sequence of transitions to more convenient and cleaner fuels (from coal to crude oil, natural gas and primary electricity), to better inanimate prime movers (from steam engines to steam turbines and internal combustion engines) and to higher share of final energy use delivered as electricity.

2. *All energy transitions have many specific attributes, but the one currently underway is truly unprecedented.* Studies of past energy transitions show substantial national differences in the composition of primary energy supply and its secular changes as well as in the adoption rates of new energy converters and in the shares of final energy demand. Such major economies as the US, Russia and China have followed the typical sequence from wood to coal to hydrocarbons and to the rising shares of primary (hydro and nuclear) electricity, while many other countries never had a coal industry. There have been major differences in the rates of electrification (and almost one billion people still have no connections to the grid), ownership of cars (its diffusion was relatively rapid in the US, in Europe it was delayed until after WW II, in China it took-off only since 2000) or household converters (for example, clothes dryers and air conditioners are very common in North America, rare in the EU). The current energy transition is unprecedented because of the

reasons for its desired acceleration, because of its requisite scale, and because of its reliance on intermittent sources with low energy and low power densities.

3. *Decarbonization of the global energy supply is taking place not because of resource shortages and excessive prices, or because of the need to do away with inferior efficiencies and to increase supply reliability.* Obviously, there is a finite mass of fossil fuels in the Earth's crust but the best available estimates indicate that their resources could cover the global needs for generations to come (WEC, 2016). Moreover, improvements in extraction, processing and transportation of fossil fuels have made them widely affordable. America's high per capita energy consumption is obviously enabled by the fact that average households spends just 5% of its disposable income on all forms of energy it uses (USEIA, 2014). Moreover, ample availability of fossil fuels has been enhanced and their cost has been reduced by substantial improvements in the efficiency of their uses: as might be expected, energy-intensive industries have seen the most impressive gains but efficiencies of common household and transportation conversions have also improved substantially: for example, today's best gas furnaces are 97% efficient (compared to less than 50% efficient coal-fired stoves of 70 years ago), and the latest jetliners consumed less than a third of kerosene per passenger-kilometers than the first commercial designs of the late 1950s. Finally, fossil fuel-based energy supply is highly reliable.

The quest for abandoning these abundant, affordable and reliable sources of energy is driven overwhelmingly by a single objective, the eventual elimination of fossil carbon from the global energy supply. There has been no shortage of irresponsible speculations about the speed of this transition, with some claims seeing the possibility of a carbon-free world, or at least carbon free national energy supplies, as early as 2030 (J.P. Morgan, 2019). Such completely unrealistic claims ignore both the scale of the required global decarbonization and the need for further increases of energy supply in low-income countries.

4. *Even moderate reductions of annual global carbon combustion are difficult because our dependence on fossil fuels is enormous and because most of the humanity needs more energy and this requirement cannot be met by a rapid expansion of renewables.* The scale of the required substitution is daunting: in 2018 the world produced

just over 8 billion tonnes (Gt) of coal, nearly 4.5 Gt of crude oil and about 3.9 trillion m^3 of natural gas, or the equivalent of about 9.2 Gt of fossil carbon whose combustion emitted the record amount of nearly 34 Gt of CO_2 (BP, 2019). In 1992, the year of the first global convention on climate change, global CO_2 emissions from fossil fuel combustion were 21.4 Gt. Not only there has been no decarbonization of global energy supply but during the past quarter century of rising concerns about global warming and constant calls for rapid decarbonization the world has been expanding its absolute dependence on fossil carbon, with coal extraction rising by about 70%, crude oil production by nearly 40% and natural gas flows by more than 80%, with the aggregate increase of about 55% for all fossil fuels.

And despite much publicized growth of installed capacities for wind and solar generation, there has been also no recent decline in the world's relative dependence on fossil fuels. After converting all primary energies to a common equivalent (with nuclear electricity equal to 9.5 MJ/kWh and with all other primary electricity at their thermal equivalent of 3.6 MJ/kWh, the UN preference), fossil fuels contributed 90.5% of the world's primary commercial energy in 2018 —compared to 90.1% in 2010 and 89.8% in the year 2000. Using the conversions preferred by the BP Statistical Review (with all primary electricity at 9.5 MJ/kWh) the shares of fossil fuels were 85% in 2018. The third option to aggregate the world's primary energy supply is used by the International Energy Agency, with the global total including the highly uncertain consumption of non-commercial traditional biomass fuels and with the fossil fuels share at about 80% in 2018.

5. *Global civilization remains highly dependent on fossil fuels and future demand for coal and hydrocarbons will rise in many middle- and low-income countries.* High relative dependence (80-90% depending on the conversions used) and its unprecedented absolute scale, now approaching the combustion of 10 Gt of fossil carbon a year, means that there can be no rapid decarbonization on the global level because even major decarbonization achievements on a national level get swiftly swamped by rising emissions in other countries. For example, between 1992 and 2018 the UK reduced its carbon emissions by 33% but that absolute reduction of 190 Mt of CO_2 was made up by India's rising emissions in less than

two years between 2016 and 2018. Given the current state of energy demand, all that any local, regional or national decarbonization gains in affluent countries can do is to reduce the growth rate of annual global CO_2 emissions – but the average atmospheric concentration of CO_2, the only metric that matters in order to moderate any future rate of climate change, keeps rising, from less than 320 ppm in 1958 (when the continuous measurements began at Mauna Loa) to more than 410 ppm by 2019 (NOAA 2019).

And large disparities in per capita energy use – in 2018 the means were 295 GJ in the US, 150 GJ in Japan, 97 GJ in China, 25 GJ in India and only 15 GJ in Africa —guarantee that low— and middle-income Asian and African countries will experience growing demand for more energy in general and for fossil fuels required for their industries and transportation in particular. Not surprisingly, Indian plans envisage quintupling total energy use by 2047 with coal's share at close to 50% (Kumar *et al.,* 2017), and Chinese energy demand, although it had almost quintupled since the late 1980s, is not expected to peak before 2040 after rising by another 30% above the 2017 level (CNPC, 2017). As a result, even a relatively rapid and continuing gradual decarbonization in affluent countries will fall short of the rising fossil fuels consumption in Asia and Africa.

This reality is recognized by all serious long-term energy forecasts. Notably, the latest IEA projection sees carbon emissions rising even under its New Policies scenario (IEA, 2018). And it was also recognized by the Paris agreement: even if all of its signatories were to fulfill their decarbonization pledges, the estimated aggregate greenhouse gas emissions in 2025 and 2030 would "not fall within least-cost 2˚C scenarios but rather lead to a projected level of 55 gigatonnes in 2030" (UNFCC, 2016: 4), that is more than 60% above the 2018 total. Given the scales of the existing emissions and of the likely future energy demand it is certain that fossil carbon will be a major component of the worldwide energy supply even by 2050. And any suggestions that the global decarbonization can be accomplished in just two or three decades are utterly unrealistic and irresponsible.

6. *Decarbonization includes energy transitions that are relatively easy to accomplish as well as carbon substitutions for which we currently do not have any commercial non-carbon alternatives.* Generating increasing shares of electricity by relying on

wind turbines and PV cells is a proven and effective choice – as long as the share of this intermittent generation remains below the level that can be easily handled by existing grids and as long as the back-up capacities are available. In some countries the share of this easy decarbonization of electricity generation is just 15% of the total output, exceptional shares might be up to 40-50%: Denmark's wind now supplies about 45% of all electricity, a high share made possible by the country's relatively small demand (the country is smaller than a medium-sized Chinese city) and high-capacity high-voltage lines sufficient to supply any shortfall by imports from Norway, Sweden and Germany. Going beyond those nation-specific limits requires either significant new storage capacities or new high-voltage transmission, or both. But available batteries limit today's storage to a few hundreds of MW (discharged over 1-2 hours) while a large city consumes electricity at the average rate of about 1 GW; and while Germany needs 7,700 km of new high-voltage transmission lines in order to allow a higher share of intermittent renewables, it has built only 950 km (Dohmen *et al.* 2019).

Decarbonization of seasonal heating in cold climates is much more difficult, but the greatest challenges are the decarbonization of long-range, mass-scale air and water transport and the elimination of carbon as a feedstock and fuel in four industrial processes that provide material pillars of modern civilization (Smil 2014 and 2017b). Electrified railroads (both passenger and cargo) have been the best choice for generations, but the low energy density of existing batteries (maxima at around 300 Wh/kg compared to refined liquid fuels at around 12,000 Wh/kg, or roughly a 40-fold difference) means that intercontinental shipping (tankers, bulk carriers, container vessels) and jet-powered flight will remain dominant for decades to come.

As for the key materials, in 2018 the world required about 4.5 Gt of cement, 1.6 Gt of steel, 300 Mt of plastics and 150 Mt of ammonia. Production of cement now accounts for about 4% of CO_2 emissions from fossil fuels. Production of two-thirds of steel starts with primary iron smelted in blast furnaces whose operation requires about one billion tonnes of coal to make the requisite coke (supplemented by natural gas). Gaseous and liquid hydrocarbons are the feedstocks and fuels for synthesizing numerous plastics, and natural gas is the dominant fuel and feedstock needed to produce ammonia without whose applications at least 40% of humanity would not be alive. Altogether these four industrial processes consume at least 15% of the world's primary energy, and although we have a variety of proposals and experimental techniques to produce these materials without fossil carbon, in none of the above cases they have been commercialized at acceptable price and even if they were already available it would obviously take decades to displace the existing capacities operating at annual rates of 108-109 tonnes.

Many other considerations – including inherently low power densities of intermittent electricity generation by wind and solar radiation and even lower power densities of biofuel production (Smil, 2015) and the unprecedented problems of reliable supply for an increasing number of Asian megacities, some with more than 20 million people (Smil, 2019) – make any rapid decarbonization of global energy supply impossible. Even on the national level the progress has been relatively slow despite some major commitments. Germany's Energiewende (began in the year 2000) is the best example of this deliberate commitment to accelerated decarbonization, but, so far, its results are hardly enviable.

During the past five years the transition to renewables cost the country at least €160 billion (Bundesrechnungshof, 2018) -- but in 2018 coal remained the single largest source of German electricity (generating 37% of the total in 2018), the country now has the second highest electricity price in the EU (behind Denmark), and since the year 2010 it lowered its CO_2 emissions by 7%, the same cut as in the US where the reduction was achieved largely not by mass-scale installation of wind turbines and PV cells but by cost-saving switch from coal- to natural gas-fired electricity generation: in 2018 coal generated only 27% of the US electricity, natural gas 35% (USEIA, 2019).

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As unique and as unprecedented the unfolding global energy transition may be, it shares the key feature with its predecessors: it will be a gradual, multidecadal, inter-generation process with different and diverging national pathways and rates of progress. Still, our commitment to innovation and to better ways of managing our energy use can make a real difference to its rate of progress.

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Key questions and uncertainties of the energy transition

Jorge Blázquez and Spencer Dale***

Abstract

The energy system is changing. There is a well-known transition towards a lower carbon system, led by the rapid deployment of solar and wind energy. But that is only one dimension. The pattern of energy demand is also in transition, driven by growing prosperity in the developing world. In this context, this article explores the following five key issues that could shape the energy transition in the next two decades: first, how much more energy does the world need?; second, what might happen if the trade wars escalate?; third, how important are plastics for the future of oil demand?; fourth, how quickly could renewable energy grow?; and fifth, what more needs to be done to ensure a rapid transition to a lower-carbon energy system? The key message from this article is that the world is facing a dual challenge: it needs more energy to support continued growth and prosperity in developing world, whilst reducing carbon emissions. This is the key challenge facing all of us.

Keywords: Energy transition, dual challenge, carbon emissions, energy scenarios.

1. INTRODUCTION

The world of energy is in transition. Today, it is very clear that the energy mix in 2040 is going to be significantly different than the current one, with renewable energy leading the shift. It also very clear that energy demand is growing in less developed economies, while in OECD countries is, in the best of the cases, flat. Finally, there is growing consensus about the need to reduce carbon emissions as fast as possible. There is a transition to a new energy system. But the certainties about the future of energy end here. It is not clear what is the speed of this transition, what is the role of different energies, which sectors are going to need more energy, or where the energy is going to be consumed.

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In this context full of uncertainties, the *BP Energy Outlook 2019* is a document designed to help company managers and policymakers in their decision-making process. It is very obvious that the distant future is impossible to forecast. In the case of energy, literally hundreds of different variables can critically impact the demand for energy and the energy mix. No one can anticipate accurately the future path of technologies, policies, prices, and social preferences and, therefore, it makes little sense to forecast the energy mix in 2040 or 2100. For this reason, the analysis and conclusions of this BP Energy Outlook 2019 are based on scenarios. These scenarios are designed to explore and better understand the uncertainties surrounding the energy transition. There is no central or base case: the probability that the world will unfold exactly in line with any one of these scenarios is almost zero.

The analysis and narrative of this study is based around the Evolving Transition scenario. This scenario gives a sense of the broad path the global energy system might travel along, if government policies, technology and social preferences all continue to evolve in a speed and manner consistent with the recent past. However, the value of BP's Energy Outlook is not the statistical description of this scenario, rather it is in identifying some of the key issues and questions affecting the energy system and how different assumptions can critically change the path of the energy transition. In particular, in this paper, we consider five key questions:

- How much more energy does the world need?
- What might happen if the trade wars escalate?
- How important are plastics for the future of oil demand?
- How quickly could renewable energy grow?
- What more needs to be done to ensure a rapid transition to a lower-carbon energy system?

The rest of the document is organized as follows. Section 2 describes the Evolving Transaction Scenario, which is used as an anchor in the rest of scenarios, section 3 to 7 answers the five key questions developing alternative scenarios, and section 8 concludes.

2. DESCRIBING THE EVOLVING TRANSITION SCENARIO IN 2017-2040

The first relevant idea of this scenario is that energy demand increases by around a third by 2040 compared with 2017, around 1.2% per year. This increase is broadly equivalent to the current energy consumption of the US, the EU, and Japan combined (BP, 2019).[1] The growth in energy demand is the result of three different elements: global population growth (0.9% per year) (United Nations, 2017), GDP per capita growth in PPP (2.3% per year) (Oxford Economics, 2018), partially offset by improving energy intensity (1.9% per year).

The main driver for the increase in energy demand is not population growth, but growing prosperity, measured by GDP per head, as productivity in developing economies increases. In this Evolving Transition scenario, billions of people move from low to middle incomes,[2] increasing their access to electricity and clean-cooking facilities, improving the housing in which they live, and the way in which they travel. This increasing prosperity –the emergence of a growing middle class in the developing world, especially in Asia– is the major factor accounting for global economic growth over the next 20 years and, likewise, it is the major factor accounting for the growth in global energy demand. Without plentiful supplies of energy, this increase in global living standards would be suppressed and with it the major factor driving global economic growth. The worlds need more energy to continue to grow and prosper.

The amount of additional energy needed to support this rising prosperity is offset by significant gains in energy efficiency which is assumed to improve at an average rate of around 2% a year, somewhat quicker than the average over the past 20 years. As a result, although global GDP more than doubles, energy demand increases by only around a third.

Any energy scenario at a global level can be explored using three different perspectives or windows: a) how the energy is ultimately used: across industry, in

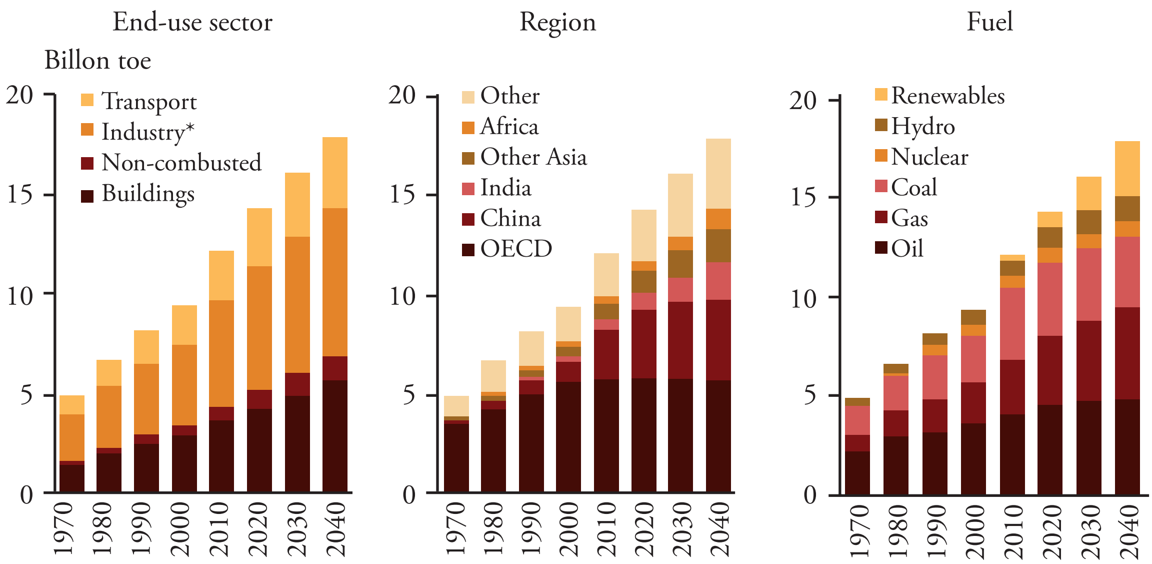
1 The primary energy consumed by these countries is around 4.400 Million of tonnes of oil equivalent.

2 Middle class and rich are as defined by the World Bank as living on more than $10 a day (measured at 2005 constant purchasing power parity (PPP)).

buildings and powering transport; b) where in the world that energy is produced and consumed; and c) what types of fuels and energies are growing to meet demand. Three different windows onto the same changing energy landscape. Figure 1 presents the same scenario from these three windows.

Exhibit 1

Primary energy demand



Despite the considerable attention many of us pay to emerging trends in the transport sector it accounts for only around 20% of energy consumption. It is important not to overweigh the significance of the transport sector (International Energy Agency, 2018). Indeed, although it typically attracts far less media and policy attention, the use of energy within industry accounts for around 50% of all the energy the world uses: almost two and a half times that used in transport. How industry's use of energy changes over the next 20 years, both in terms of efficiency and fuel choice, will have a major impact on the energy transition. Residential and commercial buildings is the fastest growing sector in terms of energy in this scenario. The vast majority of that additional use within buildings takes the form of rising power demand, as increasing prosperity and living standards in the developing world lead to greater use of lighting, household appliances and air conditioning.

From a geographical perspective, energy demand in the developed countries is essentially flat. There is no significant growth. All of the growth in energy demand comes from the developing world, led by Asia. The importance of India increases even further, overtaking China to be the largest growth market for energy over next 20 years. The big factor driving this switch is the sharp slowing in Chinese energy demand as economic growth moderates and the pattern of that growth shifts to less energy-intensive activities.[3]

Finally, this section looks at energy demand through the third window: which fuels are increasing to meet this demand. Renewable energy,[4] led by wind and solar power, is the fastest growing source of energy in this scenario, accounting for around half of the increase in primary energy, with its share increasing to around 15% by 2040. Oil demand continues to grow during the next decade, before broadly plateauing in the 2030s. All of the growth in oil consumption stems from the developing world, with a combination of US tight oil and OPEC meeting this increased demand. Natural gas grows much faster than either oil or coal; overtaking coal to be the world's second largest energy source and converging on oil around 2040. The demand for natural gas increases in almost every country and region considered, supported by the expansion of exports of liquified natural gas (LNG). Renewables and natural gas together account for almost 85% of the growth in primary energy. Nearly 85% of new energy is either clean or cleaner energy. In contrast, global coal demand is essentially flat, with falls in China and the OECD barely matched by increasing demand in India and other parts of emerging Asia.

The last critical element of this scenario is CO_2 emissions from energy use. In the Evolving Transition, CO_2 emissions continue to edge up, increasing by around 7% over the next 20 years. The good news is that this pace of growth is far slower

3 The share of industry in Chinese GDP was 41% in 2016 from 48 in 2006, according the World Bank Database. https://www.worldbank.org

4 It is important to highlight that "renewables" includes solar, wind, biomass, and geothermal. Hydro energy and traditional biomass are not included this category of energy.

than in the past two decades when emissions increased by almost 45%. So, the world is making some progress. The bad news is that the pace of this progress is nowhere near fast enough. To be consistent with the Paris climate goals, CO_2 emissions need to fall substantially over the next 20 years, not simply grow less quickly.

A sectoral analysis of emissions shows that the power sector accounts for around 40% of CO_2 emissions in 2040. It is the single biggest source of CO_2 emissions from energy use, both today and in 2040 despite the unprecedented growth in renewables envisaged in the Evolving Transition scenario. Industry and transport each account for around a quarter of emissions in 2040, and finally, buildings about 10%.

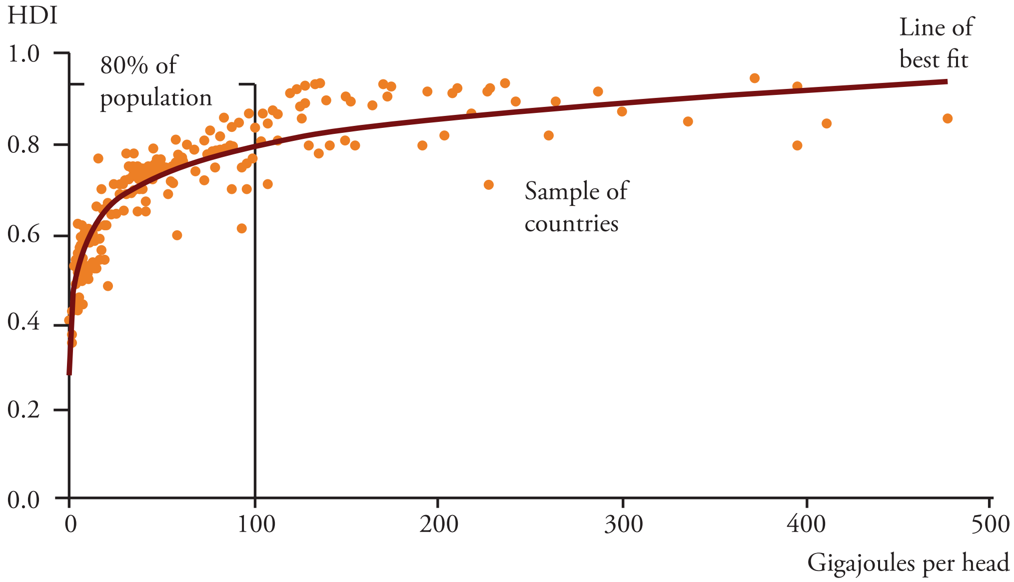
3. FIRST QUESTION: HOW MUCH MORE ENERGY DOES THE WORLD NEED?

There is a strong link between human progress and energy consumption. Figure 2 (BP, 2019) shows the relationship between human development, as measured by the UN human development index (2018) (United Nations, 2018), and energy consumption across a large number of countries.

It suggests that increases in energy consumption tend to be associated with improvements in human development, with those improvements particularly pronounced for increases in energy consumption of up to around 100 Gigajoules per head,[5] after which the relationship begins to flatten out. It is really striking is that around 80% of the world's population today live in countries where average energy consumption is less than that 100 Gigajoules per head, where increases in energy consumption and human development are particularly pronounced. In the Evolving Transition scenario, despite the substantial growth in energy demand, this proportion is still around two-thirds in 2040. The world will need substantial amounts of more energy as it grows and prospers.

5 It is similar to the annual consumption of two average dwellings in the UK or one could drive more than 16,000 miles with an average UK new car.

Exhibit 2
Human development index and energy consumption per head, 2017



Source: United Nations, 2018.

BP Energy Outlook 2019 presents an alternative scenario in which the share of the world's population living in this 'low energy' region is reduced to one-third by 2040. Other things equal, that requires around 25% more energy by 2040 than in the Evolving Transition scenario, so roughly equivalent to China's entire energy consumption in 2017. In a more prosperous world, which implies reducing the share of the world's population living in that 'low energy' region to a third, energy demand is around 65% higher than today.

As mentioned in the previous section, in the Evolving Transition scenario CO_2 emissions edge up by around 7% by 2040 compared to 2017 levels. *BP Energy Outlook 2019* develops another alternative scenario named the Rapid Transition scenario, in which CO_2 emissions fall by around 45% by 2040. This reduction by 2040 is broadly consistent with meeting the Paris climate goals.

And this is the central idea behind the dual challenge: the need to provide both more energy and less carbon. In other words, how to make compatible an increase in energy by around 65% and a reduction in emissions by around 45% by 2040? The world needs increasing levels of energy as the global economy grows and living standards improve. But at the same time, it needs a sharp reduction in carbon emissions for there to be a good chance of meeting the Paris climate goals. There is no simple solution to this challenge, but any viable, sustainable path for the energy system needs to take account of both elements: more energy, less carbon.

4. SECOND QUESTION: WHAT MIGHT HAPPEN IF THE TRADE WARS ESCALATE?

The world is facing a period of uncertainty regarding international trade. This section explores the issue of the recent trade disputes, and how they might affect the global energy system if they were to escalate further. To be clear, the aim is not to consider the implications of any particular dispute, but rather the more general issue of how the energy system may be affected if these types of disputes became more frequent and commonplace. Figure 3 shows the energy balance in different regions in 2017 and in 2040 in the Evolving Transition Scenario.

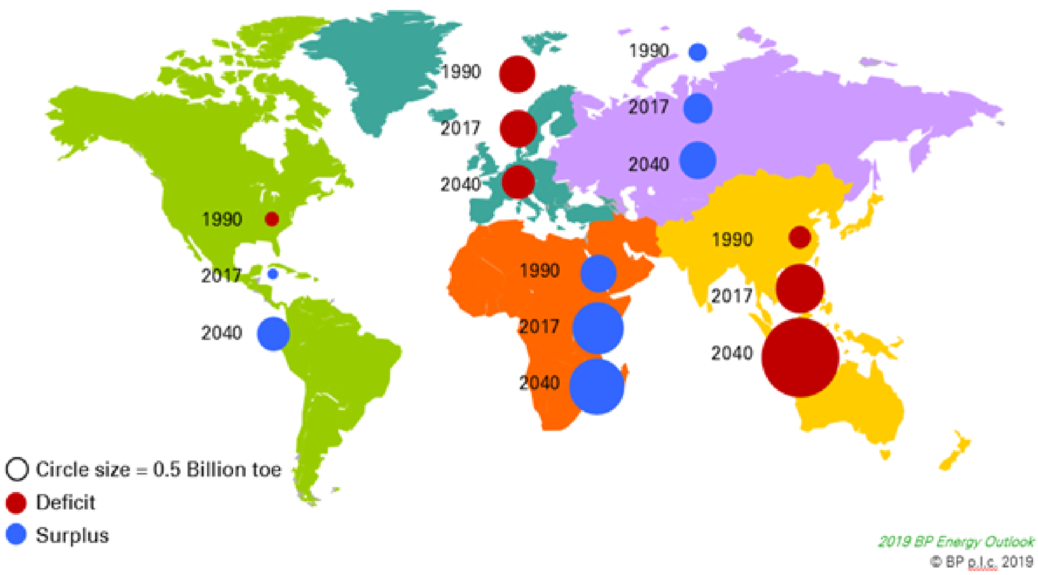
To assess their possible impact of persistent trade disputes, we consider a scenario in which increasing trade disputes lead to two persistent effects. First, the reduced level of openness and trade causes productivity advances in one part of the world to spread more slowly to other regions, leading to a slight reduction in the trend growth of global GDP. And this is based on well-documented impacts in the economics literature (See for example, Alcala and Ciccone, 2004; Ahn *et al.,* 2019; Kultina-Dimitrova and Lakatos, 2017).

In this new scenario, the level of global GDP in 2040 is around 6% lower than in the Evolving Transition scenario, and global energy demand is around 4% lower. This 4% may sound quite small, but that reduction in energy demand by 2040 is roughly equivalent to India's entire energy consumption today.

The second effect is that increased concerns about energy security leads countries to attach a small risk premium – of 10% – on imported sources of energy. So, for example, for a country importing oil, if the global oil price was $60 per barrel,

Exhibit 3

Energy balance of traded fuels (oils, gas, coal)



they would be willing to pay up to $66 for domestically produced oil or an equivalent substitute, given the extra security this provides.

This change in domestic policy to favour domestically produced fuels has an impact on trade. There is a reduction in traded fuels, particularly oil and gas, as countries switch from imported energy. The lower level of energy demand, together with the bias for domestically produced energy, leads to a sharp reduction in energy trade.

Although the assumed size of these two effects is pretty modest, it is striking is that the impacts on the global energy system in this alternative scenario are significant. For example, China's net imports of oil and gas in 2040 are 20% lower than in the Evolving Transition scenario, as they switch into domestically-produced coal and renewables. This, in turn, has a knock-on effect for energy exporters. US net exports of oil and gas in 2040 are around two-thirds lower than in the Evolving Transition scenario – with the emerging US trade surplus in oil and gas severely dented.

To put the recent trade disputes in an historical context: the share of oil in the global energy system peaked in 1973, the year of the oil embargo, and has pretty much declined ever since. The message from history and from this scenario is that concerns about energy security can have persistent and damaging effects.

5. THIRD QUESTION: HOW IMPORTANT ARE PLASTICS FOR THE FUTURE OF OIL DEMAND?

This section explores the impact of plastics on oil demand. In the Evolving Transition scenario, consumption of liquid fuels increases around 10 million of barrels per day (Mb/d) over the next 2 decades. Demand rises from around 98 Mb/d to 108 with the majority of that growth occurring over the next 10 years, after which demand gradually plateaus. This growth stems partly from increasing demand from the transport sector but the impetus from transport gradually fades as vehicle efficiency increases and other fuels penetrate the transport system.

The single largest and most persistent source of demand growth is from the non-combusted use of liquid fuels in industry, especially as a feedstock in the petrochemical sector. Much of the growth in the non-combusted use of liquid fuels is driven by the increasing production of plastics, which is by far the fastest growing source of non-combusted demand. So what might happen if increasing environmental concerns cause the regulation of plastics to tighten significantly? How could this affect the growth of oil demand?

The likelihood of some material tightening in plastics regulation is already built into the Evolving Transition scenario. In particular, the scenario includes a doubling of recycling rates to around 30%. As a result, the growth rate of plastics in next two decades almost halves relative to the past 20 years, despite only a slight slowing in GDP growth. This means the growth of oil demand decreases by around 3 Mb/d relative to a continuation of past trends. But it is possible that regulation may tighten by even more.

We consider an alternative scenario which focuses on plastics for packaging and other single uses –plastic bags, bottles, straws, etc.– which account for around 3.5 Mb/d of liquid fuels today, rising to around 6 Mb/d by 2040 in the Evolving

Transition scenario. It is worth remembering that around two-thirds of all plastics are used to produce durable products and these long-lived products are not the focus of current concerns. The alternative scenario considers the question of what would happen if the regulation of plastics tightened even faster than assumed in the Evolving Transition scenario, culminating in a worldwide ban on the use of all plastic packaging and other single uses from 2040 onwards.

The demand for oil and other liquid fuels used in the non-combusted sector still grows relative to current levels but not much. More importantly, the overall growth of oil and other liquid fuels is reduced to around 4 Mb/d, compared with 10 in the Evolving Transition scenario.

There are two main conclusions of this alternative scenario. First, although a complete worldwide ban on all single-use plastics is unlikely, it highlights that the speed and extent to which the regulation of plastics does tighten over the next 20 years could have a material impact on the pattern of oil demand growth. Second, the scenario does not account for the energy needed to produce the alternative materials that are used in place of single-use plastics. The point here is that the reason why the demand for plastic packaging and other single uses is set to increase so substantially over the next 20 years is because they provide an effective and efficient solution to many everyday needs. It is not easy to substitute these plastics without further advances in alternative materials and widespread deployment of efficient collection and reuse systems.

6. FOURTH QUESTION: HOW QUICKLY COULD RENEWABLE ENERGY GROW?

Renewables are the fastest growing source of energy in the Evolving Transition scenario, accounting for around half of the increase in primary energy and around two-thirds of the growth in power generation in 2017-2040. This rise of renewable energy is led by wind and solar power. Wind increases by a factor of 5 and solar energy by a 10 in the same period, accounting for broadly similar increments in global power. The growth in renewable energy means it replaces coal as the primary source of global power generation by 2040.

The growth of renewable energy is dominated by the developing world which accounts for around two-thirds of the increase. The particularly rapid growth of renewables in developing countries is helped by strong growth in power demand, which ensures there is considerable scope for renewables to grow. In contrast, the much slower expansion of power demand in the OECD means that the scope for renewables to grow in most developed economies is largely limited by the pace at which existing thermal power stations are retired. Indeed, *BP Energy Outlook 2019* includes an analysis which shows that a doubling in the rate at which existing thermal power stations are retired increases the penetration of renewable energy by almost as much as a doubling in the pace of technological progress. This is a particular example of the more general point that the capital intensity of the energy system acts as a speedbump on the pace at which new energies can penetrate. To sum up, continued technological gains in renewables are a necessary condition to achieve a rapid decarbonisation of the power sector, but they are unlikely to be sufficient on their own.

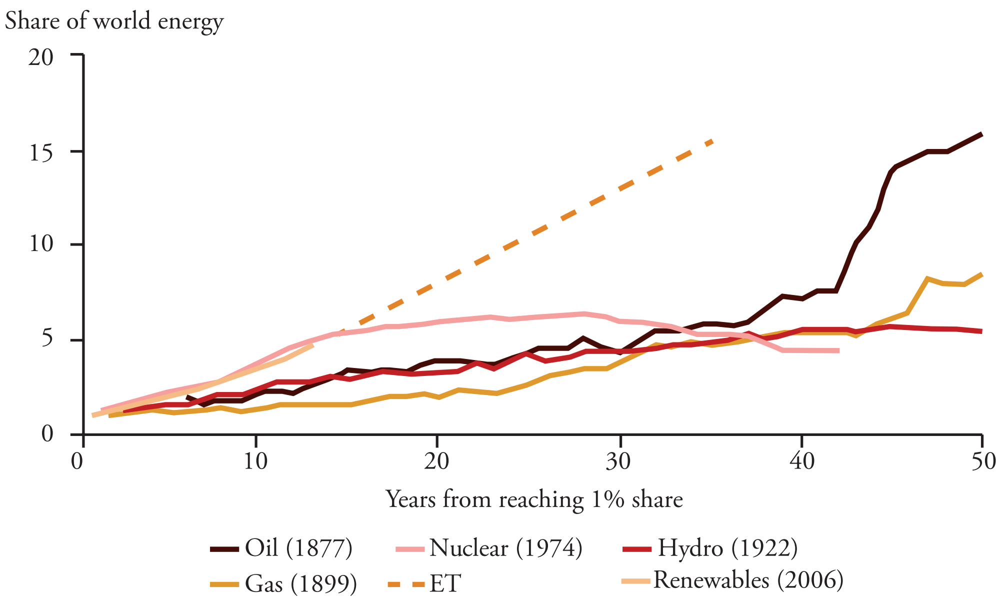
Figure 4 puts this point into a broader historical perspective. The key point to take away from this chart is the time it took for new energies to penetrate the energy system. This Figure shows the share of different energy sources, starting at the point when each one of these fuels provided 1% of world energy and considers how that share increased over the subsequent 50 years. So, for oil, the chart starts in 1877 when oil first accounted for 1% of world energy. For nuclear, it was 1974 – so in this case, we have not yet reached the end of the 50 years. This Figure 4 shows that it took almost 45 years for oil to increase its share from 1 to 10% of world energy. For natural gas, it took natural gas over 50 years. As mentioned before, the capital intensity of the energy system acts as a break on the speed at which new energies penetrate. Energy transitions in history have taken multiple decades (Fouquet, 2010).

In the case of renewable energy, the clock started ticking in 2006 when these energies achieved 1% of the global energy mix. So far, renewables have followed a path pretty similar to nuclear energy. What will happen next? The profile implied by the Evolving Transition scenario suggests that the share of renewables in world energy will increase from 1 to 10% in around 25 years. So, more quickly than any

Exhibit 4

Speed of penetration of new fuels in global energy system

(Percentage)



fuel ever seen in history, helped by policy support and sustained technological improvements.

However, this rapid growth of renewable energy is not enough to achieve the climate targets of the Paris Agreement. This rises the last question of this article.

7. FIFTH QUESTION: WHAT MORE NEEDS TO BE DONE TO ENSURE A RAPID TRANSITION TO A LOWER-CARBON ENERGY SYSTEM?

The Evolving Transition scenario is not consistent with Paris Agreement. The *BP Energy Outlook 2019* describes an alternative scenario that is broadly consistent with the Paris Agreement targets. This is called the Rapid Transition scenario. The idea behind this scenario is to consider a range of policy measures that can be applied in industry, transport, buildings and power to achieve a faster transition to a lower-carbon energy system.

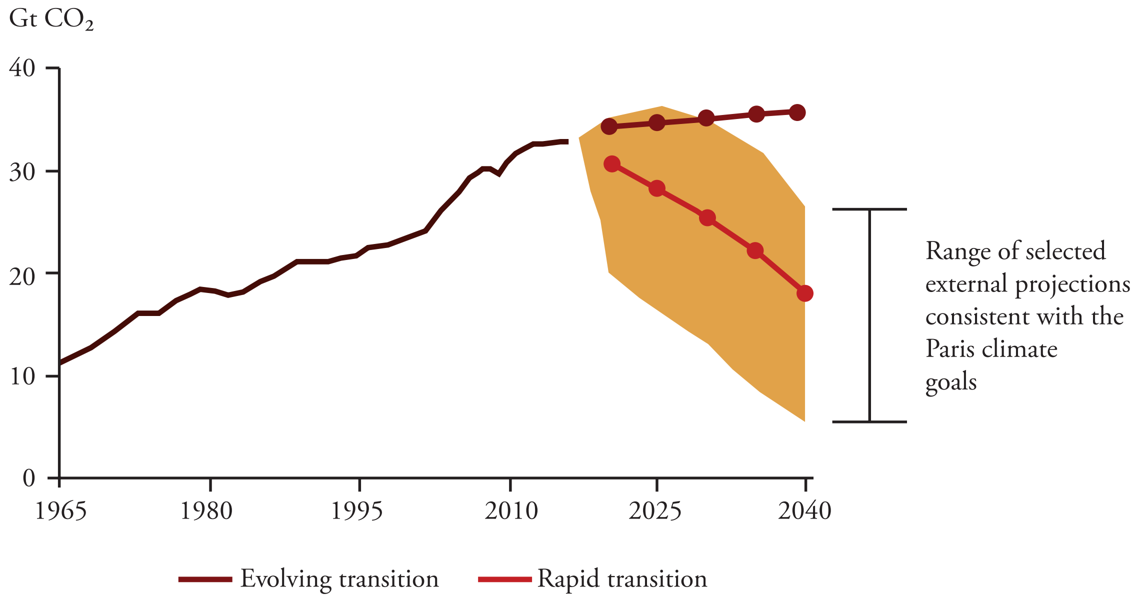
In this alternative scenario, carbon emissions from energy use fall by around 45% by 2040 compared to the Evolving Transition scenario. This reduction is in line with a sample of external projections which claim to be consistent with meeting the Paris climate goals. Figure 5 shows the path of carbon emissions in the Rapid Transition, the Evolving Transition, and a range of external projections consistent with the Paris climate goals.

This scenario has wide range of stretching measures across each sector, with the policies chosen so as to be broadly equivalent in terms of their implied costs and effort. The idea behind this strategy of multiple policy measures is that there is no silver bullet. A comprehensive set of policy measures is needed.

Carbon prices play a central role. This is particularly relevant for the power and industrial sectors, encouraging a switch into lower-carbon fuels and supporting investment in CCUS. In this scenario carbon prices reach $200 per tonne of CO_2 by 2040 in the OECD and $100 elsewhere. However, carbon prices are increased only gradually to avoid a premature scrapping of productive assets.

Exhibit 5

CO_2 emissions



This means there is a role, at least for a period, for targeted regulatory measures to help create the right incentives for new investments until carbon prices get to meaningful levels.

What is the role of the different sectors in this alternative scenario? Around 2/3 of the emissions reduction is due to the reduction in the carbon intensity of the power sector. Policies aimed at the power sector are central to achieving a material reduction in carbon emissions over the next 20 years. Much of the rest of the reduction (1/3) is due to reductions in buildings and industry. Its striking that the transport sector, despite an equally stringent set of measures being applied, accounts for only a small reduction in carbon emissions relative to the Evolving Transition scenario. For example, the number of electric cars in the Rapid Transition scenario is over 600 million in 2040 while in the Evolving Transition it is half of that number. Most of the low-hanging fruit in terms of reducing carbon emissions over the next 20 years is outside of the transport sector.

In absolute terms, the increased use of Carbon Capture Utilisation and Storage (CCUS) in the power and industrial sector –to around 4.5 Giga tonnes of CO_2 by 2040– accounts for around a quarter of the reduction in carbon emissions relative to current levels.

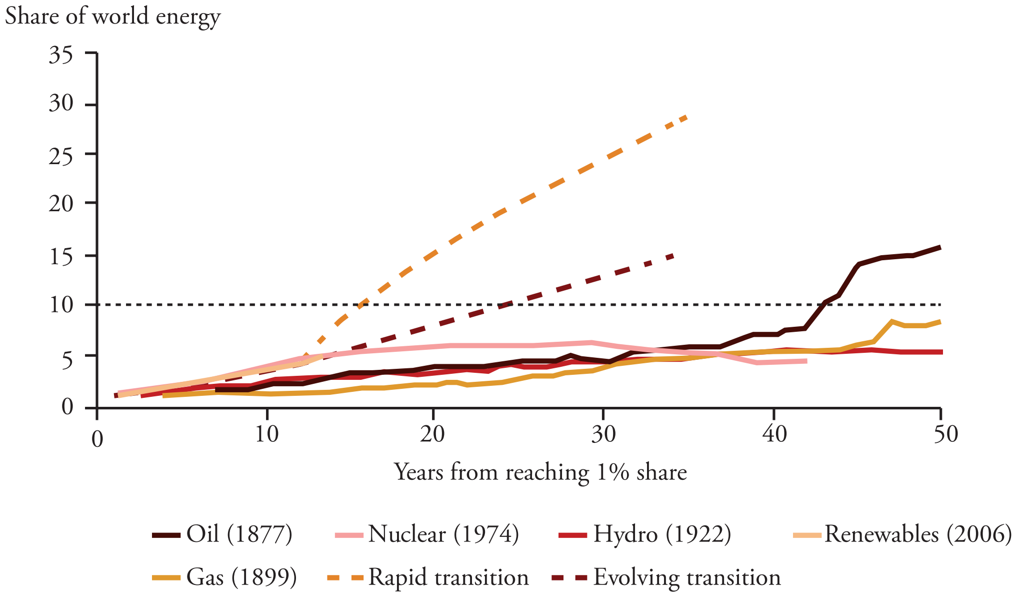
In this scenario, all of the growth in energy demand is met by increasing renewables, with their share of primary energy increasing to 30% by 2040. This brings back the question how fast can renewable energy grow. Figure 6 shows the speed of penetration of renewable energy in the energy system in the Evolving Transition and in the Rapid Transition. The growth of renewables is literally off the charts relative to anything seen in history, with renewables accelerating from 1% to 10% in just 15 years. This does not automatically suggest that this is impossible or implausible. However, to achieve a pathway consistent with Paris will require a speed of change and transition in the global energy system which is truly unprecedented.

Renewables accounts for around a 1/3 of global energy in 2040. This implies that other forms of energy need to provide the other 2/3. In this alternative, low-

Exhibit 6

Speed of penetration of new fuels in global energy system

(Percentage)



carbon scenario, oil and gas together account for almost 50% of primary energy in 2040. In the Rapid Transition scenario, oil demand falls to around 80 Mb/d by 2040. In contrast, the demand for natural gas actually increases over the next two decades, helped by the growing use of CCUS. Around 40% of natural gas consumption is used in conjunction with CCUS by 2040.

The main takeaways of this scenario are the following. First, the power sector is the lowest-hanging fruit in terms of carbon emissions. The power sector is key in that respect. Second, carbon prices are critical: they provide the correct incentives for producers, consumers, and innovators, but they have to be supplemented by targeted regulations, especially in the initial phases if carbon prices are increased only gradually. And third, many energies are likely to be required for many years.

Even if the world was to achieve everything envisaged in the Rapid Transition scenario, a significant level of CO_2 emissions from energy use would still remain in 2040. This alternative scenario represents a major step towards Paris, but it just a step. There is still a significant level of emissions remaining in 2040, concentrated in hard-to-abate processes and activities, particularly in transport and industry.

To achieve a net zero energy system in the second half of this century more things have to be done. A key development would be the need for an almost complete decarbonisation of the power sector, together with greater electrification of end-use activities. That in turn is likely to require: more renewables; CCUS to support gas and, perhaps, even coal; and energy storage and demand-side-response to help alleviate some of the growing intermittency issues associated with increased reliance on renewables. The International Energy Agency estimated that only 2/3 of final energy use has the technical potential to be electrified, highlighting the need for other low-carbon forms of energy and energy carriers, such as hydrogen and bioenergy. There will also be a need for accelerated gains in energy efficiency, including a substantial expansion of the circular economy. And, finally, a range of technologies for the storage and removal of carbon emissions, including negative emission technologies, such as land carbon. The road to Paris is long and challenging.

8. CONCLUSIONS

The global energy system is in transition. The obvious dimension of that transition in the need to shift to a lower carbon energy system. But that is only one dimension. The pattern of energy demand is also in transition, driven by growing prosperity in the developing world, as billions of people start to enjoy just a tiny fraction of the comforts and amenities that most people in developed countries take for granted. Meeting the dual challenge for more energy to support continued growth and prosperity, whilst reducing carbon emissions is the key challenge facing all of us. In this context, the *BP Energy Outlook 2019* explores some scenarios that could shape the energy transition in the next two decades. The main findings of the scenarios described in this document are the following.

First, in the Evolving Transition scenario, that describes the path of the energy system in 2017-2040 if policies, technology, and social preferences evolve in a speed and manner consistent with the recent past, energy demand increases by a third. In this context of higher demand, renewable technology penetrates the energy system faster than any other fuel in history, increasing by a factor of 5. However, this rapid growth is not enough to achieve the targets of the Paris Agreement and carbon emissions continue to grow.

Second, the world needs more energy. The Evolving Transition assumes that billions of people move from low to middle incomes. The emergence of a growing middle class in the developing world is the main force for economic growth in 2017-2040. However, in 2040 a significant share of world's population still live in countries in which increases in energy consumption tend to move hand-in-hand with pronounced increases in human development. This is the core of the dual challenge. The world needs simultaneously more energy to foster prosperity in less developed economies and less carbon emissions at a global level.

Third, an increase in trade disputes might have a material impact on the energy system due to a lower global growth and increased concerns of energy security. These two factors combined lead to a decrease in global energy demand of 4% compared to the Evolving Transition scenario, a sharp reduction in energy trade, and a different structure of international energy flows.

Fourth, non-combusted energy represents a significant share of the current and future demand for oil. The *Energy Outlook* explores the impact of a ban on all single-use plastics in an alternative scenario. This scenario is not likely, but shows that tighter regulation on plastic could have a significant impact on the pattern of oil demand growth. In particular, the growth of oil and other liquid fuels in this alternative scenario is reduced to around 4 Mb/d, compared with 10 in the Evolving Transition scenario.

Fifth, renewable technologies grow by a factor of 5 in the Evolving Transition scenario, accounting for around half of the increase in primary energy and around two-thirds of the growth in power generation in 2017-2040. However, this is not enough to be consistent with meeting the carbon targets of the Paris Agreement. The *BP Energy Outlook* develops an alternative scenario, the Rapid Transition, with a speed of reduction in carbon emissions over the next 20 years that is broadly consistent with the Paris Agreement. In this scenario, renewable energy grows by a factor of 8. The Paris Agreement requires a speed of transition which has no precedent in the history of energy.

What more needs to be done to ensure a rapid transition to a lower-carbon energy system? This is, probably, the most relevant question for policymakers and energy companies. The Rapid Transition scenario tries to answer this question. There are some takeaways of this scenario. First, power is the sector where it is easier to reduce carbon emissions over the next 20 years. The potential emission reduction in transport, industry and buildings is much lower. Second, carbon prices are a critical tool for achieving a low carbon energy system, but they have to be supplemented by targeted regulations at least in the short run. And third, many energies are likely to be required for many years. In this Rapid Transition scenario, oil and natural gas amount to 50% of the total primary energy consumed in 2040.

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Perspective on the energy transition

*Seb Henbest**

Abstract

Primary energy masks the important role of electricity and the growth and future potential of renewable energy. The "Phase I" decarbonization technologies of wind, solar PV, electric vehicles and stationary lithium-ion batteries are all on track for another record year of deployment in 2019, as technology cost continue to fall with every unit deployed. Today wind or PV is the cheapest new-build electricity for two-thirds of the world population and will soon undercut commissioned coal and gas plants. Cheaper batteries help renewables reach higher value hours when the wind isn't blowing or sun isn't shining. Battery costs are down 87% since 2010 as auto manufacturers push more models into the market. Uptake should accelerate from 2023 when EVs start to hit upfront price parity with ICE alternatives causing oil demand from road fuels to peak around 2030. Cheap variable renewables form the backbone of the new electricity system reaching as higher as 80% in some markets when supported by smart EV changing, batteries and peaker plants. Coal-fired electricity peaks in 2026 undercut by cheaper renewable and batteries as well as more flexible gas. Achieving net-zero emissions however ask serious questions about energy transition pathways for industry and buildings. And while going electric isn't a universal solution and renewables are not a one-size-fits-all solution, deploying the "Phase I" technologies to their full potential can make a big dent in emissions and buy time for development of "Phase II".

Keywords: Energy transition, renewables, batteries.

Often we hear that wind and solar might be great and may be growing fast, but despite years of deployment and government support they are still just 1% of primary energy and so can't possibly replace fossil fuels in the world energy economy.

Primary energy might be the right lens through which to think about energy when there are few alternatives to fossil fuels, or if you're an oil, gas, or coal company, for which primary energy describes the product you sell. However the world economy does not run on primary energy, it runs on final energy. That's the energy we consume to heat and light our buildings, run our vehicles, and

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power industry. The major difference between primary and final energy is waste heat, though there are also some losses from energy transport. Altogether, around a third of primary energy is lost before it can do anything useful.

Thinking about the world in terms of primary energy also masks the important role of electricity where heat losses are highest at around 63%. It can also help to explain why many of the world's most eminent energy experts have underestimated the growth to date of renewable energy, and its future potential. If we consider that the electricity sector consumes about 38% of fossil fuel production; and that renewables make up 25% of electricity, and wind and solar PV make up 25% of that, it easy to see how these technologies can get lost in the noise of a much larger primary energy analysis.

Renewables are certainly not the one-size-fits-all solution that enthusiasts sometimes claim. However if we think of the energy transition in phases, then we need to think of wind, PV and lithium-ion battery storage as "Phase I" decarbonization technologies that, if deployed to their full potential, can make a big dent in greenhouse gas emissions and buy us time to develop something else for "Phase II".

The world has been adding more renewable power capacity than fossil fuel power capacity since 2015. Today, renewables (excluding large hydro) account for almost 68% of new additions, and make up 21% of total installed capacity and 13% of generation. In 2018 a record 108GW of PV was deployed worldwide, as well as 50GW of wind power. In 2019 the industry is on track to beat all records with 121GW of PV and 67GW of wind. Looking forward to 2020 we estimate another 138GW of PV and 70GW of wind. But how might this continue?

The *New Energy Outlook (NEO)* is BloombergNEF's annual long-term analysis of the future of energy. It draws together the work of over 65 in-house analysts across the world to describe a future, least-cost, electricity system. The headline conclusion is that a combination of cheap renewables, batteries, and other new sources of flexibility grow worldwide to reach almost 50% wind and PV in the electricity supply by 2050, with solar growing from around 2% to 22% of electricity, and wind from 5% to 26%. In contrast, the share of fossil fuels in power declines to 31% from 63% today while hydro and nuclear see modest growth or remain flat, the former constrained by resource availability, the latter by a combination of high costs and a lack of flexibility.

At its core, *NEO* is a story of technology disruption and nothing reflects this better than solar PV. Since 1976 we have seen a rapid fall in the price of crystalline silicon PV modules, down from $80/W to $0.27/W in 2018, and around $0.25/W in 2019. Just since 2010 PV module prices have fallen 85%. Driving this are manufacturing scale and ongoing deployment. The relationship between price and volume can be represented by an experience curve. For PV, the experience curve describes a 28.5%, decline in cost for every doubling of capacity. That's perhaps not as steep as equivalent curves seen in the semi-conductor industry, but it's of a similar order of magnitude. How long this relationship will hold is unknown, but bottom-up analysis looking at innovation in PV manufacturing on a component-by-component basis makes us confident that the industry won't hit technical limitations anytime soon. Looking out to 2025 and 2030, we expect all-in cost of energy from new solar PV to drop another 14% and 22% respectively.

Wind technology has also been getting cheaper. The price of wind turbines is down 40% since 2010 on a per megawatt basis with an experience curve of around 11%. But while unit declines are less impressive than PV, wind remains competitive with solar energy because each MW of wind yields more energy. This improvement in capacity factor comes from taller turbines that can access faster wind speeds, and bigger swept-area-to-power-output ratios that increase the energy captured where the wind is weaker. Newer turbine models are also widening the range of locations where wind parks can be developed economically. Overall, onshore wind energy has a 15% learning rate. Recent years has also seen the cost of offshore wind come down faster than most expected. This is the combination of larger turbines that offer better park layouts as well as fewer foundations, less cabling and less maintenance; larger projects pushing the 1GW mark that offer economies of scale; growing global supply chains and developer experience; as well as better policy design.

Both solar PV and wind are the product of large-scale modular manufacturing industries that find continuous micro-innovations in production efficiency, materials and energy use. The cost of these technologies declines with every unit deployed. And this is fundamentally different to large, fuel-based power plants which are pieces of complex system engineering, and where 50% of the lifetime cost of a coal plant and 70% of that for gas plants are due to fuel prices, themselves subject to commodity cycles.

By taking technology costs, balance of plant, operations, maintenance and financing costs into account, we can calculate the levelized cost of electricity (LCOE) for new renewable and fossil fuel assets alike. The LCOE is the average offtake price needed across a project lifetime for a developer to meet its equity hurdle rate of return. When we do this, we find that the cost of renewable projects have now fallen to such an extent, that today two-thirds of the world population live somewhere where wind or PV, or both, are the cheapest new-build electricity option. And in Japan, Poland or Turkey where coal remains cheaper, or in Russia where gas remains cheaper, this first tipping point in the economics is imminent.

We are also seeing firm downward pressure on new wind and PV project costs from more and more capacity being awarded via tender or auction. Here, competition between developers continues to reveal incredibly low prices, which in turn has squeezed margins all along the supply chain. Most recently, on November 21, the Dubai Energy and Water Authority awarded a contract for 800MW of PV to Saudi-based ACWA Power and Kuwait-based Gulf Investment Corporation with an impressively low bid of $16.95/MWh. This followed the lowest bid on record of $16.30 (€14.80/MWh) from French developer Akuo Energy which won 150MW in Portugal's first solar auction in August.

Already this year we have seen 63GW of new renewable capacity awarded via auction – more than ever before – with a further 97GW announced for future rounds. The lowest bid for new onshore wind energy to date is in Mexico where Italian utility Enel won a total of 593MW, including a bid of $17.70/MWh. These prices need to be read cautiously as they hide a long list of contract particularities that obscure the full lifetime cost of the projects. For example, some bids are for delivery in future years and developers can bake-in an expectation of cheaper equipment; projects also usually have a longer life than the length of contracts awarded; and some include inflation factors or differential tariffs. However, even if we levelize these bids, they remain incredibly cheap and the costs are generally much lower than those of new coal or gas plants.

If we expect renewable technology costs to continue to decline along their experience curves, then it's a matter of when, not if, new-build wind or PV drops below the cost of running existing, commissioned coal and gas plants. This second "tipping point" happens at different times in different countries, depending on the quality of renewable resources and fuel prices, but it happens sooner than most people might think. In China, our calculations suggest new onshore wind will be cheaper than running existing coal-fired power as early as 2024. And in the U.S., which has the cheapest gas in the world, new-build wind and PV look likely to be cheaper than running most existing combined-cycle gas plants by 2030. As these critical points are reached, renewables can start to take market share from commissioned coal and gas plants, which consequently see lower capacity factors and higher generation costs.

But there is an obvious problem – wind and PV are not always available, so looking at the LCOE alone is not enough. Ultimately what's needed is additional flexibility, both on the supply and the demand side to help support variable renewables and ensure security of supply. Demand response, including both capacity turn-down and time-of-use load shifting; large reservoir hydro and pumped hydro; network interconnection; and gas peaker plants that run on-call for a small number of hours per year, can all offer flexibility. However the most compelling technology story is lithium-ion batteries. Batteries can shave peaks and can help PV meet demand when the sun has gone down, and wind meet demand when it's not blowing. However most importantly, like PV and wind, lithium-ion batteries are getting cheaper, fast.

The price of a lithium-ion battery pack is down 87% since 2010 on a volume-weighted basis from $1,160/kWh, to $156/kWh according to BNEF's December 2019 annual survey. At the same time, battery energy density and cycle life continue to improve – the former up more than 67% since 2011. Like PV and wind, this decline in costs is the result of manufacturing scale and innovation, with battery pack demand rising 100-fold from 2010 to 2018. The relationship between price and volume here describes an 18% learning rate, so as manufactured volume increases over time, we expect costs will continue to fall to around $94/kWh in 2024 and $62/kWh in 2030. Right now there is 366GWh per year of commissioned lithium-ion battery manufacturing capacity worldwide, and based on manufacturer commitments, by 2022 that number is set to rise more than three-fold, to 1,239GWh. To give a sense of future scale-up, in 2018 demand for lithium-ion batteries for electric vehicles overtook demand for lithium-ion batteries for consumer electronics, and in most markets EVs currently only make up 2% or less of the on-road fleet.

While lithium-ion battery chemistries aren't always a perfect fit for stationary energy storage applications in the power sector, they have a significant cost advantage over other technologies. Today, a four-hour lithium-ion battery system charging from the grid has an average levelized cost of around $167/MWh, and as battery costs decline we expect this to fall to $79/MWh by 2030. Today most business cases for large-scale batteries rely on stacking revenues from a combination of energy, capacity and ancillary service markets, depending on what's available. They are also being used in some markets by large energy users to lower demand charges, and grid operators to avoid costly network upgrades.

However, in the future we expect most batteries will find value in load shifting – that is, charging when renewables are abundant and prices low, and discharging during high value hours when renewables are offline and prices spike as more expensive generation ramps up. We can already see a pipeline of co-located renewables-plus-storage projects. If the battery is small enough, these can be competitive today, with lower costs larger batteries. Our calculations suggest the cost of co-located wind-plus-storage and PV-plus-storage projects with larger four-hour storage systems will fall over 40% by 2030. That means renewable energy can reach more high-value hours when they would otherwise be unavailable, competing directly with new coal or gas projects for capacity by the mid-2020s. In India, for example, we think these co-located systems will look more economic than new pithead coal-fired generation by 2024. And by the mid-2030s batteries charging either from the grid or from a co-located coal asset could be cheaper then running existing coal or gas plants.

The fall in battery prices is the result of growing demand from the electric vehicles industry. EVs sales growth has slowed a little in 2019, but we still expect a record 2.2 million vehicles, up from 1.9 million in 2018, and just over 1 million in 2017. At the end of Q3 2019 there were 6.5 million EVs on the road, over half of those in China. The uptake is being driven in part by tighter tailpipe emissions standards in U.S., China and Europe that require auto manufacturers to sell more EVs to balance sales of their internal combustion engine (ICE) models. There are currently 370 battery-electric and plug-in hybrid EV models on the market worldwide, and by this time next year there will be 428. More models means more choice, and more likely a buyer will find an EV option that suits their needs. On the other side of the ledger, purchase subsidies, tax breaks and scrappage schemes are helping drive consumer uptake. Governments are also starting to send longer-term signals to the market. So far 13 national governments, as well as 30 states and municipal governments, have announced phase-out plans for internal combustion engine vehicles. Norway is the most ambitious country-level target, aiming to ban ICEs by 2025, other European countries such as Denmark, Sweden and Netherlands are aiming for 2030, and the U.K., France and Canada at 2040. Cities tend to be more ambitious, with Madrid, Rome, Athens and Mexico City aiming to be ICE-free in six years. Los Angeles, Cape Town and Brussels are some of those aiming for 2030.

Around 30% of the cost of a battery electric vehicle is the battery pack, so cheaper batteries means cheaper EVs which, according to our analysis, should reach upfront price parity with equivalent ICE models as soon as 2023. From that point we expect uptake to accelerate, reaching 30% of new vehicle sales worldwide by 2030, and 57% by 2040, up from just 3% today. By 2040 around 42% of cars on the road in the U.S. are expected to have a plug. In Europe its 38%. Worldwide there are set to be around 576 million EVs on the road in 2040. All these EVs do two things: they add electricity demand, and they reduce oil demand.

Growth in electric vehicles accounts for 3,950TWh, or 9%, of electricity demand in 2050. Again, this differs by region. In the U.S., EVs draw 16% of electricity in 2050, in Europe 15%, in Australia 13%, and in China 10%. However the hours of the day when EVs charge will ultimately be as important as how much load they add. Many energy suppliers in the U.S. and Europe already offer EV-specific rate structures that provide a strong incentive for off-peak charging at night. If an EV can be plugged in during the 95% of the time a normal car is stationary, whether that's at home, at work, or out-and-about, then owners can charge at the cheapest times, and the power grid benefits from greater demand-side flexibility. With the growth of close-to-zero marginal cost PV and wind, we expect these tariffs to shift more vehicle charging to the middle of the day when solar generation is at its best.

Growth in EVs, and fuel economy improvements, means we think oil demand from road fuels should peak in around 2030, with the combination of alternative drivetrains and growth in shared mobility displacing around 15 million barrels of oil per day by 2040.

Consumers are not just starting to buy EVs, they are also changing the energy system by installing their own PV, and in some places they are also now adding batteries. Small-scale PV deployed on rooftops and commercial buildings has grown strongly in markets with good solar resources and high, or rising, retail electricity prices. In Australia one in five households already has rooftop PV. In the state of South Australia where I'm from, it's one in four and rooftop PV accounts for more than half the system load at certain times. As solar gets cheaper more households and commercial facilities will add PV to offset their retail electricity bills. And as the cost of lithium-ion batteries continues to fall, adding storage alongside PV also starts to look more and more attractive. Consumer uptake can be rapid when price and market penetration meet critical thresholds and a copycat effect drives steep adoption s-curves where uptake accelerates from early adopters to the mass market, before reaching saturation. Our diffusion modelling for consumer PV, and PV-plus-battery products, shows that by 2050, 10-30% of power capacity assets could sit behind-the-meter in major markets, highlighting a massive shift in system value downstream.

Looking at the *New Energy Outlook* results at a regional and country level to 2050 shows that Europe transitions furthest towards renewables, and does so fastest. The combination of low cost bulk renewables, carbon pricing, and competitive batteries, propel wind and PV to over 80% penetration by 2050 in some European states. Those where nuclear, hydro or biomass can play a major role get close to 100% zero-carbon. An 80% variable renewable energy system looks very different to the power systems with which we are familiar. No longer do large coal or gas plants run around-the-clock at high capacity factors, supported by smaller peakers. Instead, cheap variable renewables form the backbone of the system, supported by batteries and conventional plants running at low capacity factors. This configuration is characterized by large amounts of PV during the day, supported by wind in the evenings and batteries that charge and discharge over short timeframes. In this new system, back-up and curtailment are a feature, not a bug.

Firstly, there are limits to what wind, PV and batteries can do together. This is because there are days and weeks during the year when wind and PV simply can't produce enough electrons to meet demand, no matter how many batteries are installed. Some of the peakiest parts of the load might be met with demand response, but that's limited. That means these systems need to call upon dispatchable back-up.

Secondly, there are weeks and months when renewables are running flat out producing more electricity than is needed in real time and more than the battery fleet can store. At these times we have too much capacity and get curtailment. But this is still least-cost, because as PV and wind get cheaper, they remain competitive despite not producing useable electricity during every hour of operation, that is, at lower and lower capacity factors.

Ultimately, we think almost every country could technically get to around 80% wind and PV before reaching seasonal limitations, but most would need to deploy new renewables much faster to do so this side of 2050.

For example, the U.S. energy transition is dominated by cheap natural gas which grows to 45% of generation in 2030 as it replaces aging coal infrastructure. Once new gas plants are commissioned, they are cheap to run and tend not to face strong competition from battery systems for their dispatchable hours this side of 2050. Wind and PV grow too but more slowly, making up just 35% of electricity by mid-century. In China, coal generation grows with electricity demand in the short to medium term, but we think China will build its last coal plant by 2025 and sees peak coal generation in 2027. After which, coal declines at around 2% per year, and by 2050, wind and PV makes up 48% of China's electricity supply.

Coal-fired power is the first fossil fuel casualty of the transition, according to our modelling – peaking globally in 2026 and falling to just 12% of electricity in 2050, from around 37% today. This transition is most stark in Europe and the U.S., where coal-fired power continues its recent decline, down 90% to 2050 in the U.S. where it's undercut by cheap natural gas and renewables, and down 97% in Europe where coal-phase out plans, cheaper renewables and batteries, as well as carbon pricing, force it out of the mix. Coal continues to grow in China and South East Asia into the mid-2020s, and India until the late 2030s.

The outlook for gas-fired power remains relatively flat, as growth in the U.S. is offset by longer-term decline in Europe where it is increasingly beaten on cost by the combination of renewables plus batteries. In Asia gas is beaten by cheap coal and renewables. Gas grows 0.6% per year, supplying system back-up and flexibility rather than bulk generation in most markets. However, gas capacity doubles to help ensure security of supply, with combined-cycle plant up 37%, and peaker units that can ramp quickly to meet daily and seasonal extremes up 350%.

From a climate perspective, the *New Energy Outlook* is somewhat optimistic. It concludes that a least-cost deployment of renewable energy would keep power sector emissions on track for a 2-degree trajectory, but only until around 2030. Beyond that, decarbonization would need to be hastened by policy intervention. To achieve a 1.5 degree trajectory as envisaged by the Paris Agreement will need much more rapid transition than economics alone can deliver.

Achieving net-zero emissions by the second half of the century means there is nowhere to hide for those slow on the uptake, and no room for unabated fossil fuels. In particular, net-zero emissions targets ask serious questions about energy transition pathways for industry and buildings. One pathway is to switch to electricity to hitch a ride on the back of the renewable energy juggernaut. As discussed, this is already well established for road transport, even some of the commercial vehicle segments. It is also possible to use more electricity for space heating in buildings, as well as low —and medium— temperature industrial processes.

However, going electric isn't a universal solution. Yes, there is interesting progress being made in short-haul electric aviation and shipping, but moving heavy loads long distances is going to need something with better energy density than a battery. Heating is also highly seasonal which means a lot of energy demand is concentrated in a few months of the year. It also has a particular intraday pattern, ramping up in the morning as people wake up and turn on their heating, and again in the evening when they arrive home. If a country like the U.K. were to shift to 100% electric heat, the coldest days might drive a three-fold increase in winter peak power demand, right at the time when solar generation is at a nadir. In industry, high temperature heat is required for iron and steel production, chemicals, cement, aluminum and glass, among others. While electricity can technically provide high temperature heat, most technology options are still at early stages of development. Furthermore, in chemicals manufacturing, for example, fossil fuels also provide the raw materials, and in iron and steel production, they are chemically involved in the process itself. Even in the power sector, we've seen that around 20% of electricity demand is going to be very difficult to supply with wind, PV and batteries –our "Phase I" decarbonization technologies– alone. To get to net zero we are going to need a "Phase II".

Perhaps the answer is nuclear, hydro or solar thermal? Perhaps it's carbon capture with permanent sequestration? Or perhaps we are going to need a clean molecule such as hydrogen? What we know for sure is that right now, all the options we can list have limited potential or are far from commercially viable.

The good news is that "Phase I" can buy us time. But only if PV, wind, batteries and EVs are deployed as fast, or faster, than the New Energy Outlook suggests. At the same time, government needs to start making a market for the "Phase II" decarbonization technologies. And let the private sector start investing.

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