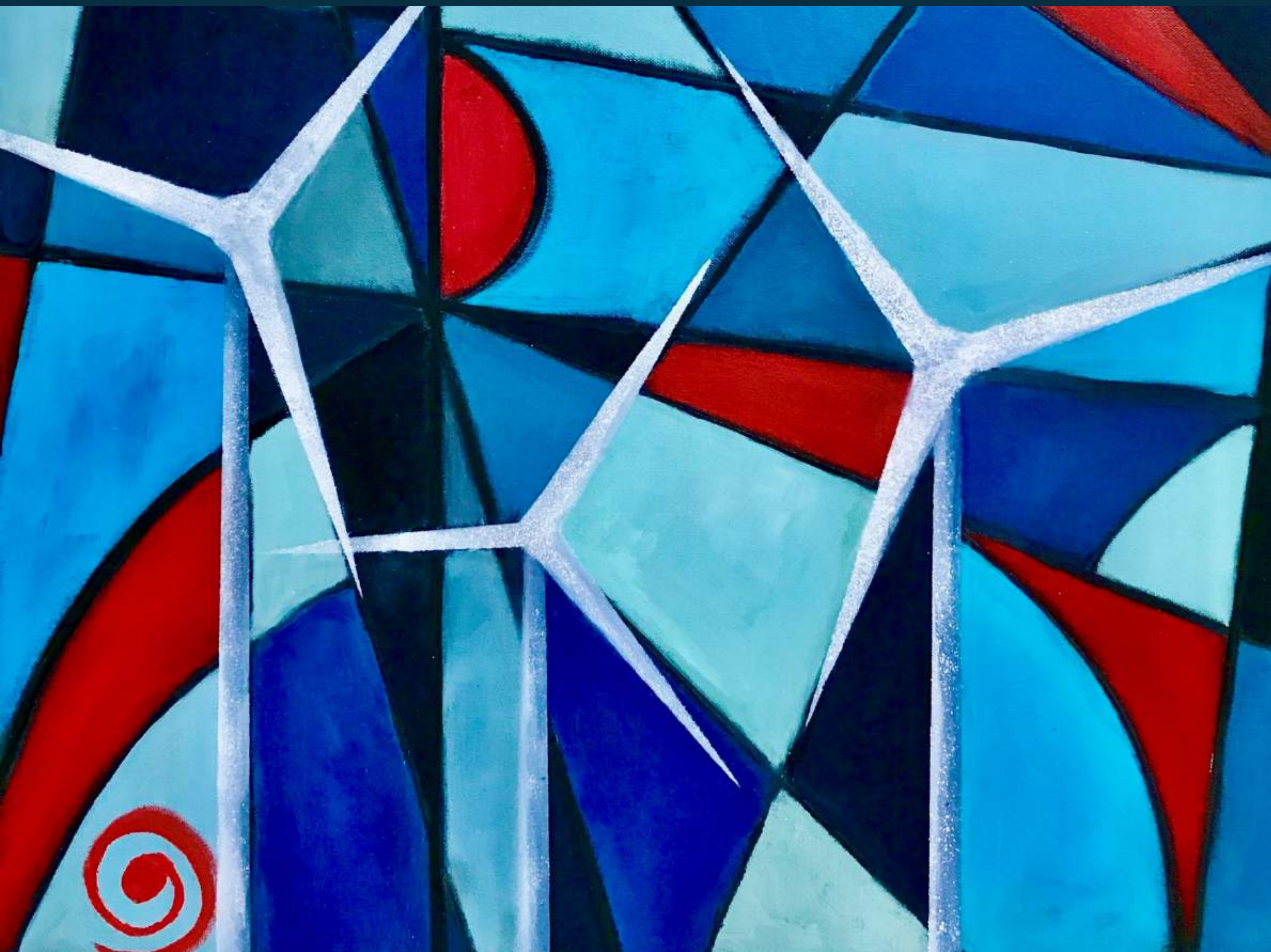
The sky's the limit

Solar and wind energy potential is 100 times as much as global energy demand



Report

April 2021

About Carbon Tracker

The Carbon Tracker Initiative is a team of financial specialists making climate risk real in today's capital markets. Our research to date on unburnable carbon and stranded assets has started a new debate on how to align the financial system in the transition to a low carbon economy.

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We are grateful for the advice of Amory Lovins in the preparation of this report.

Cover image: Sarah Bond - 'Winds of Change' painting.

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1 Key findings

There is a huge new cheap energy resource available. With current technology and in a subset of available locations we can capture at least 6,700 PWh p.a. from solar and wind, which is more than 100 times global energy demand.

The opportunity has only just been unlocked. The collapse in renewable costs in the last three years means that half of this solar and wind technical potential now has economic potential, and by the end of the decade it will be over 90% of it.

Land is no constraint. The land required for solar panels alone to provide all global energy is 450,000 km2, 0.3% of the global land area of 149 million km2. That is less than the land required for fossil fuels today, which in the US alone is 126,000 km2, 1.3% of the country.

People will take advantage of the cheap energy. Humans specialise in extracting cheap energy, and fast, as witnessed by the rapid development of shale gas. Now the opportunity has been unlocked, ***expect continued exponential growth of solar and wind deployment***.

The tide is coming in fast. The technical and economic barriers have been crossed and the only impediment to change is political. Sector by sector and country by country the fossil fuel incumbency is being swamped by the rapidly rising tide of new energy technologies.

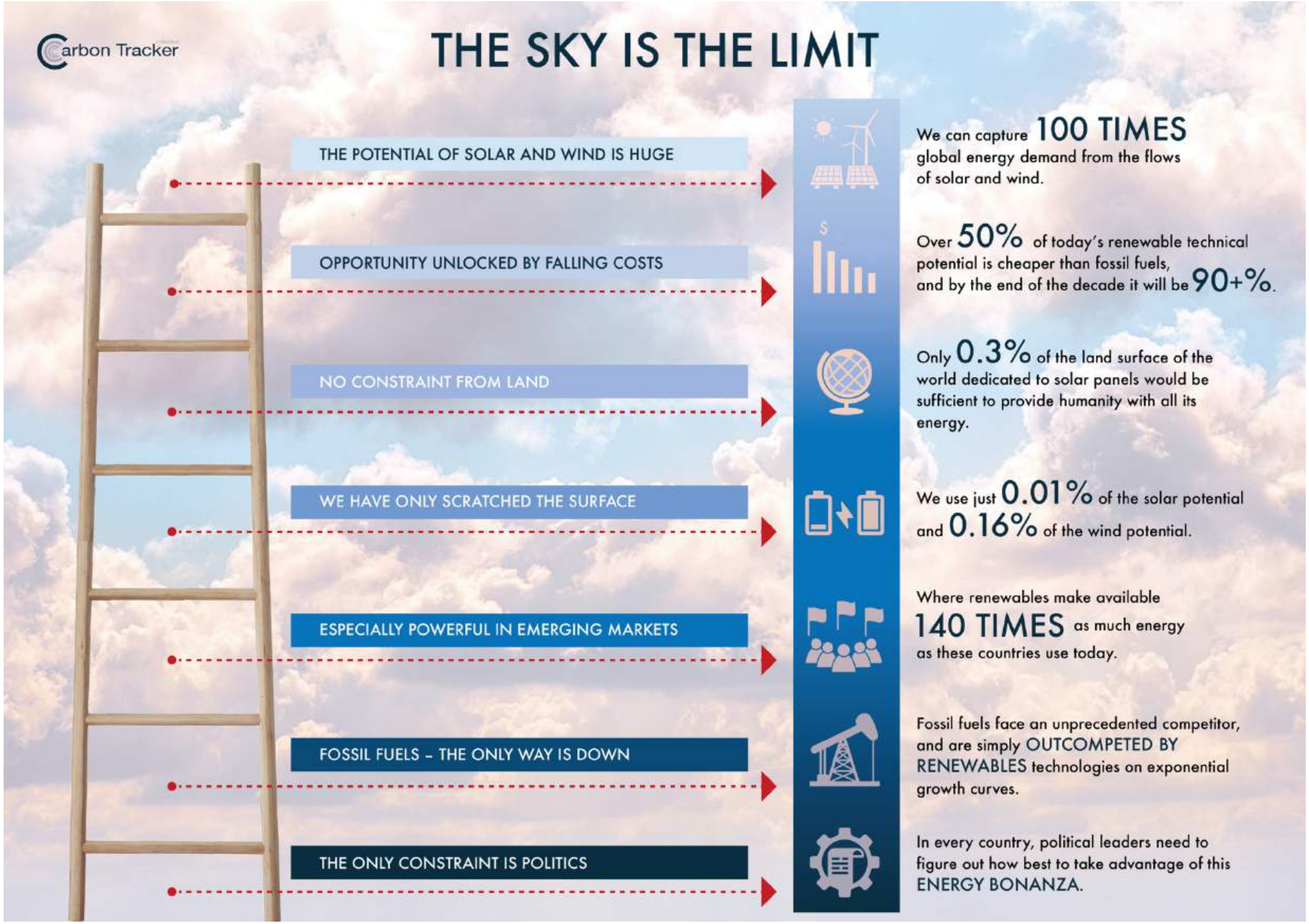
The fossil fuel era is over. The fossil fuel industry cannot compete with the technology learning curves of renewables, so demand will inevitably fall as solar and wind continue to grow. At the current 15-20% growth rates of solar and wind, ***fossil fuels will be pushed out of the electricity sector by the mid 2030s and out of total energy supply by 2050.***

There are four key groups of countries. They range from those with superabundant renewables potential, more than 1,000 times their energy demand like Namibia, all the way down to those with stretched potential of less than 10 times their demand like South Korea.

Poor countries are the greatest beneficiaries. They have the largest ratio of solar and wind potential to energy demand, and stand to unlock huge domestic benefits. The continent of ***Africa for example is a renewables superpower, with 39% of global potential***.

Germany is a special case. Germany has the third lowest solar and wind technical potential in the world relative to its energy demand. The troubles faced by Germany are therefore highly unusual, and if they can solve them then so can everyone else.

We enter a new era. The unlocking of energy reserves 100 times our current demand creates new possibilities for cheaper energy and more local jobs in a more equitable world with far less environmental stress.


Carbon Tracker
THE SKY IS THE LIMIT
THE POTENTIAL OF SOLAR AND WIND IS HUGE
We can capture 100 TIMES global energy demand from the flows of solar and wind.
OPPORTUNITY UNLOCKED BY FALLING COSTS
Over 50% of today's renewable technical potential is cheaper than fossil fuels, and by the end of the decade it will be 90+%.
NO CONSTRAINT FROM LAND
Only 0.3% of the land surface of the world dedicated to solar panels would be sufficient to provide humanity with all its energy.
WE HAVE ONLY SCRATCHED THE SURFACE
We use just 0.01% of the solar potential and 0.16% of the wind potential.
ESPECIALLY POWERFUL IN EMERGING MARKETS
Where renewables make available 140 TIMES as much energy as these countries use today.
FOSSIL FUELS – THE ONLY WAY IS DOWN
Fossil fuels face an unprecedented competitor, and are simply OUTCOMPETED BY RENEWABLES technologies on exponential growth curves.
THE ONLY CONSTRAINT IS POLITICS
In every country, political leaders need to figure out how best to take advantage of this ENERGY BONANZA.

2 Executive Summary

We summarise the report in 10 charts below and provide detailed calculation and sourcing in the rest of the document.

2.1 What is a Petawatt hour?

In this report we use the Petawatt hour (PWh) unit as the primary metric for energy measurement. What then is a PWh? Energy modellers such as BP tend to measure electricity demand in Terawatt hours (TWh) per annum, and a PWh is simply 1,000 times as much electricity as a TWh. To give a sense of how much energy that is, there are some useful points of comparison:

- Total Japanese demand for electricity in 2019 was 1 PWh.
- Total global demand for electricity in 2019 was 27 PWh, so 1 PWh is about 4% of the global total.
- The largest oilfield in the world is Ghawar in Saudi Arabia. That produces 3.8 mbpd of oil which is just under 1 PWh p.a. of electrical energy.

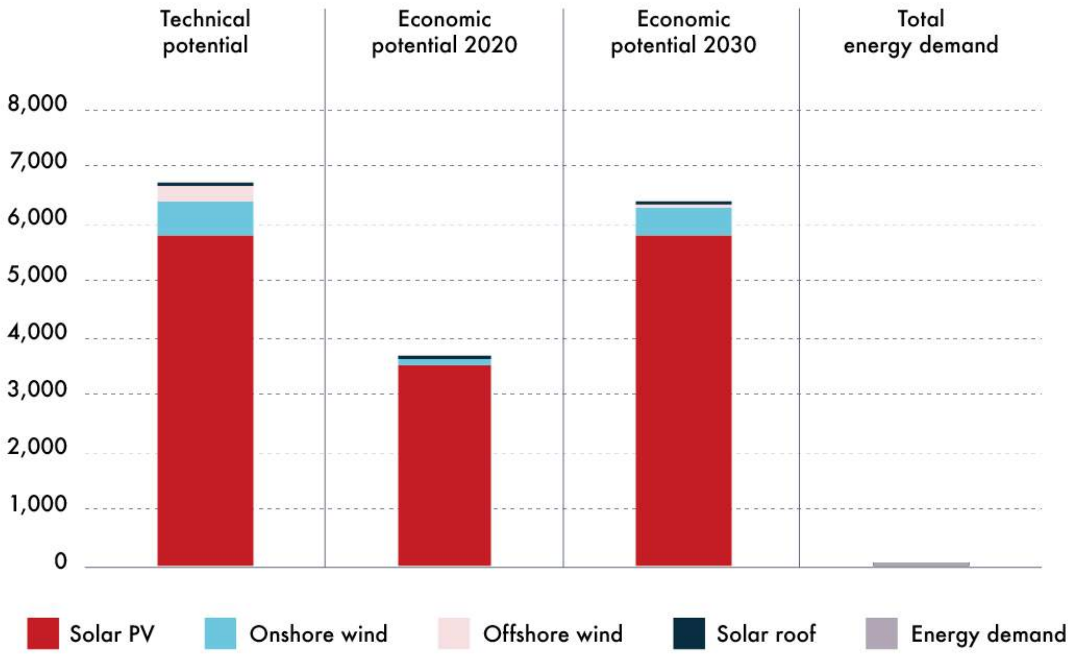
2.1.1 There is a huge new cheap energy resource available

Our focus in this report is on the technical and economic potential of solar and wind. The numbers are enormous. The technical and economic potential of solar and wind is thousands of PWh a year whilst annual electricity demand is just 27 PWh[1], and annual energy demand in terms of electrical energy is 65 PWh.[2]

[1] *Source: BP Statistical Review 2020*

[2] *See below for a discussion on how to count fossil fuel energy. Given the huge amounts of renewables, this rapidly becomes an academic debate.*

FIGURE 1: SOLAR AND WIND POTENTIAL PWH P.A.

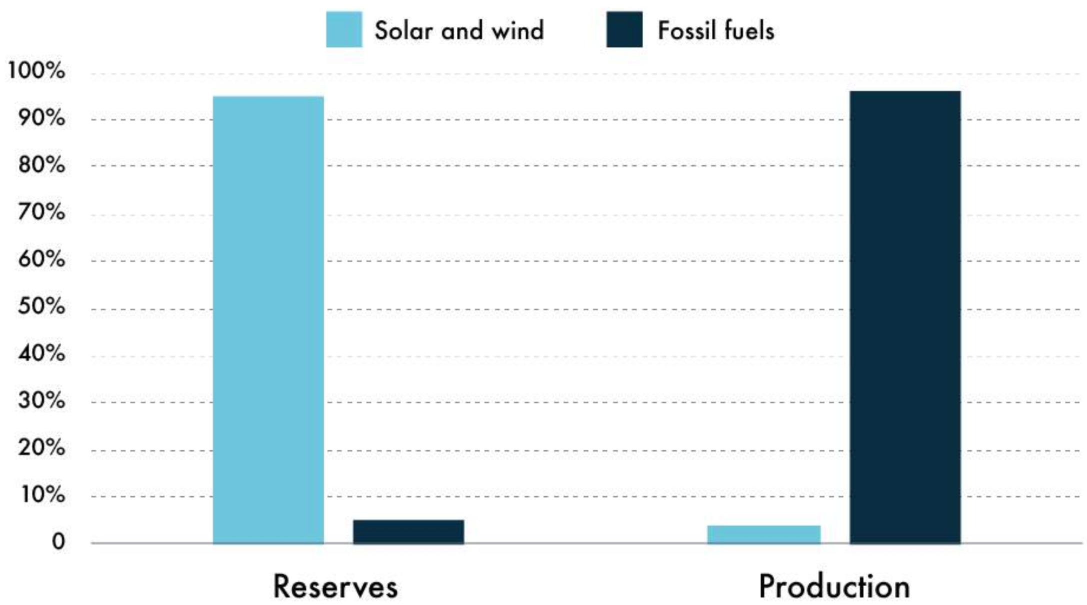


Source: BP, Solargis, NREL, Jacobson, Carbon Tracker estimates.

2.1.2 Solar and wind potential is far higher than that of fossil fuels

If you compare the energy sources as a share of reserves versus a share of production you get a sense of the disparity between the two. Solar and wind are almost all the energy reserves, and fossil fuels are almost all the production.

FIGURE 2: SHARE OF COMBINED RESERVES AND PRODUCTION



Source: BP, Jacobson, Carbon Tracker

To put the size of the renewable resource in context, consider the world's largest oilfield of Ghawar in Saudi Arabia. Put up solar panels on the same space as Ghawar (280 km by 30 km), and most countries with that space would be able to generate as much energy in terms of electricity as Ghawar.[3]

The difference of course is that only Saudi Arabia has a Ghawar, but almost every country in the world has enough space to generate 1 PWh p.a. of renewable electricity.

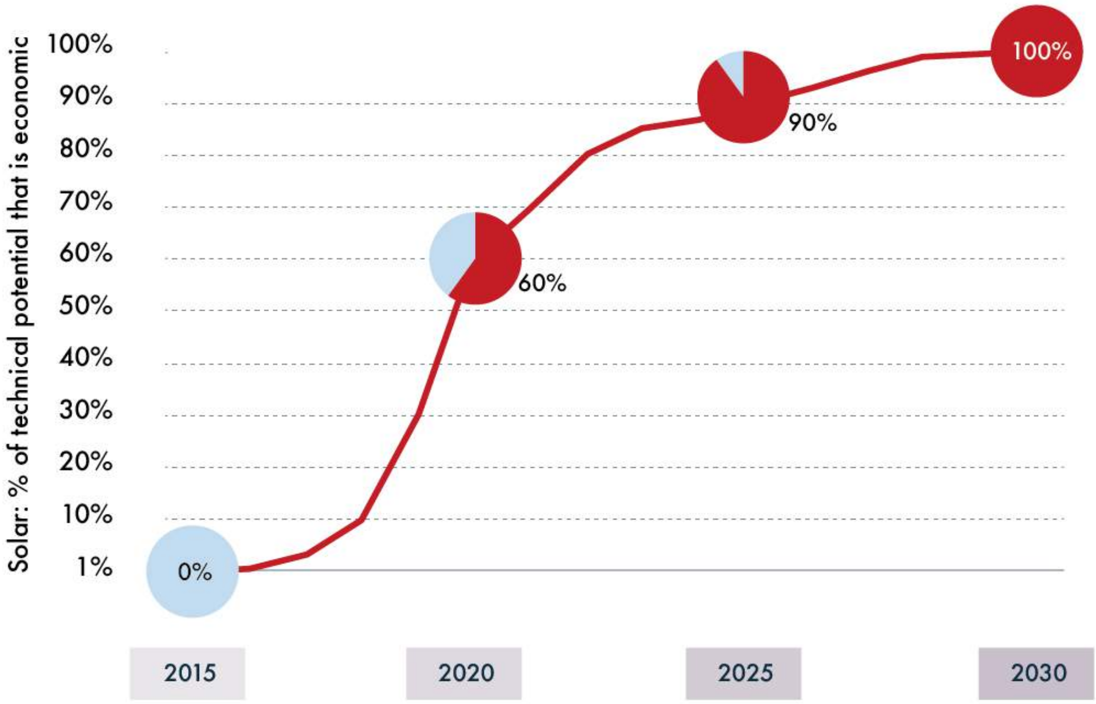
2.1.3 The economic potential has only just been revealed

The technical potential was made accessible by developments in the decade after 2005, but it is only in the last five years that this technical potential has become economic. For example, we illustrate below our estimate of the share of the solar technical potential that is economic over time.[4]

[3] *This calculation is easily checked. The Aramco prospectus revealed that Ghawar in 2018 produced 3.8 mbpd of oil. Which is 198mt or 8 EJ of oil. Converted into electricity at 40% efficiency this is 0.9 PWh. The Ghawar oilfield is 280 km by 30 km, so 8,400 km2. Solargis tells us each square metre in Saudi Arabia can generate 0.19 MWh per annum of electricity, adjusted for spacing and local conditions. Thus the space above the Ghawar oilfield could generate 1.6 PWh per annum. The average square metre globally can generate 0.14 MWh per annum, so a Ghawar sized space would generate 1.2 PWh p.a.*

[4] *As explained below in more detail*

FIGURE 3: SOLAR: PERCENTAGE OF TECHNICAL POTENTIAL THAT IS ECONOMICALLY VIABLE



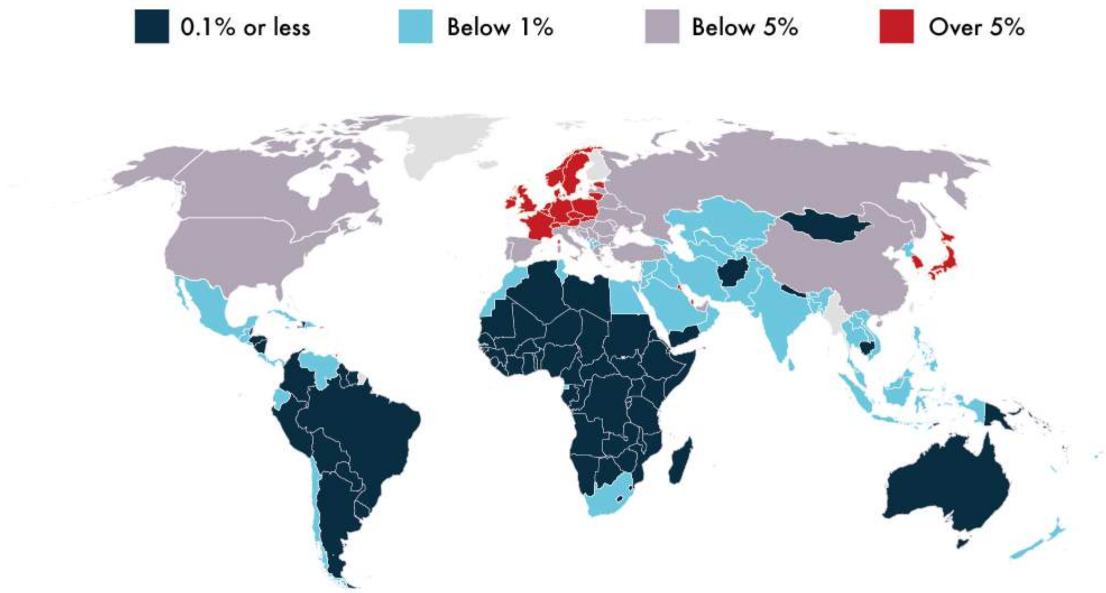
Source: Carbon Tracker based on data from BNEF, IRENA, Lazard

2.1.4 There is plenty of land

Land availability is not a major impediment to the rapid global deployment of renewables. Indeed, renewables require less land than fossil fuels. According to Solargis data, the total amount of land that is required to generate all our energy from solar alone is 450,000 km2, or 0.3% of the world's land surface. Mark Jacobson, Professor of engineering at Stanford,[5] has shown that if we deploy wind as well, we would need 0.2% of land for solar PV and 0.5% for the spacing between onshore wind turbines. The chart below shows what share of land would be required to produce all energy from renewables in a range of countries.

[5] *Source: 100% clean, renewable energy and storage for everything, Jacobson, 2021*

FIGURE 4: SHARE OF LAND UNDER SOLAR REQUIRED TO GENERATE ALL ENERGY



Source: Solargis, BP Statistical review, Carbon Tracker estimates

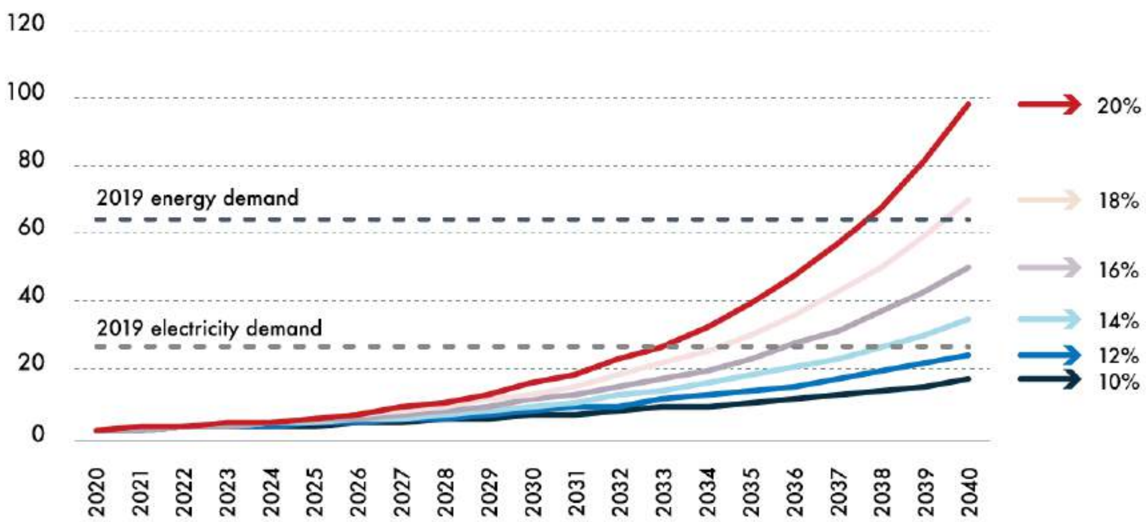
2.1.5 People will rapidly take advantage of this massive new resource

The clear lesson of energy history is that people tend rapidly to exploit cheap energy resources when they find them. So expect continued rapid exponential growth of solar and wind energy deployment, especially in light of the build back better movement and the continuous fall in the cost of solar and wind. What that means depends simply on the growth rate of the new technology. The growth rate of solar and wind over the last decade has averaged 21%, and in 2020 it was 19%. There is no evidence of a major slow-down in deployment, and every reason to imagine that growth will be maintained as costs fall and more countries realise what can be done.[6]

We show below a chart of what this means at different illustrative growth rates. It does not take long to break though current levels of energy demand. For example, at a growth rate of 15%, it will take until 2037 for electricity equivalent to 2019 demand to come from solar and wind, and until 2044 for solar and wind to generate electricity equivalent to 2019 total energy demand.

[6] *That is not to suggest this will be easy. Technology and policy will both need to change very significantly in order to accommodate the cheap energy source.*

FIGURE 5: SOLAR AND WIND ELECTRICITY SUPPLY AT DIFFERENT GROWTH RATES PWH P.A.



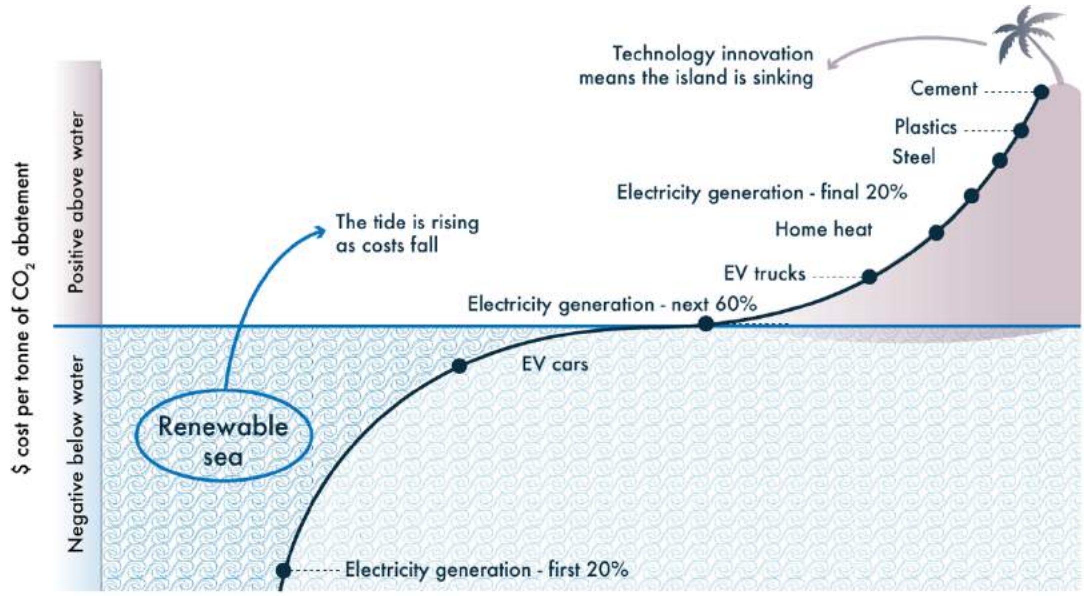
Source: BP Statistical energy review, Carbon Tracker estimates

2.1.6 One sector after the next will be transformed by cheap energy

New energy technologies can be likened to a tide surrounding an island of fossil fuels. Technology, in the shape of falling costs, means that the tide is rising at the same time as the island is sinking into the sea. One fossil fuel sector after another in one country after another is being swamped by the tide of change.

It is therefore not very relevant to the debate today to argue that the hard to solve sectors are hard to solve. These are simply the final peaks at the very top of the island of the fossil fuel system. And as we speak they are being mined by engineers and entrepreneurs across the world looking for superior solutions.

FIGURE 6: THE RISING RENEWABLE TIDE MEETS THE SINKING FOSSIL ISLAND

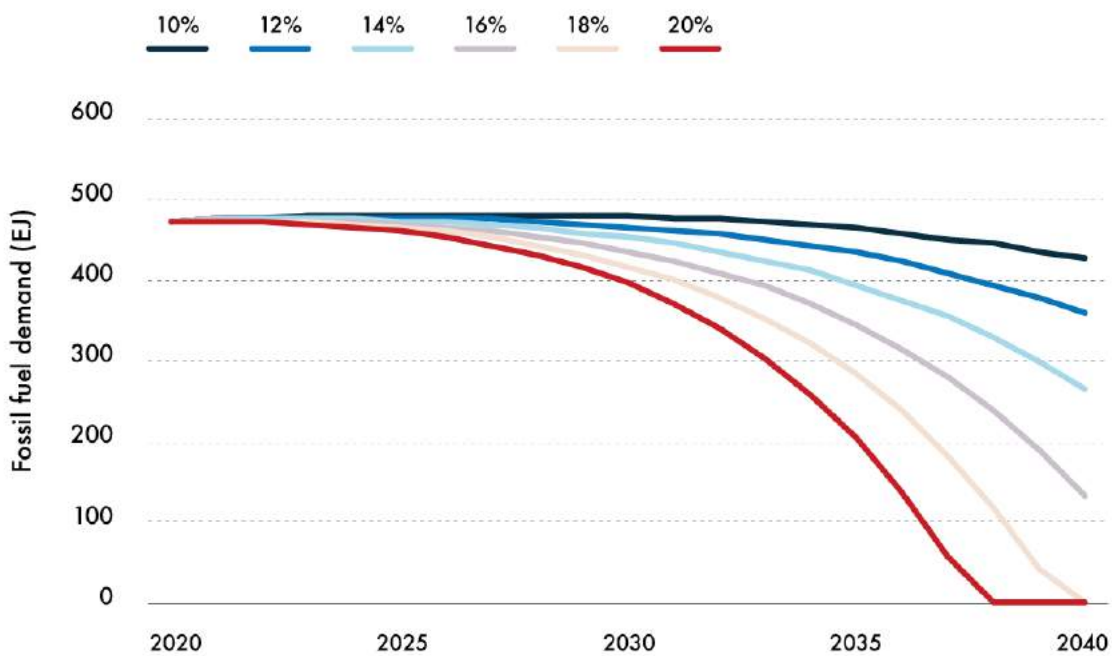


Source: McKinsey MACC, Carbon Tracker adjustments

2.1.7 The fossil fuel era is over

As solar and wind supply grows, fossil fuel demand must inevitably fall. The best way to think of the fossil fuel industry is as the residual in a zero-sum equation with a rising competitor. The only way is down. And the only people who do not realise it are incumbents. The chart below shows what different rates of renewable growth mean for fossil fuel demand.

FIGURE 7: FOSSIL FUEL DEMAND EJ GIVEN DIFFERENT SOLAR AND WIND GROWTH RATES



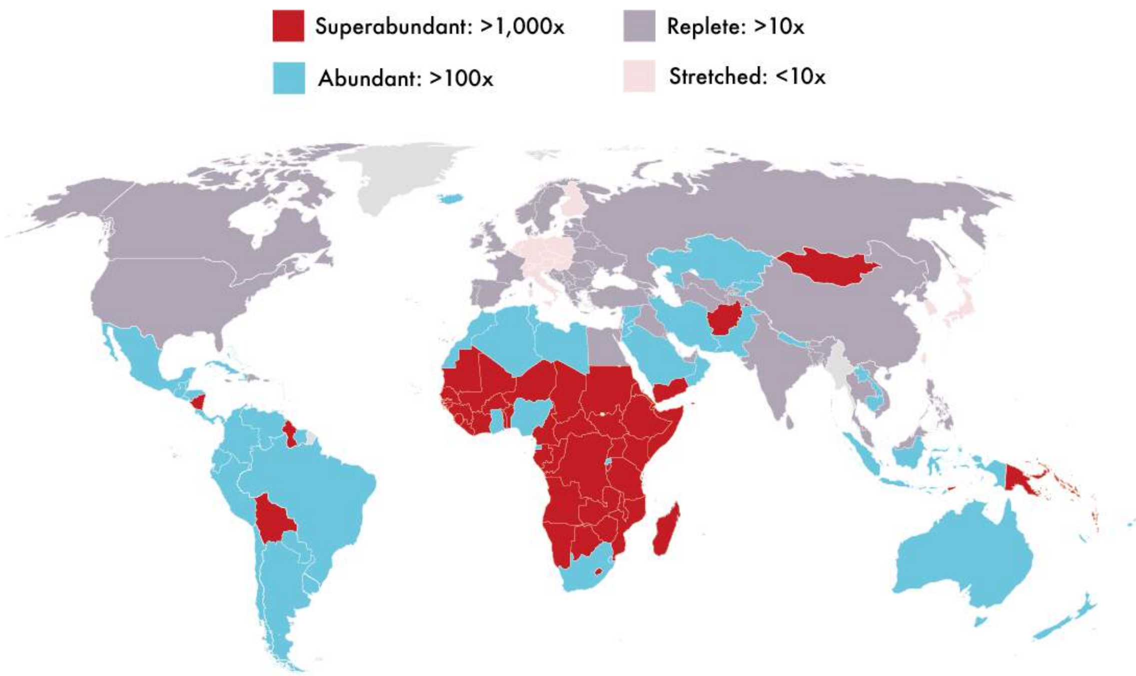
Source: Carbon Tracker estimates

2.1.8 There are four groups of countries

The world as a whole has solar and wind technical potential of just over 100 times total demand, but there are in fact four groups within that.

- Super-abundant. More than 1,000 times as much technical potential as current energy demand. Examples include Namibia, Botswana or Ethiopia. Many of these countries are of course poor (which is why demand is low) but they have a chance of a new start.
- Abundant. 100-1,000 times. Examples include Chile, Australia, or Morocco. Some of these countries have well developed infrastructure and governance systems. They can aspire to be the providers of renewables to certain other countries.
- Replete. 10-100 times. Examples include China, India and the US. Countries in this group in the most part have enough renewable energy to satisfy their energy requirements.
- Stretched. Below 10 times. Countries will need to make some tough political decisions[7] in order to figure out how to tap their solar and wind resource most effectively. Some of them may elect to import their renewable energy through cables or pipes or ships.[8]

FIGURE 8: SOLAR AND WIND ENERGY POTENTIAL AS A MULTIPLE OF ENERGY DEMAND



Source: EIA, Solargis, NREL

2.1.9 Poor countries have the greatest opportunity

It is poor countries that have the greatest opportunity from the adoption of solar and wind technologies. The graph below shows the technical potential of solar and wind as a multiple of total demand versus GDP per capital. There is a clear slope to the right, indicating the huge opportunity that solar and wind present for poorer countries.

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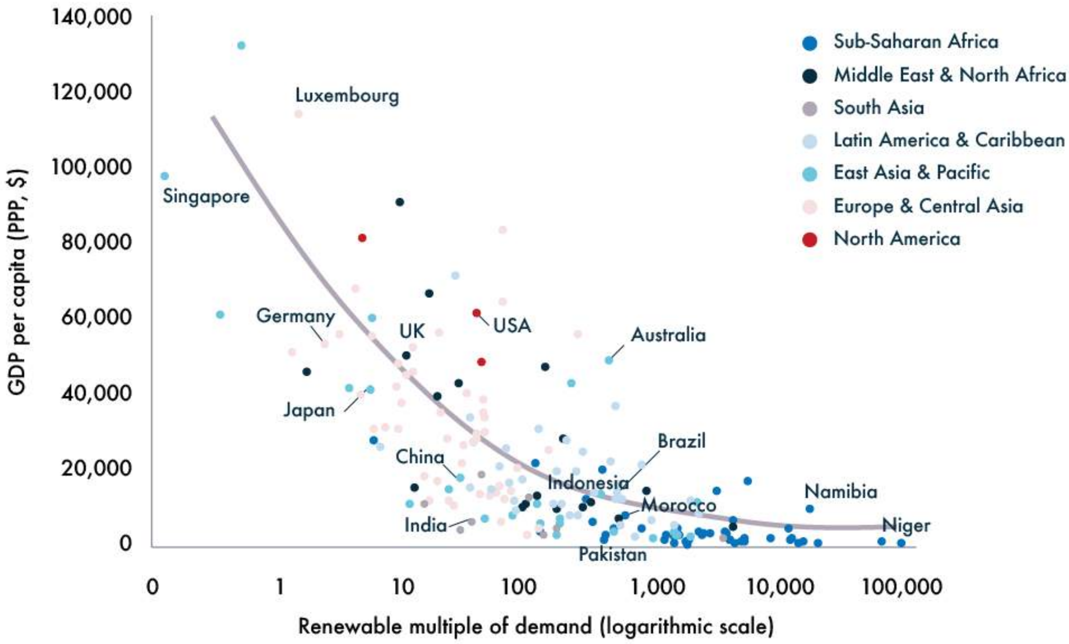
[7] *Many of these countries have nuclear for example*

[8] *We recognise that these countries may consider safety and feasibility issues from various standpoints, yet we highlight that only 6% of the global population lives in the stretched countries.*

FIGURE 9: GDP PER CAPITA AND SOLAR AND WIND AS A MULTIPLE OF DEMAND



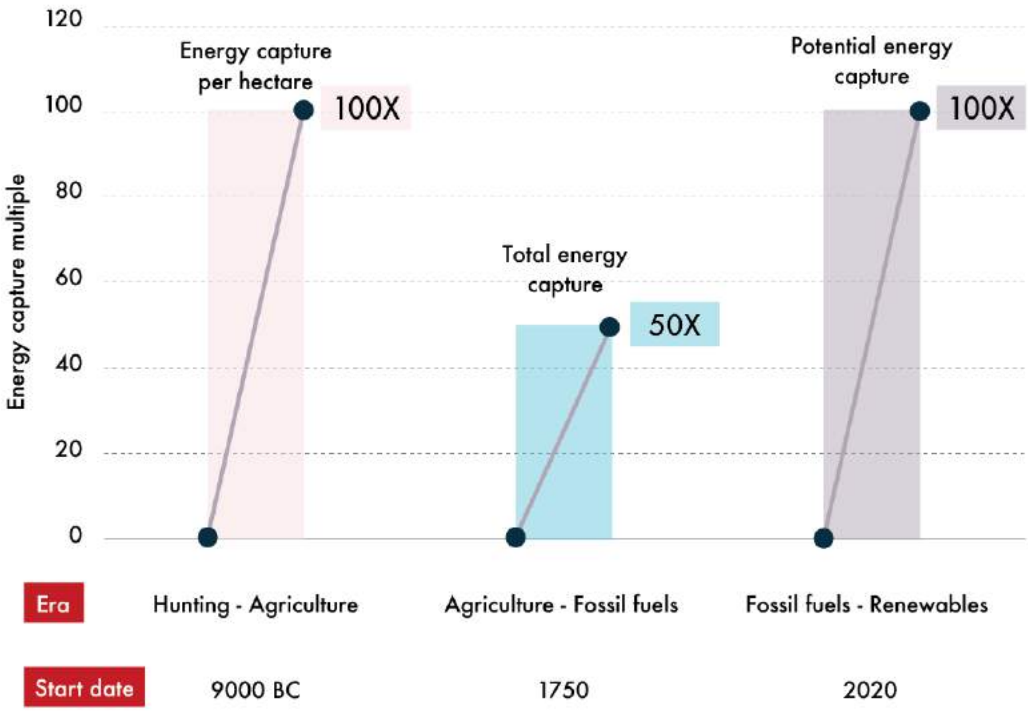
Source: BP, Solargis, NREL, Carbon Tracker analysis

2.1.10 The third great energy transition

Renewables hold out the promise that humanity can advance up the Kardashev scale[9] to make use of a much greater share of the energy of the sun. The only comparable shifts in human history have been the move from hunting to agriculture after 9,000 BC, and then the move from agriculture to fossil fuels after 1750. This shift too holds out the promise of a dramatic increase in the energy we can exploit.

[9] *In 1963 the Russian physicist Nikolai Kardashev created the Kardashev scale, a way of measuring how advanced is a civilisation based on the amount of energy it can harness. A Type I civilisation is able to harness all the energy from its sun that lands on its planet. We still have a long way to go*

FIGURE 10: STEP CHANGES IN ENERGY CAPTURE



Source: Crosby, Smil, McKay, Carbon Tracker

The consequences are profound and across many areas: Energy will fall in price. Those lacking energy will gain access to a lot more of it. Geopolitics will be transformed. The stress imposed by fossil fuels on the planet will fall. Humanity will gain access to new tools and potential; let us hope we use it well.

3 How to classify renewable energy

We set out a renewable typology and then compare it with the better known fossil fuels typology in order to see how the two energy sources are best compared.

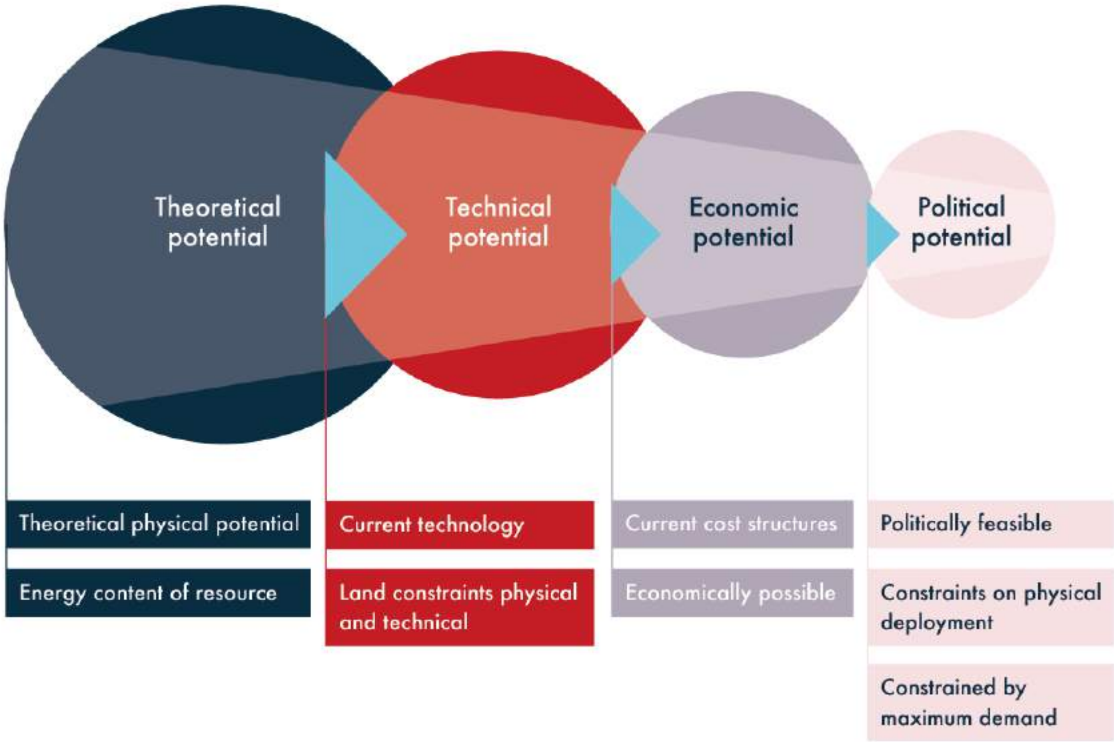
3.1 The renewable typology

In the same way that fossil fuels have resources, reserves and production, it is possible to produce a renewable energy typology, as set out in the graph below and illustrated with respect to solar PV. In broad terms this is the framework used by the US National Renewable Energy laboratory (NREL).[10]

- ***Theoretical potential.*** The amount of renewable energy that exists regardless of whether we can capture it economically. For example Jacobson calculates that the total solar resource is 170,000 PWh a year.[11]
- ***Technical potential.*** The amount of renewable energy that we can capture using current technology in suitable locations. Solargis, the solar energy consultancy, calculates this at from 5,800 to 10,000 PWh a year depending on assumptions on land use and seasonality.[12]
- ***Economic potential.*** The amount of renewable energy that is economical to capture, compared to the fossil fuel alternative. Based on data from Bloomberg NEF (BNEF),[13] we estimate that for solar, this is around 60% of the technical potential today, so at least 3,500 PWh p.a.
- ***Political potential.***[14] Just because the economic potential exists does not mean that we will exploit it. A key role of politicians is to figure out how to exploit the renewable resources that they have to best effect. There are many sectors which compete for land space. And the cap is set by total demand, which is 65 PWh p.a. of electrical energy today.
- ***Generation.*** The actual generation is the amount of renewable electricity that is produced today. Which was 0.7 PWh for solar in 2019. This means that the growth potential for the technology is still huge.

[10] Source: *Estimating renewable energy economic potential in the United States, NREL, 2013*
[11] Source: *100% clean, renewable energy, Jacobson, 2021*
[12] Source: *Global photovoltaic potential by country, World Bank, 2020*
[13] Source: *Levelised cost of energy, BNEF, h2 2020.*
[14] *Political potential is referred to by the NREL as 'Market potential'*

FIGURE 11: TYPOLOGY OF RENEWABLE GENERATION POTENTIAL



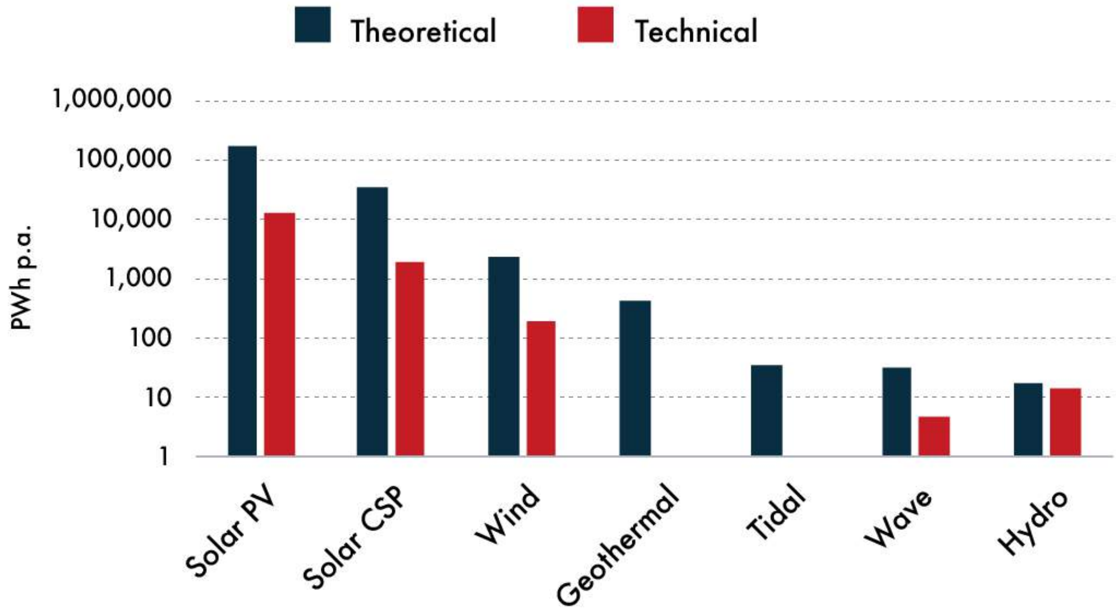
Source NREL, Carbon Tracker adjustments

3.2 Which renewable energy drives change

According to Mark Jacobson,[15] there are 6 main types of renewable energy: solar; wind; hydro; geothermal; wave; and tidal. Of these, he calculates that solar is by far the largest, and that the only other resources with more than 10 PWh p.a. of technical potential are hydro and wind. Hydro is already near the limits of its deployment, leaving wind as the only other renewable resource with enormous technical potential. Note that biomass is not considered as a sustainable renewable resource for energy generation as a result of its very low efficiency and low energy return on investment.

[15] *Source: 100% clean renewable energy and storage for everything, Jacobson, 2021*

FIGURE 12: RENEWABLE THEORETICAL AND TECHNICAL POTENTIAL PWH PA



Source: Jacobson. Note this is a log graph

Only solar PV and wind have struck the sweet spot of technology where they are growing fast, and costs are falling on learning curves. As a result these are the two technologies on which we focus this analysis.[16] As detailed below, we split solar into utility solar PV and solar rooftop. And we split wind into onshore and offshore.

It is also worth addressing directly why we do not focus in this analysis on hydro and on nuclear. Neither technology can be compared to the thousands of PWh p.a. that solar and wind can produce. Hydro in 2019 produced 4 PWh of electricity, and Jacobson calculates that its maximum technical potential is 14 PWh p.a. Nuclear produced 3 PWh of electricity in 2019, and is very low growth. As such they are both important and relevant for individual countries but not significant for the global story of vast new cheap sources of power.

3.3 How renewable potential has grown over time

The theoretical potential of the sun and the wind of course is roughly a constant. However, as we set out below in more detail, there have been profound changes in the technical and economic potential of renewables since the start of this millennium.

3.3.1 Technical potential

The technical potential of solar and wind has increased spectacularly over the course of the last two decades as we have started to master the technology. For example, a report on the potential of renewable energy from 2004[17] noted technical solar potential of 176 PWh p.a., whilst in 2020 as we show below Solargis calculates the technical potential of solar to be at least 5,800 PWh p.a., over 30 times more. When David McKay published his famous book 'Sustainable Energy without the hot air' in 2009, he calculated that the global wind technical potential was 53 PWh p.a., whilst the NREL in 2016 calculated that it was 16 times bigger at 871 PWh p.a. McKay did not bother to

[16] *In the Jacobson solution detailed below, 89% of the renewable solution is from solar PV and wind.*

[17] *Source: The potentials of renewable energy, International Institute for industrial environmental economics, 2004*

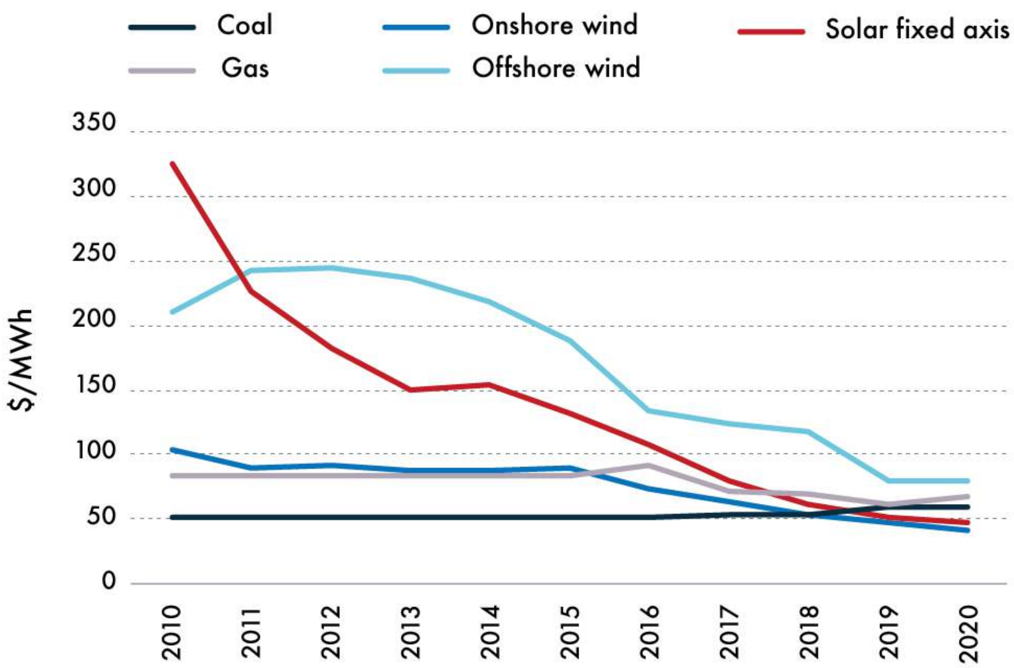
calculate the size of the global solar PV technical potential because he argued it was so unattainably expensive.

3.3.2 Economic potential

Solar and wind had very little economic potential until costs fell below those of the fossil fuel alternative. Until very recently almost all solar and deployments required economic subsidy.[18] It is the collapse in costs over the course of the last decade that has unleashed the economic potential of renewables.

The chart below from BNEF of the costs of electricity per MWh from solar, wind, coal and gas is well known. The global average price for onshore wind falls below gas and then coal by early 2018, shortly followed by solar taking the same path.

FIGURE 13: THE LEVELISED COST OF ELECTRICITY FROM DIFFERENT SOURCES ($/ MWH)



Source: BNEF

Because these are averages, there are some countries which are leaders and others that are laggards. However, because solar and wind prices remain on learning curves, over time their costs are likely to fall below the costs of fossil fuels in almost all markets.

In broad terms it is then fair to say that

- In 2015 few places had solar cheaper than fossil fuels
- In 2020, 60% of the world (by solar potential) had solar cheaper than fossil fuels for electricity generation.
- By 2030 almost everywhere will have solar energy cheaper than fossil fuels.[19]

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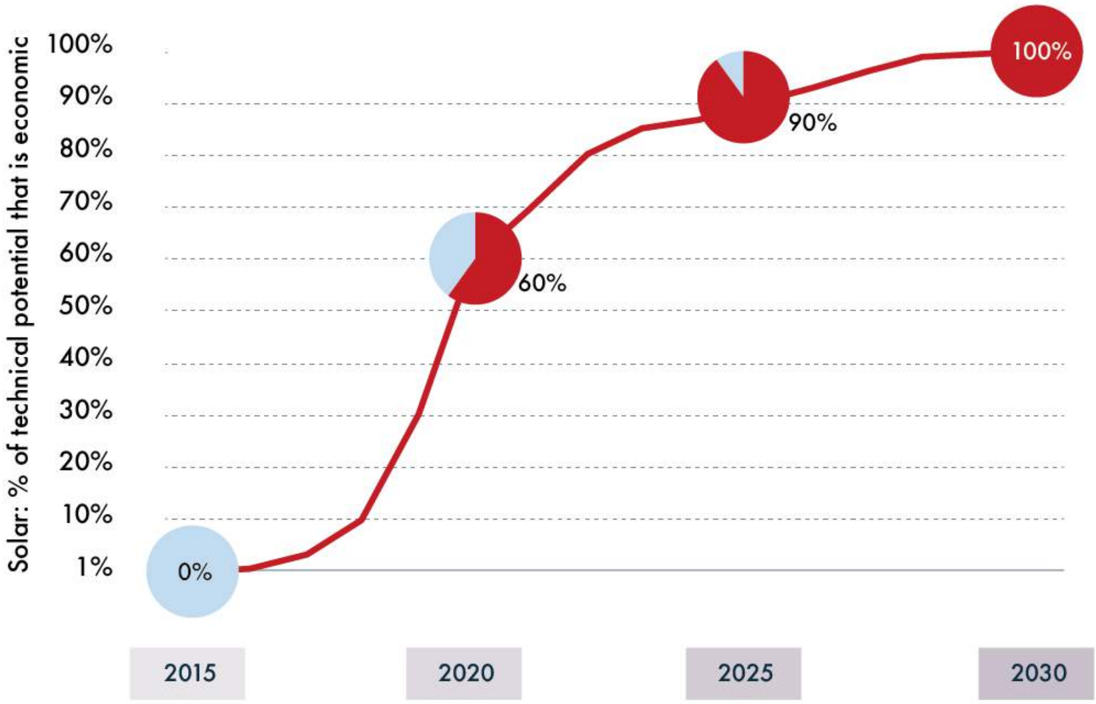
[18] *There were of course exceptions to this in especially remote locations like satellites. But the total was very small.*
[19] *We address the issue of learning curves below. This is also examined in detail by Ramez Naam and Doyne Farmer, and most recently in a paper by the Smith School in Oxford: a new perspective on decarbonising the global energy system.*

So we can illustrate in broad terms the share of the technical potential that is economic in the chart below.

FIGURE 14: THE SOLAR SINGULARITY

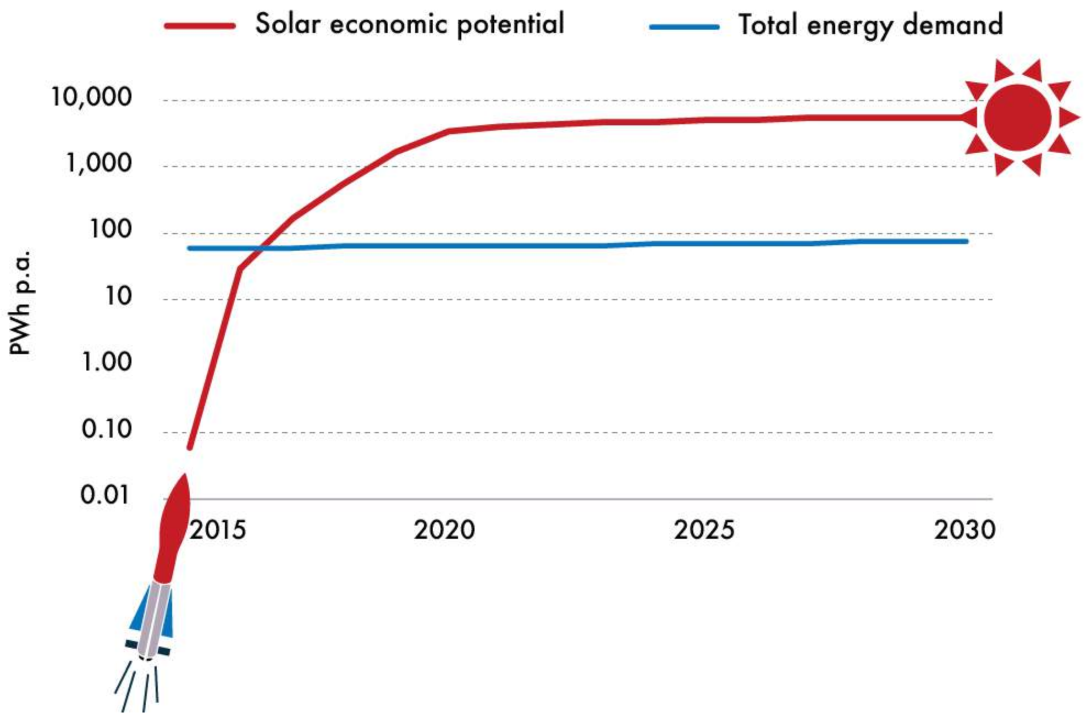


Source: Carbon Tracker based on data from BNEF

The collapse in costs is well appreciated and attested by many organisations from BNEF to IRENA to Lazard. However, what is less appreciated is what a tsunami of opportunity has been released by this apparently innocuous crossover. The technical potential of solar is at least 5,800 PWh a year, 100 times bigger than annual fossil fuel production.

As more and more of this technical potential is released, the solar economic potential overtook total energy demand in 2017 and is now far greater than energy demand.

FIGURE 15: THE SUNSHOT: SOLAR ECONOMIC POTENTIAL AND TOTAL ENERGY DEMAND PWH PA



Source: Carbon Tracker based on data from BNEF. Note this is a log chart

As we shall see below, economic potential is not the same as deployment, but over time it is hard to resist.

3.4 How to compare renewables with fossil fuels

3.4.1 The fossil fuel typology

Using the typology for oil taken from our reading of the Society of Petroleum Engineers amongst others, we broadly break down fossil fuels into the following categories:

- Resources[20]. Resources as a collective are considered to be the total geologically estimated stocks of an energy carrier which are in place but are not all necessarily regarded as recoverable economically at present, for example because recovery requires new and expensive technology.
- Reserves. Reserves constitute a subset of resources and are those quantities of petroleum which are anticipated to be commercially recovered from known accumulations from a given date forward.

There are 3 main reserve categories under the Society of Petroleum Engineers definition:

- Proved. Proved reserves are those quantities of petroleum which, by analysis of geological and engineering data, can be estimated with reasonable certainty to be commercially recoverable, from a given date forward, from known reservoirs and under current economic conditions, operating methods, and government regulations. Proved reserves can be categorized as developed or undeveloped.

[20] *For full clarity of the SPE's Petroleum Resources Classification System and Definitions see* https://www.spe.org/en/industry/petroleum-resources-classification-system-definitions/

- Probable. Probable reserves are those unproved reserves which analysis of geological and engineering data suggests are more likely than not to be recoverable. In this context, when probabilistic methods are used, there should be at least a 50% probability that the quantities actually recovered will equal or exceed the sum of estimated proved plus probable reserves.
- Possible. Possible reserves are those unproved reserves which analysis of geological and engineering data suggests are less likely to be recoverable than probable reserves. In this context, when probabilistic methods are used, there should be at least a 10% probability that the quantities actually recovered will equal or exceed the sum of estimated proved plus probable plus possible reserves.

3.4.2 Problems in comparison

There are some problems with comparing renewable and fossil fuel typologies. We set out some of these below.

- ***Stock v flow***. Fossil fuels reserves are a stock, whilst solar and wind generation is a flow. To put this in financial terms, a stock is like a share price, whilst a flow is like a dividend. In theory the value of a share price is the capitalised flow of the dividends.
- ***Quality***. Fossil fuels are a low quality primary energy source which has to be burnt to generate useful energy services such as light, heat and transport. And in the act of burning you lose about 60% of the energy. [21] Electricity is a higher quality energy carrier.
- ***Declining v rising***. At the field level, fossil fuel reserves of course reduce over time as they get burnt. Globally, fossil fuel reserves have historically increased over time as our ability to access new deposits has improved. However, over a long time horizon, fossil fuel reserves are finite, in particular as the boundary of what is extractable economically will fall with the cost of low carbon alternatives. While renewable potential rises over time as technology improves.
- ***Inflationary v deflationary***. Fossil fuels get more expensive over time as the best reserves are used up. Whilst renewables get cheaper over time through economies of scale and learning curves.
- ***Developed v undeveloped***. A large share of fossil fuel reserves are producing and developed. Renewables are in the most part non-producing and not developed. However, this distinction is not quite so dramatic as it seems because we understand solar and wind flows extremely well, and many locations are close to existing grid assets.
- ***Dispersed v universal***. Fossil fuel reserves are in specific locations, whilst renewables are universal.
- ***Externality cost***. Fossil fuels impose a major externality cost on society which is not incorporated into their cost structure.

3.4.3 How to reconcile fossil and renewable typologies

We believe it is possible to provide a rough reconciliation below. We set out in broad terms what adjustments are necessary before examining the key issue of what renewable potential to compare with proven fossil fuel reserves.

3.4.3.1 Capitalise renewable flows

The first adjustment necessary is to capitalise the annual flows of renewables, to enable them to be compared with the stock of fossil fuels. Financial markets are of course expert at reconciling stocks

[21] *The energy loss is of course dependent on the end use. Conversion into electricity loses 63% of the primary energy according to IEA data and 60% according to BP data. Conversion into heat loses much less, but conversion into transport loses more. Since the world is shifting to electricity, 60% is a good starting point*

and flows, and the classic way to do this is to capitalise the flow by multiplying it by a capitalisation rate in order to compare with the stock.

In the high risk and depreciating asset world of fossil fuels, a capitalisation rate would be 10-15. In other markets, a standard capitalisation rate would be around 20 if we were seeking to capitalise a flow of future income from say a rental property. However, renewable energy flows are eternal, they are a real asset (one MWh is always one MWh), and the cost of money is very low. It is possible to make the case that we should use a very high capitalisation rate like 60 or 100.

However, we do not want to engage in a long debate about why large numbers are warranted. For the sake of argument, we will take a capitalisation rate of 30. So when comparing annual renewable flows with fossil fuel reserves, we multiply the renewable flows by 30.

3.4.3.2 Convert all energy into electricity terms

Fossil fuels are a lower quality carrier of energy than electricity. It takes around 2.5 MWh of chemical energy in a lump of coal to generate 1 MWh of electrical energy. There are many ways that people have tried to reconcile the two, as summarised in more detail by DNV GL in their paper on counting energy,[22] and by Harry Benham in his paper on changing our energy legacy.[23] When BP compares non-fossil energy sources with fossil fuels in terms of EJ of primary energy, they multiply the electrical energy of the non-fossil sources by 2.5.[24]

Until recently this was a rather academic question. It was not really necessary to compare fossil fuels with solar because solar was so small. However, the question of comparison is becoming more important over time as the share of electricity in energy supply increases.

In our analysis we therefore propose to count all primary energy in terms of the electricity it can generate. And we convert all energy sources therefore into PWh. This means that we divide fossil fuel chemical energy by 2.5, using the same multiple as BP.

Some[25] have argued that this approach is not accurate because of course some fossil fuels are used in areas where they have higher efficiency, such as heat. Equally, they are also used in some areas like transport where the efficiency is even lower. There is no perfect answer to this issue, but conversion into electricity equivalent terms provides the most accurate reflection of what is happening at a time when most marginal growth comes from the electricity sector. After all a solar panel that generates 1 MWh of electricity replaces coal with chemical energy of 2.5 MWh.

3.4.3.3 What is the equivalent of proved reserves

To be classed as a proved reserve, an oil or gas deposit must fulfil three conditions: it must have been confirmed by drilling; it must have been accurately measured; and it must be recoverable economically at current prices using current technology.

The renewable potential that most closely meets these three conditions is economic potential. Solar and wind potential is confirmed and measured by satellite data amended by local experience. Moreover, economic potential is recoverable economically at current prices using current technology as noted by BNEF. Some note that not all of this renewable potential will in fact be used,

[22] *Source: Counting energy, DNV GL, 2018*
[23] *Source: Changing our energy legacy, Benham, 2019*
[24] *Source: BP Statistical review, BP, 2020.*
[25] *For example David McKay in Sustainable energy without the hot air, 2009*

but this is to miss the point: fossil fuel reserves are sufficient for over 100 years, and it is obvious that they will not be fully used in a Paris compliant world; yet they are still counted as proven reserves.

3.4.4 System comparison

We present below a way to compare the two energy sources.

- Theoretical renewable potential should be capitalised and then compared with fossil fuel resources.
- Technical potential should be capitalised and can be compared with fossil fuel possible reserves. They are both technically accessible but not necessarily economic.
- Economic potential should be capitalised and can be compared with fossil fuel proven reserves. Both are economically recoverable.
- Political potential can be compared with peak fossil fuel production. They are both what politicians will tolerate. Since peak fossil fuel production was probably 2019 and the political potential of renewables is the same as global demand, this is an easy comparison.
- Renewable generation can be compared with fossil fuel production in PWh terms.

TABLE 1: TYPOLOGY CHART RENEWABLES AND FOSSIL FUELS

Fossil name	Renewable name	Note
Resource	**Theoretical potential**	**Capitalise renewables**
Possible reserves	**Technical potential**	**Capitalise renewables**
Proven reserves	**Economic potential**	**Capitalise renewables**
Peak production	**Political potential**	**In PWh terms**
Production	**Generation**	**In PWh terms**

Source: Carbon Tracker based on NREL[26]

3.5 Renewable and fossil fuel size

The gap between renewables and fossil fuels shows up most clearly when one contrasts the possible with the actual. Renewables have huge potential but are tiny and enjoying exponential growth. Fossil fuels have reached the limit of their potential, and the only way is down.

3.5.1 Fossil fuel reserves

3.5.1.1 The size of fossil fuel resources

The size of fossil fuel resources is not a topic that is much covered. The Earth System research laboratory global monitoring division at the US Global Monitoring Laboratory[27] quotes a figure of total carbon resources of 3,500 Gt, which compares with the 10 Gt per annum of carbon that we burn. So the total size of fossil fuel resources is then 350 times the amount we use. This is over 4,000 bn tonnes of oil equivalent (toe), which is 170,000 EJ or 19,000 PWh of electrical energy.

3.5.1.2 The size of fossil fuel reserves

The most commonly cited source for the size of fossil fuel reserves is BP. Their statistical review tells us that the total fossil fuel reserves are 1,100bn toe, which is sufficient reserves for 104 years of demand at current usage rates. This is 51,000 EJ of primary energy and 5,700 PWh of electrical energy.

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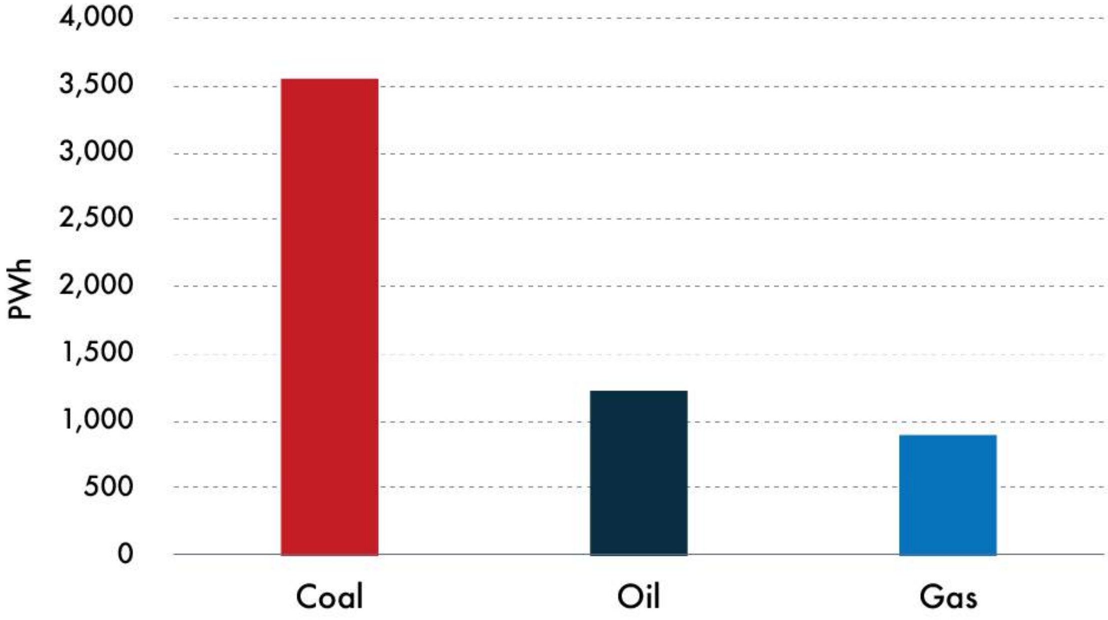
[26] *Source: Estimating renewable energy economic potential in the Unites States, NREL, 2013*
[27] *Source: Earth System Research Laboratory Global monitoring division, NOAA*

FIGURE 16: FOSSIL FUEL RESERVES PWH



Source: BP Statistical review 2020, Carbon Tracker estimates

In the definitions, we are told that these are reserves that can be recovered in the future from known reservoirs under existing economic and operating conditions. However, these numbers strain credibility. They include reserves of fossil fuels that will become stranded long before they can be used: does anyone outside the coal industry seriously think we will be burning huge amounts of coal in 132 years' time?

Moreover, they are much higher than the extremely detailed proprietary analysis that Rystad has done of the size of oil and gas reserves. For example, Rystad[28] calculates that proven reserves of oil were only 42 bn toe and that total oil resources were 246 bn toe. Which is almost the same as the total proven oil reserves number of 245 bn toe quoted by BP. The reason for this lengthy aside is to note that even the question of fossil fuel reserves is a moot point. BP numbers are clearly at the top end of the range.

Nevertheless for the sake of argument and in order to give fossil fuels a good chance to shine, we will take the BP data for proven reserves. 51,000 EJ is 14,500 PWh of chemical energy which at a 40% efficiency rate is 5,700 PWh of electrical energy.

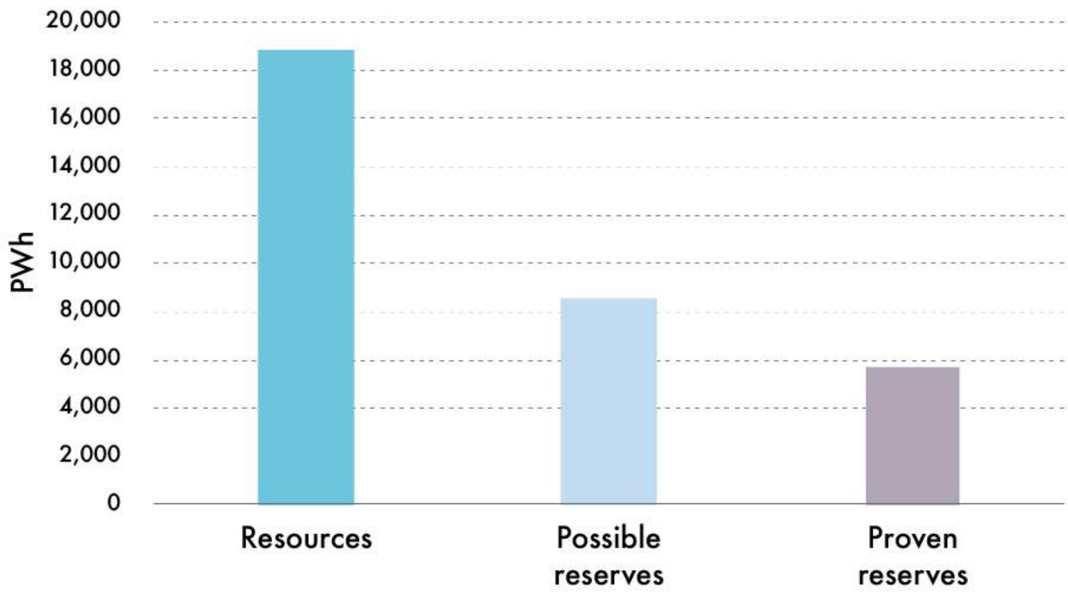
For possible reserves we simply multiply proven reserves by 1.5 which is a Carbon Tracker estimate in the absence of much formal industry analysis.

3.5.1.3 Conclusion

So the size of fossil fuel resources and reserves is as below

[28] *Source: UCube, Rystad, accessed March 2021*

FIGURE 17: FOSSIL FUEL RESOURCES AND RESERVES PWH

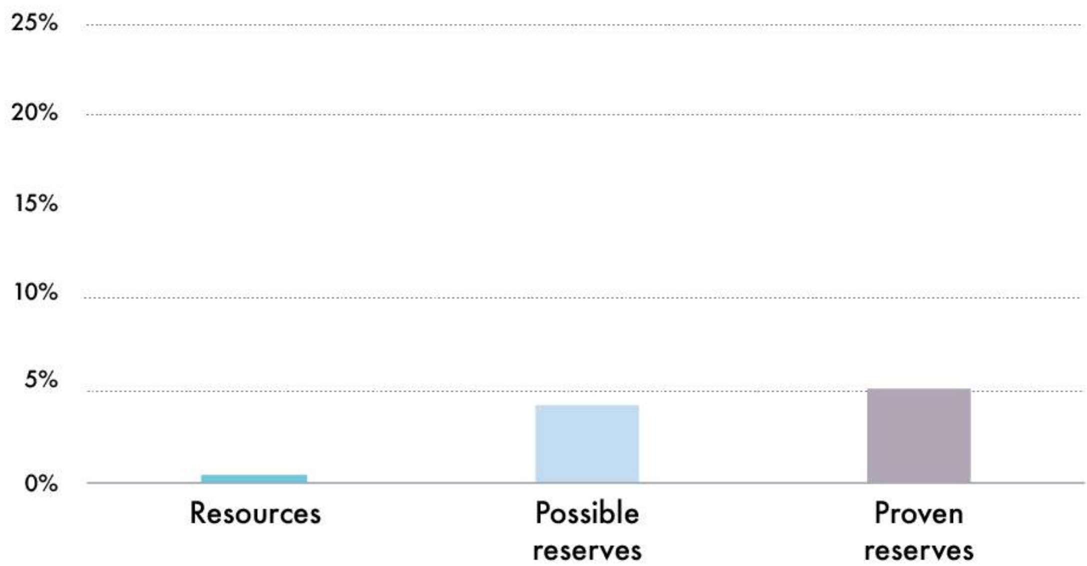


Source: BP, US NOAA, Carbon Tracker estimates

3.5.2 Fossil fuel reserves compared with renewables

Even if we then take the relatively high fossil fuel numbers as outlined above, renewable potential as we set out below is far larger than fossil fuels in every single aspect of comparison for resources and reserves.

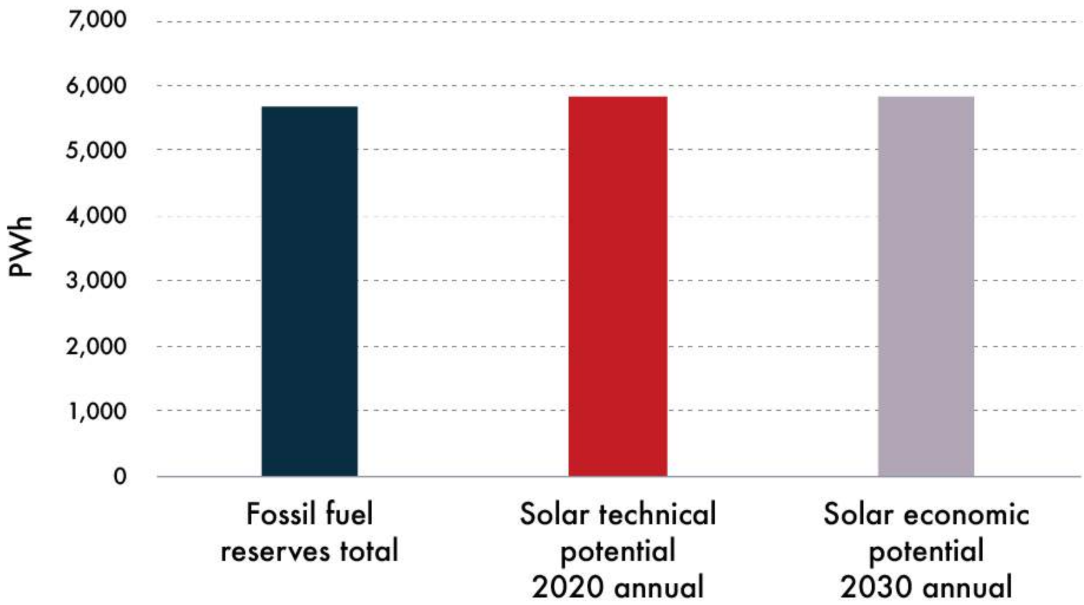
FIGURE 18: FOSSIL FUEL RESOURCES AND RESERVES AS A PERCENTAGE OF RENEWABLES



Source: BP, US NOAA, Carbon Tracker estimates

Furthermore, it is notable that the technical potential of solar today (which is a good approximation for the economic potential of solar in 2030) is slightly higher than the entire fossil proven reserves. That is to say – the amount of energy we can capture from the sun in a single year and on highly constrained amounts of land, is more than the amount of electrical energy we could get if we burnt all of our known fossil fuels this year.

FIGURE 19: FOSSIL FUEL LIFETIME RESERVES AND SOLAR ANNUAL TECHNICAL AND ECONOMIC POTENTIAL PWH

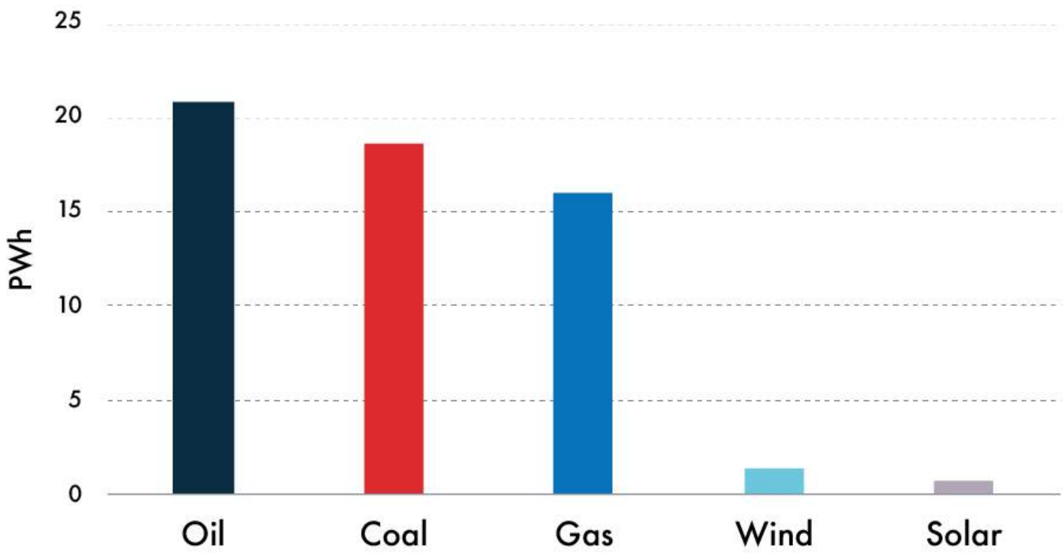


Source: Solargis, NREL, BP, Pennsylvania State University, Carbon Tracker estimates.

3.5.3 Fossil fuel production compared with solar and wind

Fossil fuel production in 2019 was 498 EJ, which is 12 bn toe or 55 PWh of electrical energy. Solar and wind generation is 2019 was just 4% of the size of fossil fuel production.

FIGURE 20: FOSSIL FUEL AND RENEWABLE PRODUCTION 2019 PWH



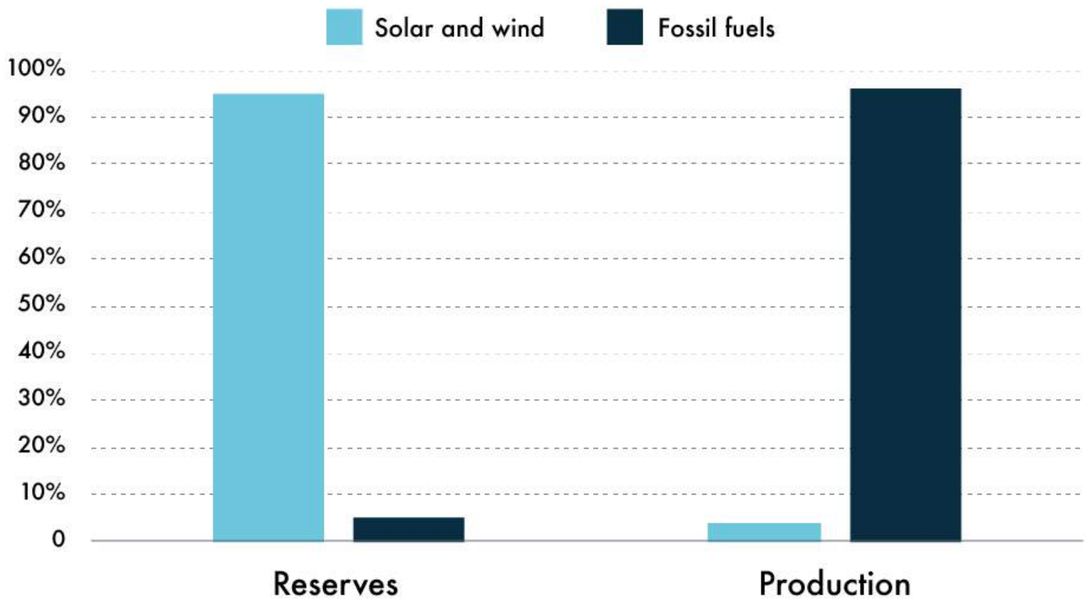
Source: BP, Carbon Tracker estimates

3.5.4 The conundrum

3.5.4.1 Reserves and production

If you compare the energy sources as a share of reserves versus the share of production you get a sense of the disparity between the two. Solar and wind are almost all the reserves, and fossil fuels are almost all the production.

FIGURE 21: SHARE OF COMBINED RESERVES AND PRODUCTION



Source: BP, Jacobson, Carbon Tracker

3.5.4.2 Fossilised solar v live solar

Total reserves of fossil fuels are 1,100 bn toe built up over around 300 million years. These reserves are the tiny remnant of what is left from and what we can capture of fossilised sunshine from ancient forests and sea creatures. Every year we burn 12 bn toe, or 1% of our reserves. So we burn every year 3 million years of fossilised sunshine.

Every year the sun provides us with energy that we can capture (technical potential) of at least 5,800 PWh. And in 2019 we used 0.7 PWh, which is 0.01% of the live sunshine. Something has to change.

4 Technical potential

We set out below the technical potential of each of the key solar and wind technologies.

4.1.1 How to handle intermittency

The intermittency of solar and wind resources is frequently raised as an issue which will hold back their deployment, but the problem is often overstated. There are many solutions to intermittency, ranging from wider grids and storage to demand side management, better forecasting, oversizing solar and wind, and system integration. However, few of these are able to address the issue of interseasonal supply fluctuations. The conservative solution that we use in this analysis is simply to assume in our calculations the level of solar availability in the lowest month of insolation.

4.2 Solar PV

For each technology we lay out how best to count the technical potential, then we examine what are the differences in the quality of the technical potential and conclude on the total size.

4.2.1 How to count it

In some ground-breaking research written for the World Bank in 2020,[29] Solargis calculated the amount of solar energy that can be captured in every country in the world. They make a series of important adjustments to make the calculation as close to real world conditions as possible.[30]

- Physical constraints. They exclude areas where it is not possible to put solar panels such as mountains, ice, rivers, large bodies of water, complex terrain, cities or forests.
- Uninhabited areas. They exclude areas more than 25 km from the nearest population cluster of a minimum of 50 people per km2. These areas lack infrastructure and demand.
- Local conditions. They adjust for dust, air temperature, terrain, soiling, shading, albedo, and other local factors based on real world experience.
- Spacing. They adjust for module tilt, configuration and shading.
- Remote latitudes. They exclude land above or below the 60th parallel. For example, Finland, Iceland or Antarctica.

4.2.2 Differences in quality

In addition to country, Solargis provide useful data on three aspects of the solar resource – land type, seasonality and insolation (the amounts of sunlight you can actually capture).

4.2.2.1 Land

Solargis focuses on two type of land availability:

- Level 1. Solar generation potential from all land that fits the constraints above, which is 61 km2 or 41% of global land. The technical potential is 10,117 PWh p.a.
- Level 2. In addition to the level 1 exclusions above, Solargis also exclude land under soft constraints, such as cropland and conservation areas. The total level 2 land is 41 km2 or 27% of global land. Generation potential is 7,045 PWh p.a.

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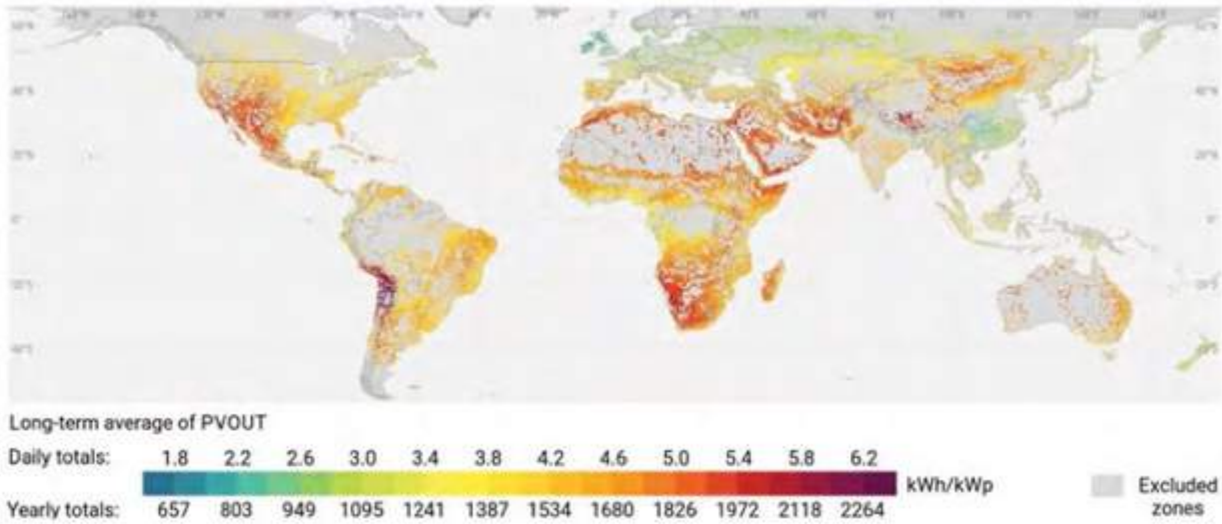
[29] *Source: Solar Photovoltaic power potential by country, World Bank, 2020*

[30] *The details are very precise and documented in the report. We summarise them here for the sake of brevity.*

As can be seen in the map below, the amount of land which is excluded by the level 2 characterisation is very considerable. Most of the Sahara desert, Tibet, Australia, Saudi Arabia and the Amazon are excluded. Only a quarter of India and a third of China are included.

Solargis also notes that the level 2 land constraint is probably excessive because in reality many countries are able to put solar panels onto cropland, to build long lines to connect remote but high resource areas, or to put solar panels onto canals or lakes. Nevertheless we focus on level 2 land as the least controversial framing of the opportunity.

FIGURE 22: PRACTICAL PHOTOVOLTAIC POWER POTENTIAL AT LEVEL 2 (LONG-TERM AVERAGE)



Source: Solargis, World Bank

4.2.2.2 Seasonality

Seasonality is a major factor for countries a long way from the equator. For example in the UK the average sunlight in July is 5 times the average amounts in January. If you plan a system based on averages, you will find yourself lacking in power in the winter months. Solargis then construct a seasonality index which compares the solar power available in the sunniest month with that available in the least sunny month.

This is an issue for Europe but much less so for the rest of the world. Very few people in fact live North of the 50th parallel. Almost half of the population lives in countries where the seasonality index is around 1.5 or less. The seasonality index for India and China is 1.7.

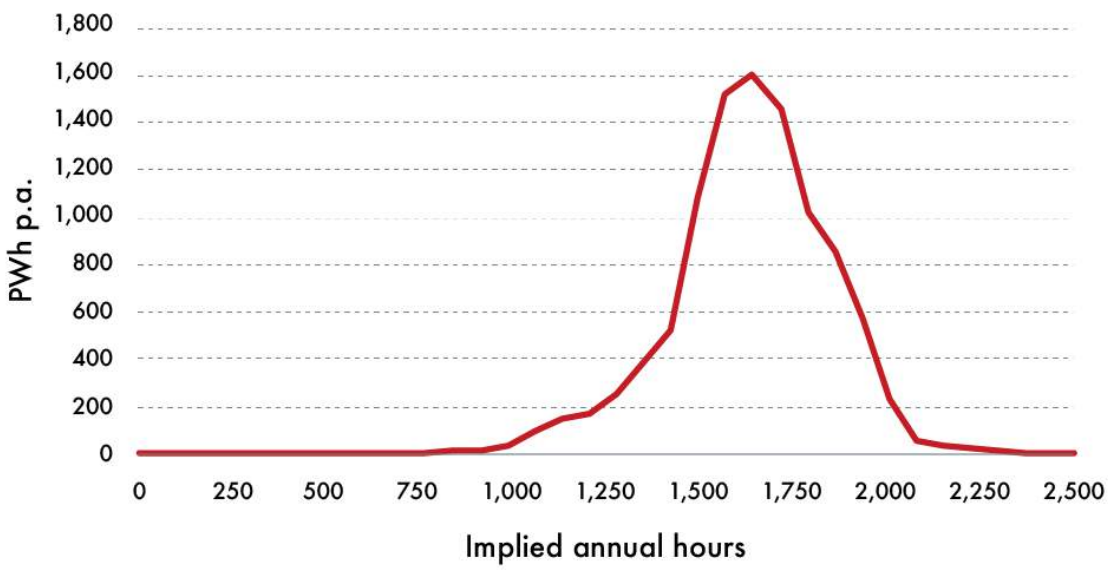
One way around this is very complex modelling. An easier way that we adopt in this analysis is simply to take as technical potential the amount of solar energy available in the lowest month. Solargis are able to calculate how much solar electricity can be captured if you just take the average for the least sunny month over the course of the year.

- For level 1 land it is 8,198 PWh p.a.
- For level 2 land it is 5,830 PWh p.a.

4.2.2.3 Insolation

Solargis calculate how many hours of full sunshine each location can produce per annum. This is determined by a range of factors, from insolation to temperature. Somewhat surprisingly, they note that the difference between the best country that they analyse (Namibia) and the worst (Ireland) is only a factor of two. The chart below shows the total PWh p.a. of sunlight produced at each band of insolation.

FIGURE 23: PWH PER ANNUM AT EACH LEVEL OF SUNSHINE HOURS PER ANNUM.



Source: Solargis for level 1 land

The gap between the best solar resources and the worst is actually quite low. Out of the total solar resource, 97% comes from locations which produce between 1,000 and 2,000 standard hours per annum of solar.

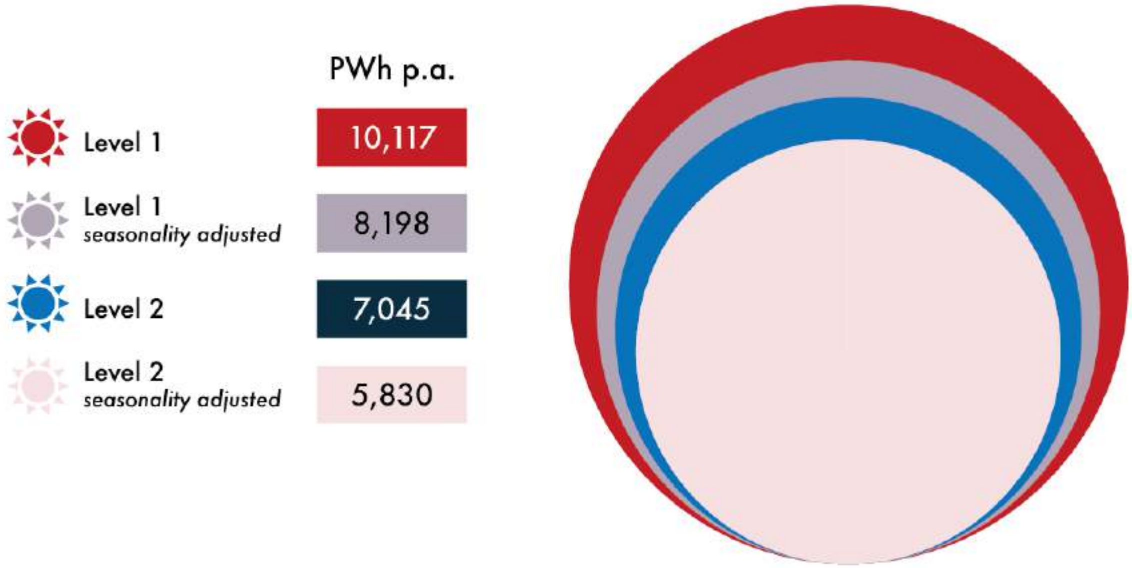
The reason why this matters is that the quality of the solar resource is then only one of a number of factors which determine the price of the electricity from solar. Others include the cost of capital, the cost of transmission lines and fixed costs. The implication is that it may be cheaper to have utility solar in a low insolation country with a low cost of capital (like Ireland) than in a high insolation country with a high cost of capital (like Namibia).

So our conclusion is that the level of insolation alone is not a sufficiently powerful differentiator to enable us to exclude certain areas of land (beyond those already excluded by Solargis) as being unsuitable.

4.2.3 Size

The four options are set out below.

FIGURE 24: SOLAR TECHNICAL POTENTIAL



Source: Solargis, World Bank

In order to be conservative we select as the technical solar resource the lowest level of the four options outlined above – that is to say the level 2 land seasonality adjusted. That implies that 27% of global land is in locations where it is appropriate to place solar and that this land could produce 5,800 PWh per annum of electricity assuming it produces all year round only at the level of its lowest month.

Again, this is a conservative assumption as in reality solar can be balanced with wind and other technologies and therefore more will be possible. As we will see below, for most countries this is an academic distinction because their resources are so large. However, for a few this will be an important distinction and they may elect for example to use farmland or to figure out ways to handle the seasonality better.

4.3 Solar roofs

In technical terms, solar roofs are also of course solar PV. However, they are not included in the Solargis analysis of the total size of the solar PV technical potential. As a result we examine them separately, using data from Mark Jacobson. They are less than 1% of the size of solar PV, but more than ten times the size of total hydroelectric generation in 2019.

4.3.1 How to count it

Jacobson calculates the total size in m2 of rooftops in each country and then makes the following adjustments.

- Exclude North facing roofs in the northern hemisphere and South facing roofs in the Southern hemisphere.
- Exclude shaded areas.
- Allow for areas between rows of solar panels for servicing. This is of course more relevant to solar panels on commercial buildings than on houses.

He estimates that roofs can accommodate 191 MW of capacity per km2 of roof (or 0.3 MWh p.a. per m2) and that the average capacity utilisation is 20%.

4.3.2 Differences in quality

Two different distinction can be made – by type and by country.

4.3.2.1 Type

Jacobson distinguishes between residential roofs and commercial/ government roofs.

- For Residential. 112,000 km2 of roof space with a technical potential of 37 PWh p.a. from 27 TW of capacity
- Commercial. 47,000 km2 with a technical potential of 16 PWh p.a. from 11 TW of capacity

4.3.2.2 Country

Jacobson also calculates the total by country. Each country of course has its own regulatory structure which helps to determine whether home and commercial solar is profitable to install. Although of course country matters for all areas, it is especially important for a technology like rooftop solar.

4.3.3 Size

The total amount of solar that can be generated on the appropriate roofs of the world is then 53 PWh p.a. This looks very small when compared to the size of the utility solar PV resource identified above. However, it is a special technology because of course it is both right next to the source of demand (houses and factories) and does not require any new land. It is for this reason we have seen rapid growth above all in commercial roofs as a source of electricity. For example, the EIA calculates that one third of US solar electricity generation is from rooftops.

4.4 Onshore Wind

4.4.1 How to count it

In 2016, the National Renewable Energy Laboratory (NREL) did a study of the technical wind potential across the world.[31] Their estimates are based on 3.5 MW composite wind turbines with 90 meter hub heights. They take into account land-use constraints and system performance.

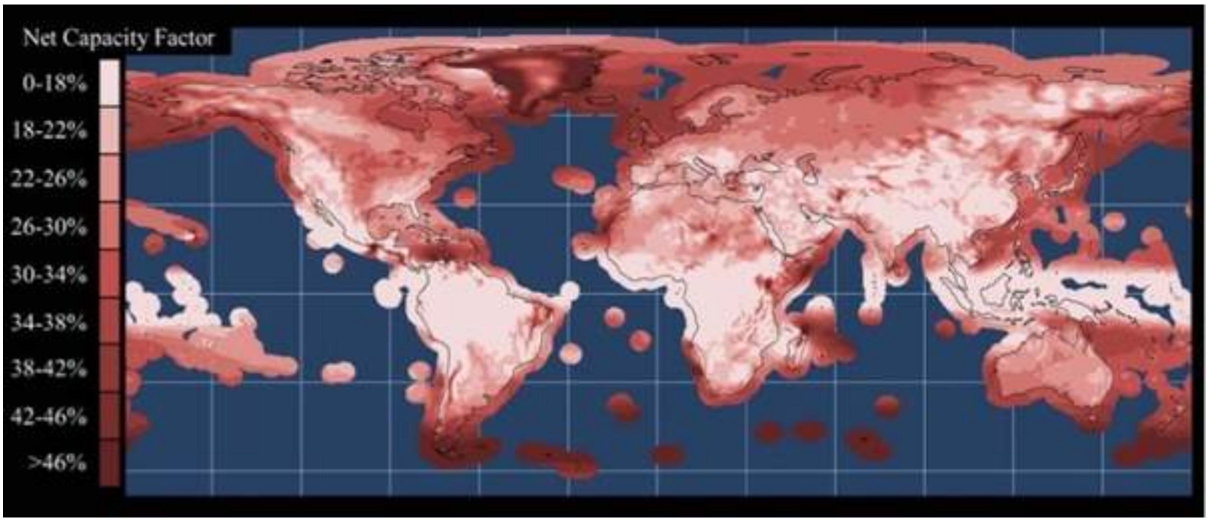
Specific assumptions that they make are:

- ***Physical constraints.*** They exclude areas where it is not possible to put wind turbines such as mountains (above 2,500m or over 20% slopes) , ice, rivers, cities, protected areas or forests.
- ***Spacing.*** They assume 5 MW/ km2
- ***Availability.*** They assume 95% availability and 90% array efficiency

From their calculations, 60 m km2 of land area (40% of the total land surface of the earth) are feasible locations on which to put wind turbines. As with solar this will probably be an underestimate, but as with solar it is only an issue for a few countries because the potential is so high.

[31] *Source: An Improved Global Wind Resource Estimate for Integrated Assessment Models, NREL, 2016*

FIGURE 25: WIND CAPACITY FACTOR



Source: NREL

4.4.2 Differences in quality

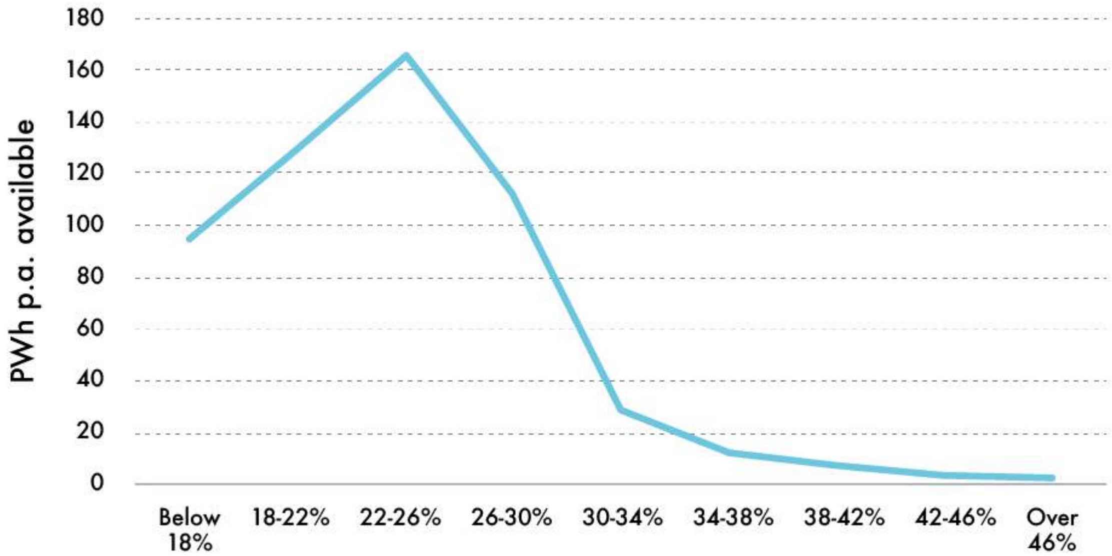
NREL splits onshore wind according to capacity utilisation and distance from areas of consumption.

4.4.2.1 Capacity utilisation

The NREL has 9 levels of capacity utilisation, from below 18% up in 4% increments all the way to over 46%. [32] The vast majority of the capacity is in lower capacity utilisation areas. Only 55 PWh per annum is in areas of wind capacity utilisation above 30%.

[32] *According to GWEC, 44% capacity utilisation is approximately 8 m/s average wind speeds, and 34% is 7 m/s*

FIGURE 26: ONSHORE WIND POTENTIAL BY CAPACITY UTILISATION (PWH P.A.)



Source: NREL

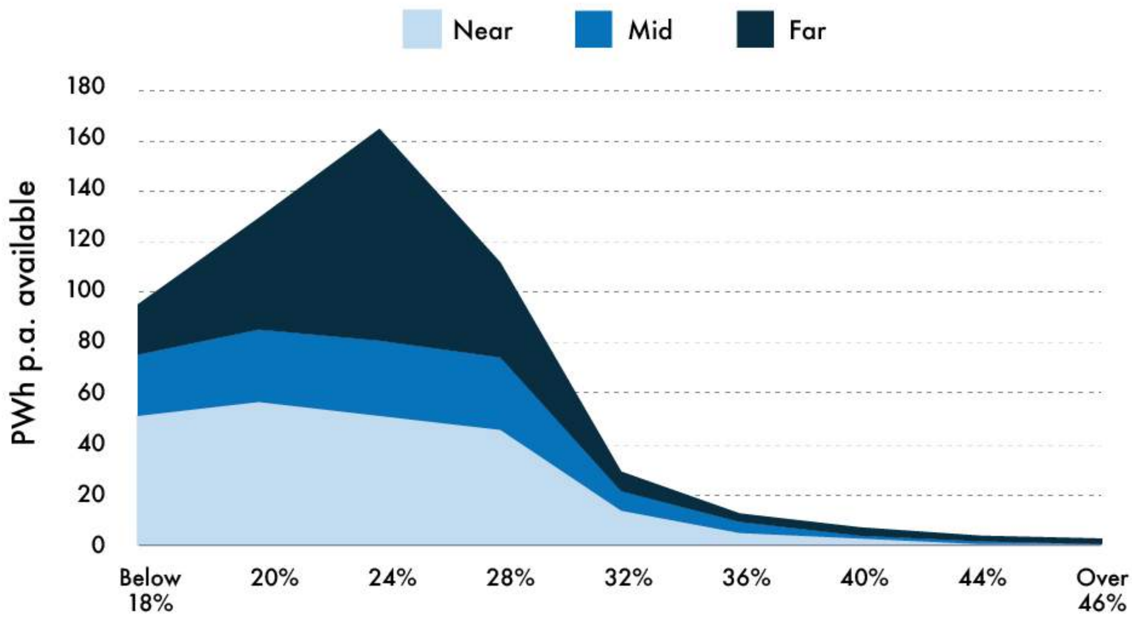
4.4.2.2 Distance

NREL specify three types of distance from transmission lines.

- Near. 0-80 km
- Mid. 80-161 km
- Far. Over 161 km

The distance from the demand centre may be less important than the capacity utilisation. That is to say, it may make sense to build long transmission lines to access high quality wind resources in more remote locations rather than lower quality ones nearer to demand centres. Again, this is all very location specific.

FIGURE 27: ONSHORE WIND POTENTIAL IN PWH P.A. BASED ON WIND SPEED AND DISTANCE TO DEMAND



Source: NREL

Of the total, 21 PWh p.a. is near to demand centres and above 30% capacity utilisation for example. Whilst this is a relatively small number in the context of the total wind supply, it is nevertheless only a little smaller than global electricity demand.

4.4.3 Size

NREL calculate that the technical potential of wind in 2016 was 557 PWh p.a. onshore.

4.5 Offshore wind

4.5.1 How to count it

In the same analysis, NREL also calculate the size of the offshore wind resource. NREL exclude the following areas.

- Less than 5 nautical miles (about 10 km) from shore because of public resistance to visual disturbance.
- More than 100 nautical miles (about 200 km) from shore because it is too remote.
- Protected areas.
- Areas of more than 1,000m in depth.

From their calculations, 23m km2 are feasible for offshore wind. This is 6% of the global oceans.

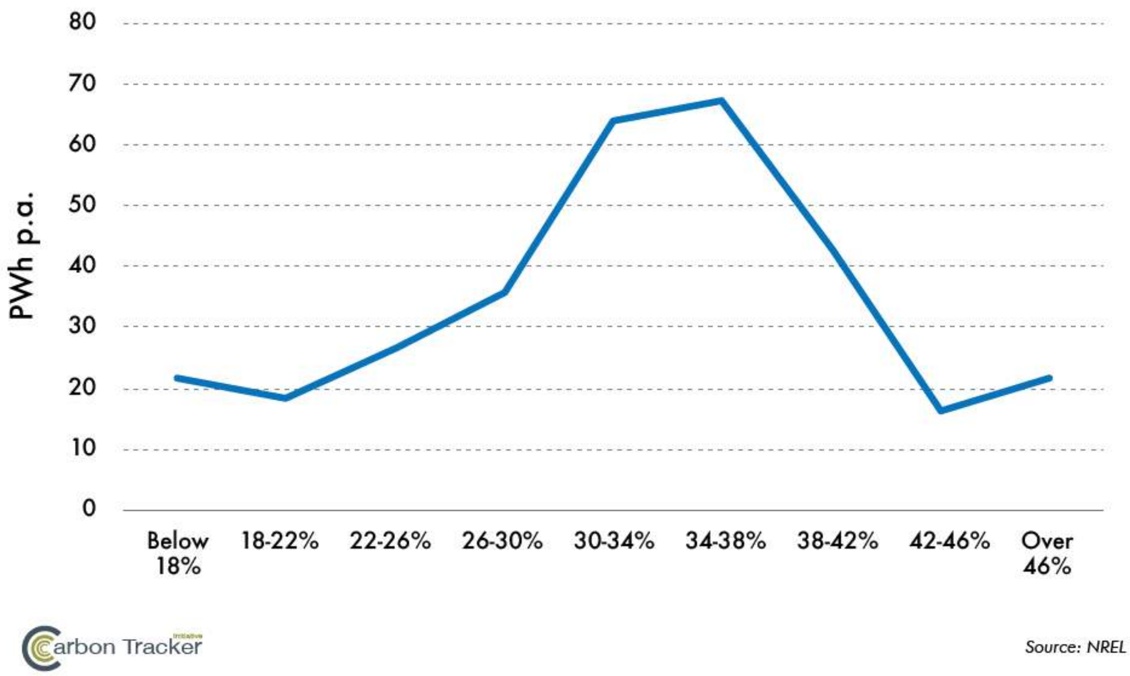
4.5.2 Quality differences

NREL splits offshore wind in three ways. By capacity utilisation, by distance to shore, and by water depth.

4.5.2.1 Capacity utilisation

They specify the same 9 levels of capacity utilisation as below.

FIGURE 28: OFFSHORE WIND POTENTIAL BY CAPACITY UTILISATION (PWH P.A.)



Source: NREL

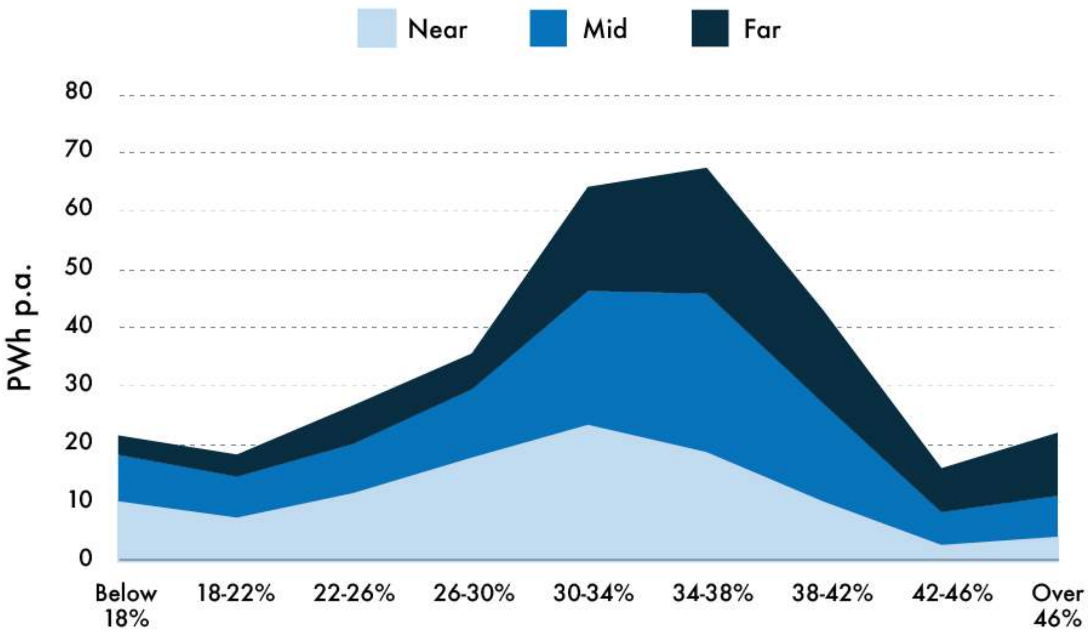
In contrast to onshore wind, a much larger amount of offshore wind is of high levels of capacity utilisation. 22 PWh p.a. has capacity utilisation of over 44%, and 212 PWh p.a. is over 30%.

4.5.2.2 Distance from demand

NREL breaks up distance to shore into three areas:

- Near: 10-40 km
- Mid: 40-100 km
- Far: 100-200 km

FIGURE 29: OFFSHORE WIND POTENTIAL BY DISTANCE TO SHORE (PWH P.A.)



Source: NREL

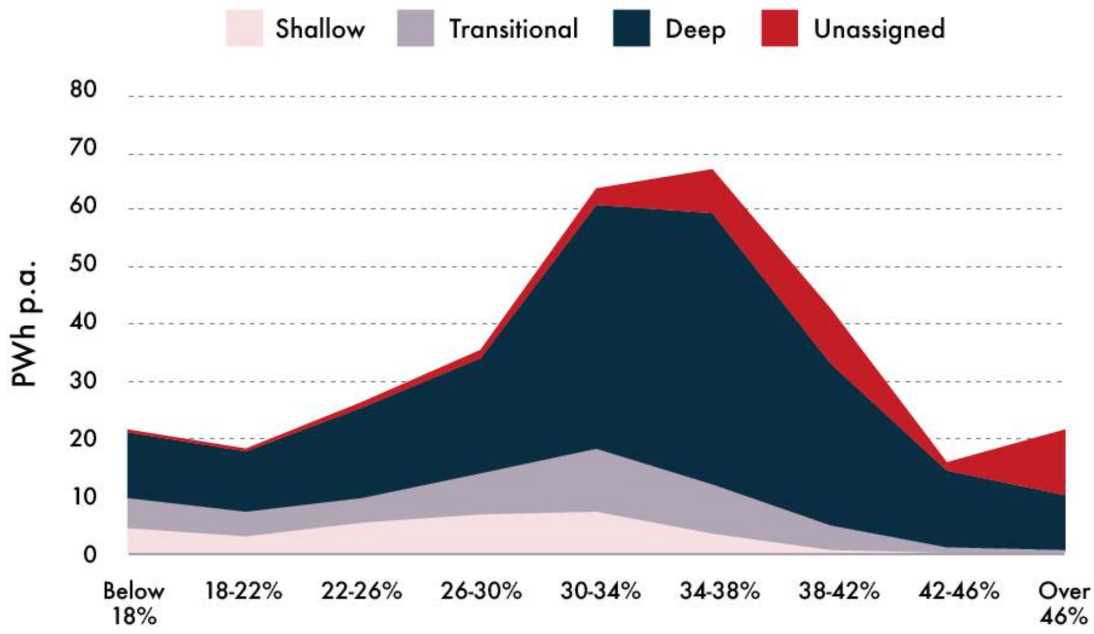
4.5.2.3 Depth

The NREL has three levels of depth in their analysis of the opportunity for offshore wind:

- Shallow (0–30m)
- Transitional (30–60m)
- Deep (60-1,000m)

The very best wind offshore sources are also in deep or unassigned areas (mainly Alaska).

FIGURE 30: OFFSHORE WIND POTENTIAL CLASSED BY DEPTH AND DISTANCE (PWH P.A.)



Source: NREL

4.5.3 Size

NREL calculated that the total amount of offshore wind available was 315 PWh per annum offshore. Of this they assign 277 PWh p.a. to countries and 37 PWh p.a. is unassigned.

Subsequent studies have suggested that the potential is of course rising as we make higher turbines and figure how to go further offshore. The IEA[33] for example analysed the size of the offshore wind technical potential in 2019 and calculated that it was 33% larger at 419 PWh per annum.

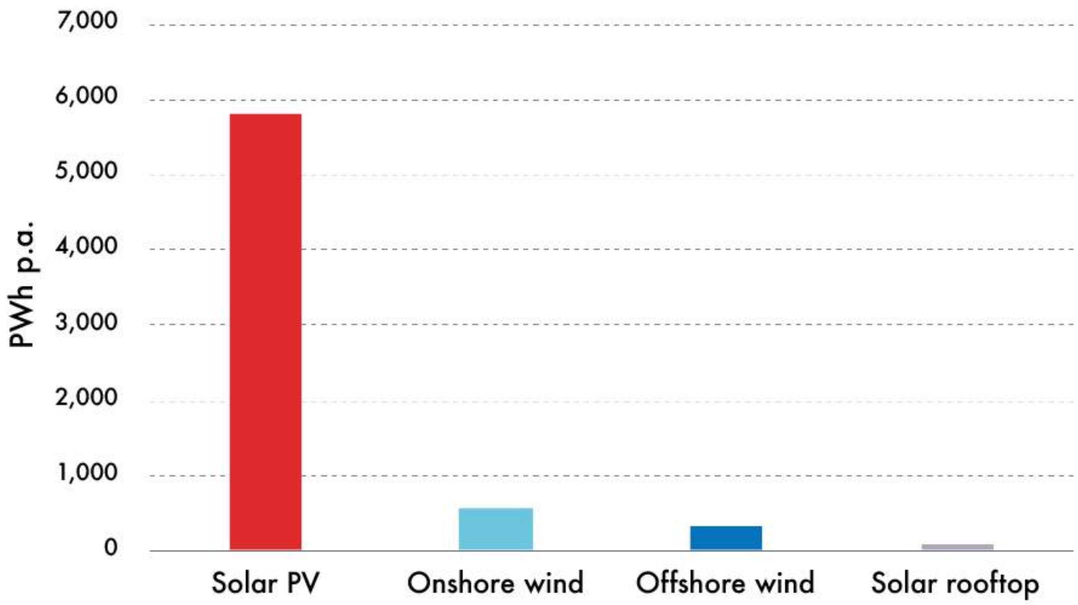
4.6 Total technical potential

4.6.1 Size today

The total technical potential of solar and wind is therefore an extraordinary 6,754 PWh p.a. using today's technology, and in the case of solar accounting for seasonality and excluding all croplands. As one would expect, it is solar PV that dominates the technical potential with 86% of the total.

[33] *Source: Offshore wind outlook, IEA, 2019*

FIGURE 31: TECHNICAL POTENTIAL OF SOLAR AND WIND PWH P.A.



Source: Solargis, NREL, Jacobson.

4.6.2 Future size

As wind turbines have got higher and solar panels have got more efficient, so the technical potential of renewables has been rising.

For example, Jacobson estimated the size of the technically available solar resource in 2008[34] at 3,000 PWh p.a. By 2021 his estimates had risen to nearly 12,000 PWh p.a.

And we would expect the technical potential to continue to rise. Drivers of this include:

- More efficient solar panels
- Higher wind turbines. Even since the NREL study which assumes 90m turbines, wind turbines have got higher and most studies now assume 100m hub height.
- Solar on the oceans and on lakes. For example Korea recently announced plans for 2 GW of solar panels on the ocean. India has been putting solar panels on canals and lakes.
- Deeper and further. In the same way as the oil industry has expanded offshore, so the wind industry is likely to expand offshore in those locations where it is necessary.

It might seem a little strange for us to be expanding the technical frontier of a technology where we already have technical potential of 100 times as much as our total demand. However, technology innovation is often driven by countries which do not have the luxury of such large amounts of renewable potential.

We do not believe it is very helpful to put a number on the total amount that the technical potential can rise. However, as we note below it is likely to be by more than the 5% increase that is necessary for us to make the simplifying assumption that all today's technical capacity (in PWh terms) will be economic by 2030.

[34] Source: *Review of solutions to global warming, Jacobson, 2008*

5 Economic potential

We define having economic potential if the resource has costs comparable with local fossil fuel alternatives for the generation of electricity. In the same way as fossil fuel reserves are classified as economic if they are recoverable economically at current prices using current technology.

Although we lay out our assumptions in detail below for each source of economic potential, there is in fact only one key assumption when it comes down to the size of renewable economic potential – how much solar to include. The other calculations are interesting and often country specific, but of much less importance. For example, offshore wind might be a little more in 2020 or onshore wind might be a little less in 2030 if different assumptions are used, but the differences will make little impact on the overall conclusion.

Furthermore, it is worth stating at the outset that cost structures will be very country specific, especially for technologies like offshore wind. A country like Morocco which is blessed with huge onshore solar and wind resources has little need to exploit its offshore wind potential. Whilst countries like the UK or Korea which have significant constraints on land availability are much more likely to make use of their offshore wind resources. We seek in the summary below to set out a broad framework, whilst being cognisant that each country will in fact be very different.

5.1 Solar PV

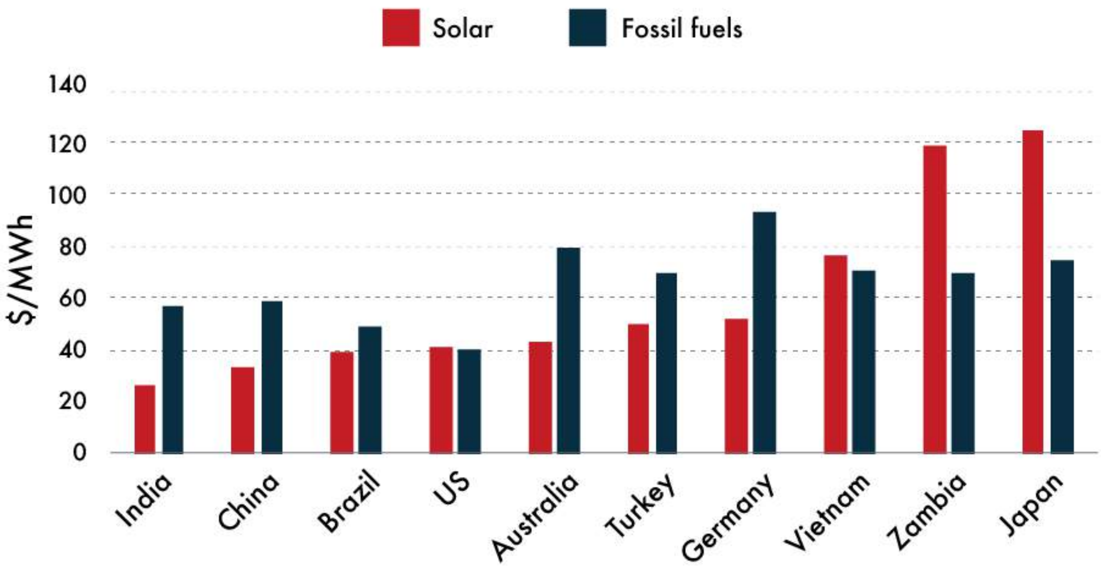
5.1.1 How much is economic today

We consider two ways to restrict the amount of technical solar generation potential which is economic – by country and by type of solar within country.

5.1.1.1 By country

BNEF analyse the cost of solar in a very wide range of countries and present the results in their LCOE cost tracker every 6 months. According to them, solar or wind were the cheapest sources of new bulk electricity production in 90% of the world weighted by demand, and 75% weighted by population. For example we show below mid prices of solar versus the cheapest fossil fuel in a representative range of countries from each region.

FIGURE 32: SOLAR VERSUS CHEAPEST FOSSIL FUEL LCOE $/ MWH 2020



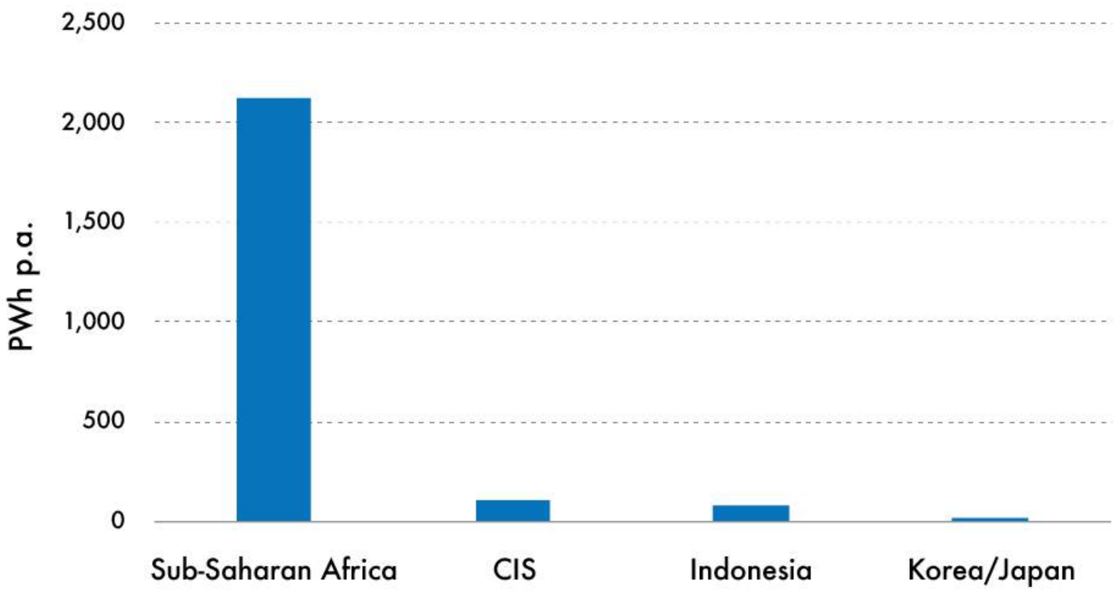
Source: BNEF LCOE calculation h2 2020

In broad terms there are three types of countries where solar in 2020 was still more expensive than fossil fuels:

- Restrictive policy. Those which suffer from restrictive policy. For example, Japan and Korea.
- Cheap fossils. Countries which have lots of cheap fossil fuels. E.g. Russia.
- Difficult business environment. Which leads in turn to a high cost of capital. For example in Zambia.

These three areas add up to around 40% of the total technical potential of solar. Most of this technical potential is in fact in Sub-Saharan Africa.

FIGURE 33: SOLAR TECHNICAL POTENTIAL PWH P.A. WHERE IT IS MORE EXPENSIVE THAN FOSSILS



Source: Solargis, BNEF, Carbon Tracker

5.1.1.2 By quality

It is clear that the solar technical potential is far larger than could be used currently. However, it is not necessary to constrain our calculation of the economic resource for that reason alone. If we consider fossil fuels, large amounts are counted as reserves even though they can never be used.

However, perhaps we can curtail the amount because some of the solar is more expensive than other solar. However, this is unlikely to make a material difference as we set out below.

- Small quality gap. As Solargis points out, the gap between the highest practical insolation level (Namibia) and the lowest practical insolation level (Ireland) is only two times. So within counties the gap will be in most cases much smaller than this.
- Distant land is already excluded. Solargis has already excluded from their analysis land which is a long way from demand centres.
- Complex land is already excluded by Solargis.
- Solar is extremely cheap in the biggest nations. In India for example the average solar price now is $26 per MWh,[35] versus the average coal price of $57 per MWh. The top end of solar costs in India is $38 per MWh.
- Costs are falling fast in any event. It might be possible to show that only a certain percentage of the land in a given country (e.g. Vietnam) is in fact capable today of supporting solar at prices comparable with fossil fuels. However, this is spurious accuracy. Because costs are falling so fast, this land will provide economically viable solar long before it is needed.

5.1.1.3 Conclusions

So our conclusion is that we take today the entire land mass identified by Solargis (for level 2 land and seasonality adjusted) of all those counties where solar is cheaper than fossil fuels as an economic resource.

[35] *Source: BNEF, LCOE report, h2 2020*

And we adjust this by excluding the 40% of the world (weighted by insolation level) where solar today is not yet cheaper than fossil fuels.

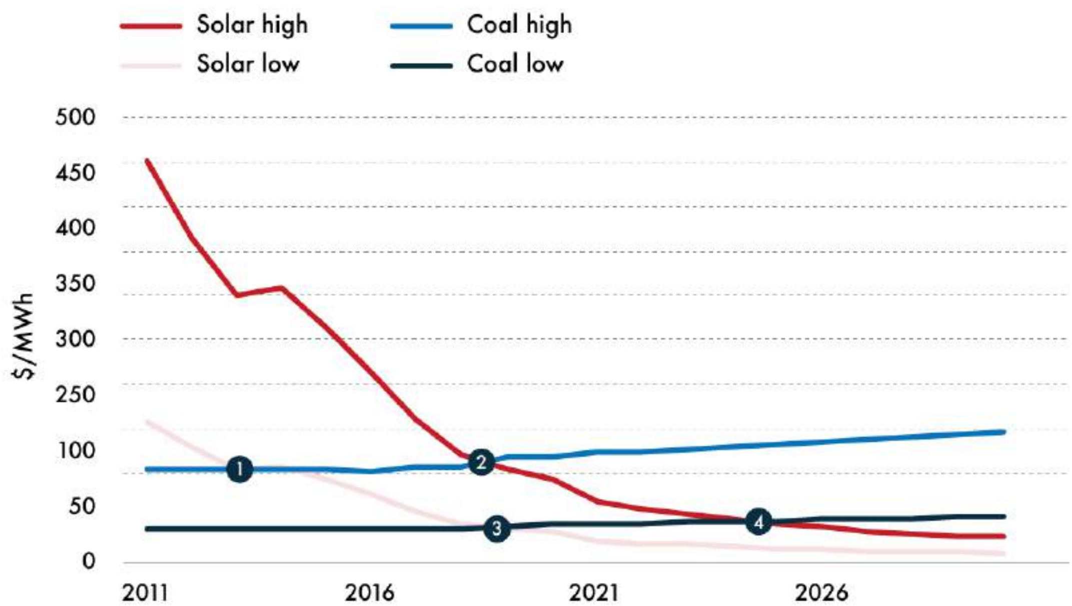
That means 60% of the total is economic, or 3,500 PWh p.a. The implications of this fact are extremely profound. Vast tracts of the world provide the economic potential to generate an enormous source of cheap electricity.

5.1.2 Economic in 2030

As is widely appreciated, costs are falling rapidly. Solar costs have fallen at an average of 18% every year for the last decade and are on learning curves which have been characterised by Doyne Farmer as being very sticky.[36] The future costs of solar even for the laggards are likely to fall below fossil fuels.

In the illustration of this below we take actual solar and coal costs for 2010-2019 from BNEF and assume that solar continues to grow at 20% growth per annum with a 40% learning rate. Furthermore we assume that the highest cost counties have twice the cost of the average and the lower cost countries are 70% of the average.

FIGURE 34: SOLAR HIGH AND LOW COSTS VERSUS COAL HIGH AND LOW COSTS LCOE $/ MWH



Source: BNEF, Carbon Tracker estimates.

Four transition points then materialise in this model, and within a decade.

1. In 2015 low cost solar is cheaper than high cost coal.
2. In 2018 high cost solar is cheaper than high cost coal.
3. In 2019 low cost solar is cheaper than low cost coal.
4. In 2025 high cost solar is cheaper than low cost coal.

[36] *Source: How predictable is technology progress, Science Direct, 2016 or Estimating the costs of energy transition using probability forecasting methods, INET, 2020*

To take the four areas where the costs of solar are higher than those of fossil fuels, it is thus highly likely that the costs of solar will fall below fossil fuel costs by the end of the decade. Reasons for this include:

- It's the same sunshine. As noted, no country has insolation two times worse than anyone else, even though the best solar locations have twice the number of sun hours than those at the lower end of the spectrum .
- Costs are falling rapidly across the world on learning curves.
- One of the main reason for the high cost in many countries is a lack of commitment to build renewable assets. The experience of renewables has been that the more you build the cheaper they get. Vietnam has just set ASEAN alight by installing the world's third largest amount of solar in 2020, and its costs are highly likely to fall to below those of fossil fuels. Meanwhile both Japan and Korea have embarked on ambitious net zero programmes which are highly likely to drive prices lower.
- Sub-Saharan African has a massive solar resource, and is likely to take advantage of it in order to drive development and wealth across the continent. Local talent allied to international capital will eventually drive prices lower.
- Developers are hunting down the opportunity presented by huge solar resources and large demand.

Consequently it is likely that the entire landmass where solar can be placed (27% of the world according to Solargis) will have economic potential by the end of the decade. That implies that the economic potential will be 5,830 PWh a year. In reality, as noted above, it will be more than this because the technical potential is rising all the time and because we have significantly constrained the land available.

5.2 Solar roofs

5.2.1 How much is economic today

5.2.1.1 In general

The economic potential of solar roofs is even more complex than the economic potential of utility solar. It depends very heavily on the local regulatory environment.

In theory, more solar roofs are in fact economic today than utility scale solar. We saw that there are four areas where solar PV is more expensive than fossil fuels for utility solar PV. It is notable that in at least two of these locations rooftop solar Is demonstrably a cheaper option.

- In Japan where BNEF notes that rooftop solar is cheaper
- In sub-Saharan Africa which has been a world leader in rooftop solar deployment for dispersed communities.

5.2.1.2 By technology

Commercial roofs are of course more economically attractive than household roofs. They have an almost perfect combination of demand for energy during the day, large size, buyers motivated to reduce electricity costs, and capital availability.

5.2.1.3 Conclusion

Although a larger share of roofs are likely economic today, we make the same assumption as for solar PV – that 60% is economic today.

5.2.2 Economic in 2030

We make the same broad assumptions as for solar utility assets about their economics. That is to say 100% by the end of the decade. That implies 53 PWh p.a. of economic potential by the end of the decade.

5.3 Onshore wind

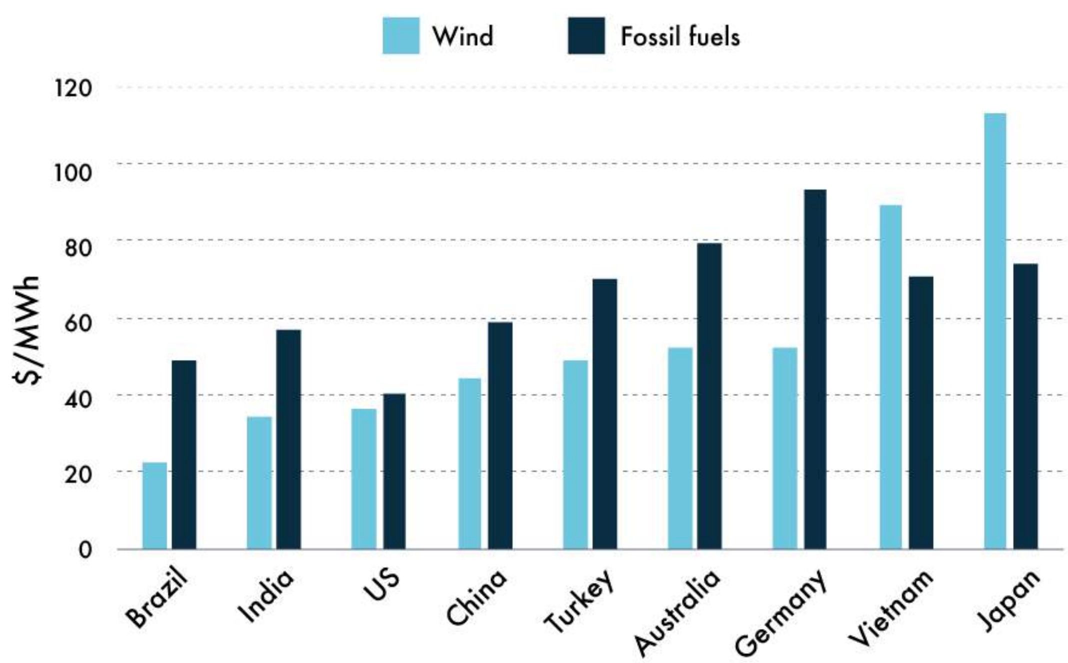
5.3.1 How much is economic today

We apply the same logic as for solar – and seek to curtail the technical potential by country and then by type within country.

5.3.1.1 Country

If we take data from BNEF on the costs of wind generation versus fossil fuels, a very similar picture emerges to what we have seen for solar. In all countries except Japan, parts of SE Asia, Russia and Sub Saharan Africa, wind is cheaper than fossil fuels for electricity generation.

FIGURE 35: WIND VERSUS CHEAPEST FOSSIL FUEL LCOE $/ MWH 2020



Source: BNEF for H2 2020

5.3.1.2 Resource – capacity utilisation

The second issue is which onshore wind resources are not economic today. Based on feedback from developers, we assume that resources with capacity utilisation of less than 22% are not economic.

5.3.1.3 Resource – distance

We assume that all technical potential at less than 160 km from a grid connection is economic.

5.3.1.4 Conclusion

When we apply these three filters, it reduces the available economic resource from onshore wind to 127 PWh per year.

5.3.2 Economic in 2030

5.3.2.1 Country

The story of rapidly falling wind costs is similar to that for solar. So we assume that all countries will have economic wind potential by 2030.

5.3.2.2 Resource – capacity utilisation

We assume superior technology, so the point at which the technology becomes economical for capacity utilisation drops by one category in the NREL framing to 18%.

5.3.2.3 Resource – distance

We assume all resources are accessible as it becomes possible to build longer transmission lines where necessary.

5.3.2.4 Conclusion

Therefore the amount of economic potential from onshore wind increases to 461 PWh p.a. in 2030.

5.4 Offshore wind

5.4.1 How much is economic today

Offshore wind has only recently become economic in optimal locations, The average global cost in terms of LCOE of offshore wind in h2 2020 according to BNEF was $79 per MWh, which is higher than the cost of electricity from fossil fuels in most locations.

Floating offshore wind (which is needed for deep-water) is a new technology and costs are falling fast but it is not yet economic without government support.

Realistically the only offshore wind which is economic today then will be near shore shallow water and with capacity utilisation of over 40%. If we filter according to the same countries as onshore wind and solar, that is only around 1 PWh p.a. of economic potential.

5.4.2 Economic in 2030

The offshore wind industry has extremely ambitious plans for growth. Today there are around 32 GW of capacity offshore. The ocean renewable energy action coalition (OREAC) wants to get to 1400 GW[37] producing around 4 PWh p.a. by 2030.

It is highly likely that supply chains will be developed for new areas, which drives down costs. And that floating offshore wind will become standardised and much cheaper. In large part because advanced countries like South Korea and Japan lack sufficient renewable resources from other sources.

It is also fair to say that there will be large parts of the world which have such large alternative renewable resources that they simply will not need to build much offshore wind. For example Australia or Africa or Russia.

Assumptions for 2030 are then as below. In reality, the mix will vary from country to country as all of these factors are brought together in the planning for a project.

- Country. We include all countries.

[37] *Source: The power of our ocean, 2020*

- Depth. We include all depths up to 1,000m on the assumption that floating offshore wind will be economic.
- Distance. We exclude locations more than 100 km from shore.
- Capacity utilisation. We assume over 40% capacity utilisation.

The conclusion is that 35 PWh p.a. of offshore wind might be economic by 2030. Again this is small in the context of solar but large in the context of total demand.

5.5 Total economic potential

5.5.1 Size today

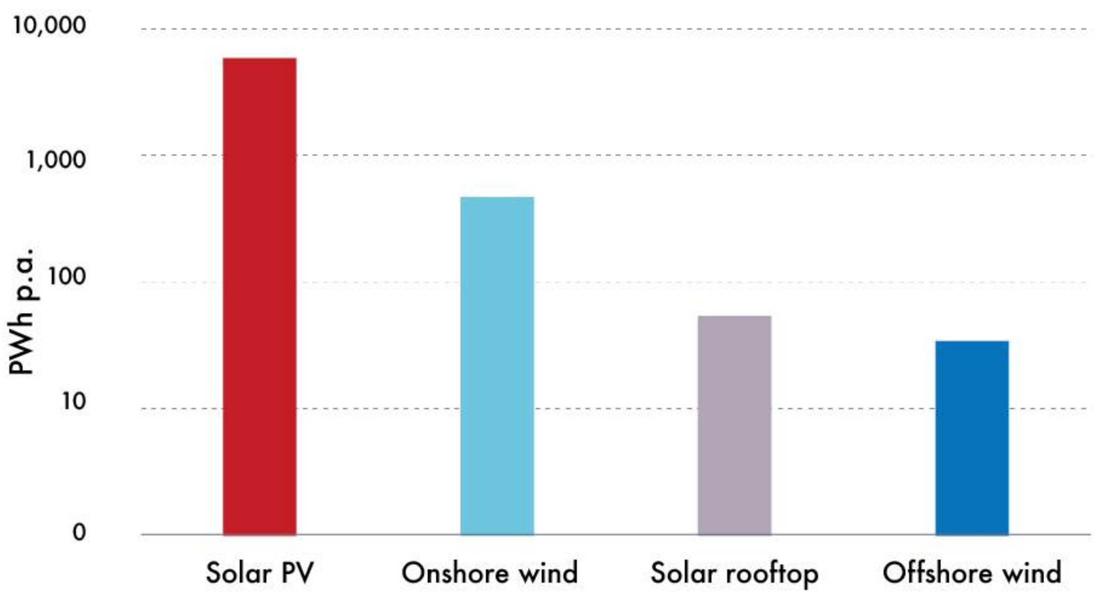
If we add up all the economic potential it is 3,680 PWh p.a. But it is in fact the future economic potential which matters more because this is the number which energy planners should be looking at.

5.5.2 Size in 2030

As per our discussion above, by the end of decade the economic potential will be 6,378 PWh p.a. The reality is that countries with limited solar endowment will figure out solutions to exploit their wind potential. And if they put in enough resource the costs are likely to fall to make the solution economic, at least for them. For example the UK has embraced offshore wind. Korea is looking at solar on the ocean and Japan at deep-water wind.

6,378 PWh p.a. of economic potential is 95% of the technical potential today. Given that the technical resource will certainly be at least 5% higher by the end of the decade, the total technical potential today is thus a good approximation for what will be economic by the end of the decade.

FIGURE 36: ECONOMIC POTENTIAL 2030 PWH P.A.



Source: Carbon Tracker estimates. Note this is a log chart

6 Political potential

With abundant domestic renewable energy removing most of the need for imports, the key issue is how to make smart domestic political choices. Clearly there are limits to the share of land that can have solar panels or wind turbines placed upon it. And this means political involvement in the process. A country like Morocco with around 500 times as much renewable technical potential as energy demand is going to face less pressure than Belgium with less than 2 times.

It is possible to calculate the political potential available per country based on some general assumptions of the share of land that people will tolerate being dedicated to solar or wind. For example, it might be possible to use a relatively large share of solar roof capacity (Jacobson uses 60% of commercial roofs in his solution) and a relatively large share of the economic offshore wind resource (the World Bank runs simulations with 10% of total usage) but a much smaller amount of space dedicated to onshore wind and solar.

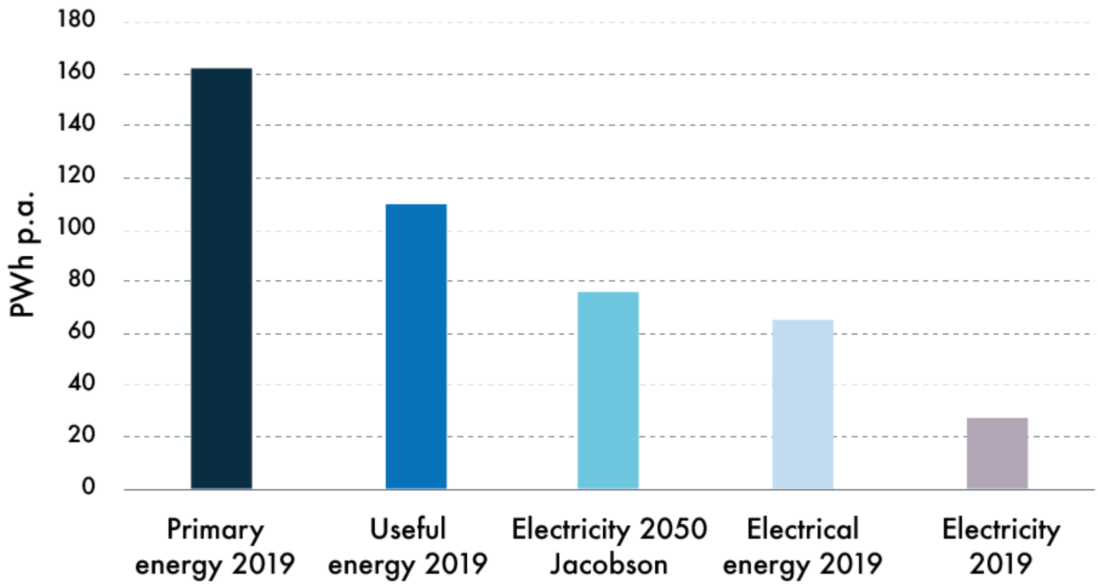
However, this is again very country specific and beyond the realm of a top-down strategy perspective. Instead, we set out below what is required versus where we are today, set out the four types of country dependent on the amount or renewable energy they have, and consider which are the countries which do have land constraints and what they are doing.

6.1 How much renewable energy do we need

As we set out below there are various ways to calculate the amount of electrical energy the world needs. But in the context of the huge amounts of renewable energy resources available, these differences very rapidly become academic. There are five numbers to consider:

- Electricity. In 2019, the world used 27 PWh of electricity according to BP.
- Primary energy. According to BP the world used 584 EJ of primary energy in 2019. Since 1 Watt is a Joule per second, 1 Wh is 3600 Joules. That means the world used 162 PWh (584/3600 * 1000) of energy in terms of primary energy using the BP methodology.
- Useful energy. According to Jacobson, the world used 110 PWh of useful energy in 2016. This is a slightly different methodology which accounts for losses from fossil fuel conversion into electricity and does not gross up renewable energy sources as BP does.
- Electrical energy. As noted above, it is misleading to use primary energy from fossil fuels in a world that is rapidly moving to electrical energy. If we convert primary fossil fuel energy into electrical energy on the assumption of a 40% thermodynamic efficiency, it is 65 PWh (162 * 40%) of electrical energy.
- Mark Jacobson calculates that global energy consumption in a world powered entirely by electricity in 2050 will be 76 PWh.

FIGURE 37: ENERGY DEMAND PWH P.A.



Source: BP, Jacobson, Carbon Tracker

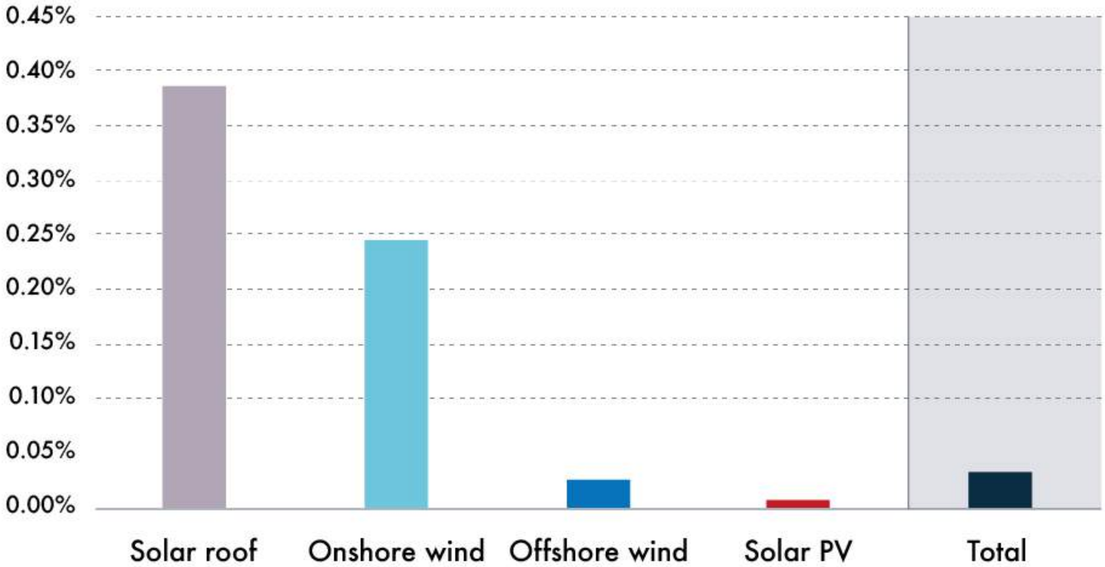
We believe it is reasonable to assume therefore that politicians should aim to get to 76 PWh p.a. of renewable electricity by 2050. And as we shall see below, that can be achieved at a very low land footprint.

6.2 Solar and wind generation today

In 2019, global electricity supply from solar was 0.7 PWh and from wind was 1.4 PWh.

Therefore we are using just 0.03% of our technical potential in total, and 0.01% of our solar potential. Even on solar roofs we are using only 0.4% of our technical potential.

FIGURE 38: ACTUAL DEPLOYMENT AS SHARE OF TECHNICAL POTENTIAL



Source: Carbon Tracker, Jacobson

6.3 Types of country

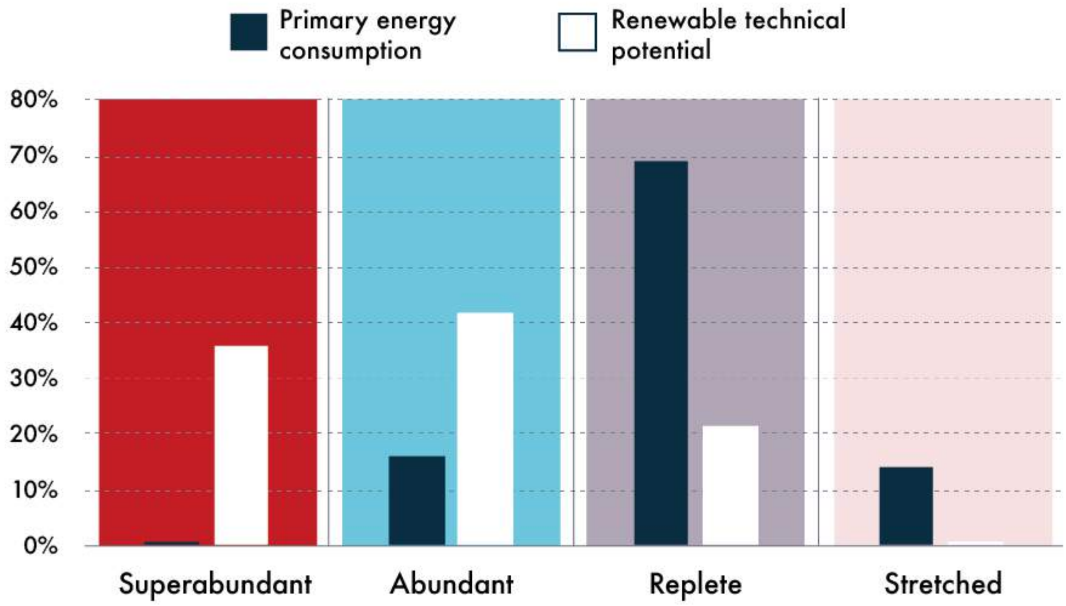
It might seem unnecessary to ask if renewable resources are large enough to meet energy demand given that the current technical potential and the future economic potential are around 100 times total demand. However, 100 times is a global average and not all countries have huge renewable potential relative to their land area. There are four types of country when it comes to the technical renewable potential compared to their energy demand.

- Super-abundant. More than 1,000 times as much technical potential as actual energy demand. Examples include Namibia, Botswana or Ethiopia. Many of these countries are of course poor (which is why energy demand is low) but they have a chance of a new start.
- Abundant. 100-1,000 times. Examples include Chile, Australia, or Morocco. Some of these countries have well developed infrastructure and governance systems. They can aspire to be the providers of renewables to other countries.
- Replete. 10-100 times. Examples include China, India and the US. Countries in this group in the most part have enough renewable energy to satisfy their energy requirements.
- Stretched. Below 10 times. Countries will need to make some tough political decisions in order to figure out if the stretch is realistic and how to tap their renewable resource most effectively. Some of them may elect to import their renewable energy through cables or pipes or ships.

These numbers can be charted to give a new world map as in the first section. It is also possible to show the big gap between the energy consumption of the groups.

- The superabundant group has 36% of global technical potential but is only 1% of global energy demand.
- The stretched group is 14% of energy consumption but has only 1% of the technical potential.

FIGURE 39: SHARE OF ENERGY CONSUMPTION AND SHARE OF RENEWABLE POTENTIAL PWH

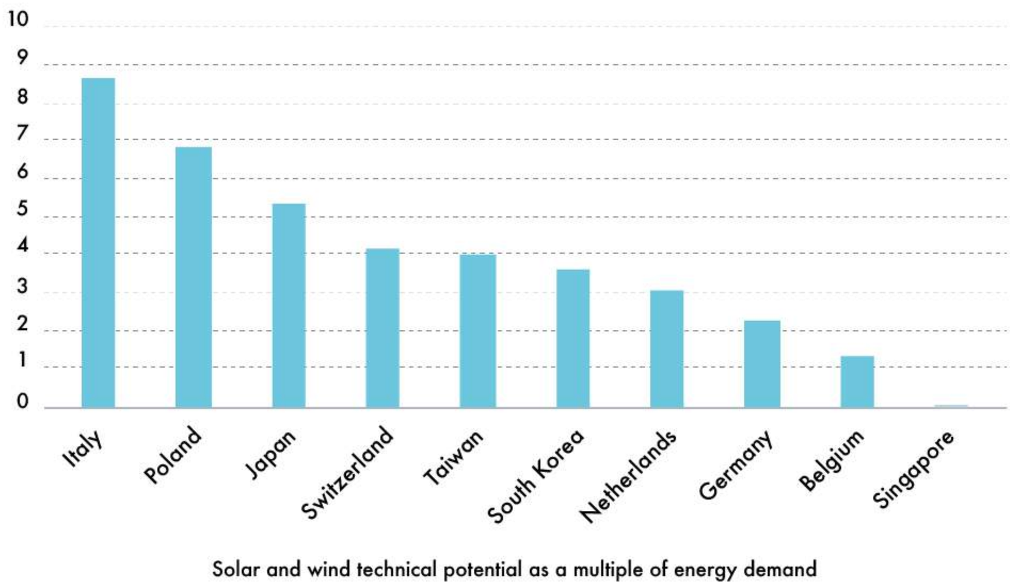


Source: Solargis, NREL, EIA, Carbon Tracker assumptions

6.4 Countries with limited renewable potential

We set out below the list of the main countries where the technical potential is below 10 times energy demand. When renewable potential is only 10 times energy demand, that necessitates some slightly more complex planning in order to avoid local resistance to too many renewable assets.

FIGURE 40: TECHNICAL POTENTIAL AS MULTIPLE OF TOTAL ENERGY DEMAND: THE STRETCHED COUNTRIES



Source: Carbon Tracker

Most notable include Japan, Korea, Germany and much of Europe. Currently, 466m people (6% of the global population) live in countries where the solar and wind technical potential is below 10 times demand. This chart helps explain some of the more innovative approaches to energy we have seen in the last few years:

- Singapore (which has a technical potential of less than 1 times its energy demand) is planning to build an underwater power line from Australia and to import hydrogen by sea.
- Germany is obliged to spend very heavily in order to find solutions. And also finds domestic opposition to more wind turbines. But the key point is that Germany is at one end of the spectrum, albeit it is a prime example of an industrial country, the challenges of which are faced to greater or lesser degree by others as well. It has the third lowest solar and wind resources in the world compared to its total demand. Germany is not very sunny, densely populated, and has high energy demand. The reason to dwell on this is that the problems being faced by Germany are not ones that will be faced by most of the rest of the world. Or to put it in more optimistic terms: if the Germans can find solutions, then so can everyone else.
- The UK (with a technical potential of just over 10 times its energy demand) is building out a huge resource base in the North Sea. Not because of the exciting prospect of becoming the Saudi Arabia of wind (offshore wind is more expensive than onshore wind) but because it is the best available resource given political constraints.
- Switzerland is planning to get 40% of its electricity from solar rooftops.[38]
- It was reported in April 2021 that Korea is planning to spend $43bn on offshore wind.[39]

[38] *Source: Ziebild Klimaneutrale Schweitz 2050*
[39] *Source: Bloomberg*

7 What happens next

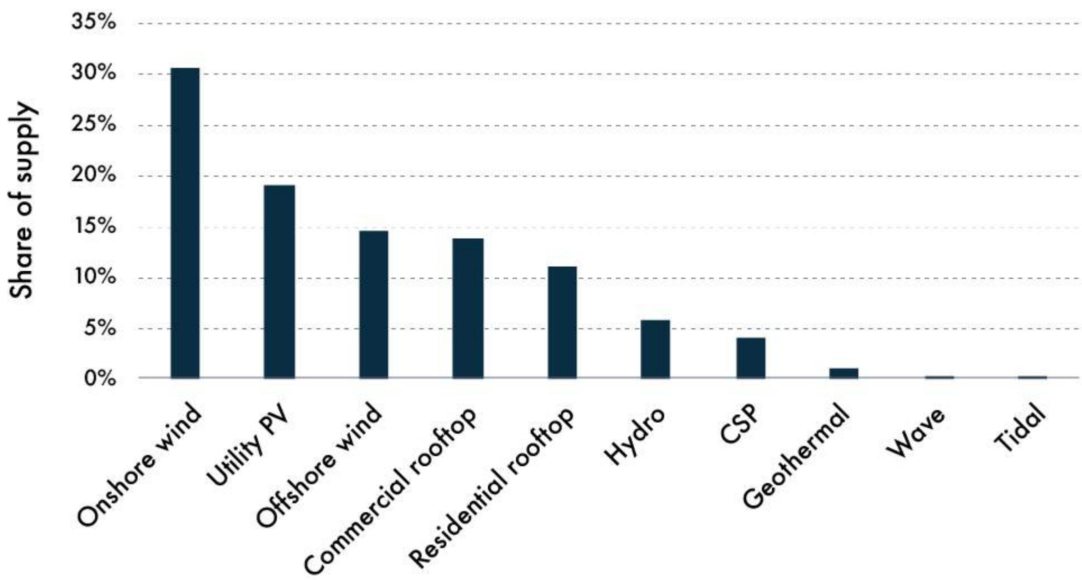
7.1 Countries figure out which is the best renewable resource for them

The world as a whole does not need to exploit its entire renewable technical potential. Developing just 1% is enough to replace all fossil fuel usage. The implication is that the energy minister of every country in the world can now sit down with a blank sheet of paper and figure out what is the best suite of options for the energy supply for their country.

As Benjamin Sovacool noted,[40] humanity tends to take advantage of cheap local energy sources when it finds them, and fast. Examples include Holland exploiting peat in the seventeenth century, the UK exploiting coal in the eighteenth century, America exploiting sperm whales in the nineteenth century, Holland extracting gas in the 1960s or the very rapid (and unexpected) rise of the shale industry in the US in the 2010s. The consistent observation from all these episodes is that cheap local energy sources are quickly brought to use.

The Solutions Project, using data from Mark Jacobson, has worked out for every country in the world[41] how they can get to 100% renewable energy. They have even sought to factor in the impact of intermittency and to figure out for each location how to deal with it. We show below the Jacobson solution for the world as a whole.

FIGURE 41: SHARE OF 2050 ENERGY SUPPLY: GLOBAL



Source: Jacobson

Attempts to carry out this analysis are now going on at an ever more detailed level across the world. To highlight some of these below:

- US. Berkeley University recently released a report[42] in which they calculated how to get a clean energy future for the US.

[40] Source: *Fact and fiction in global energy policy, Sovacool, 2016*
[41] Source: *The solutions project. They even have solutions for Belgium and Germany.*
[42] Source: *2035 report. Plummeting solar wind and battery costs can accelerate our clean energy future, Berkeley, 2021*

- UK. The Climate Change Committee has been a pioneer in thinking through the mechanics of the energy transition. Notable documents include the many documents surrounding the sixth carbon budget,[43] published in 2020.
- Japan. The Renewable Energy institute in 2021 released a report on how to get to a renewable energy future for Japan.[44]
- Pakistan. the World Bank's renewable energy potential document,[45] prepared for the government of Pakistan, analyses the entire country, works out the location of the best renewable resources based on the quality of the resource, the distance to the grid and the distance to areas of demand.

Every resource has its advantages and disadvantages. But what is new is the element of choice. This is not a luxury that most energy importers have enjoyed for the last century or so as they were forced to buy fossil fuels at whatever price they could. The solution is very country dependent, but usually involves: solar rooftops; hydro where available; lots of solar PV; wind where the above are not sufficient; renewable imports for the small number of countries that are stretched but willing to overcome the challenges inherent in the proposition.

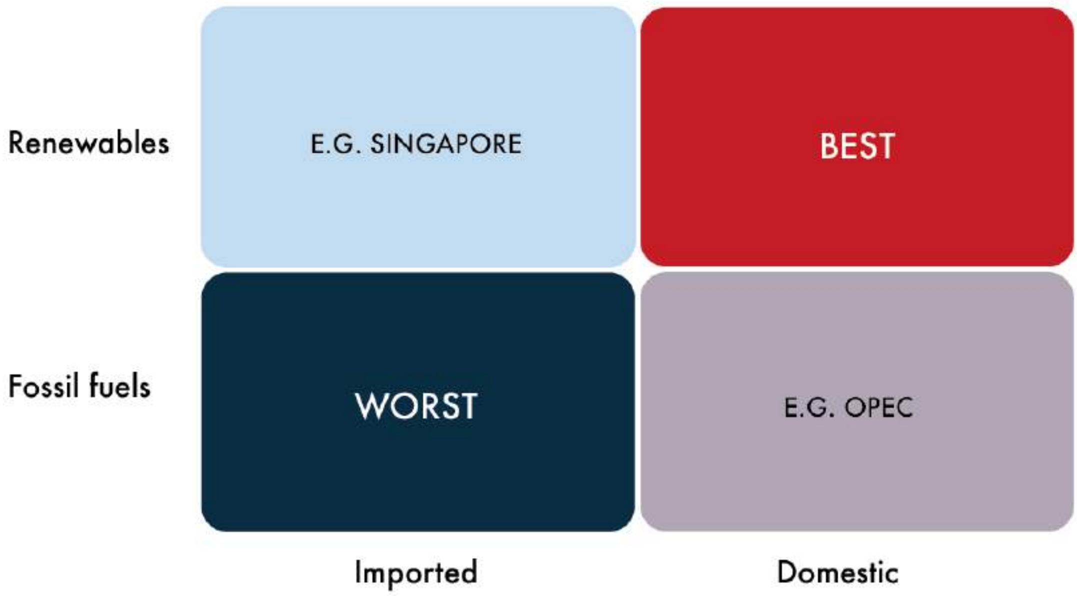
This complexity can be resolved into a four part framework for energy in the new era:

- Domestic renewables.
- Imported renewables.
- Domestic fossil fuels.
- imported fossil fuels.

Domestic renewables will likely be preferred, and then imported renewables to the degree that countries find the proposition practical and acceptable. Fossil fuels will of course hang on for a while but domestic sources will be preferred to imports, and it is likely that imported demand will fall rapidly.

[43] *Source: The sixth carbon budget: the UK's path to net zero, Climate Change Committee, 2020*
[44] *Source: Renewable pathways to climate neutral Japan, Renewable Energy Institute, 2021*
[45] *Source: Variable location energy study Pakistan, World Bank, 2021*

FIGURE 42: ENERGY OPTIONS IN THE ERA OF RENEWABLES



Source: Carbon Tracker

7.2 Cheap renewables get used in more ways

It is a quaint error of incumbent energy fossil fuel modellers to believe that the future will look just like the past. The same thinking that predicted in 1894 that London would be 9 feet deep in horse manure in 1930 now predicts that in 2050 fossil fuel demand will be higher than today. At heart this is a simple failure of imagination.

One way to think about the rising suite of solutions provided by cheap solar and wind energy is to look at the marginal abatement cost curves (MACC) produced by McKinsey,[46] BCG and others. These show the cost of replacing a particular type of energy with renewable alternatives. For some technologies (e.g. electricity and light transport) renewable technologies are cheaper than the fossil fuel alternatives, and the cost is in fact negative. For others (e.g. cement production) it is a lot higher.

So if we think of renewable energy as a tide and the cost curve as if it is an island, then the story becomes immediately apparent. The tide comes in, it swamps the lower easier end of the cost curve first, and then moves up the beach as we saw in the summary section.

The analogy can be extended. As the tide of change rises, government action and technology innovation are in fact causing the land to slip downwards every year, making it easier for the tide to advance. And from time to time a large sector that had once seemed well out of the range of the tide suffers a technology shift and comes crashing down. Think about how electric vehicles moved from being the derided toy of the rich to the future of the auto industry over the last 5 years.

[46] *See for example: Net zero Europe, McKinsey, 2020*

To do this will not be easy, in the same way it was not easy to electrify the world after 1880.[47] Major changes in technology and regulation will be required.[48] Engineers will need to keep solving problems of intermittency, electrification and the production of alternative fuels. Technology will need to be developed in order to make use of the cheap resources, and the development of batteries, electric vehicles, the digitisation of energy[49] and green hydrogen are all examples of this.

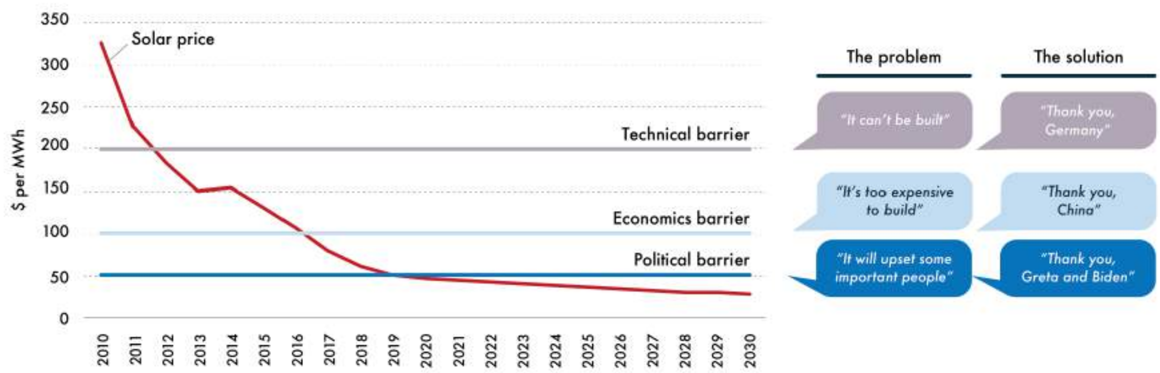
In the same way that humanity invented all the technologies of the fossil fuel era so we will have to invent the new technologies of the renewables era, and to the winner will go the spoils. Meanwhile major changes in regulation are needed: the regulatory structure is designed to accommodate fossil fuels; it needs to be retooled for renewables.

7.3 Incumbency barriers are crossed

The fond hope of the fossil fuel industry is that the growth rate of solar and wind will slow down. After all that is what happened to hydro and then nuclear. But this is a delusional hope – renewable potential is two orders of magnitude higher than hydro or nuclear, renewables are everywhere, and their costs keep falling.

We have established that technical and economic barriers have been crossed by falling costs. It follows that the main remaining barrier to change is the ability of incumbents to manipulate political forces to stop change. To put this in terms of barriers below.

FIGURE 43: HOW FALLING COST OVERCOMES BARRIERS TO CHANGE: CONCEPT CHART



Source: BNEF, Carbon Tracker

There are three main reasons why incumbents will not be successful at holding back the tide of change.

- Economics. Renewable costs are lower. And keep falling.
- The public. Pollution and global warming outrage more people every year. They will tend to vote out politicians who side with the fossil fuel incumbents.
- Geopolitics. Currently 80% of people live in countries that import fossil fuels. It is one thing to support continued domestic production. But much easier to stop imports. Countries that import fossil fuels have the opportunity to move to renewable technologies that will create local jobs, reduce pollution and reduce energy dependency.

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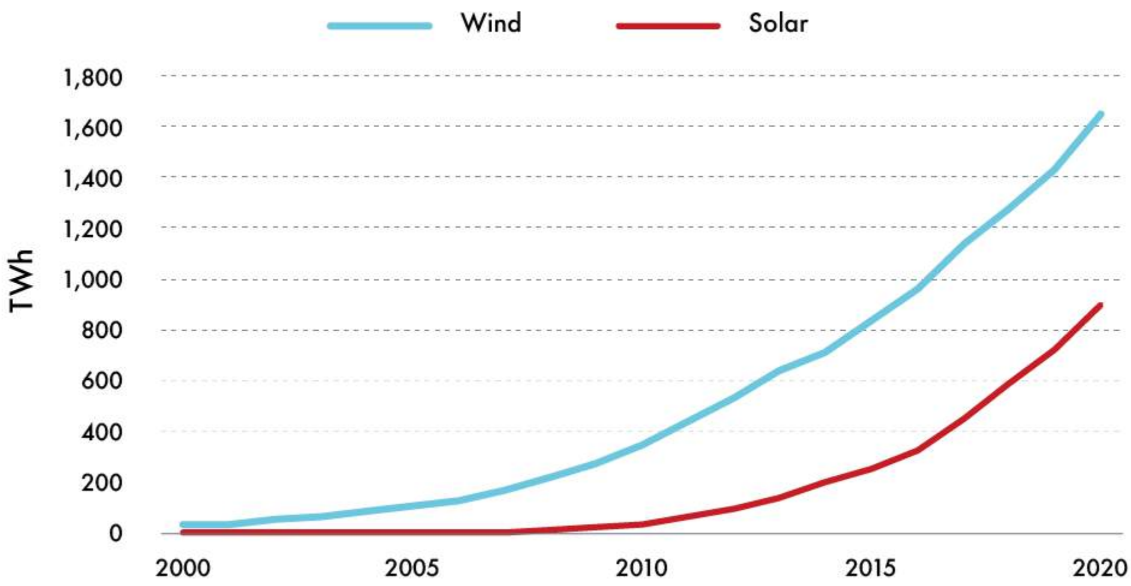
[47] *See for example: Networks of power: electrification in Western society 1800-1930, Hughes, 1983*
[48] *For a detailed discussion of this, see: A new perspective on decarbonising the global energy system, Smith School Oxford, 2021*
[49] *Source: More than the sun: solar outlook, DNV, 2021*

7.4 Exponential growth continues

Solar and wind demand has been growing exponentially for many years even when costs were high. Growth was from a low base and was initially assisted by subsidy.

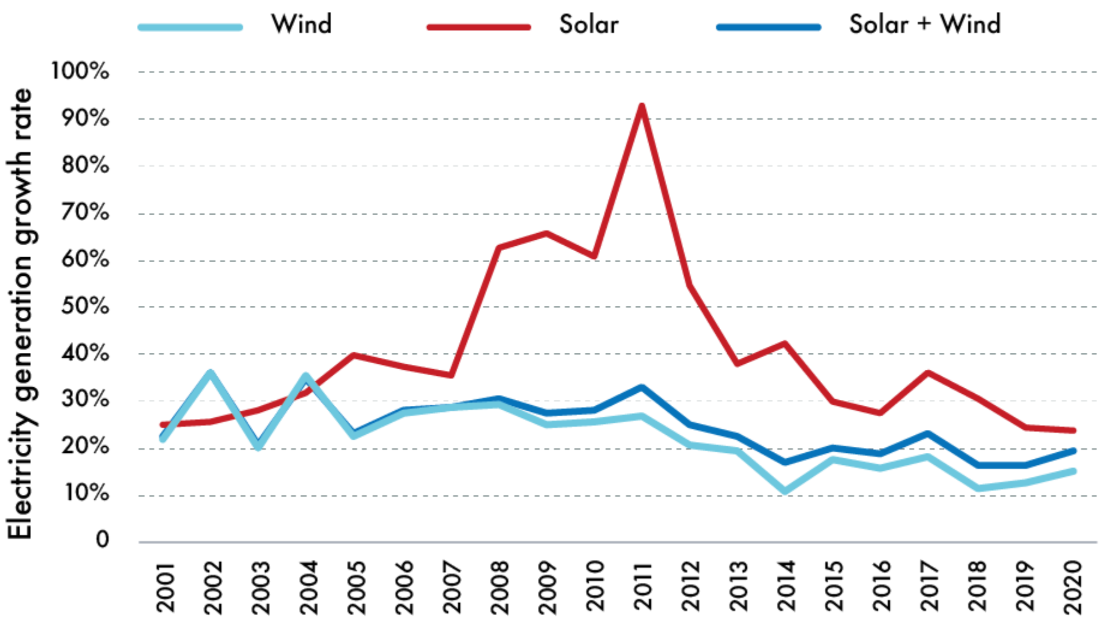
FIGURE 44: SOLAR AND WIND ELECTRICITY GENERATION TWH



Source: BP, Carbon Tracker estimates for 2020

However, even as the technologies have grown they have maintained high growth rates as we show below.

FIGURE 45: SOLAR AND WIND GENERATION. ANNUAL GROWTH RATE

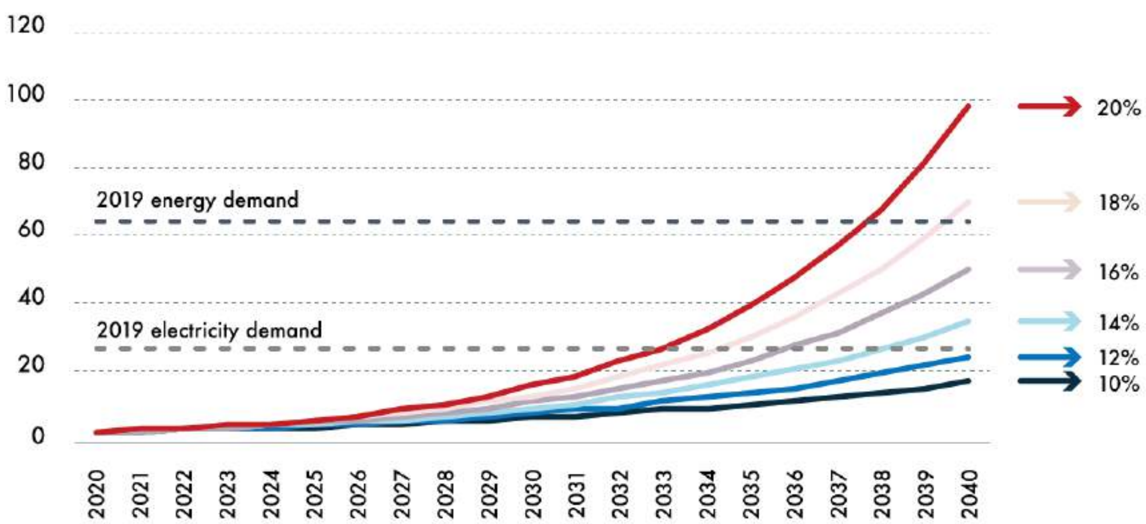


Source: BP, Carbon Tracker estimates for 2020

Now that solar and wind costs have fallen below the costs of alternative sources, it is to be expected that growth will continue at exponential rates. The average growth rate of the last 5 years and the growth in 2020 has been 19%. If that type of growth rate is maintained, then solar and wind generation will push fossil fuel supply out of electricity provision in the 2030s and out of the entire energy system in the 2040s. As the chart below shows, solar and wind growth would have to slow very markedly in order for fossil fuels to remain in the electricity generation mix in the 2040s.

In the chart below we show the size of solar and wind given different growth rates.

FIGURE 46: SOLAR AND WIND SUPPLY PWH VERSUS 2019 ENERGY DEMAND



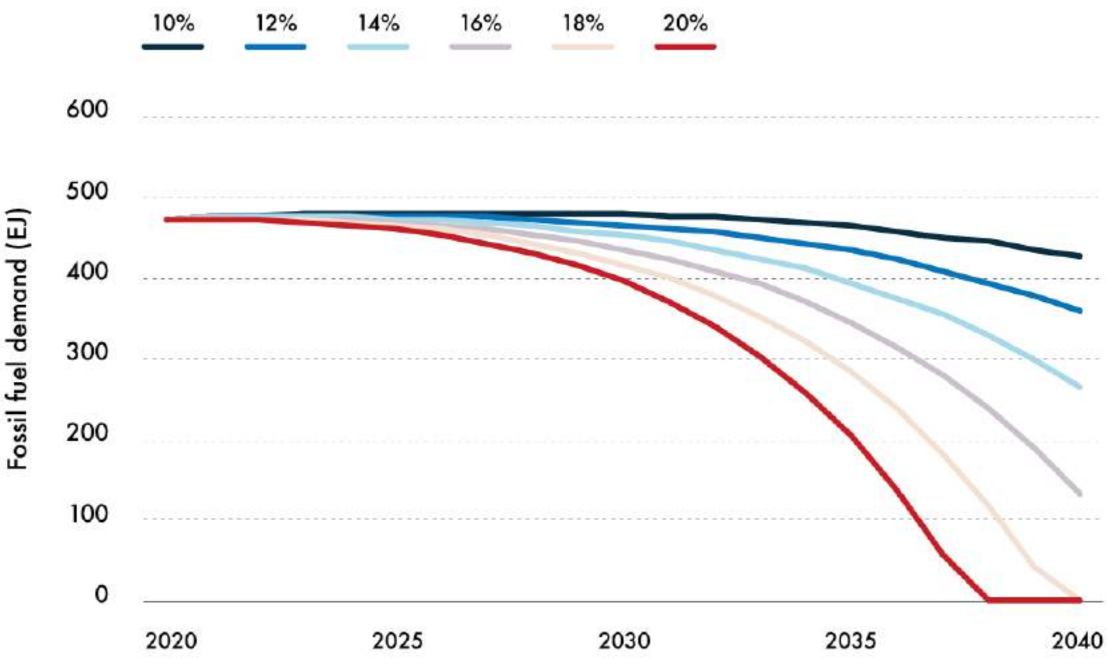
Source: Carbon Tracker

7.5 Fossil fuel demand falls

There is often a long debate with incumbent fossil fuel producers and their cheerleaders about future demand for fossil fuels. Incumbents extrapolate their past of high and rising demand into a non-existent future to argue that demand will hold up. In the face of overwhelming pressure from economics, financial markets, technology and governments, none of these models is valid any more.

In reality, fossil fuels are simply the residual in an equation with limited total growth and exponential growth of solar and wind. There is nowhere to go but down, and this is why we are already seeing hundreds of billions of dollars of write-downs of fossil fuel assets. We show below the implied level of fossil fuel demand based on the different rates of solar and wind growth.

FIGURE 47: FOSSIL FUEL DEMAND IN EJ BASED ON SOLAR AND WIND GROWTH RATES



Source: Carbon Tracker

7.6 Other consequences of the rise of renewables

7.6.1 Energy prices fall

Because of learning curves, rapid growth in demand means a rapid fall in prices for renewables. And they will challenge fossil fuels in a rising number of areas of demand. And as new and cheaper solutions come into the mix, so energy prices will continue to fall.

7.6.2 Poor countries are the greatest beneficiaries

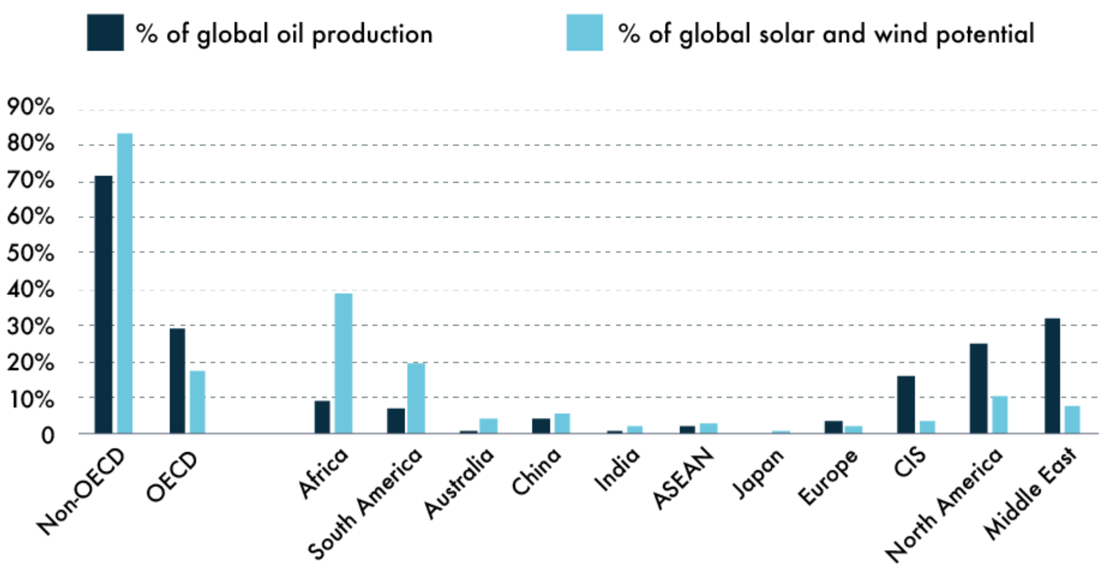
Poorer countries tend to have much larger amounts of renewables available relative to their energy demand. This is not of course surprising, but it is very notable. What it means is that the adoption of renewables is a profoundly just process because it will benefit the poor and the many. We show this in the chart in the first section.

7.6.3 Realignment of geopolitics

The fossil fuel system allocates power and influence to a small number of owners of fossil fuels. In a world powered by renewables, most countries will have their energy resource, and this will lead to a profound realignment of geopolitics.[50] One way to demonstrate this is to contrast the split of oil production with the split of renewable technical potential.

The three regions which have a much greater share of oil reserves than of renewables potential are the CIS, the Middle East and North America. Conversely those with a much greater share of renewables than oil are South America, Africa and Australia. Both India and China also have a greater share of solar and wind technical potential than of oil reserves.

FIGURE 48: SHARE OF OIL PRODUCTION VERSUS SHARE OF RENEWABLE POTENTIAL



Source: Solargis, NREL, Jacobson, BP, Carbon Tracker assumptions

7.6.4 Development of renewable markets

The gap in renewable resources between countries is extreme. On our assumptions, Belgium has technical potential of less than 2 times demand and Germany of less than 3, while Botswana has 5,000 times as much, Uruguay has 700 times and Morocco has 500 times as much.

The total demand from counties with less than 10 times their total potential is only 10 PWh p.a. which is 14% of total energy demand. These requirements are likely to be met in large part by regional resources not by inter-continental shipping.

[50] *Source: A new world: the geopolitics of the energy transformation, IRENA, 2019*

8 Appendix 1: Technical potential in context

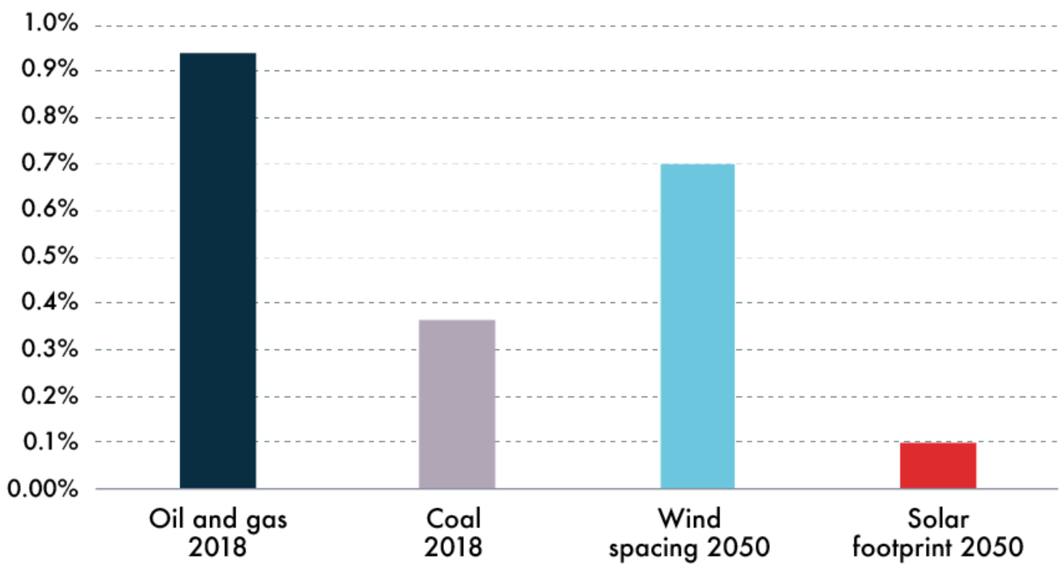
Given the large and rapidly growing share of economic potential within technical potential, we believe it makes most sense to look at the technical potential when we are searching for points of comparison. It is very instructive to look back at past attempts to do this. Analysts do very carefully constructed models of the cost for each country and end up with an answer which is wrong within 6 months because costs fall so rapidly. So it is more reasonable to make the working assumption that most of the technical potential (except for offshore wind, which is a small part of the total in any event) will be economic by the end of the decade, and see what are the implications of that.

8.1 Land requirement compared to fossil fuels

We do not have data on the fossil fuel land area used globally but we do have it for the US. Jacobson calculates that the total area in the US taken up by fossil fuels is 126,000 km2, 1.3% of the country.

The Jacobson solution for renewables for the US[51] would take up 0.1% of the land area for the footprint and a further 0.7% for wind turbine spacing. Between wind turbines can of course be placed solar panels or indeed crops.

FIGURE 49: US LAND REQUIREMENTS FOR ENERGY. FOSSIL FUELS TODAY VERSUS RENEWABLES 2050



Source: Jacobson, The Solutions Project

8.2 Compared to the two great energy transitions

It is possible to compare this energy transition with the two great energy transitions in terms of scale and time. The scale is comparable, but the time is massively compressed.

8.2.1 Scale

According to Iain Morris[52], there have been two great leaps forward in human usage of energy: from hunting to agriculture and from agriculture to fossil fuels. The development of agriculture after

[51] *Source: The Solutions Project, accessed March 2021*

[52] *Source: Foragers, farmers and fossil fuels, Morris, 2015*

around 9,000 BC in the fertile crescent enabled people to increase their energy capture per hectare by 100 times according to Crosby.[53] And then the exploitation of fossil fuels enabled global energy capture to increase 50 fold from 12 EJ in 1800 to 584 EJ in 2019.

As we have seen, the exploitation of renewables could enable us to increase energy use by 100 times. So the available resource is comparable to the two previous transitions. And would advance humanity further along the Kardashev scale.

8.2.2 Time

The agricultural energy transition played out over millennia. The fossil fuel transition took place over centuries. This transition is likely to happen over the course of decades.

8.3 Compared to the rise of other energy sources

From 1800 to 2000 the world saw five energy technologies rise beyond 10 EJ of production: coal; oil; gas; hydro; and nuclear. Since 2010 they have been joined by solar and wind. But there is a difference – solar and wind are unique for their speed, their ubiquity and their cost declines. And the necessity to decarbonise provides a new driver of change.

8.3.1 Speed

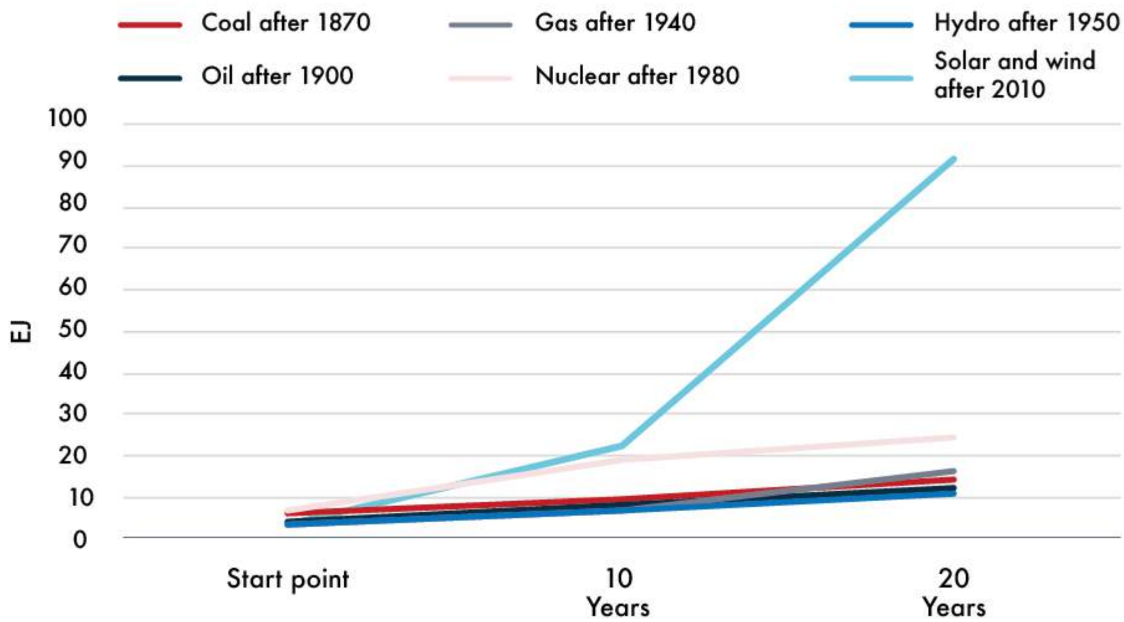
The speed of growth of solar and wind has far exceeded that of any preceding technology at this scale. Solar capacity has been growing at a CAGR of 40% since 2000 and 28% since 2015. Over the last decade solar and wind together have been growing at a CAGR of 21%. In contrast, coal demand growth in the decade after 1870 was 5% a year; oil demand growth in the decade after 1900 was 7% a year; gas demand growth was 8% a year after 1940. And these differences matter a lot. At 21% growth, you double every 3.5 years. At 7% growth you double every 10 years. By which time the first source has enjoyed 3 doublings.

We show below demand for each of the core energy technologies with a start point at the decade closest to 4 EJ or 100 mtoe of demand. In this framing, solar and wind has only ten years' of history, but they have already far outstripped every other technology in the decade since 2010.[54] The only one that came close in its first decade after reaching the size threshold was nuclear, but in that case the growth stopped abruptly as the result of cost and safety issues.

[53] *Source: Children of the sun, Crosby, 2006*

[54] *For the second decade from 2020-2030 we assume annual growth rates of 15% for solar and wind*

FIGURE 50: ENERGY DEMAND EJ FOR KEY TECHNOLOGIES WITH DIFFERENT START POINTS



Source: Smil, BP, Carbon Tracker estimates

8.3.2 Breadth

The world is now linked as never before. So the number of counties able to exploit this new technology is totally different to the last energy revolution after 1750, when England was the global leader for decades.

8.3.3 Necessity

The third big difference to the past is the categorical imperative to prevent global warming. Which means that governments are searching actively for new energy solutions. This was not a feature of previous energy transitions, which were largely led by market forces.

8.3.4 Cost

This time round there are clearly defined cost learning curves for the new technologies. The more you build the cheaper they get.

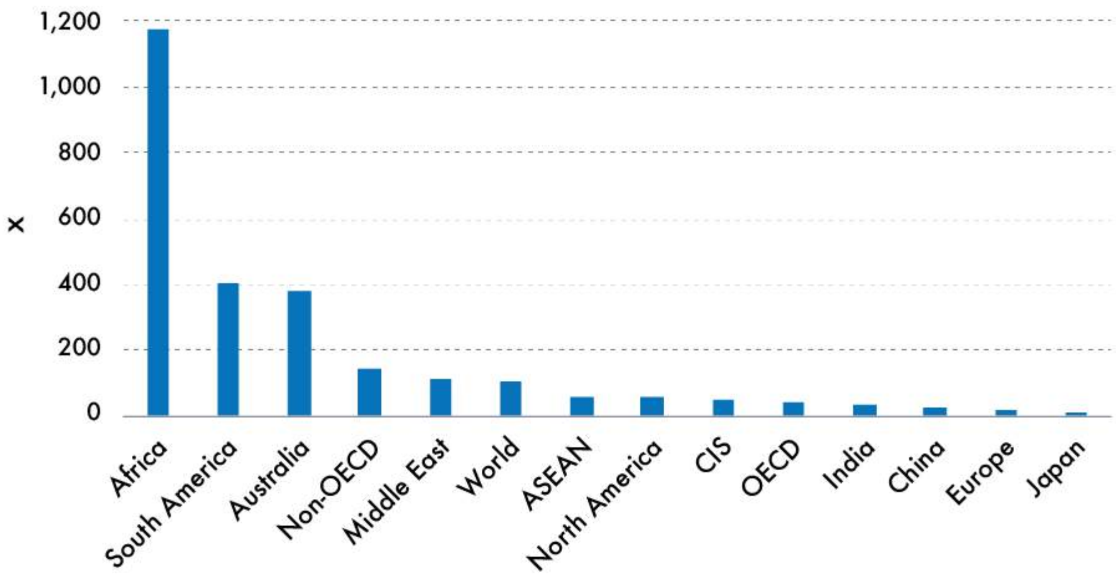
9 Appendix 2: Technical potential by region

Given the huge numbers, every country has the opportunity to exploit this new cheap domestic energy resource. However, some are especially favoured by their renewable endowment, and we set out below an initial framing of this issue for major regions and countries.

9.1.1 Versus energy demand

Africa, Australia and South America stand out as having huge technical potential compared to energy demand. Emerging markets have more renewable potential relative to their demand than developed markets. Reflecting lower energy demand in general but also higher levels of insolation and lower population density. The energy bonanza from renewables is therefore especially attractive for them as they seek to build out new energy systems.

FIGURE 51: SOLAR AND WIND POTENTIAL AS MULTIPLE OF TOTAL ENERGY DEMAND



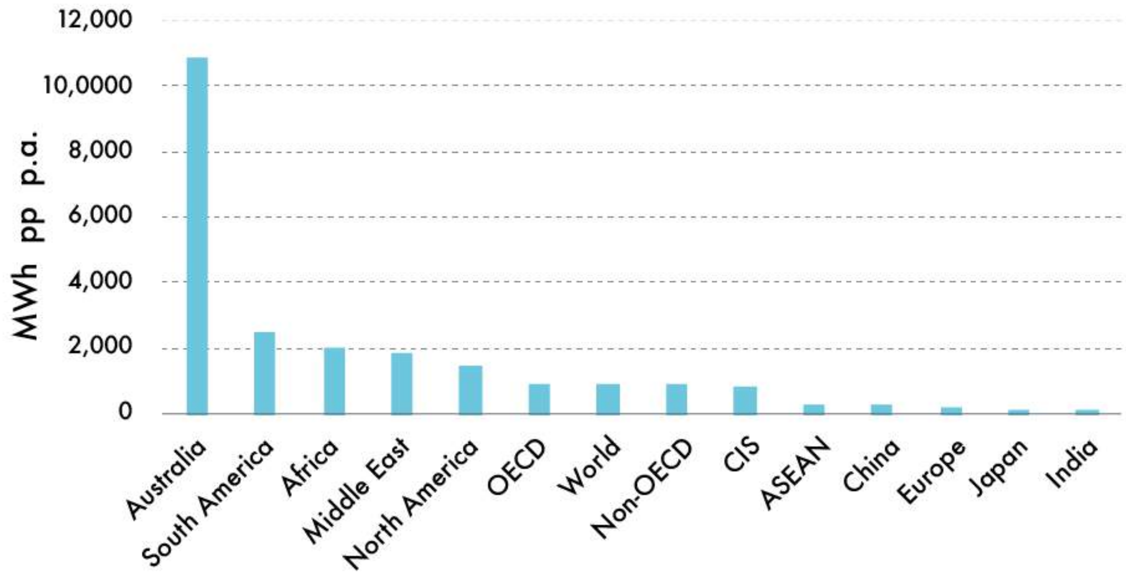
Source: Solargis, NREL, Jacobson, BP, Carbon Tracker assumptions

9.1.2 Per capita

In terms of the renewable energy potential per person, Australia is in a league of its own with over 10,000 MWh per person per annum. With vast renewable potential and a low population, it is thus well positioned to become the battery of the world, even though we recognise that its geographic characteristics may not necessarily lend themselves for exports.

Amongst the regions and countries we highlight below, India is a laggard with 91 MWh per person. Nevertheless this is still much higher than the global average annual energy demand per person today of 9 MWh or even the 32 MWh pp in the US (in electricity terms).

FIGURE 52: SOLAR AND WIND TECHNICAL POTENTIAL PER CAPITA MWH PP P.A.



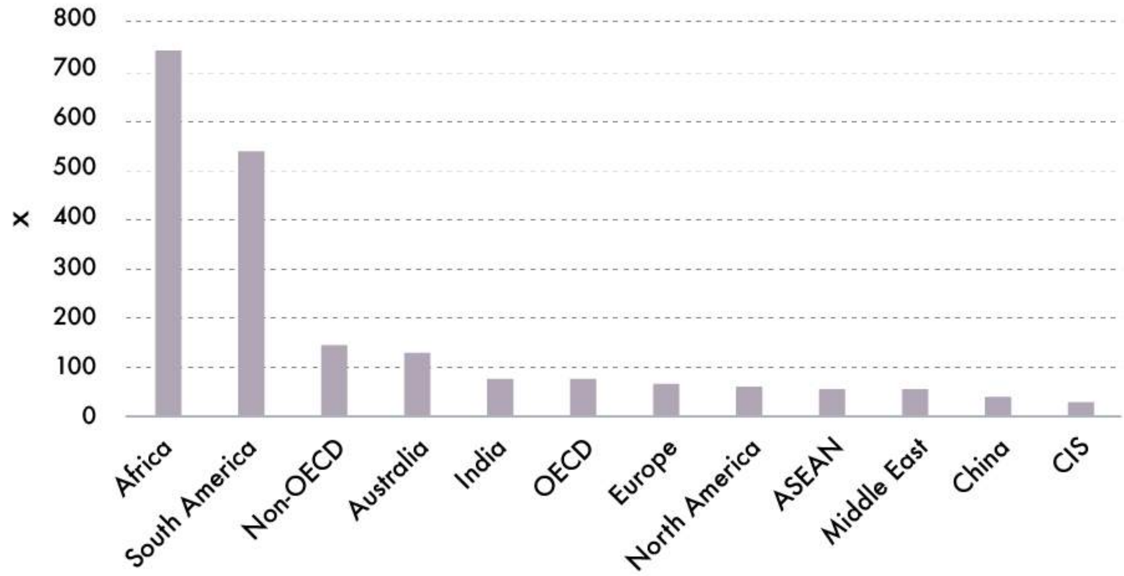
Source: Solargis, NREL, Jacobson, BP, Carbon Tracker assumptions

9.1.3 Versus fossil fuel production

It is interesting to consider renewables as a multiple of fossil fuel production. Because this shows to what degree counties can prosper by exploiting their renewable assets rather than their fossil fuel assets.

South America and Africa stand out as having renewable potential hundreds of times their fossil fuel production. Even the CIS and the Middle East have renewables potential much higher than fossil fuel production.

FIGURE 53: SOLAR AND WIND TECHNICAL POTENTIAL AS MULTIPLE OF FOSSIL FUEL PRODUCTION

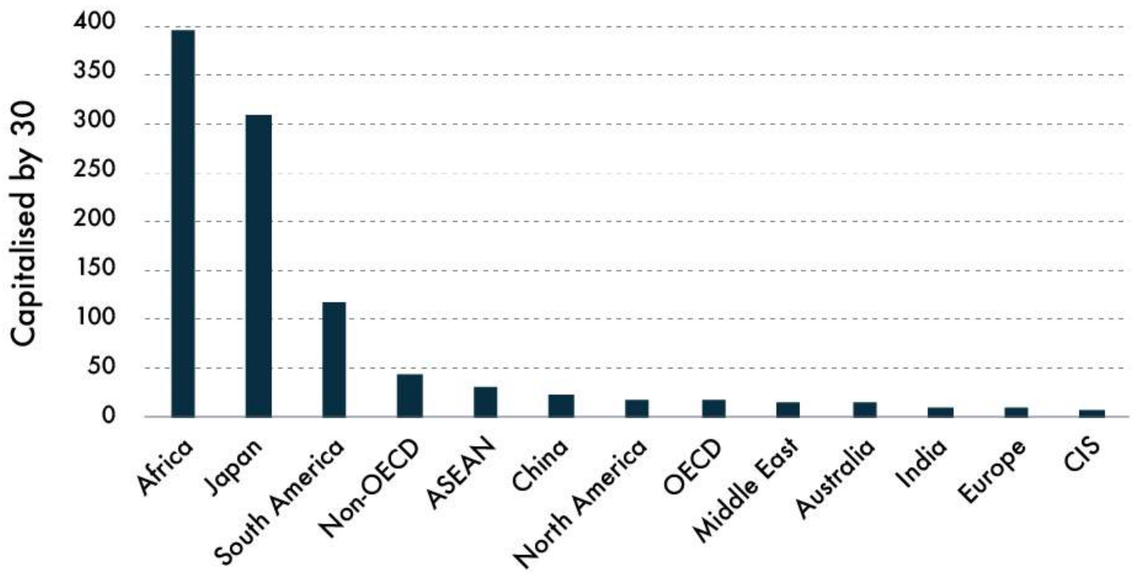


Source: Solargis, NREL, Jacobson, BP, Carbon Tracker assumptions

9.1.4 Versus fossil fuel reserves

And most regions even have higher renewable potential than their entire fossil fuel reserves. Europe, Africa and Japan stand out as having much higher renewable potential than their entire reserves. We show capitalised technical potential of solar and wind versus fossil fuel reserves.

FIGURE 54: SOLAR AND WIND TECHNICAL POTENTIAL AS A MULTIPLE OF FOSSIL FUEL RESERVES.

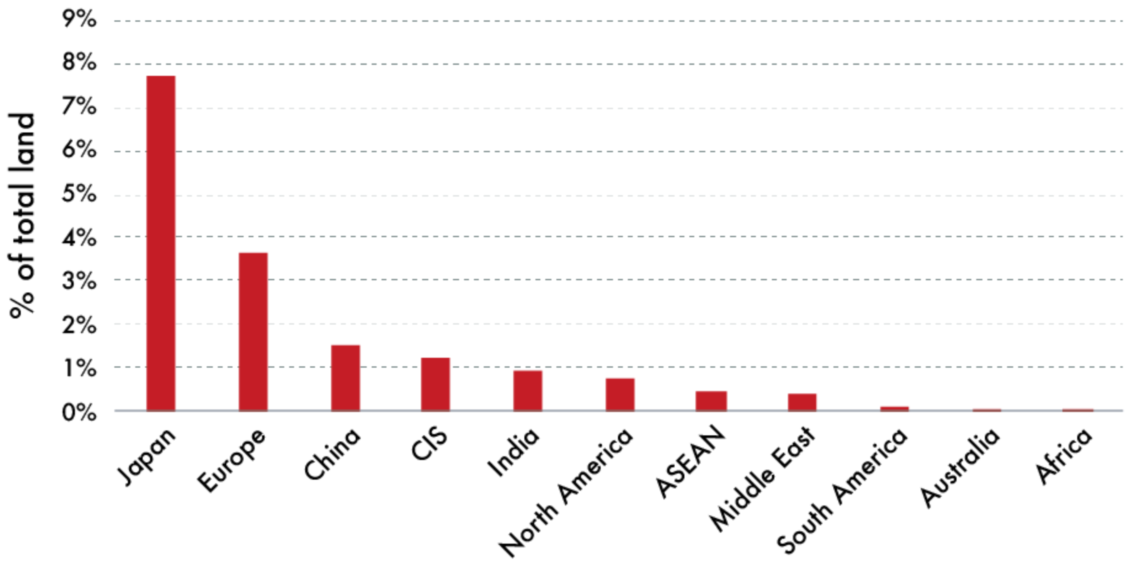


Source: Solargis, NREL, Jacobson, BP, Carbon Tracker assumptions

9.1.5 As a share of the space

It is instructive to look at what share of the space in each country would need to be given over to solar panels in order to provide all the energy. As we have seen, there are many other energy sources that will be used in addition to utility solar, but this chart does at least give a sense of scale.

FIGURE 55: SHARE OF TOTAL LAND NEEDED TO PRODUCE ALL ENERGY FROM SOLAR

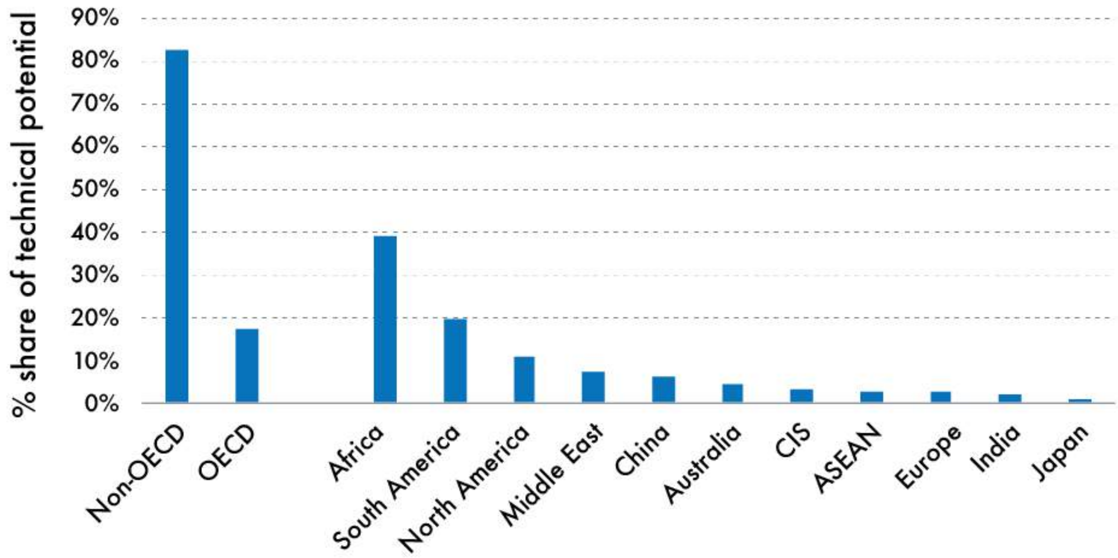


Source: Solargis, NREL, Jacobson, BP, Carbon Tracker assumptions

9.1.6 Share by technical potential

If we consider the size of the technical potential of solar and wind, Africa is the standout leader, with nearly 40% of global technical potential.

FIGURE 56: SHARE OF SOLAR AND WIND TECHNICAL POTENTIAL



Source: Solargis, NREL, Jacobson, BP, Carbon Tracker assumptions

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