# The Energy Pivot

## Issues Arising as we Transition to a Sustainable, Equitable and Resilient Energy System in the Wake of Covid-19

Contributors

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# Foreword

This paper forms one strand of a broader 'Pivot Projects' study (https://www.pivotprojects.org), which includes over 20 interconnected thematic areas, all approached from a systems perspective.

The objective of the broader study is as follows: "By collaborating with existing research programmes and accessing existing sources of data and evidence, to identify policy changes and other measures, in the light of COVID-19 impact, to enable meeting the UN Sustainable Development Goals (SDGs) and the Paris Climate Change Agreement following the relaxation of Covid-19 restrictions, and to provide evidence to support such measures."

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# Executive Summary

Energy is a key input to the wealth and welfare of modern society; without energy nearly all economic activity stops. This Pivot Project Energy Subgroup report looks at three key aspects of energy: constraints to the energy transition, the connection between energy and the UN Sustainable Development Goals, and the interaction between the Covid-19 pandemic and energy supply and demand. Recommendations are given on how some of the issues identified might be addressed.

## 1.0 Constraints to the Energy Transition

As widely recognised, society needs to transition to low-carbon energy sources for reasons of climate change. But this transition looks to be far more difficult than most analysts consider because of likely threats to energy availability, adequacy of finance, and adequacy of minerals supply. These constraints are as follows:

### 1.1 Threats to global energy availability

There are potentially very large resources of energy available on Earth, but the global availability of energy is currently under threat due to the following:

- **Peak conventional oil**: Oil is currently the largest single source of commercial energy. But the global production of *conventional oil* has been at maximum since 2005 (at least for oil prices up to $100/bbl) due to fundamental limits of resource availability. To meet global demand for oil the world has had to turn since 2005 to increased production of non-conventional oils and other liquids. Compared to conventional oil, these fuels generally have significantly higher production costs, require greater amounts of capital expenditure, and exhibit higher $CO_2$ emissions and lower net-energy ratios.

- **The energy transition still has a long way to go**: The low-carbon energies of nuclear, hydro and the ‘new’ renewables currently contribute in total about 16% of global primary energy. And while renewables such as wind and solar have seen rapid deployment and rapidly falling costs, the ‘new’ renewables of wind, solar, biomass and geothermal energy in total contribute only 5% of global primary energy (BP, 2020). An extraordinarily large build-out of energy infrastructure is thus required if the energy transition is to be achieved.

- **Energy-return ratios**: A crucial but little-understood constraining factor to the energy transition is net-energy. For most low-carbon energies, their ratio of energy return on energy invested (EROI) is fairly modest, and for many the energy investment comes mainly before production starts. When combined with the rapidly rising rate of installations of these energies they yield far less net-energy to society during their growth phase than standard calculations indicate. This is likely to significantly restrict the *rate* of energy transition that is achievable.

### 1.2 Adequacy of finance for the energy transition

Next we look at finance. To bring about the energy transition, calculations indicate that perhaps a 50% increase in the funds currently invested in the energy sector will be needed annually over the coming 30 years. Moreover, these funds will need significant redirection, with low-carbon energy production and transmission, increases in efficiency of energy use, and energy saving needing to see annual investments increase by perhaps three times over what is currently invested. And if the energy-return constraints mentioned above are onerous, the finance required will be significantly greater, while returns will be lower.

On the positive side, it seems likely that this level of funds can be made available, from redirection of capital investments by companies, investment houses and pension funds, and by increases in government spend, and in government and institutional debt. However, significant changes will be required in both investment markets and government initiatives if the investment changes of the magnitude required are to occur.

### 1.3 Link between mineral requirements and energy availability

Finally, in this discussion of energy constraints, consideration is needed of energy requirements for the extraction of key resources. The world's population is still growing rapidly, currently adding about 80 million people per year, or an expected 2 billion extra in total by 2050. This growth is likely to place increased energy demands on all energy-using parts of society, but especially on the vital sectors of food and minerals supply. These are large consumers of energy, and society's success in achieving price reductions in both sectors over many decades has in no small measure been the result of replacing low-energy production with production that is more energy intensive.

For minerals in particular, much of the increased extraction of these has been possible only by using ever more energy to process lower concentration ores. For some minerals, absolute limits to their resource base are expected to pose significant constraints to future supply, while for a range of other minerals the constraints on energy listed above may also pose supply constraints. Minerals from both these classes will be essential for the extensive renewables build-out referred to above

Overall, this report indicates that there are likely to be considerable under-recognised constraints to the anticipated energy transition. Few groups are currently modelling these, but initial results from those that do suggest that the transition to a low-carbon world is likely to be difficult, and very possibly accompanied by less energy being available per capita.

## 2.0 Energy and the UN SDGs

Two of the UN's Sustainable Development goals relate directly to energy use, and a further nine are significantly impacted by access to energy. Fortunately, many of the 'newer' energies (biomass, wind, solar, deep geothermal) are widely distributed, and point to the potential for a more equitable and sustainable society if widely deployed.

In particular, energy availability can lead directly to gains in productivity, and hence to increases in economic wealth. Moreover, increases in wealth, transport and lighting all contribute to improved education, and hence the potential to lower pressures on population growth, where the latter is a driver for many of the problems the sustainability development goals seek to address, including food and water scarcity and access to health services.

## 3.0 Energy and Covid-19

The Covid-19 pandemic has caused a significant short-term reduction in global energy use, and the reduced levels of economic activity have limited the funds available for energy investments. Many governments and organisations have called for the financial stimulus packages planned for mitigating the impacts of the pandemic to include significant contributions to a 'greener' world.

The pandemic also looks like introducing some longer-term effects, including increased use of remote working and conferencing, and reduced flights, which may in turn have impacts on global energy demand. However, it is too early to know how significant these impacts will be.

## 4.0 Recommendations

### Oil Supply

Governments, industry, analysts and the public need to be aware of the changes which resulted since 2005 from the world reaching its resource-limited maximum (at least for oil prices up to \$100/bbl) in the production of *conventional* oil. This changed the composition of global oil supply by oil type, increased the average production cost and $CO_2$ emissions, and lowered the average EROI ratio of oil production, and introduced new risks for both oil exporters and importers. In addition, a significant number of major oil exporting countries are judged to be now past their resource-limited peak in *all-oil* production, and others are expected to pass their peak soon.

### Oil Data

In terms of oil data, compilers of public-domain proved oil reserves data by country, including the IEA, EIA, OPEC, BP and the *Oil and Gas Journal* and *World Oil*, need to add strong caveats to these data. Although accepted at face value by many analysts, these reserves data are unaudited, often political, and are often wildly different from a country's proved-plus-probable (i.e., 'most likely') oil reserves as assessed by oil industry sources.

### Gas Supply

The total potential resources of gas (conventional plus non-conventional) are very large. But governments, industry, analysts and the public need to be aware of the approaching resource-limited maximum in the global production of *conventional* gas. As with conventional oil, this is likely to change the composition of global gas supply by type, alter its price structure, and introduce new risks for gas exporters and importers.

### Emissions from Gas Supply

Gas is seen as a transition fuel to achieving net-zero-carbon energy. But this transition period cannot be long, as emissions of $CO_2$ from the use of gas, and of fugitive methane during its extraction and storage, threaten achievement of the Paris Climate Change Agreement.

In particular, methane is a significantly more potent greenhouse gas over the short term than $CO_2$, and although new agreements have been made by a number of major gas producers to limit fugitive emissions, more needs to be done.

### Energy Return on Energy Investment (EROI)

This report strongly recommends that attention be paid to the constraints and implications set by the EROI ratios of energy sources on the *rate* that the energy transition can be achieved.

This topic is not widely enough appreciated, particularly by economists, and is amplified in the main text of this report (and see also the recommendations on modelling, below). The limited research that has been carried out on this to-date suggests that such EROI constraints may well be onerous, and the implications far-reaching.

We are concerned in particular that failure to take account of the generally falling trend in EROIs of energy sources comes with a high risk that economic models will underestimate the role of energy in terms of economic activity. This in turn is likely to lead to unexpected economic consequences that negatively impact the global economy.

We recommend inclusion of EROI analysis in all energy forecasting in order to better guide policy and investment options during the energy transition.

## Minerals Supply

We recognise that significant attention has been paid in recent years to scarcity risks of a variety of 'critical' minerals. But these studies have generally just considered the potential size of mineral resources. We recommend that the additional constraints to the supply of critical minerals likely to result from the constraints on global energy supply indicated above need to be factored into such assessments.

## Magnitude of the Energy Build-Out to Achieve the Energy Transition

Society needs to be aware of the magnitude of the task required to achieve the energy transition.

It is one thing to double the installations of a new source of energy if this is from a low base, as then the requirements in absolute terms on the supply of minerals, skilled manpower, finance and energy itself are relatively low. It is another thing to require a doubling (let alone several doublings) from a higher installed base, as then the absolute requirements on these resources become very large.

As shown above, the energy infrastructure build-out needed to achieve the energy transition is large, particularly if focussed mainly on the 'new renewables', as the latter currently make up only 5% of global primary energy. In particular, analysts need to be cautious about reliance on *rated capacity* of newly installed systems, and on low-carbon energy having achieved a certain percentage of a region's *power* requirement. The energy transition requires meeting global *annual energy* needs, not just capacity; and for this to be for all-energy, not just power.

## Modelling

In light of the information given above, we recommend that the richer nations urgently commission and fund rigorous and detailed modelling of the energy transition. This needs to include the following:

- oil and gas supply constraints
- EROIs of non-conventional fossil fuels and of the new energy sources (including factoring in up-front energy investment and rates of anticipated growth by energy type)
- the economic implications of falling EROIs
- the increased demand for food, housing, heating and cooling, and transport due to population growth
- the increased energy requirements due to falling mineral concentrations
- the impacts of energy availability on society
- the adequacy of finance.

In addition, we recommend specifically that EROI analysis be included in the following two energy models:

- UK BEIS (DECC): *2050 Pathways* on-line software
- IEA: *World Energy* Outlook.

### International Agreements to Handle Resource Disputes

In the light of the high possibility of competition and global tensions over increasingly scarce energy and other resources including minerals and food, we strongly recommend a proactive effort to develop internationally-binding agreements for equitably managing global supply constraints.

### Support for UN SDGs

We judge that the international community in general seeks a fairer world and supports the UN SDGs. But concrete plans to achieve these are largely embryonic. These will need concerted action between countries and significant resourcing, and also to address the existing power structures that constrain such global advancement.

### Energy Post Covid-19

Post Covid-19 there is a strong desire among many to 'build back better'. Given the importance of energy in underpinning nearly all of societal activity, we recommend that the 'build back better' philosophy include all energy-related matters.

## Overall Recommendation:

### Support for Climate Change Action - Mitigation & Adaptation

Like many other observers, we suggest that Humankind is at an existential crossroads. Radical, concerted and focussed action to mitigate climate change is urgently required. Nations need to be on a 'war footing' to address the depth and breadth of the threat humankind faces as a result of the warming climate. Not only is human civilisation at threat, but so too survival of many other lifeforms.

The urgency cannot be underestimated. The energy-related choices we have made in the past are in large part to blame for the crisis. Many people are now questioning whether the changes required are possible within the current economic paradigm. We are not able to answer this, and hence recommend that **a comprehensive study be commissioned and funded that examines a range of alternative economic models that carry fewer eco-systemic risks.** Such a study would need also to set out how an international consensus for such a transition might be achieved. Within the study, the links between the actions recommended and energy supply and constraints, as well as investment and political economy constraints, need to be understood.

It is clear that a concerted global effort is required, needing the support of all.

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# 1.0 Introduction

## 1.1 Background and objectives

The aim of this report is to examine how global energy supply and demand relate to the three foci of the Pivot Projects: Covid-19, the Paris Agreement and the United Nations Sustainable Development Goals (SDGs).

In terms of Covid-19, it is widely recognised that this has put into much sharper relief a wide range of already-existing problems and opportunities. From an energy point of view these include the rapid transition to a low-carbon (hence low-fossil-fuel) world, and the opportunities that renewable energies offer for a more equitably distributed energy supply. Moreover, Covid-19 has itself hastened changes in energy use, including much increased use of work-from-home and on-line meetings, and (so far at least) much reduced miles flown and driven. But perhaps most importantly, the pandemic has shown how large-scale changes can be effected quickly in the face of an emergency, and how much of the existing 'rule-book' on priorities and spending can be re-written if the need is deemed sufficient and the political will can be mustered.

In terms of actions necessary to meet the Paris climate agreement, these are now the subject of a very wide range of detailed studies and forecasts; of policies on energy supply and use from governments, companies and other organisations; and of commitments again by governments, companies and other organisations to specific greenhouse gas targets. This report does not seek to review these studies, policies and commitments, but instead to highlight what we see as a number of critical issues too often omitted from these. It is a goal of this report to get the likely impacts and constraints set by these critical issues to be more widely understood, considered and addressed.

In terms of meeting UN SDGs, the impacts of energy systems are most directly relevant to SDG 7 (accessibility to clean, affordable energy) and SDG 13 (climate action). However, energy considerations also underpin SDG 8 (economic growth), and the attainment of several other goals indirectly (SDGs 1, 2, 3, 6, 9, 11). The extraction, harnessing and use of energy also impacts the natural environment (SDGs 14, 15). However, it is important to recognise certain inherent tensions among the SDGs (e.g. economic growth and improving access to basic services versus ecological degradation and resource constraints), and hence to find synergistic solutions that minimise the trade-offs.

## 1.2 Research questions

Specifically, this paper investigates three research questions:

1. What are the key features of the current global energy system that need to be properly understood in order to appreciate the complexities of the challenge presented by the transition to a carbon neutral global society, and to a society one where everyone's basic energy and other fundamental needs as enshrined in the UN SDGs are met?
2. What are the possible impacts of the Covid-19 pandemic on global energy systems in the short, medium and long term, in terms of both supply and demand patterns, and taking into account economic, technological, social, behavioural and

environmental factors? How might these impacts spill over into other critical systems connected to the energy system?

3. From a policy perspective, how can these risks be mitigated while accelerating the transition from fossil fuels to renewable and sustainable sources of energy, in line with climate mitigation and adaptation?

## 1.3 Key contentions

The key contentions of this report are as follows:

- Energy systems need to be understood within the context of their interlinkages with other human and natural systems, including natural resources and sinks, economic and financial systems, geopolitics, and societal behaviour in general.
- Available net-energy and Energy Return on Investment (EROI) are key variables determining the long-term viability of complex adaptive systems, including human civilisations. In particular, net-energy is a 'master resource' which underpins all economic and social activities. Failure to take account of the energy required to produce energy will likely lead to unpleasant energy supply surprises because - increasingly and in a non-linear fashion - society is forecast to use ever more low-EROI energy to meet its increasing demand for energy.
- Our global civilisation is still overwhelmingly dependent on fossil fuels, and oil especially because of its key role in the transport that underpins nearly all economic activity and trade. Resource limits to 'all-oil' supplies have already been experienced by a number of significant oil-producing countries, and the global supply of conventional oil has been on plateau since 2005. Non-conventional oil and gas supplies generally have higher extraction costs in both economic and energy terms, and are also generally more polluting.
- The roll-out of new renewable energy (RE) infrastructure using currently available technologies is critically dependent on the use of fossil fuels and key minerals, for example in the manufacture, transport and construction of solar PV panels, concentrated solar power, wind farms, hydropower and geothermal plants. This implies not only that a substantial portion of the remaining "carbon budget" needs to be dedicated to constructing more sustainable energy infrastructure, but also that energy research and development will be needed to develop RE technologies that can be built with much-reduced or zero fossil fuel inputs.
- Many, perhaps most, governments and mainstream economists do not appreciate the above points, and therefore do not give energy policies sufficient weight in national strategies and policies.
- While Covid-19 presents an immediate systemic threat to business-as-usual human systems, it is generally recognised that climate change presents a greater long-term threat to human civilisation.
- There is a significant risk that short- to medium-term disruptions to energy markets wrought by the pandemic could have major socio-economic impacts (not least via financial markets). If this is the case, this may well divert attention away from energy and climate policies in the short run unless the interconnections are better appreciated and addressed by policy-makers.
- The pandemic is occurring at a time of huge vulnerabilities and fragilities in human and ecological systems, raising the likelihood of large-scale disruptions and long-term impacts.

- In the absence of mitigating policies, feedback effects from the economic and financial systems (e.g. demand destruction leading to a collapse in investment) could lead to serious energy system disruptions in the medium term.
- On a more positive note, the pandemic has opened up potential opportunities for more radical policy changes than have been seen in the past, including policies aimed at accelerating the transition from fossil fuels to sustainable energy sources, and to more resilient and accessible energy systems.
- This energy transition will require a massive mobilisation of financial resources, which involves issues of societal priorities and distributive justice on global and national scales.

Sections 2, 3 and 4 of this report follow the sequence of the research questions set out above, and are followed by the report's Conclusions and Recommendations. Annexes provide further detail on the topics addressed.

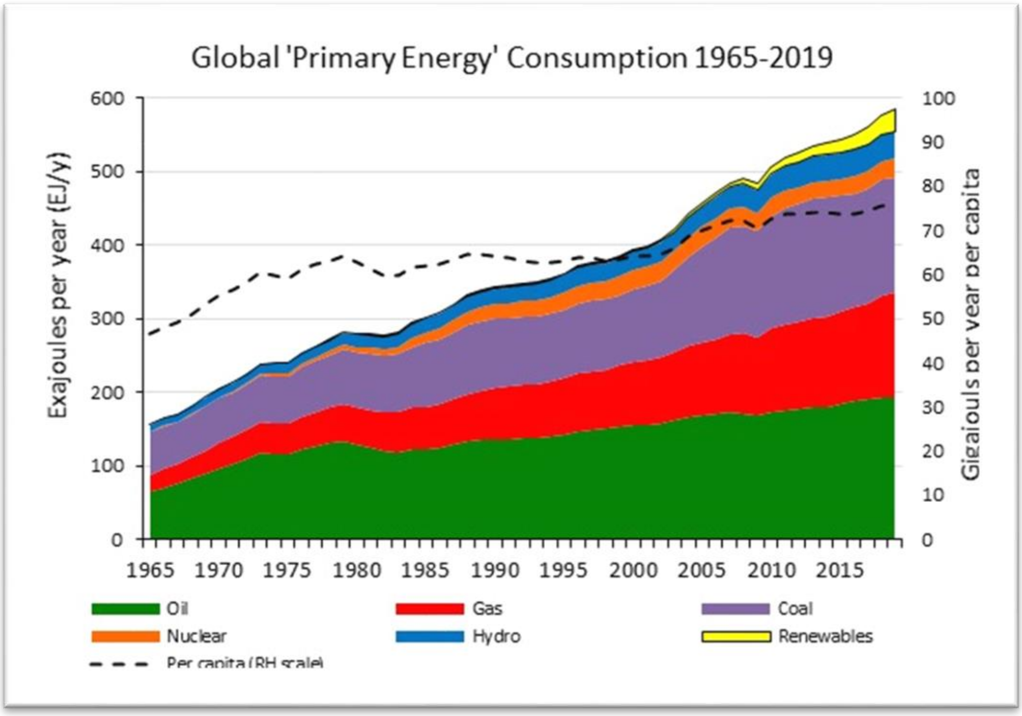
# 2.0 The Energy System

Energy needs to be seen within the context of socioecological systems, a theoretical approach which studies the interactions between human societies and nature, see Annex 1. A key concept of this approach is that both energy and material flows sustain the biophysical structures of society, and that energy use in particular rests on the laws of thermodynamics and is the 'master resource' in its role of enabling use of all the other material resources required to support human needs and desires.

## 2.1 Energy supply

Despite significant advances in the deployment of new sources of energy, the world's continuing overwhelming reliance on fossil fuels is made clear by Figure 1, which shows global total primary energy consumption by energy source.

**Figure 1. Annual Global Consumption of 'Primary Energy', 1965 – 2019**



*Source: BP Statistical Review of World Energy, 2020 edition*

Notes: - For definition of 'primary energy' see Annex 2. 'Renewables' refers to commercially-traded fuels from biomass, and electricity from wind, solar, biomass, tidal, wave and geothermal.

As depicted, in 2019 fossil fuels still comprised about 85% of world commercial primary energy, with oil providing the largest share (33%), followed by coal (27%) and natural gas (24%). Hydro contributed a bit over 6% of total energy, nuclear 4%, while the 'new renewables' of solar, wind, biomass, tidal, wave and geothermal in total contributed just 5% (BP 2020).

As the figure also shows, primary energy per person has been roughly constant (at about 75 GJ/y per capita) since 2010, which partly explains why many economies have struggled to grow in per capita GDP terms in the past decade; and indeed this per capita level is not so very much higher than the 65 GJ per capita that was reached in 1980.

Note that the above data refer to energy measured in terms of energy equivalent, as not all energy carriers are equally useful to society. For example, substantial fractions of coal and gas are transformed into electricity, which involves considerable energy losses compared to the electricity directly generated from solar, wind and hydro resources. Annex 2 examines the alternative ways of looking at energy data, including 'direct energy' use, 'primary energy' use, energy per capita, constraints on the rate of energy change, carbon emissions, and efficiencies in the conversion of energy, and in society's needs for energy.

The main sources of energy all suffer from serious drawbacks, some of which are elaborated in later sections. Drawbacks include:

- Oil, gas, coal: Finite resources subject to depletion and reductions in quality, or energy content; production peaks and declines; carbon emissions; other forms of pollution.
- Current nuclear: Finite, depleting uranium resources (unless breeder; or to a lesser extent if thorium powered); ageing power plants; risk of accidents/terrorism; significant cost over-runs for new plant; decommissioning costs; the unsolved problem of nuclear waste disposal.
- Renewables: Intermittency of resource (solar, wind, wave and tidal) needing energy storage and grid balancing; and typically have low EROIs. (In particular, liquid biofuels can have very low EROIs, and often compete with food production and water resources; solid biofuels can have limited sustainable yield.)

The following subsections explore how a range of key aspects of the energy system – fossil fuel resource constraints, energy return, dependence on minerals, and energy costs – will impose constraints on the practicality and speed at which climate change and UN Sustainable Development goals can be met.

## 2.2 Future global oil and gas supplies

As non-renewable finite fuels, oil, gas and coal are subject to depletion. For *conventional* oil and gas the long-run production profiles of these resources in general follow a well-established curve, rising to a peak when about half the totally recoverable resource of the fuel has been produced, with production then declining towards zero (Hubbert 1949, 1956; Campbell and Laherrère, 1998; Bentley, 2016). Over 70 countries out of the total of 125 or so oil-producing counties in the world now appear to be past their resource-limited peak in the production of 'all-oil', at least for oil prices up to well in excess of $100/bbl (Globalshift Ltd., 2020). In terms of global supply, it is still not widely recognised that global production of conventional oil has been at its resource-limited plateau since 2005, again at least for oil prices up to well above $100/bbl (see Annex 3 for details).

The marginal barrels of oil liquids since 2005 have therefore been of non-conventional oils, NGLs and 'other liquids'. This group of fuels are generally more expensive to produce than conventional oil, and the transition to these becoming the marginal barrels was the major cause of the sharp rise in the price of oil from 2004. This price rise was a significant factor in the 2008/9 global recession, which in turn added significantly to global debt. Furthermore, these marginal barrels generally have a lower net-energy ratio (EROI) than conventional oil; see Campbell (2015), Murphy (2014) and Solé et al. (2018), and also the discussion of EROI in Section 2.3. Likewise, these marginal barrels since 2005 generally have higher emissions of $CO_2e$ per unit of energy than conventional oil; see Nduagu and Gates (2015), McGlade and Ekins (2015), and Masnadi et al. (2018). The high price of oil, combined with the high production cost of many of the initial marginal barrels such as tar sands and coal-to-liquids, and with the introduction of significant technical innovations, led to the rapid increase in shale ('light-tight') oil production in the U.S. For further discussion of the consequences of the world reaching its resource-limited production of conventional oil, see Bentley et al. (2020).

The future production of global all-liquids is an open question. Well before Covid-19 many recognised forecasting organisations pointed to global *demand* for oil peaking, but there was disagreement over the date of this peak; from just a few years away to 2030 or beyond. However, most of these forecasts were not aware of the oil supply constraints outlined above. The expectation of future all-liquids production depends on how fast global demand for oil returns post Covid-19. The IEA's Executive Director has recently warned that the world could quickly return to an all-liquids demand close to last year's 100 million barrels per day and thereafter continue its rising trend (Blas, 2020). In that case, the global resource-limited peak in production of conventional oil will likely soon bite, the oil price will rise to high levels, and any post Covid-19 return to economic normality will be stalled. On the other hand, global economic weakness post Covid-19, or successful efforts to wean the world off oil for climate change reasons, may cause global demand for oil to fall. If this falls faster than the expected intrinsic supply-limited decline, then the price of oil will stay relatively low. Until the global oil demand trend post Covid-19 becomes clearer, society should be prepared for both outcomes.

For gas, as with oil, and for the same underlying reason that the global discovery of conventional gas declined many years ago, the world will soon face its resource-limited production peak of conventional gas. As with oil, there are large resources of non-conventional gas potentially available. These include shale gas, gas from coal (produced at surface and in-situ), in deep brine reservoirs, and also potentially in very large quantities in permafrost and methane hydrates. But many of these types of gas face production problems (for example, for shale gas those of public acceptance, micro earthquakes and fugitive methane emissions) and it is not obvious that global gas production can rise rapidly – if at all – once conventional gas production has peaked; see e.g., Campbell (2013).

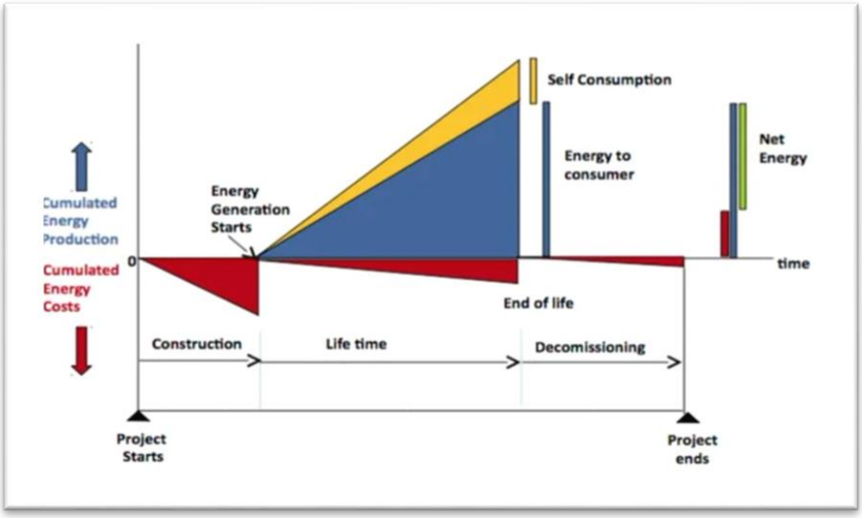
## 2.3 Energy return on energy invested (EROI) and available net-energy

For an energy source its EROI is its energy return on energy invested. For example, for a fossil fuel this is the ratio of the amount of energy produced when the fossil fuel is burned to the amount of energy needed to find, extract, refine and transport that fuel to its point of use. The concept has been recognised for many years, but it is still far from being central to the thinking of most energy analysts, and as a result many current forecasts of the global 'energy transition' are significantly misleading. As **Hall notes, a lower EROI means that society must divert more of its total economic activity to get the energy needed to run the rest of the economy., and**

**where EROI integrates the counteracting effects of resource depletion vs. technological improvements (Hall, 2017).**

EROI has two aspects, 'static' EROI and 'dynamic' EROI (see Annex 4 for further details). The normal EROI statistic used is the 'static EROI', when no consideration is given to changes over time in the use of the energy source. Such static EROI ratios have been as high as perhaps 100 for US coal a few decades back (Hall, 2016), and says that the energy yielded when the coal was burnt was 100 times that required to extract and transport the coal. By contrast, an EROI can be as low as 3 (or perhaps even below 1 in particular circumstances) for bio-ethanol produced from maize in the U.S., where here the energy from burning the ethanol (usually in a mix with gasoline) is only three times that required for the farming of the grain, its water and fertilizer requirements, transport to the ethanol-producing plant, energy used in the plant, and transport to point of use (Hall, 2016). The principle of 'static' EROI are illustrated in Figure 2.

**Figure 2: Illustration of the principle of 'static' EROI**

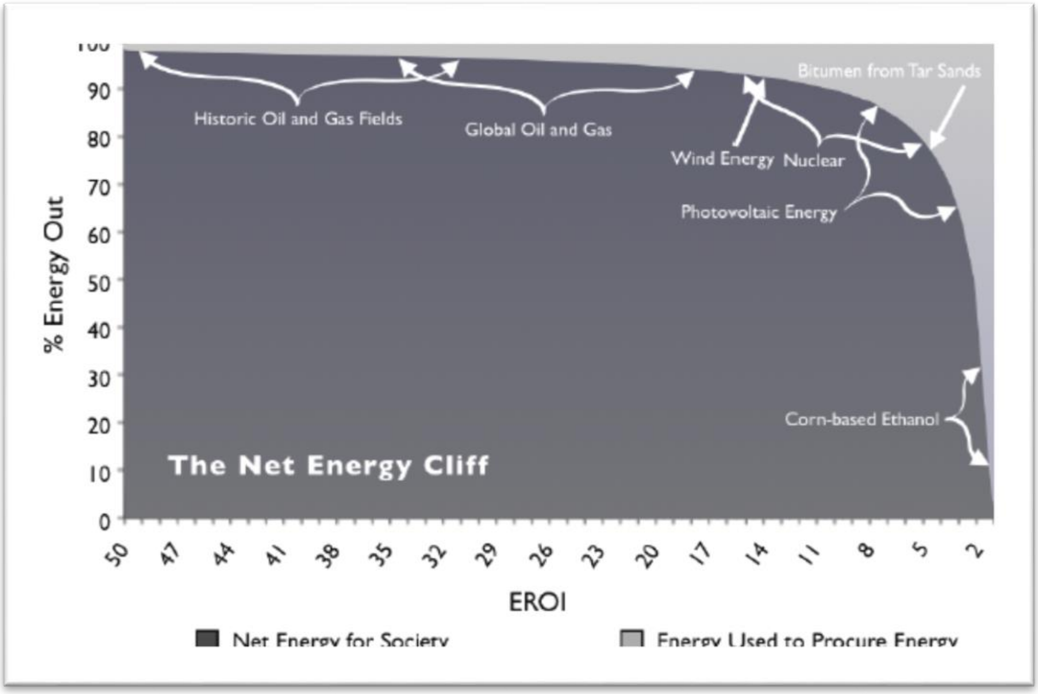


*Source: http://euanmearns.com/eroei-for-beginners/; based on an original plot by Prieto and Hall.*

Note: Indicative, not to scale.

The static EROI of oil, gas and coal has been declining globally for decades as a consequence of the fact that resources that are easier to find and extract are generally utilised earlier. The EROI of nonconventional fossil fuels is usually considerably less than that of conventional sources (Lambert et al., 2013). Furthermore, the EROI of most renewables (except hydropower) are generally considerably lower than that of fossil fuels – at least the historically high ratios recorded earlier last century. It has been suggested that there may be a minimum average EROI, perhaps around 10:1, that is required for industrial societies to function (Hall et al., 2009). If this is the case then certain energy sources, such as liquid biofuels, need to be augmented by energy sources with better energy returns. Because the world is almost certainly in a transition from higher EROI fuels to lower EROI ones, and because modern society is so dependent on energy use, then the transition can be expected to be problematic. Figure 3 illustrates the non-linear relationship between EROI and net-energy for society.

**Figure 3: The "Net-Energy Cliff" showing EROI vs Net-energy delivered**



*Source: Lambert et al. (2013)*

As the figure shows, historically oil and gas have had high EROI values, and that the more recently extracted energy sources such as tar sands, solar PV and corn-based ethanol have considerably lower EROI values. Note that **large shifts in high EROI values (e.g. from 100 to 50:1) denote only modest increases in the energy required to produce energy, and hence have only marginal impacts on the net-energy available to society, while small variations in low EROI values (e.g. from 5 to 2.5:1) denote a large shift in the energy required to produce energy, and hence far greater impacts on society.**

The above 'static' EROI problem is compounded when use of an energy source is increasing rapidly (as with a number of the renewable energies) and here examination is needed of the 'dynamic' EROI (sometimes termed power returned on power invested, PROI). This is because for many energy sources a significant part of the energy needed to produce energy is required before any energy has been produced, for example the large amount of energy required to construct a nuclear plant. This aspect is even more pronounced for some of the renewables, such as wind or solar, where nearly all the input energy required over the lifetime of the energy source is required before any energy is produced. A specific exemplar is photovoltaic (PV) systems where the rapid global growth of such systems, combined with their up-front energy requirement and moderate EROI, has meant that to-date PV systems have yielded surprisingly little net energy in total to society (see Annex 4).

As far as we know there are very few models of the global energy transition that include the impact of PROI ratios. One of these is that of King and van den Bergh (2018), who report that: "*Correcting from gross to net energy, we show that a low-carbon transition would probably lead to a 24–31% decline in net energy per capita by 2050, which implies a strong reversal of the recent rising trends of 0.5% per annum*." A more recent study is that by Capellán Pèrez et al. (2020). This is based on the MEDEAS integrated assessment model, and its findings are even more dramatic, concluding that: "*Our results suggest that the continuation of current trends will drive significant biophysical scarcities and impacts which will most likely derive in regionalisation (priority to security concerns and trade barriers), conflict, and ultimately, a severe global crisis which may lead to the collapse of our modern civilization. Despite depicting a much more worrying future than conventional projections of current trends, we however believe it is a more realistic counterfactual scenario that will allow the design of improved alternative sustainable pathways in future work.*"

Some commentators consider net-energy to be the 'elephant in the room',[1] and one of the consequences of PROI is that the world may well need to live with less per capita energy in the coming years. For a fuller discussion of EROI vs. PROI see Carbajales-Dale (2019), and also the discussion and references in Jefferson (2019).

## 2.4 Energy and mineral dependency

Now we turn to the linkage between energy and mineral dependency. Modern renewable energies (e.g. solar PV, concentrated solar power, wind turbines, hydropower, and geothermal plants) and also energy storage (e.g. lithium-ion batteries) depend on a range of finite minerals such as rare earth minerals, cobalt and lithium. Furthermore, the construction of most RE infrastructure requires substantial amounts of steel and concrete, which in turn require other bulk mineral resources (iron ore, building sand and stone) and are produced using fossil fuels (e.g. coking coal for steel and clinker production).

Mining is an energy intensive process and the mining sector consumes some 10% of the world's primary energy supply (Bardi, 2014: 114). Energy is required at all stages of the mining value chain, including extraction, transportation of ores, crushing and processing of ores, and smelting and refining, and disposal of waste rock. Mining would not be possible at its current scale without fossil fuels. In particular, oil is used intensively in mining operations to power digging machinery and vehicles, while coal (and coal-fired electricity) is used for processing mineral ores into usable concentrated mineral products.

The mineral content of ores is generally declining over time, as the mining industry typically extracts high-yielding, more accessible ores earlier, as these are more profitable. This means that over time, increasing amounts of energy are required to deliver the same amount of usable minerals, i.e. the energy intensity of mining is increasing over time. (Technological improvements offsets this to some extent, but not completely.) Therefore, the mineral resources remaining tend to be more costly to extract in both energy and economic terms and are often located in riskier or less accessible geographies (e.g. countries in central Africa where infrastructure is limited). These resource and energy constraints point to the need for much greater recycling of metals and minerals to reduce the reliance on primary extraction. While there is significant scope for such recycling, e.g. for metals such as copper, the recycling process itself requires energy.

The dependence of RE infrastructure on minerals, and currently ultimately on fossil fuels, has two critical implications. First, a certain fraction of remaining fossil fuel resources (i.e., a portion of the remaining carbon budget) needs to be dedicated to the build-out of RE infrastructure over the

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[1] https:/thedig.nz/transitional-ecology/wishes-vs-reality-the-role-of-net-energy-analysis-in-our-future/

coming decades. Second, current RE technologies are not truly sustainable, in that they are currently constructed and operationalised largely with fossil fuels.

## 2.5 Energy costs

While the market prices of coal and gas can fluctuate significantly, over recent decades there has been no consistent real-terms rise in these prices (BP, 2020), indicating a balance between depletion of higher-grade resources vs. technological improvement and economies of scale in extraction. Oil presents a different case, as its production cost has risen significantly in a step-wise manner over the past century, reflecting the need over this period to increasingly access oil that is difficult to produce, see Section A3.5 of Annex 3.

By contrast, the trend in costs of many renewable energies has been strongly downward in the past 10-15 years, driven by a combination of improving technologies, economies of scale in production, increasingly competitive supply chains, and cumulating experience among developers (IRENA, 2020). According to the International Renewable Energy Agency, costs for electricity produced by utility-scale solar photovoltaics (PV) declined by 82% in the past decade and "*new solar and wind projects are undercutting the cheapest and least sustainable of existing coal-fired power plants*." (IRENA, 2020).

Nevertheless, fossil fuels continue to attract subsidies (for both production and consumption), and have massive external costs to society (e.g. health) and the environment (pollution). To level the financial playing field and address the externalities, these subsidies should be replaced with instruments such as carbon taxes (see Section 6, Recommendations). Furthermore, it is not clear whether the current economic system adequately prices in the growing scarcity of mineral resources and the reliance of RE technologies on a fossil fuel base. Effectively, coal (mainly in China) and oil are subsidising the construction of solar panels and wind turbines. This implies a need for government support for energy research and development to reduce the fossil fuel content of these technologies.

## 2.6 Energy consumption and dependencies

As mentioned earlier, virtually no economic activity takes place without the use and transformation of energy. Real economies need energy services to function, and this applies across all sectors, including the primary sector (agriculture, fishing, mining), secondary (manufacturing) and tertiary sectors (wholesale and retail trade, hospitality, finance and government services). In terms of energy dependencies, oil products play a pivotal role in today's socioecological systems, as does electricity – whatever the underlying primary energy source. Some energy sources are consumed as they are (e.g. coking coal burned in industrial furnaces), whereas some are converted into other energy carriers (e.g. natural gas burned to generate electricity). According to the IEA (2020a), refined oil products (petrol, diesel, jet fuel, etc.) satisfy 41% of final energy consumption, natural gas accounts for 15.5%, coal for 10.5%, electricity for 19.4%, and biofuels and waste for 10.7%, with heat accounting for the remaining 3%. This underscores just how essential oil is for the global economy. In terms of shares of world Total Final Energy Consumption (TFEC), industry and transport account for 29% each, residential for 21%, commercial and public services for 8%, agriculture, forestry and fishing for 2.2%, non-energy use for 9%, and 1.5% is non-specified (IEA, 2020a; and see also IEA, 2019).

An overview of the energy dependencies of key systems is below.

- **Transport systems** are overwhelmingly dependent on oil products, which provide 92% of energy consumed by the transport sector (the main exception is electric railways); with some 65% of global oil supply being consumed in the transport sector (IEA, 2020a). Globalised trade and supply chains are enabled by cheap and plentiful supplies of oil for maritime, road, rail and air freight transport (Gilbert & Perl, 2008). Passenger transport, including essential trips like commuting to work and school, business trips, and shopping, and also non-essential trips for leisure and tourism, is also largely dependent on oil, as are essential services (fire, emergency, police and military).
- **Telecommunication systems** are 100% dependent on a stable supply of electricity.
- **Health systems** rely on petrochemical inputs for the manufacture of pharmaceuticals and for distribution. Meanwhile, air pollution resulting from the combustion of fossil fuels and biomass contributes to respiratory and other diseases.
- Industrialised and globalised **food systems**, which account for much of the world's food supply, are critically dependent on fossil fuels (especially oil) at all stages of production (e.g. fertilisers, pesticides, fuel, packaging), processing and distribution (Pfeiffer, 2006; Wakeford *et al.*, 2015). Furthermore, pollution from the use of fossil fuels has a negative feedback on food production through, for example, acid rain and water pollution.
- Similarly, **water systems** also depend on reliable energy supplies all along the supply chain, including abstraction, purification, conveyance, distribution, and wastewater treatment (Wakeford *et al.*, 2015). Moreover, pollution from fossil fuels (eutrophication, oil spills, fracking, acid mine drainage, etc.) contaminates water supplies.
- The **built environment** in much of the world (especially urban areas built in the last century) has been constructed on the back of cheap, plentiful supplies of oil. This is especially evident in the phenomenon of suburbia. Furthermore, commercial and residential buildings in many parts of the world have to be heated and/or cooled, which is a major use of energy globally.

These interdependencies imply that reducing our reliance on fossil fuels – and oil in particular – will require far-reaching changes in many connected systems, including notably transport and food systems.

## 2.7 Inequality in access to energy

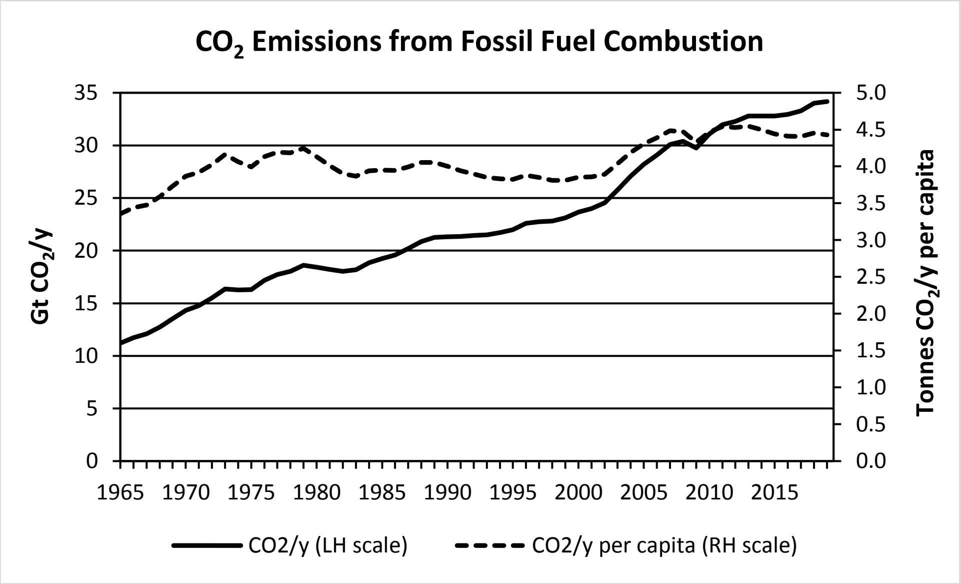
Energy consumption has increased in lockstep with economic growth for over a century. However, access to energy is highly unequal, with per capita levels of energy consumption varying ten-fold across the world. The poorer countries are characterised by extensive energy poverty, with dire need for expanded modern energy supplies. Some 940 million people lack access to electricity and around 3 billion lack access to clean cooking fuels (Ritchie & Roser, 2019).

The UN projects that the global population will grow to around 9.7 billion by 2050, with the majority of growth in Africa, whose population is expected to double to 2.1 billion (UN DESA, 2019). This implies a rising demand for energy to meet basic needs (as well as propel economic development) amongst a significant portion of the world's population. The distribution of energy resources depends largely on spending power (effective demand). This means that energy supplies are often consumed in profligate ways, e.g. air travel, leisure driving, and single-use consumption, rather than in the most efficient ways (producing and distributing basic goods and services to all who need them). Therefore, the challenge of energy access is not just one of supply infrastructure, it also relates to income distribution. Future energy systems should address these access and affordability dimensions, as highlighted by SDG 7 (access to affordable, reliable, sustainable and modern energy for all).

## 2.8 Energy and climate change

In addition to the issues of maintaining adequate energy supplies and improving access, the other major concern about energy is clearly its contribution to anthropogenic climate change through greenhouse gas (GHG) emissions (especially carbon dioxide, $CO_2$). In terms of carbon emissions from energy use, we present in Figure 4 data from the BP *Statistical Review*, on $CO_2$ emissions from the combustion of fossil fuels. As this indicates, $CO_2$ emissions from fossil fuels have been rising continuously since 1965, except for slight falls in the recessions following the 1970s oil shocks and the financial crisis in 2008/9. Currently, the combustion of fossil fuels accounts for about half of annual total global GHG emissions, which amount to approximately 55 Gt/year. The other main sources are direct emissions from industrial activities such as steel and concrete production, from land-use change and deforestation, and from agriculture, including livestock production (IPCC, 2014).

**Figure 4: Global $CO_2$ Emissions from Fossil Fuel Combustion, 1965 - 2019**



*Source: BP Statistical Review, 2020 edition.*

> *This notes that: "[These emissions] reflect only those through consumption of oil, gas and coal for combustion related activities, and are based on 'Default $CO_2$ Emissions Factors for Combustion' listed by the IPCC in its Guidelines for National Greenhouse Gas Inventories (2006). … [They do] not allow for any carbon that is sequestered, for other sources of carbon emissions, or for emissions of other greenhouse gases, [and are] therefore not comparable to official national emissions data."*

As the figure also shows, *per capita* $CO_2$ emissions from the combustion of fossil fuels, despite showing some increase post-2000 (primarily due to a rapid rise of coal use in China), have held fairly steady since the first oil shock of 1973. Thus, the main driver of the rise in total $CO_2$ emissions over the years shown has *not* been from people individually using more fossil fuels, even though globally on-average standards of living have been rising, but from population growth.

In order to meet the Paris Agreement target of limiting the global temperature increase to below 2 degrees Celsius compared to pre-industrial averages, while avoiding undue economic constraints later, many now agree that GHG emissions need to peak very soon and decline steadily thereafter. The aspirational goal set under the Paris Agreement of limiting the temperature increase to 1.5 degrees Celsius will require annual global $CO_2$ emissions to be reduced by about 45% from 2010 levels by 2030, and to reach net-zero around 2050 (IPPC, 2018).[2] Given that energy consumption and economic growth and development have almost always been positively correlated, this clearly presents enormous challenges which have to be addressed on both the supply side (shifting to sustainable, zero-carbon energy sources) and the demand side (improving consumption efficiencies).

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[2] It should be noted that a number of authors have pointed out that international (IPCC) 'high-$CO_2$' scenarios look improbable in terms of realistic *rates* of access to the global carbon resource base (see Annex 2).

# 3.0 Potential Impacts of Covid-19

This section sketches possible scenarios for the impact of Covid-19 on global energy systems, and also briefly explores the spill-over effects from energy to related systems.

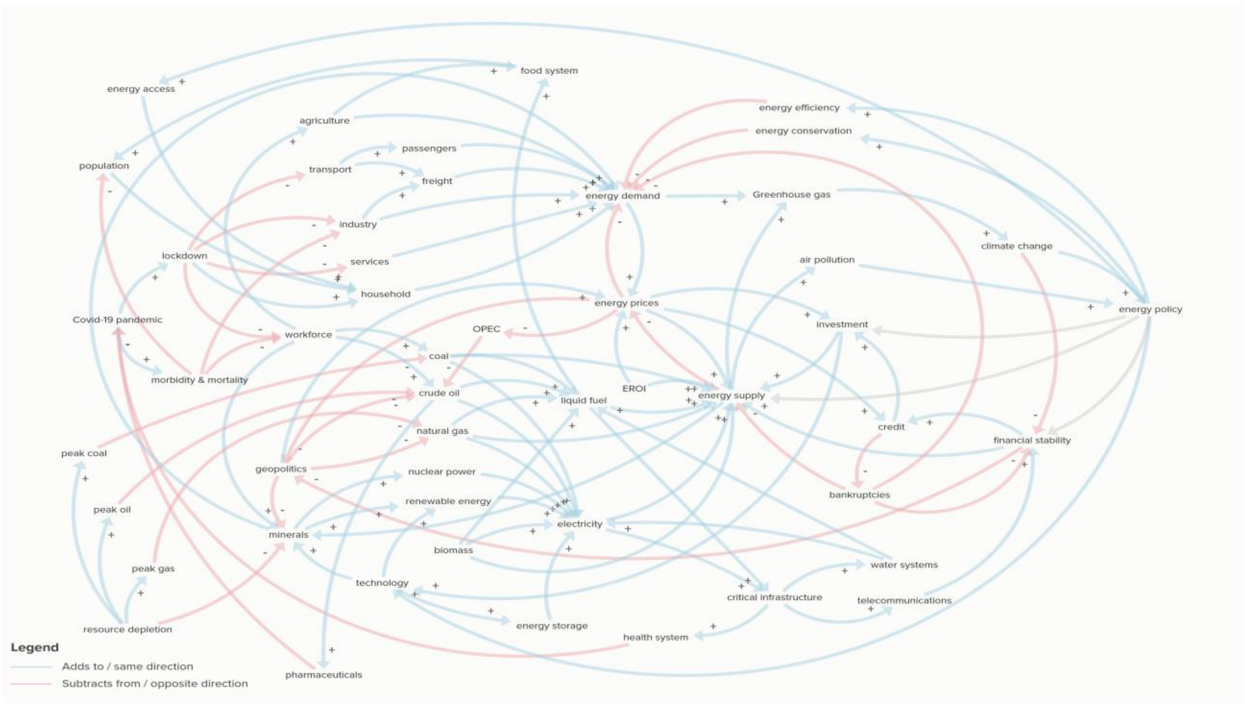
There are several critical variables that will influence the longer-term outcome:

1. How long will the pandemic last?
2. How long will it take to vaccinate significant portions of the global population before the virus is no longer a threat to people conducting their lives normally?
3. How will governments respond, in terms of policies that attempt recovery to business-as-usual (BAU) versus purposive sustainability transition?
4. How will businesses respond, in terms of technologies, investment, business models?
5. How will individuals respond, in terms of changing behaviours and consumption patterns; cooperating with or defying authorities, etc.?

## 3.1 Scenarios for possible impacts of Covid-19 on global energy systems

Figure 5 indicates some of the potential areas of impact of the Covid-19 pandemic on global energy systems. It maps the complex interactions between major elements of these and related systems and includes those places where the pandemic influences these interactions.

**Figure 5: Systems map showing impact of Covid-19 on energy systems, and interactions among major elements and related systems**



As can be seen, the interactions are many, emphasising the need to see the underlying problems – and potential solutions - from a complex systems perspective. In the following sections we examine the possible impacts of the Covid-19 pandemic on global energy systems in the short, medium, and longer-term.

### 3.1.1 Short-term (1-2 years): collapsed demand and low prices

As we have already witnessed since the imposition of lockdowns, the main driver of energy system changes in the short term has been much lower demand. Demand for oil for example is estimated to have fallen by approximately 16.4 million barrels per day (Mb/d) – somewhat less than 20% - globally in the second quarter 2020 (IEA, 2020b), due mainly to travel and mobility restrictions, and a rapid shift to work-from-home in some sectors. Demand for electricity has also fallen as industrial and commercial operations were sharply curtailed in many countries across the globe.

This collapse in demand led in turn to a sharp fall in oil prices in March/April 2020, with the Brent crude oil benchmark falling from around $65 per barrel in January to around $20 per barrel in late April. Some futures contracts (West Texas Intermediate front-month) even dipped into negative prices briefly as a supply glut that overwhelmed storage facilities in the US. The over-capacity was initially exacerbated by a breakdown of cooperation between oil cartel OPEC and Russia, leading to a price war. Subsequently, OPEC and Russia reached a new agreement on supply cuts, which helped to raise oil prices somewhat. In June and July 2020, the price recovered partially to a range of $40 - 45/bbl. However, the Saudi-Russia battle is not over, with both countries possibly ready to sell off their reserves while there is still a respectable market for fossil liquids.

Demand for energy – especially oil – is expected to remain suppressed as long as expanding or renewed waves of the virus spread across different parts of the world. Already, we have seen some governments re-impose certain levels of lockdown, thus subduing demand again. This situation seems likely to persist well into 2021, as efforts to manufacture and administer vaccines in the volumes required will take time. Under these circumstances, the oil price has the potential to stay relatively low for quite a while, as long as production capacity exceeds demand. The same dynamic will broadly apply to other energy sources as economic activity remains curtailed. Nevertheless, many drivers will want to be back in their vehicles as soon as possible, particularly if they regard their car as a safer space than public transport in terms of exposure to the virus.

In terms of oil demand from the aviation industry, in the absence of any global fully effective cheap vaccine, quarantine at borders is likely to be long-term, and the aviation industry will continue to suffer badly. Flying will cost airlines more if they properly distance passengers, but the airlines may be obliged to charge less because of the extraordinary competition likely to occur before sufficient capacity is destroyed. Surviving airlines may operate at huge losses for some years simply to remain in business.

Energy supplies are typically slower to respond to price changes, and we explore potential medium-term effects in the following sub-section. However, one area that has been impacted in the short term is shale ("light tight") oil production in the United States. This is partly because production from these shale facilities can be scaled down more quickly, and also because they have higher production costs than many conventional oil sources. Production of tight oil in the US has already fallen by over one million barrels per day. Output has also fallen among other high-cost producers, such as Canada's oil sands.

While lower energy prices are good for consumers, energy access at the household level is driven mainly by income. Those households experiencing a decline in income may have to curtail energy consumption. This applies principally to discretionary energy consumption, for example for leisure travel. For those millions who have lost their jobs, the impact on household demand will be more severe.

### 3.1.2 Medium-term (2-5 years): restructuring and investment

The collapse in demand and ensuing low energy prices have two major implications for supply in the medium term. First, the destabilisation of energy markets (especially oil markets) is likely to lead to significant restructuring, with bankruptcies of marginal producers and industry consolidation. Tight oil (shale oil) in particular will suffer. The resource remains, and some of it will be profitable at current prices of $40/bbl, but many, and perhaps most, of the producers are reportedly financially extended and have been surviving on cheap loans. The appetite to extend new debt by Wall Street banks has declined, and there is likely to be a very large shake-out with many bankruptcies, and perhaps a new generation of operators with fresh money. But the peak of tight oil production in the US is quite possibly already in sight. Given that this has been the largest source of new oil supply since the plateau in conventional oil from 2005, this could have a significant impact on global all-oil markets.

Second, the current low oil price is destroying global upstream investment in both conventional and unconventional oil production. It has been estimated that such investments may fall to a 15-year low of $383 billion in 2020.[3] Furthermore, a prolonged shut-in of supply may be detrimental to the longer-term performance of conventional oil wells. These factors set up the possibility of a significant supply squeeze in the medium or longer term.

Electricity markets have also been hit, but not to the same extent as oil markets, given that transport (the main consumer of oil) has been affected to a greater extent than industrial production and residential electricity consumption. In general, however, the massive increase in economic uncertainty wrought by the pandemic makes it very difficult for energy companies to plan investments.

### 3.1.3 Long-term (5+ years): structural shifts

It seems likely that the Covid-19 pandemic will add impetus to long-term energy supply and use transitions that are already under way. On the supply side, this relates to the gradual shift from fossil fuels to renewables (as shown earlier, renewables still make up only a very small share of global primary energy supply). Even though demand for oil may remain suppressed for a long time as a result of the economic fallout from the pandemic and changed consumption patterns, oil prices will not necessarily remain at low levels because of the supply-side resource constraints and production capacity constraints (from falling investment) described earlier. At the same time, renewables were already becoming competitive with oil in some markets by end-2019 and are likely to continue getting cheaper as technology improves. It is now possible that we have reached a

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[3] See https://edition.cnn.com/2020/06/18/investing/oil-price-spike-jpmorgan/index.html

turning point where the cheaper alternative for new energy consumption is renewable, i.e. oil might be fast approaching a demand-led peak.

On the energy use side, various structural transitions may be accelerated by the pandemic. First, the automobile industry may be approaching a tipping point in terms of a shift from internal combustion to electric vehicles. The revelation of cleaner smog-free urban environments may have initiated a grass-roots desire to maintain this air quality improvement. The eventual effect may be a faster roll-out of electric vehicles. India and poorer parts of Asia may see the breakthrough development of the affordable all-electric car; they have the need and consumer desire, the innovation skills, less inertia from an existing conventional car industry, few cheap oil resources, and now the hope of better air too. Second, the widespread shift to work-from-home may prove to be permanent for a substantial portion of city workers, who have been freed from the drudgery of commuting and traffic. Third, if the effects of the pandemic persist for several years, many airlines will likely go bankrupt and it is possible that the industry will not recover its former scale in the foreseeable future. Fourth, for the economy more broadly, Covid-19 is clearly accelerating the digitalisation of economic processes. By highlighting the fragility of global supply chains, it also seems to be adding momentum to the forces of deglobalisation, regionalisation and re-localisation of economic activities. These changes could reduce overall demand for energy (and see in particular, Hepburn et al., 2020).

Nevertheless, given the scale and urgency of the climate imperative and need to address the SDGs, as well as the uncertainties and economic dislocations brought on by Covid-19, policies will definitely be needed to accelerate and manage the above transitions.

Broadly speaking, we suggest three theoretically possible long-term scenarios (and see Figueres and Rivett-Carnac, 2020, pp 96-97):

- Scenario 1 - *Return to business-as-usual* ('Snap back', economic imperative, and driven by the 'taut economy' that is intrinsic to capitalism, *cf* Fleming, 2016).
- Scenario 2 - *Economic and social collapse* (Greater Depression, debt bubbles bursting, financial meltdown, collapse of critical systems, widespread social unrest, possible civil conflict and even wars).
- Scenario 3 - *Fundamental change* (restructuring of global value chains/deglobalisation of goods trade, accelerating digitalisation ...). There are two major variants:
  a. authoritarian control and maintenance or increase of concentrated power and wealth;
  b. decentralisation of power, more egalitarian distribution of wealth.

In practice, we are likely to see elements of all three scenarios unfolding in different parts of the world and at different times. However, given the globalised nature of our economies (including global energy and resource value chains) and financial systems, it seems likely that the world as a whole will tend towards one of these trajectories. Of these, Scenario 1 seems the least likely, given the complex fragilities in the global economy as well as the underlying resource constraints discussed earlier.

### 3.2 Spill-over impacts from energy systems to connected systems

Energy systems are linked to many other critical societal and natural systems, including the global financial system, transport systems, food and water systems (for details see Wakeford et al., 2015), telecommunications (principally via electricity supply), health systems (e.g. via pharmaceuticals) and political and geopolitical systems. These complex, systemic linkages (including positive and negative feedback loops) imply that disruptions to energy systems are likely to have knock-on impacts in related systems. Here, we briefly raise what we consider to be some of the most important of these potential spill-overs for the financial system and geopolitics; more detailed analysis is beyond the scope of this paper.

Disruptions in the energy system carry at least three risks for the global financial system. First, possible sovereign debt defaults could occur among states that are highly dependent on oil revenues (e.g. Venezuela, Iraq, Angola, Nigeria, etc.), which would have ripple effects on bond markets. Second, the US shale oil debt bubble could burst as a result of persistent low oil prices, involving a wave of bankruptcies and debt defaults, possibly triggering a financial crisis not unlike the 2007 US mortgage crisis. Third, there could be a long-term undermining of the petrodollar system as a consequence of the transition away from oil to renewable energy and electrified transport systems. The global pricing of oil in US dollars has arguably been one of the major pillars supporting the dollar's status as global reserve currency.

Changes to the energy landscape could also precipitate destabilising political and/or geopolitical developments, as energy (particularly oil and gas) often underlies geopolitical fault lines. The major short-to-medium term risk appears to be socio-political instability in oil exporting countries that are experiencing collapsing government revenues and export revenues. In the longer term, there could be more profound realignments that create flash-points. Concentrated sources of energy (fossil fuels and nuclear power) have arguably laid the basis for the concentration of wealth and political power during the industrial age. By contrast, a distributed energy production and distribution system could in the long term radically alter the distribution of political power and income/wealth. Heightened geopolitical uncertainties and risks – including the possibility of national and international conflicts among major energy producers – will compound other economic uncertainties and fragilities brought on by the pandemic.

### 3.3 Potential Impacts of Covid-19: Summary

The pandemic has already wrought major impact on global energy systems, and it seems likely that large-scale disruptive changes are likely to persist in the medium to longer term. If left purely to market forces, the changes could be chaotic and damaging to society. Based on these systemic risks, the position of the contributors to this report is that attempting a BAU recovery would be unfeasible or carry unacceptable risks that end in a collapse scenario, or - if no collapse – delay, and compound the existing systemic risks posed by climate change and ecological breakdown. Hence, the next section considers ways to bring about the positive version of Scenario 3b, i.e. a purposive transition to a more sustainable, just and resilient energy system.

# 4.0 Managing the Energy Transition

## 4.1 Existing studies, policies and $CO_2$ commitments

In recent years and there have been many studies examining the energy transition, policies proposed to achieve this, and specific commitments on reducing greenhouse gas emissions.

These include:

- Studies: There are now very many studies examining possible detailed routes to achieving the energy transition, usually either for specific countries or for the world as a whole. Initially such studies were mainly produced by academics or by isolated pressure groups, but are now generated by a wide range of actors including the IPCC, IEA, energy companies, consultancies, think tanks as well as pressure groups and academics.
- Policies: Following these studies, many governments, regions, cities, companies and other institutions have proposed policy measures designed to bring about the energy transition. At government level, these policies include those recently enacted by the UK (the government's £12bn '10-Point Energy Plan') and by the EU (its 'European Green Deal'), and in the 'Green New Deal' proposed for the US and supported by the incoming Biden administration.
- Commitments on greenhouse gas reductions: Generally more recently still, a similar gamut of organisations ranging across governments, cities and private companies have committed to target dates for specific reduction levels in $CO_2$ (or wider GHG) emissions. Explicitly, a number of governments have set into law their target dates to achieve net-zero emissions, including Sweden (net-zero by 2045), UK, France, Denmark, Hungary, Japan, South Korea and New Zeeland (net-zero by 2050), and China (by 2060).

Note, however, that often there is no detailed quantitative linkage between a government's energy policy and its aim of achieving a target date for net-zero. This has recently been pointed out, for example for the UK, by Chris Stark, Chief Executive of the UK's Committee on Climate Change. But a government can retort with some justification that no-one knows in advance the take-up of new approaches encouraged by government (for example, the rapid take-up of offshore wind in the UK surprised many), and as long as the mechanism to achieve net-zero has adequate teeth, it may be reasonable to expect specific emissions reduction targets to be reached.

The above wide range of studies, energy policies and GHG commitments is indeed now impressive and laudatory. But as mentioned previously, the purpose of this report is to indicate a number of energy-related factors that are missing from nearly all of these; factors which if not considered mean that these studies, policies and commitments are unlikely in our view to be sufficiently realistic to be useful guides to the future.

In the sections below we explore in general terms the following: (1) elements of a desirable future energy system that is in line with the SDGs and the Paris Agreement, and (2) policy aspects that could facilitate a managed transition to such an outcome.

Key drivers include:

- incentives (policies, institutions)
- values
- technologies
- resources
- infrastructural lock-in

## 4.2 Elements of a desirable future energy system

To counteract the cautions set out earlier in this report on limits to oil and gas supply, and on constraints imposed by EROI ratios and minerals supply, comfort can be taken from what is already known about ways to reduce energy requirements, and from the many promising new and improved energy sources under development (and where the latter reinforce the message that significant post Covid-19 funds should be spent on 'Green R&D').

In terms of what we already know, there are very large energy savings to be had in better design and thermal insulation of buildings, in increased recycling of materials, and in design for much longer product lifetimes. In addition, the redesign of urban transport systems potentially offers significant energy savings.

In terms of new and improved energy technologies, these include floating offshore wind (which considerably expands the potential resource-base available); the many developments towards long-life perovskite and other thin-film solar cells; technical roadmaps for major improvements in vehicle batteries offering standard vehicle ranges in excess of 400 miles per charge and battery life up to perhaps to 1 million miles; improvements in electricity storage; 'hyperloop' and similar low-energy transport options; developments in geothermal energy (after all, we live on a 'hot earth'); and further investment in innovative fusion energy approaches (the latter currently standing at $1.7 billion, in addition to the ~$40 billion full cost of the international ITER fusion project).

However, one energy innovation we suggest be resisted at all costs is modular small-scale nuclear fission plants (SMRs) unless their high risks of nuclear proliferation (especially if sold into export markets) have been addressed in a convincing and watertight manner.

Other energy innovations increasingly being implemented include:

- Smart grids, embedded generation
- Much higher efficiency in energy production, distribution and consumption
- Changes in energy consuming systems such as:
  - Industrial production: circular flows, eco-industrial systems
  - Urban design: work/home/retail distance; bicycle- & pedestrian-friendly cities
  - Buildings: efficiency of heating & cooling
  - Transport systems (electrification, mass transit, integration of EVs with smart grids, cycling)
  - Sustainable food systems: local food gardens

## 4.3 How to get from here to there

Currently, globally we still have a 'nearly-all-fossil-fuel' society, where, only 5% of global primary energy comes from the 'new renewables' of wind, solar, biomass and geothermal, and where the bulk of these 'new renewables' are almost entirely manufactured, shipped and installed using fossil fuels. In addition, we seek a transition to fairer society with universal access to low-cost, low $CO_2$ energy. The questions this raises are: 'Can we make this transition? And if so: How do we get from here to there?

Governmental responses to the Covid-19 crisis have already ushered in game-changing policies, showing what can be done when there is sufficient political will (in most cases, there was little public consultation and mustering of broad-based support before the imposition of such policies). These policies have included unprecedented societal lockdowns, travel bans, shutting down of industries, etc., as well as massive economic support packages (government spending on corporate bailouts, support for small businesses, household income support and in some cases even the assumption of near war powers over production). By doing so, governments have 'broken the mould' of conventional policies and opened the door to radically transformational policies.

### 4.3.1 Using the remaining carbon budget to build sustainable energy infrastructures

The Paris Agreement includes an aspirational goal to limit global warming to "well below" 2 degrees Celsius relative to pre-industrial times. This implies humanity has a limited "carbon budget", i.e. how much more GHG can be emitted to the atmosphere. This, in turn, implies a limited fossil energy budget – and one that is considerably less than estimates of available resources (McGlade and Ekins, 2015).

Given that current renewable energy infrastructure requires fossil fuel inputs (e.g. oil to power mining machinery, coal for concrete and steel production, oil for transport and installation of components and infrastructure), a certain amount of the remaining fossil fuel budget must be used to build the sustainable energy infrastructure.

A "just transition" requires that opportunities need to be created in new sectors for those currently deriving their livelihoods from fossil fuel industries. This could take the form of re-skilling. For both unskilled and skilled occupations (such as coal mining), this is a massive task.

### 4.3.2 Financing the energy transition

> *"Governments have a once-in-a-lifetime opportunity to reboot their economies and bring a wave of new employment opportunities while accelerating the shift to a more resilient and cleaner energy future."*
>
> - Dr Fatih Birol, launching the IEA's *Sustainable Recovery* report, June 2020.

#### (a) Current energy investment vs. that required

Financing the sustainable energy transition requires a redirection of finance from fossil fuel industries to renewable energies. This section explores estimates of how much investment in renewables will be required over the coming decades.

According to IEA data, global total investment in energy infrastructure in 2018 was some US$1.85tn, of which about one-third was invested in low-carbon energy production and transmission. This finding is in general agreement with an earlier estimate from the Climate Policy Initiative (CPI), which estimated global 'climate finance' investments for both mitigation and adaptation in 2015 - 2016 at just over $0.5tn/yr., with renewable energy generation representing about two-thirds of this. (CPI, 2018; and see also CPI, 2014). Detailed charts on current 'climate finance' spend by source and by category of use are given in Annex 7.

To understand the future, the levels of current energy investment need to be compared to estimates of the amounts that will be required to meet climate change and UN Sustainable Development goals.

The IPCC (2018), for example, estimated that between $1.6 - 3.8 trillion per year energy system investment - essentially all devoted to low and 'negative' carbon energy sources and to energy saving - would be required to keep global warming within 1.5 degree Celsius so as to avoid the most harmful effects of climate change.

And the IEA estimated in its 'Sustainable Development Scenario' designed to meet the UN's three main energy-related SDGs (3: healthy lives and well-being for all; 7:access to affordable, reliable and sustainable energy; and 13: combating climate change) that average annual investments from 2019 to 2050 would need to be:

| | $tn/yr. |
|---|---|
| Power (energy generation & transmission) | 1.35 |
| End-use (energy saving, switch to electric vehicles, etc.) | 1.64 |
| **Total:** | **~ 3.00** |

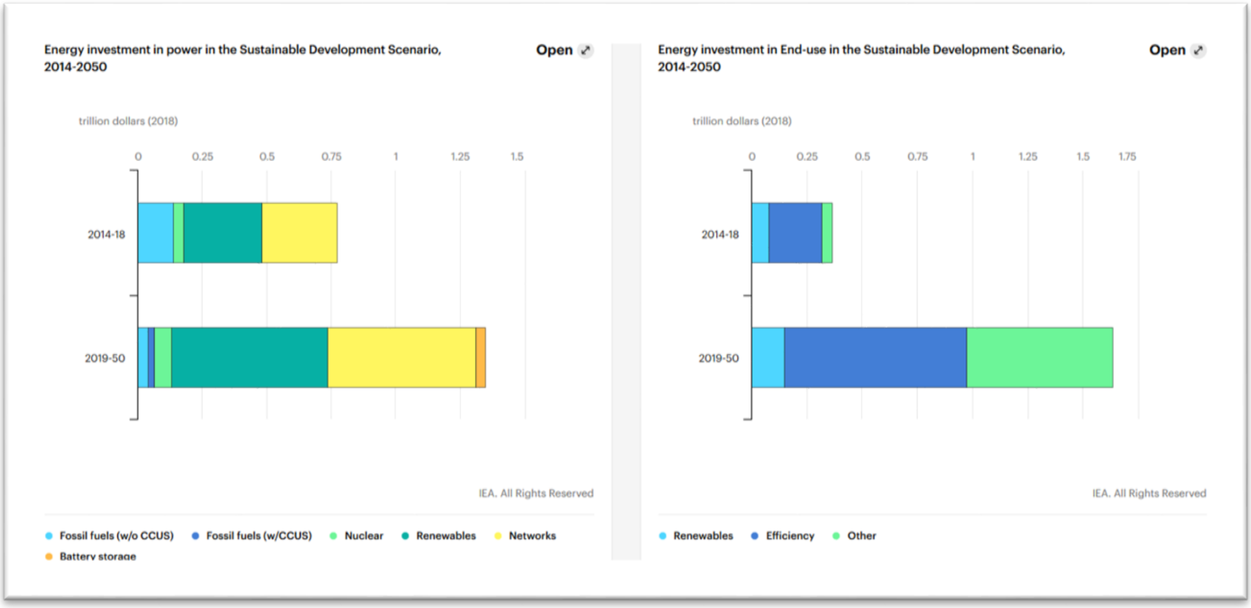
On the basis of the above two studies it is probably not too far off to assume that something in the region of $3tn/yr. is likely to be required as total annual investment in energy infrastructure and energy saving from now to 2050 if the desired energy transition is to be met. At first sight this perhaps does not look too out-of-line with the total current spend on energy infrastructure and saving, of about $2tn/yr. But recall that only perhaps a half of the latter is currently spent on renewable energies and other climate-change measures including energy saving, so the ~$3tn/yr. - which will virtually all need to be spent on renewables and other climate change measures - represents more like a three-fold increase on current investment in these areas.

In terms of the details of this investment, the requirements by category are given in the IEA data, where their World Energy Model assumes three scenarios as follows:

- Current Policies Scenario (CPS)
- Stated Policies Scenario (STEPS)
- Sustainable Development Scenario (SDS).

The required annual investments by category for power generation and transition, and for 'end-use' purposes, for meeting climate and UN goals under the SDS scenario, are shown in Figure 6.

**Figure 6: Annual Power and End-use energy investment by category in the IEA Sustainable Development scenario: Comparing current (2014-18) vs. that required (2019-50)**

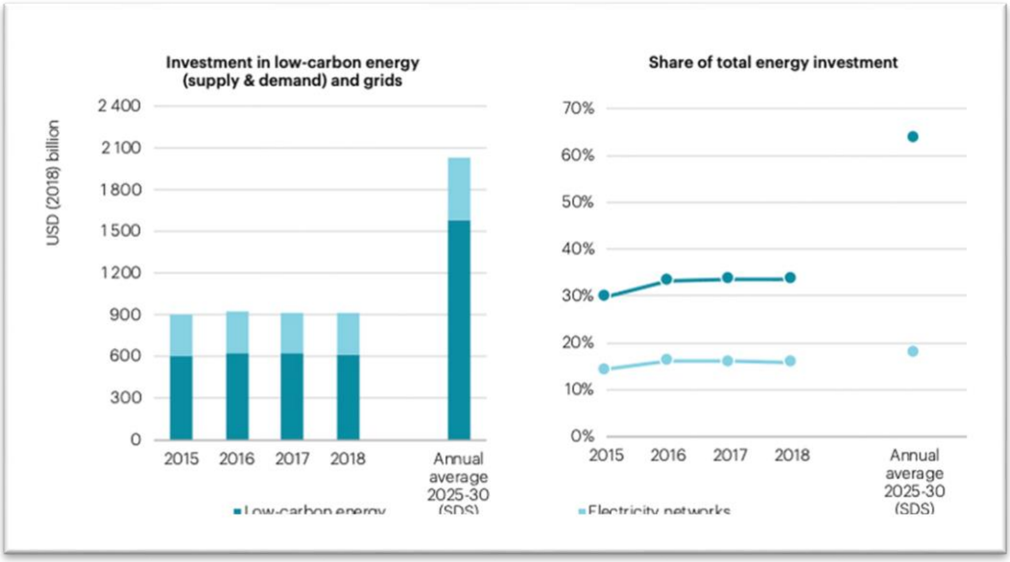


*https://www.iea.org/reports/world-energy-model/sustainable-development-scenario*

The SDS requires an increase in overall energy investment compared to STEPS of around 25% over the period to 2050. The largest increase in energy supply investment under SDS comes from renewables-based power, which is on average double today's level between 2019 and 2050. This is supported by significant additional spending on electricity grids and battery storage, in order to ensure reliable electricity supply. The other major shift in spending is on the demand side, to take advantage of the huge potential for energy efficiency. This means additional spending on more efficient buildings, industrial processes and transport, as well as new demand-side infrastructure, e.g. for electric vehicle (EV) recharging.

In particular, as Figure 7 shows, the SDS scenario sees energy investment on low-carbon energy (supply and demand, and grids) as growing from some $0.9tn/yr. today to ~$2tn/yr. in the 2025-2030 period, and increase from about one-third of total energy spend now to two-thirds.

**Figure 7: Annual global energy investment in low-carbon energy and grids: today vs. that required under the SDS scenario in the 2025-30 period**



*Source: https://www.carbonbrief.org/iea-low-carbon-spending-must-more-than-double-to-meet-climate-goals*

Turning specifically now to the investment needed to meet the UN's SDG 7 for universal energy access, the IEA calculates under the SDS scenario this will require some $45 billion per year between 2019 and 2030, with the lion's share being for electricity access. While this is more than double that assumed in the Stated Policies Scenario, it is still a relatively small amount, representing only about 1.5% of the total annual energy sector investment envisaged in the Sustainable Development Scenario.

### (b) Will the required funds be available?

Given the information above on the investments needed for the energy transition, perhaps some $3tn/yr. or so, the question must be whether the required funds will actually be available?

The primary answer depends on the will of the public and their governments, and on the specific measures adopted to encourage (or, indeed, mandate) such investment, where some of the potential measures possible are discussed in Annex 6.

But here we look briefly at three rather more fundamental factors that bear directly on this issue: whether sufficient investment funds *in total* are available; whether investors are likely to make such investments, and whether such investments might be circumscribed by existing power structures within society? We discuss these in turn:

#### (i). Potential funds available

The Climate Policy Initiative report (2014) indicated that in that year there was $85.7tn in potentially investible assets, an amount comparable to the global GDP, of $88tn (World

Bank 2019 data), itself equivalent to 'International' $142tn if measured in US dollars, but adjusted for purchasing power parity (Statista data).

However, after regulatory and commercial constraints are applied to these investment funds, only $257bn (0.3%) was actually available in the capital markets, i.e., those markets dominated by pension and insurance funds which are subject to such constraints. This highlights the discrepancy between the investments required and what these investment managers can currently deploy, and hence the investment criteria that need to be changed.

### (ii) Investor attitudes

Next, we look briefly at investor attitudes. Rational investors tend to look for returns above market average deriving from investments with risk profiles below market average. But investment risk can be mitigated by creating a regulatory environment conducive to that end, and where creating a regulatory environment that pays investors above-average returns for below-average risk, investment will flow into that sector. This has been demonstrated on numerous occasions; for example by the investments in the UK solar industry over the 2010-2015 period, where government support meant that effectively typical infrastructure project returns were offered for investments which essentially reflected a risk profile close to that of government bonds.

### (iii). Power structures within society

Finally, we mention an under-researched aspect of society that needs consideration, that of how a society's power structures operate. This is illuminated by the theory of 'Capital as Power' which examines the role of financial capital, and how society's dynamics can be influenced by the role of the state in terms of institutional infrastructures. The transition from a world powered by fossil-fuels to one that is not will create both winners and losers. As a result, it is reasonable to expect an increasing emergence of government support for the energy transition, including greater application of carbon taxes, with this support being to the benefit those advancing the transition.

# 5.0 Conclusions

## 5.1 Key features of the global energy system

Modern industrial economies and their critical systems, including transport, food, water, health, and telecommunications, are overwhelmingly dependent on energy in general, and fossil fuels in particular.

Combustion of fossil fuels is the leading source of greenhouse gas (GHG) emissions. In order to meet the Paris Agreement target of limiting the global temperature increase to below 2 degrees Celsius compared to pre-industrial averages, GHG emissions need to peak by 2030; and to peak about now if the 1.5 C target is to be reached.

The ratio of energy return on energy invested (EROI) is a critical variable underpinning complex societies. But EROI ratios are generally in decline for fossil fuel production, and most current renewable energy technologies have lower EROI ratios than oil, gas and coal had in their heyday.

The build-out of renewable energy infrastructure is dependent on critical minerals that are finite, and many of which have falling ore concentrations, and hence require increasing amounts of energy for their extraction.

Per capita rates of energy consumption are highly unequal across the world, with extensive energy poverty in much of Africa and South Asia, while increasing numbers of people are adopting middle-class consumptive lifestyles in Latin America, China and other countries in Asia. As a consequence, there is still a massive latent demand for energy in the developing world, where population growth is the fastest, and where renewables such as solar PV can be the cheapest energy source.

Probably only a 'systems dynamics' or a similar modelling approach (e.g. Meadows et al., 1972, 1990, 2004; Randers, 2012; and see the references in Annex 4) can properly capture the interconnections, positive and negatives feedbacks, and non-linearities of the real world to let us know with some degree of certainty what lies ahead.

## 5.2 Conclusions by Sector

The findings of this report suggest that achieving the energy transition is likely to be significantly more difficult than most analyses envisage. The reasons for this are as follows:

### 5.2.1 Oil

**(a). Oil reserves data**

Much of past and current analysis of global oil supply has been hindered by the very misleading public domain data on proved oil reserves by country, such as those provided by the US EIA, OPEC, and publications including the *Oil & Gas Journal*, *World Oil*, and the BP *Statistical Review of* World *Energy*. Analysts need to treat these data with considerable caution, and if possible use instead the oil-industry proved-plus-probable ('2P') oil reserves data; see Section A3.2 in Annex 3, and Bentley (2018).

### (b). Oil supply

The world reached its *resource-limited* plateau in the global production of *conventional* oil in 2005 (unless the price of oil in future goes very high), see Section A3.4 in Annex 3. This plateau caused the oil price to climb to over $100/bbl and was one of the triggers of 2008/9 recession. The plateau forced the world to turn increasingly to the production of non-conventional oils and other liquids. These are typically more expensive to produce, yield less net-energy per barrel, and have higher GHG emissions.

To-date, out of a global total of some 125 oil-producing countries worldwide, the majority - over 70 - are almost certainly past their resource-limited oil production peak, at least up to oil prices well in excess of $100/bbl.[4] These include the major oil producers of Venezuela, Kuwait, Iran, Indonesia, UK, Norway, Mexico, Algeria and China. In addition, other large oil producers including Russia and Nigeria are close to their resource-limited peaks in oil production.

Should oil supply shortages occur, geopolitical tensions are likely to intensify. Countries and the global community will need to choose between conflict over scarce resources or collaboration to manage the tensions that are likely to arise. Though many authorities now expect global *demand* for oil to fall due to climate change mitigation measures (and more recently, Covid-19 reductions in economic activity), the near-term resource-limited decline in the global production of conventional oil may well result in significant stresses across society.

### 5.2.2 Gas

The world has adequate medium-term supplies of gas, but is likely to reach its resource-limited maximum production of *conventional* gas in the not-too-distant future. Current concerns for gas are the $CO_2$ emissions from its combustion, and fugitive methane emissions from its production, pipelines and shut-in wells.

### 5.2.3 The requirement on energy infrastructure build-out

The desired energy transition still has much further to go than much of current energy reporting would seem to indicate. Great progress has indeed been made in the deployment of renewable energies and their costs have fallen significantly, but the 'low-carbon' energies of nuclear, hydro and the 'new renewables' combined currently only contribute 16% in total to global 'primary' energy; and the 'new renewables' alone, of wind, solar, biomass, wave and geothermal, contribute in total only some 5%; see Section 2 above, and Annex 2.

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[4] Modelling by Dr. Richard Miller, Rystad Energy, and Globalshift Ltd. suggest that if the oil price goes very high for a long time, significant quantities of new conventional oil can be brought on-stream. For countries past resource-limited oil production peak see the data from Globalshift Ltd. (www.globalshift.co.uk), where these forecasts apply to: "Fossil oil from on and offshore reservoirs, including tight sands/shales; and liquids extracted from gas" and thus exclude oil produced from biomass, and by coal or gas to liquids.

### 5.2.4 Energy return on investment (EROI)

The energy return on energy invested ratio (EROI) gives the energy delivered by a source of energy divided by that required to obtain this energy. For finite energy resources, it integrates the counteracting effects of an energy resource's depletion against technological improvements in its production. More widely, it is a metric which avoids some of the problems of financial analysis alone, generating insight into present and future energy prices and energy availability. Hall (2017) notes that a lower EROI ratio globally means that society must divert more of its total economic activity to obtaining the energy required to run the rest of the economy.

The normal EROI statistic used is the 'static' EROI, when no consideration is given to changes over time in the use of the energy source. The static EROI of non-conventional fossil fuels is usually less than that of conventional fossil fuels (Lambert et al., 2013), while the EROI of most renewable energy sources - except for hydropower - are generally lower than that of fossil fuels - at least lower than the high EROI ratios of the latter until recently.

When use of an energy source is increasing rapidly, as is currently the case with many renewable energies, examination is needed instead of the 'dynamic' EROI (PROI), and this is especially so for those energies, such as solar, wind, nuclear and deep geothermal, where the major part of the input energy occurs before energy has been produced.

Unfortunately, calculation of the impacts of EROI ratios of energy sources are nearly always absent from existing energy studies. Those few studies that do include these ratios (see Section 2.3 above, and Annex 4) suggest it will be far harder to achieve the energy transition than most expect, and indeed may lead to a significant fall in energy available per capita.

Overall, unless there is a dramatic improvement in the EROI ratios of current and prospective energy sources, the world seems set on a path of moving from generally higher-EROI fuels to those with lower EROIs, with the result that the global energy transition is likely to be more problematic than generally expected.

### 5.2.5 Minerals supply

Societies seek increasing usage of minerals for reasons of population growth, increasing economic expectations, and the need to build new energy infrastructure to meet climate change goals. However, the future supply of minerals faces three significant problems: geographical restrictions in terms of source locations for some, absolute resource limits for a few minerals, and declining ore concentrations for many others. Unfortunately, the latter forms a nexus with energy availability, as lower-concentration ores generally require more energy for the mineral to be extracted.

### 5.2.6 Availability of finance

Calculations from a range of sources, see Section 4.3.2. above, indicate that the global annual investments needed to achieve the energy transition are not so very much larger - perhaps 50% more - than is currently invested in global energy infrastructure. However, these funds will need to see significant redeployment, by an increase of perhaps three-fold, into specifically low-carbon energies. Moreover, these investment requirements may well be significantly more onerous if the energy and mineral supply constraints indicated in this report are taken into account.

### 5.2.7 The energy-economy linkage

Finally, if the energy constraints discussed in this report begin to have significant impacts the knock-on effects on the global economy are far from clear. This is because the basic linkages between energy supply and economic activity are still poorly understood and need further research.

## 5.3 UN SDGs

This report's findings on meeting the UN's Sustainable Development Goal 7 goal to "ensure access to affordable, reliable, sustainable and modern energy for all" are encouraging. Compared to the investment envisaged for the global energy transition, the investment required to meet SDG 7 is relatively modest. And as has long been recognised, the widespread energy resource bases of solar, wind, biomass and deep geothermal mean that resource-availability in most counties, except for very small densely populated ones, is not in general an issue.

Note that quite a number of the current energy policies proposed for the richer world seek also to help meet UN SDG 7. This is because many are now realising that failure to make appropriate global choices represents an existential threat to humanity, and to all of the earth's ecosystems. More specifically, the energy choices we make are increasingly understood as vital to a sustainable global future. It is very encouraging to see that in response, bold visions are emerging from many sectors within the wider global economy.

# 6.0 Recommendations

The recommendations of this report are as follows:

## 6.1 Oil reserves data

Compilers of proved oil reserves data into the public domain, such as the US EIA, OPEC, *Oil & Gas Journal*, *World Oil*, and BP *Statistical Review of World Energy*, need to add strong caveats to these data, as currently they are very misleading.

## 6.2 Oil and gas supply

It is possible that global demand for oil falls in light of actions taken to avoid climate change. But if these actions are not soon, nor large, then the constraints to oil supply from the near-term resource-limited decline in the global production of *conventional* oil may be severe. Governments, organisations and the public need to be adequately informed about this risk, and suitable contingency planning put in place.

In particular, those countries past their resource limited peak in oil production, or who will soon pass their peak, need to be aware of the impact on their country's finances, especially those which depend on oil revenues for a significant portion of government income.

While total global gas resources are adequate, the global resource-limited peak in the production of *conventional* gas is expected in the fairly near term, and awareness is needed of this.

## 6.3 Gas emissions

There has recently been greater attention to methane emissions from gas production, its supply chain, and abandoned gas wells, and some significant industry agreements have been signed. But industry and government methane monitoring bodies point to significant extra work required to tackle this aspect of the climate change problem. There is growing concern also of the increase in methane released from the melting of the Arctic permafrost.

## 6.4 Modelling

If there is one key message that we seek this report to get across it is that currently there are a number of key factors affecting humankind's access to and use of energy that are not adequately being considered in the majority of energy transition studies, energy policies, and commitments on GHG reduction.

Thus, we recommend that well-funded nations urgently commission and fund rigorous and detailed modelling of the energy transition that includes the following:

- Oil and gas supply constraints.
- EROI ratios of non-conventional fossil fuels and of 'low-carbon' energy sources, including factoring in up-front energy investment, and rates of anticipated growth by energy type.
- Increased demand for food, housing, heating and cooling, and transport due to population growth.
- Increased energy requirements due to falling mineral ore concentrations.

- Adequacy of investment finance.
- An improved understanding of the linkage between energy price and economic activity.
- Impacts of energy availability on society, particularly if *per-capita* energy availability falls.
- 'Hubbert-type' constraints to total fossil fuel potential availability, to inform the realism of high-$CO_2$ scenarios.

In addition, we recommend specifically that EROI analysis be included in the energy models of:

- UK BEIS (DECC): *2050 Pathways* on-line software.
- IEA: *World Energy Outlook* modelling.

## 6.5 International Agreement

In the light of the possibility of global tensions and competition for increasingly scarce energy resources, we recommend a proactive effort to develop an internationally binding agreement for equitably managing global energy supply constraints, and that of other scarce resources. Such an agreement would need to acknowledge the following:

- The increasing global population, and growing consuming middle-class in particular.
- The high levels of dependence of the global energy system on finite fossil fuels.
- The levels of fossil fuel energy required to fuel the global transportation system.
- The high levels of fossil fuel energy required by the agricultural sector to feed the growing world population.
- The concentration of oil resources in a small number of oil-producing countries.
- The need to carefully and fairly manage the allocation of key depleting resources.
- To seek ways to reduce waste, and increase efficiency of use, to extend the life of the finite resources.
- To seek mechanisms for international collaboration rather than conflict over increasingly scarce resources.
- To ensure that such mechanisms are aligned with international efforts to address climate change.
- To increase research and development budgets seeking alternative sustainable energy sources.
- To tie such an agreement to other aspects of international law; *cf.* Ben Ferencz's dictum of 'law not war' (Avrich, B., 2018).

## 6.6 Support for UN SDGs

We judge that the international community in general seeks a fairer world and supports the UN SDGs. However, concrete plans to achieve these goals are still largely embryonic. To achieve these goals will need concerted action between countries and significant resourcing, but also addressing the existing power structures that often constrain such global advancement.

## 6.7 Support for Climate Change actions: Mitigation & Adaptation

Humankind is at existential cross-roads. Radical, concerted and focussed action to mitigate climate change is urgently required. We believe that nations need to be on a 'war footing' to address the depth and breadth of the threat humankind faces as a result of the warming climate.

Not only is human civilisation under threat, but so too are many other lifeforms and ecosystems. The urgency cannot be overestimated, and where the energy related choices we have made are in large part to blame for the crisis. Many people are now questioning whether the changes required are possible within the current economic paradigm. We are not able to answer this question in this report, and instead recommend that a comprehensive study be commissioned and funded that examines a range of alternative **economic models that carry fewer eco-systemic risks.** This would need to set out how international consensus for such transitions might be achieved. The links between such actions and energy as well as the investment, political economic constraints need to be understood.

## Summary: A comprehensive transition to sustainable energy and related systems is required

The findings of this report call for a bold vision that suggests the need for more energy-centric economic policy development, for greater international collaboration, greater stakeholder engagement and massive changes in individual and corporate behaviour that is based on the centrality of energy to economic development. This will require individuals, professionals, engineers, politicians and economists to think very differently about what is important. We believe that very high on this new list needs to be a much greater emphasis on thinking about the resource related limitations to growth, including both economic and population, climate change, and tools and policies that lead to genuine sustainability.

Resolving the issues discussed in this report will drive a huge increase in renewable energy infrastructure, that will require a fundamentally different model. It is likely to be based on distributed generation connected via smart grids.

Massive increases in energy efficiency (especially on the consumption side) will be required, as will greater resource efficiencies with respect to a range of scarce resources, since resource extraction and processing requires energy.

Many of the systems we take for granted will require significant reconfiguration. These include the way in which our cities are planned and the way they function, particularly their transportation and food systems. Urban economies will increasingly need to be based on 'circular economy' principles where waste from one system becomes an input for another system.

In addition, considerable increases in R&D spend will be required to pursue technological and scientific breakthroughs in all aspects of energy delivery.

A global all-renewable energy future, with renewable sources widely dispersed, coupled with lifestyles in the developed world based on expectations of potentially lower available energy per capita, could contribute significantly - over time - to attenuating the risks related to climate change and fossil fuel depletion.

# ANNEXES

## Annex 1: The Role of Energy in Socioecological Systems: The 'Master Resource'

This report's point of departure is to view energy within the context of socioecological systems, a theoretical approach which studies the interactions between human societies and nature (Fischer-Kowalski & Haberl, 2007). This conception views "socioeconomic systems (such as national economies) as systems that reproduce themselves not only socially and culturally but also physically through a continuous exchange of energy and matter with their natural environments and with each other" (Fischer-Kowalski and Amann, 2001: 12). One of the fundamental notions of the SES approach is that any society (or socioeconomic system) has a 'metabolism', which "refers to the sum total of the material and energetic flows into, within, and out of a socioeconomic system" (ibid.). Thus, energy and material flows sustain the biophysical structures of society. In particular, the biophysical perspective (which rests on the laws of thermodynamics) recognises energy as the 'master resource' that enables the use of all other material resources to satisfy human needs and desires.

Throughout human history, three basic socioecological regimes have been identified, each relying on a different fundamental energy/material metabolism – namely, hunter-gatherer, agrarian and industrial societies (Fisher-Kowalski and Haberl, 2007). The first two were essentially limited by solar energy captured through photosynthesis (actively managed in agrarian societies). The key ingredient in the industrial metabolism is fossil fuels, which enabled an exponential expansion in the human population as well as its biophysical structures and economy. A very large literature within economics studies the close correlation (and essentially bidirectional causality) between energy and the economy: economic growth gives rise to increasing demand for energy, and growing energy supplies fuel economic activity. The disciplines of ecological and biophysical economics regard energy as absolutely critical to all forms of economic development (Hall & Klitgaard, 2012; Smil, 2019). Fossil fuels (coal, oil and gas) have presented humanity with a vast store of concentrated energy, accumulated over millions of years through photosynthesis, decomposition and subsequent geological forces. Essentially, the harnessing of fossil fuels has enabled an expansion of the human population from roughly one billion in 1800 to around 7.8 billion currently, by being put to use in myriad ways, including in the production and distribution of food and modern medicines.

# Annex 2: Energy Data

To understand the global energy situation we currently face, and in particular the challenges of the 'energy transition', it is important to look at the underlying data from a range of perspectives.

Here we examine global energy in terms of the following: total energy potentially available; total energy required; 'direct' energy use; 'primary' energy use; two common misapprehensions about energy data; energy per capita; a caveat on high carbon emissions scenarios; constraints to the rate of energy change; positive developments including rapidly falling costs of some energies, financing aided by low interest rates, and efficiency gains in energy conversion; and 'efficiency' in our need for energy.

## A2.1 Total energy potentially available

It is important to recognise first that there are immense resources of energy *potentially* available on earth, resources very much larger than humankind's annual commercial energy use. These include the remaining fossil fuels (including the non-conventional fossil fuels of tight, very heavy, and tar sands oil, and oil from kerogen; shale gas, gas in deep aquifers, and possibly in methane hydrates; and coal in deep and thin seams); solar energy; nuclear fission from uranium (but only if breeder reactors are used) and from thorium; deep geothermal; and energy from nuclear fusion.

## A2.2 Total energy required

And it is important to recognise also that technically we can use *much less* energy for the same quantities of desired outputs. The latter include, for example, heating and cooling by use of vastly better insulation such as 'passiv-haus' design; distance travelled, where significantly more efficient modes of travel are possible; and in material things produced, for example by the design of products for long life, improved recycling, and by implementing a 'circular economy'; see Section A2.10, below.

## A2.3 Global energy use by energy source

But despite the above two realities (that there is lots of energy potentially available, and we can use far less for the same outputs), factors considered in this report indicate that the energy transition will not be easy.

This is indicated in part by Figure A2.1, a figure which is somewhat surprising even to those aware of the data. This shows annual global consumption of commercial energy by energy source, where this plot shows actual energy consumed, as measured for example in joules.[5]

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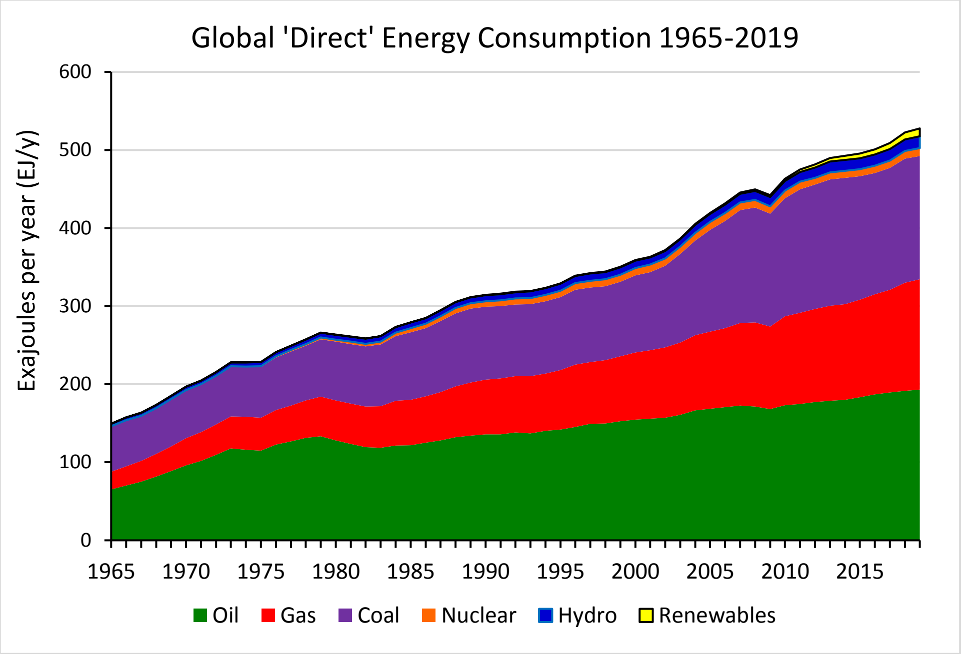
[5] Note that the analysis here looks only at *commercial* energy, i.e., that bought or sold. Human society also makes use of enormous amounts of non-commercial energy. Some of this is in the form of biomass for cooking etc. (as reported in IEA global energy statistics), but far larger quantities are in the sunshine needed to grow crops, sustain forests and support wildlife on land, grow plankton in the seas that provide food for marine life, and also some of the oxygen we breathe; and to evaporate the rainfall needed for crops and for $CO_2$ removal by rock weathering that helps stabilise the climate.

**Figure A2.1: Global 'direct' (i.e., actual) energy consumption by energy source.**



**Notes:** Shown are the 'direct' (i.e., actual) amounts of energy consumption by source.[6] 'Renewables' refer to the 'new renewables' of wind, solar, biomass, geothermal, wave and tidal.

*Source: BP Statistical Review of World Energy, 2020 edition*

As the figure shows, despite nuclear and hydro being important sources of low-carbon energy, and the publicity around electric vehicles and the growth of wind and solar, in actual energy terms the low-carbon sources of energy in total currently provide only 7% of the commercial energy we use. And more narrowly, the 'new renewables' of wind, solar, biomass, geothermal, wave and tidal in total contribute less than 2%. Measured on this basis, the energy transition still has a very long way to go.

## A2.4 Global 'primary' energy use by energy source

This is an example of where energy data need to be seen from several points of view. This is because Figure A2.1, while correct, is not the whole picture. As indicated in the main report, electricity from sources such as wind and solar is used directly in most applications without further

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[6] Note that the BP *Statistical Review* reports both energy produced, and energy consumed. At the global level these two numbers are close for each class of fuel, and in total. (They are not identical because of definitional differences, and more importantly in how the data are collected.) For 'primary energy' the Review reports energy consumed, so here we have stayed with this terminology. But given the discussions later in this document on what is really meant by 'consumption' of energy (including its conversion form one energy source to another, and its finally producing an entity serving a human need such as 'food on the table'), readers are warned to be clear about these rather slippery notions of 'energy consumption'; and - where it helps - to think simply in terms of 'energy produced'.

processing, but where, by contrast, electricity produced from fossil fuels is associated with a significant energy loss.

As a result, for many years now it has been customary (as in BP *Statistical Reviews*) to compare different types of energy source in terms of their 'primary' energy. The latter assumes that the energy from 'direct' electricity sources, such as hydro, wind and solar, should be counted as if produced by burning fossil fuel in a power station, the latter process typically having a conversion efficiency of around 35% (and up to about 40% in more recent years).[7] This assumption leads to Figure 1 in the main report, where energy sources that produce electricity directly as their output have the quantities of 'direct' energy they produce in joules multiplied by about three when calculated in 'primary energy' terms.

As Figure 1 shows, if the global energy consumption data are presented in this way the low-carbon energy sources in total contribute about 16% of total primary energy, a figure which, if not large, is at least significant on a global scale; and where the 'new-renewables' currently contribute about 5% to global 'primary' energy.

And as Rathi (2020) points out, it is not actual, nor primary, nor final energy, but 'useful' energy that counts when measuring progress towards the energy transition. As the world moves increasingly to low-carbon energy sources, such adjustments to the data will need re-examination from time to time if comparisons between different energy sources are to remain meaningful.

## A2.5 Two common misapprehensions in the understanding of energy data

That the data in Figure A2.1 may come as something of a surprise to most of us is partly due to two common misapprehensions about much of the energy data we are presented with; as follows:

### (i). Plant capacity vs. Annual energy generated

Often we read something like: 'PV capacity installed last year exceeded that of all fossil fuel capacity added.' But PV (and to a lesser extent wind, and some of the other renewables) has a low capacity factor, which is the ratio of the annual energy produced by a plant to the plant's rated capacity multiplied by hours in a year.

For PV for example, a plant's rated capacity is usually given in kilowatts peak (kWp; the kW out from the plant when illuminated at 1000 W/m2, and with the solar cells at 25 °C). But there is no insolation at night, and most of the time insolation on the plant is less than 1000 W/m2; and also usually the cells run hotter (less efficiently) than at 25 °C. As a result, multiplying a PV plant's stated capacity by the number of hours in a year significantly overstates the actual energy the plant produces; with capacity factors of large PV plants typically running at 25% or less, and in northern Europe closer to 10%. This compares to typically around an 80 to 90% capacity factor for nuclear plant, and typically around 60% or so for gas- and coal-fired plant.

The lesson is not to be misled when comparing *capacity data* across different types of plant, and to compare instead on the basis of annual energy produced.

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[7] Note that the rules for converting 'direct' (actual) energy to primary energy are not fixed, and can vary between datasets, and also within a given dataset for different years.

### (ii). Electricity ('power') produced vs. All-energy

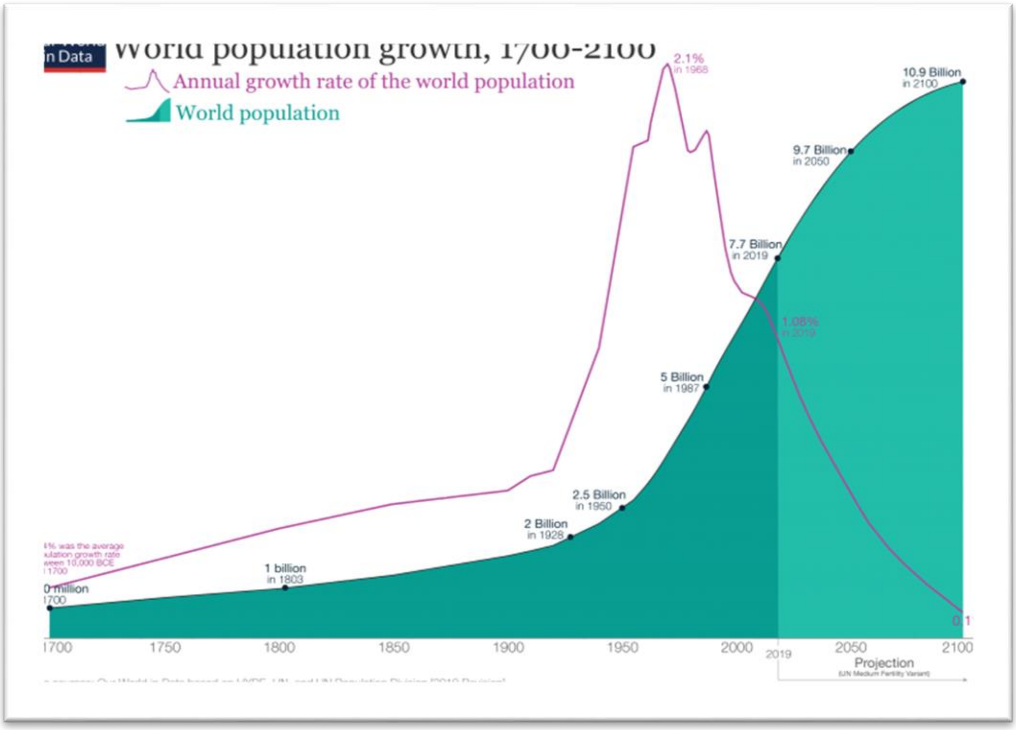
A second problem with the data available is that often these refer only to energy used for *electricity* production, not to all forms of energy that the economy uses. Thus a statement like: 'German renewables nears 50% of the country's total power requirement' means 50% of the annual *electricity* requirement; not 50% of total energy.

(Note that a third common misapprehension relates to proved oil reserves data; this is discussed in Annex 3.)

## A2.6 Energy per capita

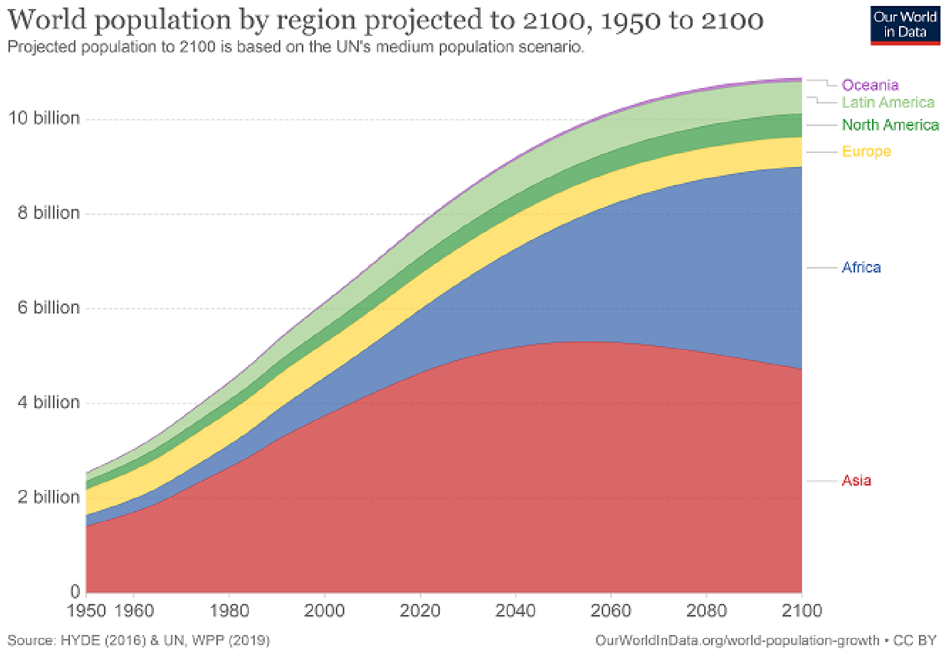
Next, we look at energy per capita. As is well known, over recent decades the world's population has grown rapidly, from about 2 billion in 1930 to nearly 7.8 billion today. Some 11 billion people are expected on the planet by 2100 in the UN's 'medium projection' case, see Figure A2.2; with the bulk of the increase expected to be in Africa, Figure A2.3.

**Figure A2.2: Global population from 1700, and projected to 2100.**



*Source: 'Our World Data' (https://ourworldindata.org/future-population-growth)*

**Figure A2.3: UN 'Medium population' scenario 1950-2100, by region**

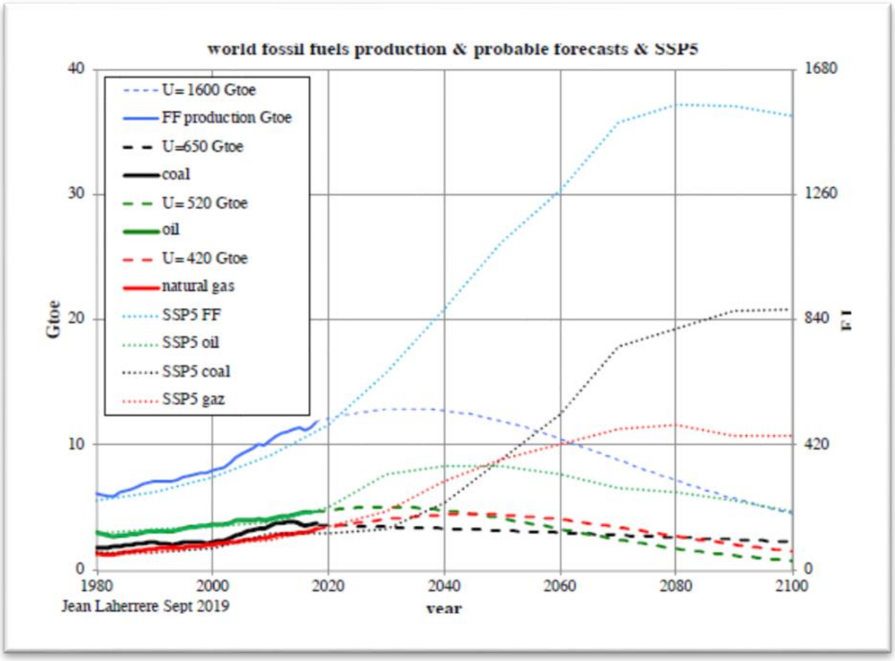


The growth in population shown in the above two figures adds an additional perspective to the global primary energy data of Figure 1 in the main text. As mentioned, the dotted line in that figure shows that while primary energy per capita has grown a little in the last couple of decades, in broader terms it has been pretty much on-plateau since the second oil shock of 1978. Given the rapid reductions climate change is asking in the production of fossil fuels, this report recommends that it is important to carry out adequate modelling to understand how *energy per capita* is likely to evolve over the coming years.

## A2.7 Caveat on high forecasts of global carbon emissions

Next, we look at forecasts of global carbon emissions, where a number of authors have pointed out that the IPCC's 'high-$CO_2$' scenarios look improbable in terms of realistic rates of access to the global fossil fuel resource base. This is illustrated in Figure A2.4, which compares the global annual energy available from gas, oil and coal as envisaged in the IPCC's SSP5 scenario with that modelled by Jean Laherrère on the basis of what he considers the realistic recoverable resources of these fuels.

**Figure A2.4: Forecast of Global Fossil Fuel production: Comparison of IPCC SSP5 Scenario vs. forecast of Laherrère.**



**Notes:**

- Vertical axes: LHS: Gigatonnes of oil equivalent per year; RHS: Exajoules per year.
- Global annual production of each of the fossil fuels, and in total:
- Actual data from 1980 to 2018: Solid lines.
- IPCC SSP5 scenario: Dotted lines.
- Laherrère's forecast: Dashed lines, based on assessed URR's for gas, oil, and coal (and total fossil fuels), respectively, of 420, 520, 650 (and in total 1600) Gtoe.

*Source: Jean Laherrère, Oct. 2019.*

Laherrère's forecasts are based on making what he considers realistic estimates of the ultimately recoverable resource (URR) of each of the three fuels, including consideration of likely rates of access and production costs, and declining annual production of each fuel once the mid-point of its URR has been reached; a so-called 'Hubbert' approach. As can be seen from the figure, the IPCC's high SSP5 scenario of energy production from these fuels out to 2100 in each case is much higher than that deemed technically and economically possible by Laherrère.

This information is supported by the analysis of a range of authors (e.g. Ritchie and Dowlatabadi, 2016; Hausfather and Peters, 2020), and needs to be fed into climate change models so as to avoid modelling 'worst case' scenarios that in fact are very unlikely, and hence which risk distorting policy-making. But at the same time, this information should not detract from the urgency of tackling the 2 °C and 1.5 °C climate goals, and where the carbon emissions remaining to be burnt to stay within these goals are now frighteningly small, as covered under the general heading of 'un-burnable carbon' (see, e.g., carbontracker.org).

## A2.8 Constraints on the rate of energy change

In the main report and in Annex 4 we draw attention to the strong constraints set by EROI ratios (or, more strictly, PROI ratios) to the *rate* that the global energy transition will be possible. Though these constraints are likely to be significant, they are overlooked in nearly all current energy-transition modelling.

## A2.9 Positive developments: Rapidly falling costs of some energies, financing aided by low interest rates, and efficiency gains in energy conversion

To partly offset the somewhat gloomy findings in the sections above, there are indeed places where the energy future looks less daunting.

Firstly, the costs of some of the 'new renewables' have fallen rapidly in recent decades due to both technological innovations and economies of scale; and this trend is expected to continue.

Secondly, for those energies requiring much of their financial investment 'up front' before production begins, such as nuclear, hydro, wind and solar, the current environment of extraordinarily low interest rates considerably lowers financing cost.

Thirdly, the switch to electrification can bring significant efficiency gains in the use of energy in some sectors. An example is the switch to electric power for transport, where a fossil fuel burnt in an internal combustion engine provides motive power at around 20% efficiency, but electricity in an electric motor provides the same motive power at about 80% efficiency, resulting in an up to four-fold reduction in the amount of energy required for the same distance travelled.

## A2.10 'Efficiency' in our need for energy

And finally, in this review of global energy use, it is important to remember that it is not *energy* we seek, nor even, for example, motive power for our farm tractors and transport vehicles, or heat or cooling to our homes, etc. Instead it is the *end results* of energy use that we require, where these end results are food on our tables, shelter over our heads, this shelter to be adequately warm or cooled, manufacture of the goods that make life liveable, and transport of these goods to the places we live, and ourselves to our places of work and enjoyment.

From the point of view of physics, few of these requirements *fundamentally* need large amounts of energy. Food can be grown locally, and fertiliser use can be reduced; homes need little energy to build if well designed, with little energy to heat or cool if well insulated and use made of heat-exchange ventilation; transport does not require energy intrinsically (see 'Hyperloop'; where quite a lot of our usual energy use for road transport involves pushing away the air that the vehicle in front has likewise just pushed away!); and the products that we need can be designed for long-life and high-percentage recycling. We can undoubtedly live just as well with much less energy; and if reasonably forewarned on a daily or weekly basis, probably also with a significant amount of energy intermittency.

## A2.11 Summary

Future energy supply is a complex topic and needs to be looked at from a variety of viewpoints.

Specifically:

- The world has immense resources of energy potentially available, and we can use much less energy for the same desired outputs.

- Energy data need to be handled with care. This includes data on *installed capacity*, *power generated*, and *proved oil reserves*.

- In terms of actual energy produced, the low-carbon energy sources, though growing rapidly, still contribute very little to global total commercial energy; some 7% overall; and just 2% if only the 'new renewables' of wind, solar, biomass, geothermal, wave and tidal are considered, see Figure A2.1. Put another way, oil, gas and coal currently still provide 93% of actual global total commercial energy. On this measure the global energy transition still has a very long way to go.

- If the quantities of energy produced by energy sources that provide electricity directly (nuclear, hydro and the 'new renewables') are multiplied by about 3 to reflect the fact that converting fossil fuels to electricity typically loses about 2/3rds of the fuel's energy, then on such a 'primary energy' basis the global supply of the low-carbon energy sources looks somewhat better, at currently about 16% of total commercial energy; and the 'new renewables' at 5%, see Figure 1 in the main report. But even on this measure the transition is still in its early phase.

- Global energy use *per capita* has stayed roughly constant since about 1980, and thus for many decades the growth in global energy use has been driven mainly by population growth. With this predicted to continue growing for many decades yet, unless major changes are made to the structure of energy demand, the latter will likewise continue to increase.

- Fossil fuel resource limits mean that high $CO_2$ scenarios based on major increases in the use of these fuels should be regarded as very unlikely. Note that this caution does not exclude rapid warming from other sources, including melting of the polar caps, thawing of northern permafrost, and perhaps methane hydrate melting; increased ocean stratification; and land-use changes.

- A key energy perspective is the constraints to the energy transition imposed by EROI ratios. These are only just being modelled adequately, but look as if they may be onerous.

- Among the energy positives is the fact that many renewable resources are widespread; that the costs of most renewables have fallen sharply in recent decades; and that switching to electricity can reduce energy use (for example, electricity for transport uses only perhaps a quarter of the energy a fossil-fuelled internal combustion engine uses for the same distance travelled).

- Finally, in the drive to meet climate change goals and to provide adequate energy for all, it should not be forgotten that large energy savings are possible if the focus is not on energy *supply per se*, but on the various human *needs* that energy provides.

Overall, this report suggests that the energy transition is likely to be more difficult than many envisage, and as a result, the transition will almost certainly cause considerable social stress. To achieve the twin goals of a low-carbon economy and access to adequate energy for all will require the underlying constraints to energy supply to be correctly understood, explained and addressed.

# Annex 3: Global Oil Supply

## A3.1 Oil category definitions

There is no agreed classification of types of oil, but the following definitions are used fairly generally, albeit often with significant modification:

**Conventional oil**: Light or medium density oil occurring in discrete oil fields, usually having an oil-water contact, produced by primary (own pressure, or pumping) or secondary (natural gas or water injection) recovery techniques. Currently this class of oil supplies about 70% of global 'all-liquids', and has constituted the vast majority of oil produced to-date.

**Enhanced oil recovery (EOR)**: This category covers a wide range of techniques to enhance oil production from a reservoir, sometimes classed as tertiary recovery, and includes thermal stimulation, $CO_2$ or nitrogen injection, and injection of a range of other chemicals to improve recovery. EOR may increasingly include the use in conventional oil fields of techniques developed for recovery of 'light-tight' oil.

**Non-conventional oils:** Typically, these refer to oils from extensive accumulations, and includes: light-tight ('shale') oil produced by horizontal drilling combined with hydraulic fracturing and use of proppants; heavy oils produced by thermal means; and oil from tar sands and the Orinoco basin. These oils are distinguished from conventional oil as their production is typically more complex and energy intensive (and hence usually more costly) than for conventional oil because either the oil itself, or the material in which it is located, needs physical alteration for the oil to be produced.

**Natural gas liquids (NGLs):** These are liquids produced from gas reservoirs, either on production, or after treatment of the gas by a processing plant (where the latter are classed as natural gas plant liquids, NGPLs).

**'Other liquids'**: These include:

- Oil produced chemically from kerogen ('oil shale' oil), coal (coal-to-liquids, CTLs) or gas (gas-to-liquids, GTLs).
- Oil produced from biomass, either directly or via chemical conversion.
- Synthetic oil produced chemically from non-oil feedstocks.

As with the non-conventional oils these 'other liquids' are usually more expensive to produce than conventional oil, and have low or very low EROI ratios; and in the case of kerogen, may have an investment/production profile more akin that of mining (where production can be level or increase almost to the point where the mine is exhausted), as compared to that of conventional oil (where because of field size distributions, production reaches a maximum when roughly only half the recoverable resource has been produced).

**Refinery gain**: This is the increase in volume (but not energy) resulting from the processing of oil to produce lighter fractions.

## A3.2 The need for strong caveats on proved oil reserves data by country

Much of past and current analysis of global oil supply has been hindered by the very misleading public domain data on proved oil reserves by country, such as those provided by the US EIA, OPEC and publications including the *Oil & Gas Journal*, *World Oil*, and the BP *Statistical Review of World Energy*; see Campbell and Laherrère (1998), Bentley *et al.* (2007) and Bentley (2018). The problems with these data are four-fold:

- For many countries, and especially in the past, the public-domain proved oil reserves data have been significant *understatements* of the quantity of oil discovered, where the 'most likely' such quantities have been given by the oil industry's 'proved-plus-probable' reserves estimates. However, getting access to the latter data has generally been either difficult or expensive. Over time, a country's proved oil reserves grow towards its proved-plus-probable reserves, but where this growth has been incorrectly ascribed by many analysts as resulting from new oil discoveries and technology gain.

- For a number of the Middle East OPEC countries their declared proved reserves are *overstatements*; being considerably larger than the oil industry estimates of their proved-plus-probable oil reserves. These countries typically overstated their 'proved' reserves between 1982 and 1988 to secure a larger share of OPEC production quotas, and where for at least one such country it is thought that their declared proved oil reserves simply states the country's proved-plus-probable reserves before production started.

- For some countries, in particular Canada and Venezuela, the public-domain proved oil reserves are likely also *overstatements,* in the sense that the data include large amounts of non-conventional oil, the extraction of which is in some doubt.

- And finally perhaps the greatest problem with public-domain proved oil reserves is that the data are often *not stated*, in the sense that commonly the estimates do not get updated, and hence remain unchanged year-on-year, and sometimes unchanged for decades.

As a result of the above data problems, analysts need to treat public-domain proved oil reserves with considerable caution.[8] (Note that there is an initiative underway by the Fossil Fuel Treaty Campaign for a global registry of fossil fuels. This, *inter alia*, aims within 2021 to put into the public domain the proved-plus-probable reserves of the world's oil fields, with these data being collected by Global Energy Monitor and Carbon Tracker, see: https://fossilfueltreaty.org/registry.)

## A3.3 Countries past resource-limited peak in oil production.

Over 70 countries out of a total of 125 or so oil-producing counties in the world now appear to be past their resource-limited production peak of 'all-oil', at least at oil prices up to well in excess of $100/bbl. Such production peaks have had significant impacts for the countries themselves, and in some cases also globally. Examples of countries past resource-limited peak include the major oil producers of Indonesia, the UK, Norway, Venezuela, Iran, Algeria, Kuwait and China, as well as the politically unstable countries of Libya, Syria and Yemen. Major oil producers

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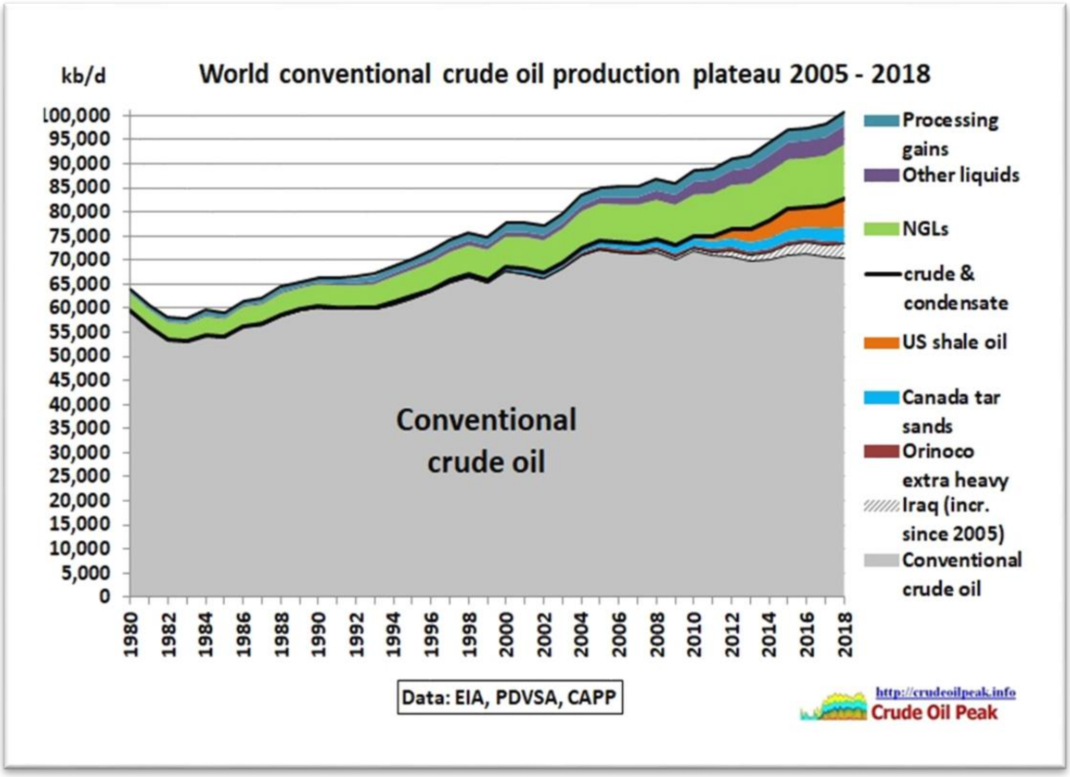
[8] See also Mitchell: 'Petroleum Reserves in Question', Chatham House, 2004; Bentley: "Global oil & gas depletion: an overview", 'Energy Policy', 30 (2002), 189-205.; the UK Energy Research Centre 2009 Sorrell *et al.* report: 'Global Oil Depletion'; and its seven Technical Reports; and Jefferson (2012).

relatively recently past resource-limited peak include Mexico (oil peak in 2004), Nigeria (in 2010) and Russia (possibly in 2018); see Bentley *et al.* (2020).

## A3.4 Resource-limited plateau of global conventional oil production

It is still not widely recognised that global production of conventional oil has been at its *resource-limited* plateau since 2005, again at least for oil prices up to well above $100/bbl; see Figure A3.1. (For definitions of types of oil see above.)

**Figure A3.1: Global production of conventional oil has been on-plateau since 2005, despite on-average high and very high oil prices**



*Source: M. Mushalik; http://crudeoilpeak.info*

The concepts underlying this plateau are as follows:

- The world has large quantities of oil and 'other-liquids' potentially recoverable. But because of production declines in large oil fields, global production of *conventional* oil is on-plateau, and near its resource-limited peak, at least for oil prices up to well above $100/bbl.
- To forecast conventional oil production, one needs to use oil industry proved-plus-probable (2P) oil reserves data, not public-domain proved (1P) reserves. Oil industry 2P data show that global discovery of conventional oil has been in decline for over 50 years.
- Analysing when the global resource-limited plateau of conventional oil will occur requires either estimates of the ultimately recoverable resource (URR) of this class of oil, or else detailed bottom-up by-field modelling. The estimate of the global URR of conventional oil has changed little over the last 50 years, and hence also the expected date of the peak (or plateau) of this oil.

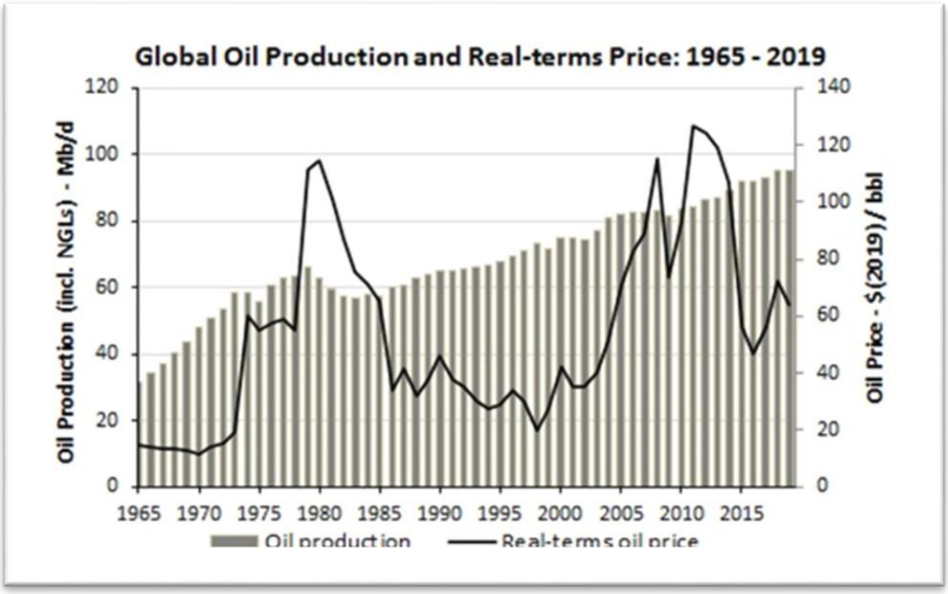
- A higher oil price can certainly bring on more oil. But in the past at least, an oil price above about $100/bbl damages economies and leads to recession.

For further discussion of the above see Hubbert (1949, 1956, 1982), Campbell and Laherrère (1995) and related publications (see References), Bentley *et al.* (2007), Bentley (2016, 2020), and Campbell (2013, 2015).

## A3.5 Explaining the price of oil

In the final section of this Annex on oil supply, we look at the fundamental drivers of the oil price over the last nearly 100 years. Global oil production and real-terms oil price for the somewhat shorter period 1965 to 2019 is shown in Figure A3.2.

**Figure A3.2: Global oil production, and real-terms oil price, 1965 - 2019.**



*Source: BP Statistical Review of World Energy, 2020 edition. Chart design: E. Mearns*

**Notes:**

- Oil production: left-hand scale; real-terms oil price: right-hand scale.
- Oil prices are annual averages; real-terms as deflated by the US CPI.
- Real-terms price during 2005-2014 was approximately the same as of 1978 oil shock.

As Figure A3.2 shows, over this period global production of oil has followed a trajectory of general increase: very rapid increase up to 1972; production declines following the oil price shocks of 1973 and 1978; and more gradual production increases since then, albeit punctuated somewhat by recessions, including that of 2000 and the financial crisis of 2008.

But as the figure also shows, the variations in the real-terms price of oil over this period have been far greater, with a range of about 10:1. Moreover, the fundamental drivers of the oil price changes shown have often been seen as something of a mystery, with a large number of academic papers - often conflicting - written on the topic.

But if access is available to reliable data on the quantities of oil discovered, and when these were discovered, then the general picture of why oil prices have been what they were is not too complex.

The data that must be used come generally from commercial oil industry datasets such as those by IHS Markit, Wood Mackenzie, Rystad Energy and Globalshift Ltd., although the data can be independently collated with considerable effort, as was done by Robelius and others within Aleklett / Höök's group at Uppsala University.

Based on these oil industry data, and drawing heavily also on the outstanding account of the history of oil given by Yergin (1990), the real-terms oil price trajectory for the nearly a century from 1923 to today can be summarised over the following periods, and where the oil prices quoted are the averages over each of these periods of annual-average real-terms $2019 prices:

**a). The 50 years 1923 - 1973, average real-terms oil price: ~$17/bbl.**
This period reflected a large excess of oil discovery over production, plus downward pressure on oil prices from gains from scale and technology. A range of company agreements and US pro-rationing were invoked to prevent oil prices from falling too far.

**b). The nearly 10-year period where oil prices responded to the first and second oil shocks:**

- **First oil shock, 1974 - 1978: ~$55/bbl**.
- **Second oil shock, 1979 - 1982: ~$105/bbl**.

The underlying causes of these shocks were twofold: Unhappiness within OPEC at the low oil prices they were receiving, and the US's resource-limited conventional oil peak in 1970. After this date, US prorationing oil taps were fully open, and hence subsequent OPEC oil restrictions (initially triggered by the Yom Kippur war, and later by the Iranian revolution and the Iran-Iraq war) could not be offset by the US opening its oil taps, as had happened in the past.

**c). Nearly 20 years, 1986 - 2004: ~$35/bbl.**
Over this period the oil price reflected increasing production from already-discovered, but intrinsically more-expensive, oil basins, including the North Sea, Alaska, in Mexico, and far inland in the FSU.

**d). 10 years, 2005 - 2014: ~$100/bbl (spot peak: $140/bbl).**
Oil prices in this decade were a response to the global resource-limited production plateau of conventional oil, where the marginal barrels of oil to meet demand were from expensive non-conventional oils and other liquids, including Canadian tar sands oil, NGLs, biofuels and early oil from fracking.

**e). 4 years, 2015 - 2019: ~$60/bbl.**
This period reflected significant increases in US tight ('shale') oil production.

**f). 2020: ~40/bbl.**
The low oil price in 2020 was caused initially by the OPEC / Russia stand-off over 'OPEC+' quotas, and later by demand destruction due to Covid-19. WTI oil is currently (Feb. 2021) back up to ~$60/bbl due to demand resumption in Asian countries that successfully controlled Covid by lock-down and strict border controls, and in Western countries due to reductions in lock-down plus expectation of successful vaccination programmes.

Based on the data above we can draw the following fairly simple (and perhaps unsurprising) conclusions about oil's real-terms price trajectory over this near-century: that the price of oil is set mainly by the marginal production cost of oil, overridden at times by imbalances in supply/demand; and where these imbalances over two key periods (1974 - 1982 and 2005 - 2014, though not 2020) reflected fundamental oil *resource limits*.

Specifically:

- When there is large potential over-supply due to excess of cumulative discovery over cumulative production (as in the period 1923 - 1973) the oil price can go very low, and company agreements and pro-rationing are needed to stop the price from falling too far.
- When supply is tight, as from 1974 - 1982 due to the resource-limited peak of US conventional oil production, and 2005 - 2014 due to the resource-limited plateau of global conventional oil, the oil price goes high. It can go very high on a spot basis; but is limited over a longer period by demand-destruction (post-1973 and 1978, and briefly post-2008), and by bringing on-stream sources of oil more expensive than those generally previously accessed.
- When supply and demand are roughly in balance (even if this is achieved by company agreements, pro-rationing, or OPEC quotas for conventional oil; or by faster/slower drilling of tight oil), the oil price is set essentially by the cost of the marginal barrels, where these marginal-barrel production costs were:
    - ~$17/bbl (1923 - 1973), due to production from large (and very large) conventional oil fields, mostly onshore, and also reflecting over this long period gains from economies of scale and technical advances in oil discovery and production.
    - ~$35/bbl (1986 - 2004), due to production of intrinsically more expensive conventional oil, including from Alaska, the North Sea, and far-FSU.
    - ~$60/bbl (2015 - 2019), due to production of yet more expensive oil, including primarily shale oil, but also conventional oil from deep offshore, other non-conventional oils such as tar sands and Orinoco oil, NGLs, and 'other liquids' such as CTLs and biofuels.

For greater detail on the above analysis, see Bentley and Bentley (2015a, b).

# Annex 4: The Impact of EROI on the Energy Transition

In this Annex we look at three aspects of the importance of EROI ratios in understanding future energy supply. These aspects are: A general perspective of the analytical usefulness of the ratio; a specific example of why the 'dynamic' EROI ratio needs to be considered, that of the growth of PV installations; and an overview of current EROI modelling as this pertains to the energy transition.

## A4.1 Energy Return on Energy Invested (EROI)

The ratio of energy return to energy invested (EROI) calculates the energy delivered by an energy source divided by the energy required to produce this energy. EROI is an important metric that avoids some of the problems of financial analysis of energy supply while generating additional insights into the factors that influence both present energy prices and future energy availability.

EROI has two aspects, 'static' and 'dynamic'. The normal EROI statistic used is the 'static' EROI where no consideration is given to changes over time in the use of the energy source. Note that the static EROI of many non-conventional fossil fuels is often considerably less than that of the corresponding conventional fossil fuel (Lambert *et al.*, 2013). Furthermore, the EROI's of most renewable energy sources (except for hydropower) are generally considerably lower than those of fossil fuels – at least than the high EROI ratios that were generally the case for fossil fuels some decades back.

By contrast, the 'dynamic' EROI includes consideration of changes over time in the use of the energy source, and is discussed briefly in Section A4.2, below.

As Hall (2017) notes, the EROI ratio is useful as it integrates the counteracting effects of resource depletion vs. technological improvements in energy production. In particular, as Hall points out, a lower overall EROI ratio means that a society must divert more of its total economic activity to obtaining the energy needed to run the remainder of the economy, and where an earlier paper (Hall *et al.*, 2009) suggested that a minimum average EROI of perhaps around 10:1 may be required for industrial societies to function. If this is the case, then those energy sources such as liquid biofuels with EROIs below this ratio will need to be augmented by energy sources with higher energy returns.

Because the world is almost certainly in transition from higher-EROI fuels to lower-EROI ones, and because modern society is so crucially dependent on energy use, this transition in energy sources can be expected to be problematic.

Hall (2017) notes also that the general view of economists historically has been that energy resource depletion is not an issue for the future of economic production because the higher price that results from the depletion of an energy resource encourages a reduction in its use, and the substitution of alternatives, including in particular production from lower-grade sources.

However, consideration of the EROI ratio provides a powerful response to the latter argument (that ever-lower resource grades can be used economically). This is because as higher grade energy sources are depleted, unless significant advances are made in resource extraction techniques, the energy required to produce energy from lower-grade sources increases, and - unless energy costs decline - this raises the cost of energy from that resource. Moreover, at some point the energy input to produce the energy source is as great as its total energy output, and then the energy resource is simply uneconomic (unless a cheaper fuel is used to produce a more expensive one).

While this debate with the traditional economists is likely to continue, we note that they have explained away the declining quality of energy (and of mineral resources in general) by arguing that the increase in GDP of the US economy during most of the 20th century correlated with increases in capital and labour together with increases in technology and human ingenuity. These arguments however fall down when energy is included in the economic analysis. For example, Cleveland (1991) found that when the price of energy declined this enabled an increase in the use of energy which compensated for resource depletion without an increase in production costs. And Kummel (2020) showed that energy was more important than capital or labour in explaining increases in GDP.

In this report we are concerned that failure to take account of falling EROI ratios comes with a high risk that economic models will underestimate the role of energy in terms of future economic activity. EROI analysis thus needs to be incorporated into energy forecasting to better guide policy and investment decisions during the energy transition.

## A4.2 Example of 'dynamic' EROI of global PV installations

In this section we illustrate the potential impact of a 'dynamic' EROI calculation when applied to a rapidly growing energy source, in this case that of photovoltaics (PV).

We start by making the assumption that on-average fully-installed PV systems take 3 years to pay back the energy involved in their manufacture, shipping and installation (including installation of any additional roads, transformers and power lines needed). If PV system life is assumed to be 30 years, then on average such systems yield a respectable 'static' EROI of 10.

But if the *rate* of PV installations globally grows by 33% a year, then while this growth continues no net energy returns to society. That is, such PV systems have a 'dynamic' EROI of only 1 during this growth phase, as each year the energy that the existing PV systems produce is fully used up in building the ever-larger number of new PV systems.

Since the actual growth of PV systems installed globally over the period 2007 - 2018 was 45% per year, if the simple assumptions on system life and energy payback time made here are about correct, then globally PV systems made no net energy contribution to society over this period.

These data can perhaps be appreciated more vividly if considered from three points of view: The person who installs the PV system is happy, obtaining electricity from the system from the day it is turned on. A person who owns the system, but also worries about energy return, is also fairly happy. They have to wait three years before the system returns net energy, but then yields net energy for the remaining 27 years of its life. Only the person who worries about net energy globally is unhappy: he or she knows that if PV installations grow globally at greater than 33% annually, and if the data assumptions made above are correct, then the world as a whole gets no net energy back until this growth phase slows.

Note, however, that a number of important things need to be kept in mind when doing such calculations. Firstly, EROI calculations are not straightforward, and correct system boundaries in making such calculations should follow now-established best practice. And the input energy cost considered must be of fully-installed PV systems; not just that of PV modules at the factory. Secondly, we need renewable energy systems for climate change reasons, so may well be happy to invest energy (still largely fossil) now in order to have renewable energy systems available in the future. Thirdly, the energy cost of producing installed PV systems has fallen fast now for many years, and with new cells such as tandem perovskite / silicon in sight, can be expected to fall further. And finally, as indicated elsewhere in this report, in such calculations the efficiency of energy use also needs to be taken into account, where for example the electricity in an electric vehicle is used perhaps four times more efficiently in terms of motive power than fossil fuel in an internal combustion vehicle.

## A4.3 A brief survey of energy modelling that takes account of EROI ratios

This section gives brief survey of the energy modelling known to us that takes account of EROI ratios.

While there are now many academic papers on EROI ratios, so far few papers seek to examine the impact these ratios might have on the energy transition, and where, as explained above, the importance of considering EROI ratios is that they can significantly reduce the net-energy available to society, especially during the *growth phase* of those energies where energy investment comes largely before energy production.

Note that the information here requires checking and elaboration. Moreover, this list is almost certainly missing other models in this area; we will be pleased to receive information to augment this list. Note also that the section on modelling in the main text of this report lists a range of factors that in our view need to be included in energy models if a sufficiently detailed view of future global energy supply is to be obtained, but where in general the models listed below are more limited, and include only a number of these factors.

We look in turn at models as follows: those that include EROI ratios for global oil supply; those that include these ratios for other specific energy sources, and those models which include EROI ratios for the energy transition as a whole. In each case we reference the paper where the model is discussed, and – where available – give the abstract.

### A4.3.1 Modelling the impact of EROI on future global oil supply

Those models known to us where the impact of EROI ratios on future global oil supply is examined are as follows:

**i). Murphy, D.** ***The Net Hubbert Curve: What Does It Mean?***
Website: *The Oil Drum: Net Energy*; http://theoildrum.com/node/5500; posted June 22, 2009.
Conclusion: "The implications of these results are vast, but in general, declining EROI is going to make it very difficult to meet the net energy needs of future society."

[Note: Murphy may have been one of the first to look formally at this topic, but as the title of the paper indicates, Hubbert had earlier pointed out that if the energy return of a fossil fuel resource falls too far, the resource will no longer be worth extracting.]

**ii). Campbell, C.J. *Modelling Oil and Gas Depletion***

*The Oil Age* **1** (1) 9-34 (2015).

Abstract: This paper describes the data and methodology used in the author's forecast model for oil and gas production. This models the world's 64 largest oil and gas producing countries individually, plus a category for remaining countries. For oil, forecasts primarily cover production of 'Regular Conventional' oil (oil in fields, less Arctic, deep offshore, and very heavy oil); and separate forecasts are made for the production of NGLs and the non-conventional oils. The modelling involves the following steps:

- Obtain data on past production by year by hydrocarbon category since production started for each of the 65 regions modelled.
- Likewise, assemble estimates on the total quantities of oil and gas likely to be produced by each region by the year 2100. A number of techniques can be used for this, including extrapolation of the following: 'creaming curves' of oil or gas discovery – i.e., plots of discovery over time vs. number of exploration ('new field wildcat') wells drilled; parabolic fractal representations of discovery; and production plots using a linearised 'Hubbert' curve approach. The data used need to be based on proved-plus-probable ('2P') estimates of remaining reserves, not on 'proved' ('1P') reserves; and checked against geologically based evaluations of the oil and gas remaining to be discovered.
- Subtract past production from this 'total production to 2100', and then estimate the percentages of this that will come from already-discovered fields ('2P reserves'), and the yet-to-find.
- Assess for each region the future production rate, taking into account 'mid-point' peak; and realistic post-peak production decline rates.
- Add in data on expected production on NGLs and non-conventional oils in those regions where these liquids will be important to give global forecasts.
- In addition, the modelling allows the different ratios of energy return on energy invested ('EROI') of the different categories of hydrocarbons to be accounted for, to yield forecasts of the net-energy that will be available to society.

Based on the above modelling the paper finds that the First Half of the Oil Age is about over, and the Second Half will see declining global oil and gas production due to resource depletion. The paper concludes that this need not be a 'doomsday' message, provided society acts in positive and constructive ways to these constraints imposed by Nature.

**iii). Solé *et al. Renewable transitions and the net energy from oil liquids: A scenarios study***

Jordi Solé, Antonio García-Olivares, Antonio Turiel, Joaquim Ballabrera-Poy

*Renewable Energy*, Volume 116, Part A, February 2018, Pages 258-271

Abstract: We use the concept of Energy Return on Energy Invested (EROI) to calculate the amount of the available net energy that can be reasonably expected from World oil liquids during the next decades (till 2040). Our results indicate a decline in the available oil liquids net energy from 2015 to 2040. Such net energy evaluation is used as a starting point to discuss the feasibility of a Renewable Transition (RT). To evaluate the maximum rate of Renewable Energy Sources (RES) development for the RT, we assume that, by 2040, the RES will achieve a power of 11 TW ($10^{12}$ Watt). In this case, by 2040, between 10 and 20% of net energy from liquid hydrocarbons will be required. Taking into account the oil liquids net energy decay, we calculate the minimum annual rate of RES deployment to compensate it in different scenarios. Our study shows that if we aim at keeping an increase of 3% of net energy per annum, an 8% annual rate of RES deployment is required. Such results point out the urgent necessity of a determined policy at different levels (regional, national and international) favoring the RT implementation in the next decades.

**iv). Delannoy *et a*l.: *Gross vs. net energy of oil liquids at global scale: the reconsideration of peak oil.***

Authors: Louis Delannoy, Pierre-Yves Longaretti, David Murphy, Emmanuel Prados
Submitted to *Energy Policy*.

### A4.3.2 Modelling EROI for other specific energies

There are a number of such papers, for example:

**Dale, M. and Benson, S. M. (2013) *The Energy Balance of the Photovoltaic (PV) Industry - Is the PV Industry a Net Energy Provider?***
*Environmental Science & Technology*, 47(7), 3482-3489, 2013.

Abstract: A combination of declining costs and policy measures motivated by greenhouse gas (GHG) emissions reduction and energy security have driven rapid growth in the global installed capacity of solar photovoltaics (PV). This paper develops a number of unique data sets, namely the following: calculation of distribution of global capacity factor for PV deployment; meta-analysis of energy consumption in PV system manufacture and deployment; and documentation of reduction in energetic costs of PV system production. These data are used as input into a new net energy analysis of the global PV industry, as opposed to device level analysis. In addition, the paper introduces a new concept: a model tracking energetic costs of manufacturing and installing PV systems, including balance of system (BOS) components. The model is used to forecast electrical energy requirements to scale up the PV industry and determine the electricity balance of the global PV industry to 2020. Results suggest that the industry was a net consumer of electricity as recently as 2010. However, there is a >50% that in 2012 the PV industry is a net electricity provider and will "pay back" the electrical energy required for its early growth before 2020. Further reducing energetic costs of PV deployment will enable more rapid growth of the PV industry. There is also great potential to increase the capacity factor of PV deployment. These conclusions have a number of implications for R&D and deployment, including the following: monitoring of the energy embodied within PV systems; designing more efficient and durable systems; and deploying PV systems in locations that will achieve high capacity factors.

### A4.3.3 Modelling EROI as it affects the Global Energy Transition

There are many tens of global energy transition models, most from very respected groups. But to-date very few of these include the crucial aspect of EROI constraints. Those known to us that include EROI ratios are:

**(i). King, L.C. and van den Bergh, J.C.J.M: *Implications of net energy-return-on-investment for a low-carbon energy transition***

*Nature Energy* **3**, 334–340 (2018).: https://doi.org/10.1038/s41560-018-0116-1

Abstract: Low-carbon energy transitions aim to stay within a carbon budget that limits potential climate change to 2 °C - or well below - through a substantial growth in renewable energy sources alongside improved energy efficiency and carbon capture and storage. Current scenarios tend to overlook their low net energy returns compared to the existing fossil fuel infrastructure. Correcting from gross to net energy, we show that a low-carbon transition would probably lead to a 24–31% decline in net energy per capita by 2050, which implies a strong reversal of the recent rising trends of 0.5% per annum. Unless vast end-use efficiency savings can be achieved in the coming decades, current lifestyles might be impaired. To maintain the present net energy returns, solar and wind renewable power sources should grow two to three times faster than in other proposals. We suggest a new indicator, 'energy return on carbon', to assist in maximizing the net energy from the remaining carbon budget.

**(ii). Capellán-Pérez *et. al. MEDEAS: a new modelling framework integrating global biophysical and socioeconomic constraints***

Inigo Capellán-Pérez, Ignacio de Blas, Jaime Nieto, Carlos de Castro, Luis Javier Miguel, Oscar Carpintero, Margarita Mediavilla, Luis Fernando Lobejon, Noelia Ferreras-Alonso, Paula Rodrigo, Fernando Frechoso and David Alvarez-Antelo

Energy Environ. Sci., 2020, 13, 986.

Abstract: A diversity of integrated assessment models (IAMs) coexists due to the different approaches developed to deal with the complex interactions, high uncertainties and knowledge gaps within the environment and human societies. This paper describes the open-source MEDEAS modelling framework, which has been developed with the aim of informing decision-making to achieve the transition to sustainable energy systems with a focus on biophysical, economic, social and technological restrictions and tackling some of the limitations identified in the current IAMs. MEDEAS models include the following relevant characteristics: representation of biophysical constraints to energy availability; modelling of the mineral and energy investments for the energy transition, allowing a dynamic assessment of the potential mineral scarcities and computation of the net energy available to society; consistent representation of climate change damages with climate assessments by natural scientists; integration of detailed sectoral economic structure (input–output analysis) within a system dynamics approach; energy shifts driven by physical scarcity; and a rich set of socioeconomic

and environmental impact indicators. The potentialities and novel insights that this framework brings are illustrated by the simulation of four variants of current trends with the MEDEAS-world model: the consideration of alternative plausible assumptions and methods, combined with the feedback-rich structure of the model, reveal dynamics and implications absent in classical models. Our results suggest that the continuation of current trends will drive significant biophysical scarcities and impacts which will most likely derive in regionalization (priority to security concerns and trade barriers), conflict, and ultimately, a severe global crisis which may lead to the collapse of our modern civilization. Despite depicting a much more worrying future than conventional projections of current trends, we however believe it is a more realistic counterfactual scenario that will allow the design of improved alternative sustainable pathways in future work.

### (iii). Solé *et al. Modelling the renewable transition: Scenarios and pathways for a decarbonized future using* pymedeas*, a new open-source energy systems model*

Solé, J., Samsó, R., García-Ladona, E., García-Olivares, A., Ballabrera-Poy, J., Madurell, T., Turiel, A., Osychenko, O., Álvarez, D., Bardi, U., Baumann, M., Buchmann, K., Capellán-Pérez, Í., Černý, M., Carpintero, Ó., De Blas, I., De Castro, C., De Lathouwer, J.-D., Duce, C., Eggler, L., Enríquez, J.M., Falsini, S., Feng, K., Ferreras, N., Frechoso, F., Hubacek, K., Jones, A., Kaclíková, R., Kerschner, C., Kimmich, C., Lobejón, L.F., Lomas, P.L., Martelloni, G., Mediavilla, M., Miguel, L.J., Natalini, D., Nieto, J., Nikolaev, A., Parrado, G., Papagianni, S., Perissi, I., Ploiner, C., Radulov, L., Rodrigo, P., Sun, L., Theofilidi, M.

*Renewable and Sustainable Energy Reviews*, Volume 132, October 2020, 110105

Abstract: This paper reviews different approaches to modelling the energy transition towards a zero carbon economy. It identifies a number of limitations in current approaches such as a lack of consideration of out-of-equilibrium situations (like an energy transition) and non-linear feedbacks. To tackle those issues, the new open source integrated assessment model *pymedeas is* introduced, which allows the exploration of the design and planning of appropriate strategies and policies for decarbonizing the energy sector at World and EU level. The main novelty of the new open-source model is that it addresses the energy transition by considering biophysical limits, availability of raw materials, and climate change impacts. This paper showcases the model capabilities through several simulation experiments to explore alternative pathways for the renewable transition. In the selected scenarios of this work, future shortage of fossil fuels is found to be the most influential factor of the simulations system evolution. Changes in efficiency and climate change damages are also important determinants influencing model outcomes.

# Annex 5: Mineral Supply

Many mineral resource studies have fallen into two traps, as follows:

1. **Studies that use published data on the global *reserves* of a particular mineral to forecast how long the mineral's supply will last.**

   Generally, mineral *reserves* refer to what has been found, and is considered economic to extract at current mineral prices. By contrast, often a mineral's *recoverable resources* are far larger (up to 100 or even 1000 times larger) than current reserves, particularly if the energy and technology are available to mine ever lower-concentration ores of the mineral.

   Many minerals studies have thus been misleading, as they have relied only on published reserves of the mineral in question.

2. **Studies that ignore the 'mid-point' production peak**

   An individual mineral quarry or mine may see constant - or even increasing - production over much or all of its life, up to the point where the mine is judged exhausted at the existing mineral price, and production stops.

   But for total production of a mineral in a region, or globally, there are usually numerous individual potential sources. In this case, a common profile for regional or global production is for this to rise to approximately the mid-point of the mineral's total availability, and then to enter a long decline. This profile reflects the underlying effect of the slower rates on-stream of the smaller, later, more difficult, and often more expensive, sources of the mineral.

   Proper modelling of mineral availability needs therefore to take into account estimates of total recoverable resources, extraction cost (itself often a strong function of energy cost), and likely global production profile of the mineral, the latter usually reflecting a 'mid-point' rule or similar. Some studies have properly incorporated these factors, but unfortunately many have not.

On the wider issue of declining mineral resources globally and corresponding quantities of energy used for extraction, see, for example, Calvo (2016).

# Annex 6: Some Notes on Government Support for the Energy Transition

## A6.1 Policy options

Actions to tackle climate change can come from a wide range of actors, including individuals (switching to a lower-meat diet, installing a heat pump, flying less); pressure groups (encouraging disinvestment in fossil fuels, or the recent news that investors managing $13 trillion in assets have called for an international climate treaty to 'catalyse massive global investments' in low-carbon technologies); corporations (Google achieving zero-carbon and aiming to offset past emissions, and BP and other oil company commitments to drastically reduce $CO_2$ emissions); cities and regions (e.g., California's strong commitments); countries (e.g., the UK's legislated commitment to achieve zero-carbon by 2050); and by international agreement, such as that of the IPCC.

In this annex we focus mainly on government policies. These can range from general encouragement of the populace to outright diktat, and where recent history warns that unless carefully thought out such measures can have considerable undesirable consequences, see Section A6.2.

In the table below we list some of the policies and regulations available to support the energy transition, and indicate briefly caveats that need to be kept in mind.

| Policy | Caveats | Note |
|---|---|---|
| Scrapping fossil fuel production subsidies | Unemployment; loss of economic activity; loss of energy security | 1 |
| Scrapping fossil fuel consumption subsidies | Fuel poverty, public unrest, revolution | 2 |
| Switching fossil fuel subsidies to renewables | Economic distortion, risk of 'backing the wrong horse' | 3 |
| Taxing fossil fuels | Economic distortion | 4 |
| Government fiat limiting fossil fuel production | Economic distortion; loss of energy security | 5 |
| Buying-up $CO_2$ producers | Economic distortion, cost | 6 |
| Tradable Energy Quotas / Feasta's 'Cap & Share' | Potentially more effective than a carbon tax, but so far untested | 7 |
| Carbon taxes | Does not guarantee achieving specific carbon reductions. Taxes must be quite high to achieve useful results. | 8 |
| Carbon 'cap and trade' policies | Currently applied only to certain industrial sectors | 9 |
| Feed-in tariffs | Can exacerbate fuel poverty, and risk 'backing the wrong horse' | 10 |

| | | |
|---|---|---|
| Contracts for difference | Economic cost | 11 |
| Supporting 'green' R&D | Many R&D projects fail | 12 |
| 'Green Deals': Investments in renewable energy | Experience shows that pitfalls in implementation abound | 13 |
| Feasible measures in developing countries | Often reliant on aid and capacity building | 14 |
| IPCC NDC's | So far inadequate to meet 2 ºC | 15 |

**Notes**

1. Many fossil fuel producing countries provide a range of subsidies on the production of such fuels, ranging from direct volume-related subsidies that help ensure profitability of these sectors of the economy, and support domestic production in the face of energy security risks, to lesser subsidies such as depletion allowances, lower pollution restrictions, and training grants etc. Over recent years the value of such subsidies have probably reduced.

2. Findings by the IEA and others indicate that far larger subsidies on fossil fuels are those on consumption, where a number of major oil producers for example have – at least in the past – heavily subsidised the cost of fuel by charging domestic customers prices below (and sometimes very much below) international prices. However, the examples of countries raising subsidised domestic fuel prices and encountering serious domestic backlash are many, especially if the price increases are sudden and large. (Information on fossil fuels subsidies is given in the 2019 IMF Working paper: *Global Fossil Fuel Subsidies Remain Large: An Update Based on Country-Level Estimates*, by Coady *et al.* This indicates that fossil fuel consumption subsidies (at around $300bn annually) are indeed very much larger than production subsidies; and that if externalities are included, the overall cost of societal harm from the use of fossil fuels might be as high as $5tn/year.)

3. Such 'ring-fencing' can assist in getting legislation passed, but as pointed out under 'caveats' risks economic distortion and 'backing the wrong horse'.

4. Fossil fuel use is taxed in nearly all countries, and even within major fossil fuel producers in many cases. In Europe fuel duties on vehicle fuel are especially high and raising these (or threats of doing so) have provoked backlash. (For a recent perspective on such taxes, see the OECD Jan. 2021 report: *Taxing Energy Use for Sustainable Development - Opportunities for energy tax and subsidy reform in selected developing and emerging economies*.)

5. This potential policy has so far been somewhat overlooked, although it provides a direct way to achieve $CO_2$ targets from fossil fuel combustion. The Montreal Protocol on limiting CFCs has worked reasonably well by constraining not use (where there were millions of users), but manufacture, where these were very limited. A parallel situation applies to fossil fuels where globally only a relatively few producers generate nearly all of production. A problem here, only somewhat similar to CFCs, is the different nationalities of fossil fuel producers and the conflicting perspectives of the countries in which these producers are registered.

6. A suggestion has been made that major governments could buy up the shares of major $CO_2$ producers. For the US this is estimated at US $½ trillion. See: *The Policy Weapon Climate Activists Need. Government can save the climate from burning the same way it saved the economy from depression: Buy out the companies behind the crisis*. By Gar Alperovitz, Joe Guinan and Thomas M. Hanna. The Nation, April 26, 2017. https://www.thenation.com/article/archive/the-policy-weapon-climate-activists-need

7. By assigning energy or GHG quotas to the population, and allowing trading among those who use less, climate change goals can be met, and measures to avoid energy or GHG emissions can be rewarded. See: *https://www.flemingpolicycentre.org.uk/lean-logic-surviving-the-future*

8. Carbon taxes are widely suggested, they have the advantage of allowing industry to select which technologies to pursue, and market forces to decide which get adopted in volume. However, they do not guarantee meeting climate change goals, and some past attempts to institute such taxes have failed.

9. Widely adopted in richer nations for high-$CO_2$ manufacturing sectors; judged by-and-large a success.

10. Feed-in tariffs to support the adoption of renewable energies has been a great success. Originally suggested elsewhere, there were first adopted at scale in Germany. They have the advantage they are not a government subsidy (and hence are not government expenditure), but are mandated costs that energy utilities must bear. Their drawback is in increasing the cost of energy, and hence steps to help with ‘energy poverty’ can sometimes be needed.

11. The UK government website says: “The Contracts for Difference (CfD) scheme is the government’s main mechanism for supporting low-carbon electricity generation.”; see: https://www.gov.uk/government/publications/contracts-for-difference/contract-for-difference

12. University academics are good at dreaming up novel ideas, and most of the low-$CO_2$ innovations we have today had their birth in academic research. But it needs to be recognised that R&D projects intended to innovate or advance a technology often fail.

13. Large ‘Green-Deals’, whether in the US, Europe or elsewhere are the current zeitgeist (see, e.g., Hepburn et al., 2020). But as Section A6.2 indicates, they can be hard to implement successfully.

14. Investment in renewable energy in developing countries is mostly reliant on aid. International investment funds, such as the Green Climate Fund, have been established to support the energy transition in these countries, and where such investment is often accompanied by capacity building.

15. Global agreement on carbon emissions is not a history lesson to be proud of. The IPCC initially moved to a global-wide agreement on GHG emissions in the Kyoto Protocol. But President George W. Bush announced that the U.S. would not ratify this. Finally, at COP 21 in 2015 parties adopted the Paris Agreement. This represents a hybrid of the ‘top-down’ Kyoto approach and the ‘bottom-up’ approach of the Copenhagen and Cancun agreements, and establishes common binding procedural commitments for all countries, but leaves it to each

country to decide its nonbinding 'nationally determined contribution' (NDC). As indicated in the table above, current NDC's are not sufficient to secure the 2 °C goal; although on the plus side the Agreement establishes an enhanced transparency framework to track countries' actions, and calls on countries to strengthen their NDCs every five years. President Obama ratified the Paris Agreement through executive action without seeking Senate advice and consent, and the agreement entered into force in late 2016, much earlier than expected. In June 2017, President Trump announced his intent to withdraw the United States from the Agreement stating: "The Paris accord will undermine [the U.S.] economy," and "puts [the U.S.] at a permanent disadvantage." Formal withdrawal took effect on Nov. 4th, 2020. On January 20, 2021 President Biden signed an executive order to re-join the agreement. *[Adapted from: https://www.c2es.org/content/history-of-un-climate-talks/]*

## A6.2 Examples of how 'Green-energy' support can go wrong

Policymakers need to be aware that well-intentioned 'green-energy' support policies can go badly wrong. Examples include France's fuel tax increases to address climate change which led to the *gilets jaunes* movement; the UK's delaying implementation of its fuel duty escalator in the face of increasing public resistance; The UK's 'Green Deal' which was subsequently heavily criticised by the National Audit Office; Northern Ireland's 'cash for ash' Renewable Heat Incentive scandal which reportedly cost the public purse up to perhaps €500 million; Ontario's Green Energy Act which reportedly failed disastrously on several fronts; and the US' loan guarantee loss of $528 million under the American Recovery and Reinvestment Act resulting from the failure of the PV company Solyndra.

Below we give brief quotes on four of these examples, but warn that we have not examined these cases ourselves, and simply quote the sources indicated.

### Case 1: A Comment on the UK 'Green Deal', following a National Audit Office report

***'Why the UK Green Deal failed and why it needs a replacement'***

- April 18, 2016 by David Thorpe; from: https://energypost.eu/uk-green-deal-failed-needs-replacement/

"The National Audit Office in the UK has concluded that the Department of Energy and Climate Change's (DECC) £240 million Green Deal has achieved virtually nothing. David Thorpe, independent consultant and author of several books on energy efficiency in buildings, explains what went wrong. He compares the British approach with the successful German scheme and argues that a new scheme is urgently needed."

### Case 2: 'Cash-for-Ash' fiasco: Northern Ireland's Enron on Craggy Island'

- Rory Carroll Ireland correspondent; @rorycarroll72; 28 Sep 2018 12.59 BST

*From: https://www.theguardian.com/uk-news/2018/sep/28/cash-for-ash-arlene-foster-accountable-but-not-responsible*

And: ***'Cash-for-ash inquiry delivers damning indictment of Stormont incompetence: Findings lay bare 'multiplicity of errors and omissions' behind bungled green energy scheme'***; 13 Mar 2020 15.25 GMT

*From: https://www.theguardian.com/uk-news/2020/mar/13/cash-for-ash-inquiry-delivers-damning-indictment-of-stormont-incompetence*

"The former first minister Arlene Foster recently appeared at a public inquiry to rebuff accusations that she was to blame for a fiasco which led to the collapse of Northern Ireland's power-sharing government, and which may cost taxpayers hundreds of millions of pounds. … The official report … laid bare a "multiplicity of errors and omissions" behind a bungled green energy scheme. … However, Coghlin absolved participants of corruption, a crucial finding that will limit the political fallout …"

## Case 3: 'Ontario's Green-energy Catastrophe'

- Babatunde Williams; on-line article, 17th September 2020 at: *https://www.spiked-online.com/2020/09/17/ontarios-green-energy-catastrophe/; extract re-published here with permission.* [Babatunde Williams is a public policy student at the Hertie School in Berlin.]

***'A transition to renewables sent energy prices soaring, pushed thousands into poverty and fuelled a populist backlash.'***

"In February 2009, Ontario passed its Green Energy Act (GEA). It was signed a week after Obama's Economic Recovery and Reinvestment Act in the US, following several months of slow and arduous negotiations. It also had grand plans to start a 'green recovery' following the financial crash – although on a more modest scale. … But on 1 January, 2019, Ontario repealed the GEA, one month before its 10th anniversary. The 50,000 guaranteed jobs never materialised. The 'decolonisation' of energy didn't work out, either. A third of indigenous Ontarians now live in energy poverty. Ontarians watched in dismay as their electricity bills more than doubled during the life of the GEA. … By 2015, Ontario's auditor general, Bonnie Lysyk, concluded that citizens had paid 'a total of $37 billion' above the market rate for energy. They were even 'expected to pay another $133 billion from 2015 to 2032', again, 'on top of market valuations'."

## Case 4: US Government Support for Solyndra

- *From: https://en.wikipedia.org/wiki/Solyndra*

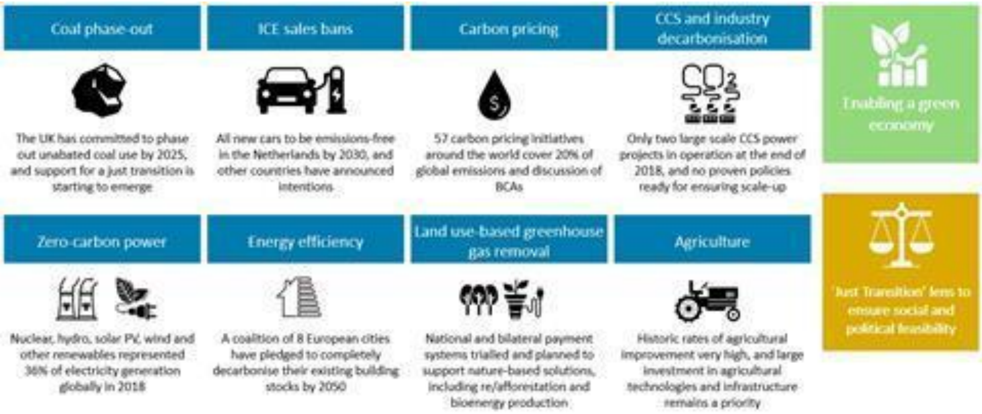
"Solyndra was a manufacturer of cylindrical panels of copper indium gallium selenide (CIGS) thin film solar cells based in Fremont, California. Although the company was once touted for its unusual technology, plummeting silicon prices led to the company's being unable to compete with conventional solar panels made of crystalline silicon. The company filed for bankruptcy on September 1, 2011. … Solyndra received a $535 million U.S. Department of Energy loan guarantee, the first recipient of a loan guarantee under President Barack Obama's economic stimulus program, the American Recovery and Reinvestment Act of 2009. However, Solyndra officials used inaccurate information to mislead the Department of Energy in its application. While the overall loan program was in the black in 2014, it took a $528 million loss from Solyndra."

# Annex 7: The Energy Transition: Graphics

This annex presents a number of charts that help explain some of the key issues covered in this report.

## Inevitable Policy Response (IPR)

The most likely policy levers to secure an accelerated and just transition are starting to emerge.



The UK has committed to phase out unabated coal use by 2025, and support for a just transition is starting to emerge

All new cars to be emissions-free in the Netherlands by 2030, and other countries have announced intentions

57 carbon pricing initiatives around the world cover 20% of global emissions and discussion of BCAs

Only two large scale CCS power projects in operation at the end of 2018, and no proven policies ready for ensuring scale-up

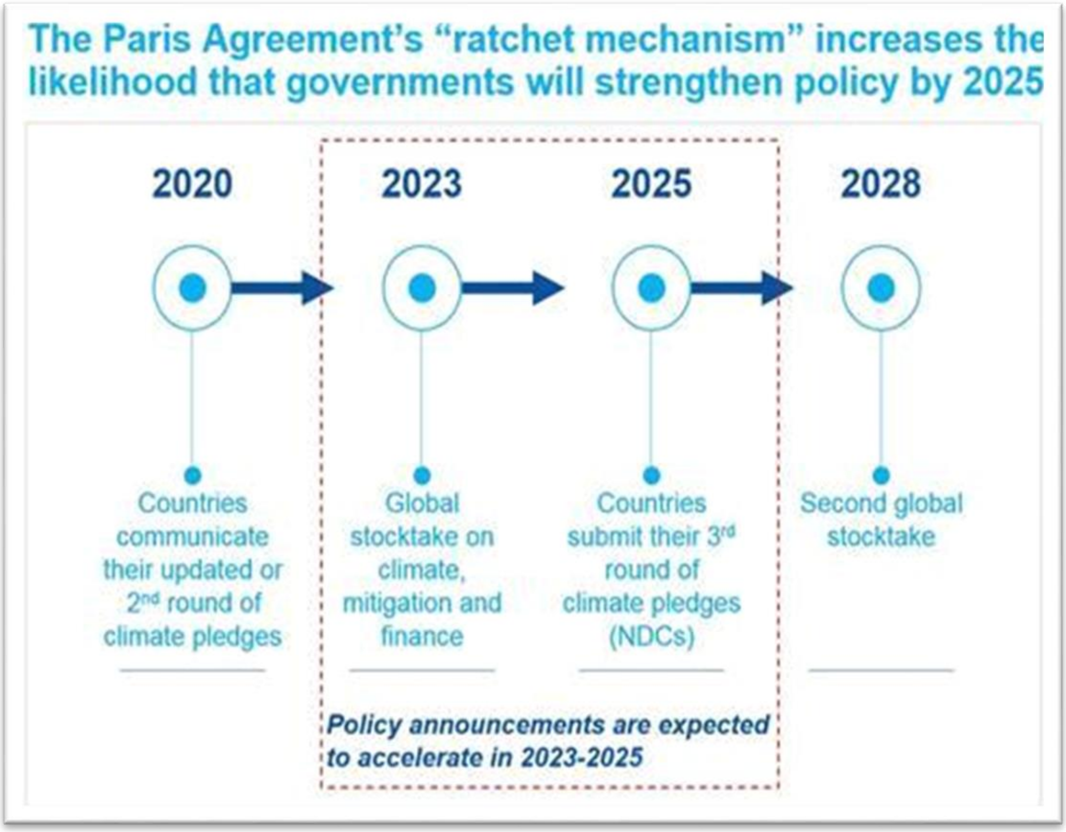
Nuclear, hydro, solar PV, wind and other renewables represented 36% of electricity generation globally in 2018

A coalition of 8 European cities have pledged to completely decarbonise their existing building stocks by 2050

National and bilateral payment systems trialled and planned to support nature-based solutions, including re/afforestation and bioenergy production

Historic rates of agricultural improvement very high, and large investment in agricultural technologies and infrastructure remains a priority

*https://www.unpri.org/inevitable-policy-response/what-is-the-inevitable-policy-response/4787.article*


The Paris Agreement's "ratchet mechanism" increases the likelihood that governments will strengthen policy by 2025

2020: Countries communicate their updated or 2nd round of climate pledges

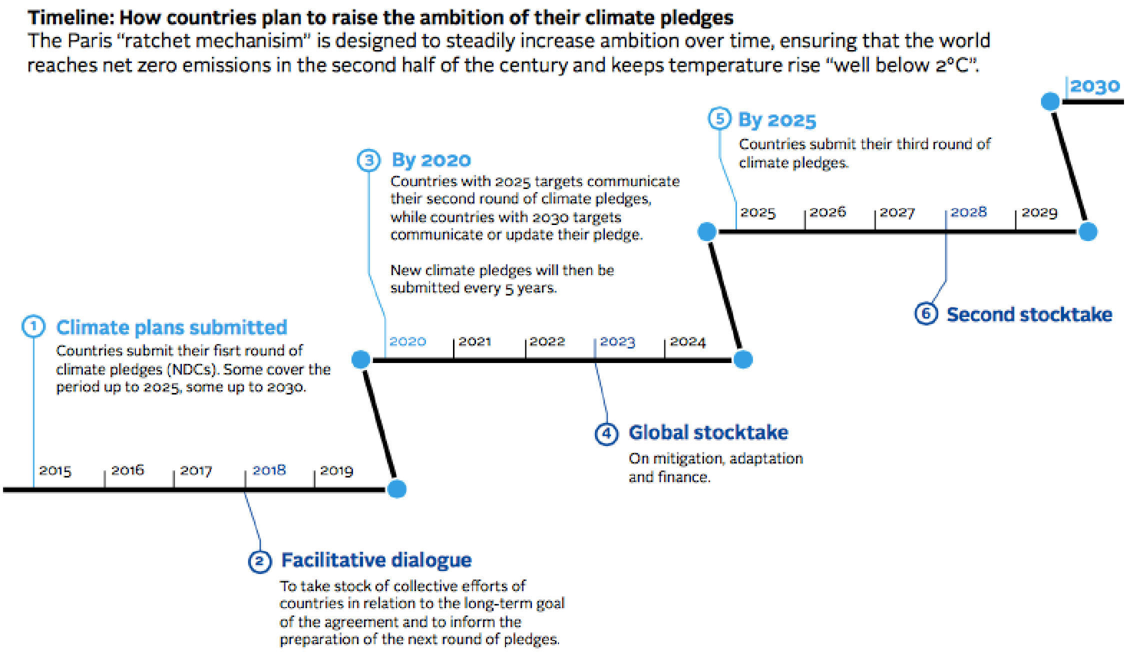
2023: Global stocktake on climate, mitigation and finance

2025: Countries submit their 3rd round of climate pledges (NDCs)

2028: Second global stocktake

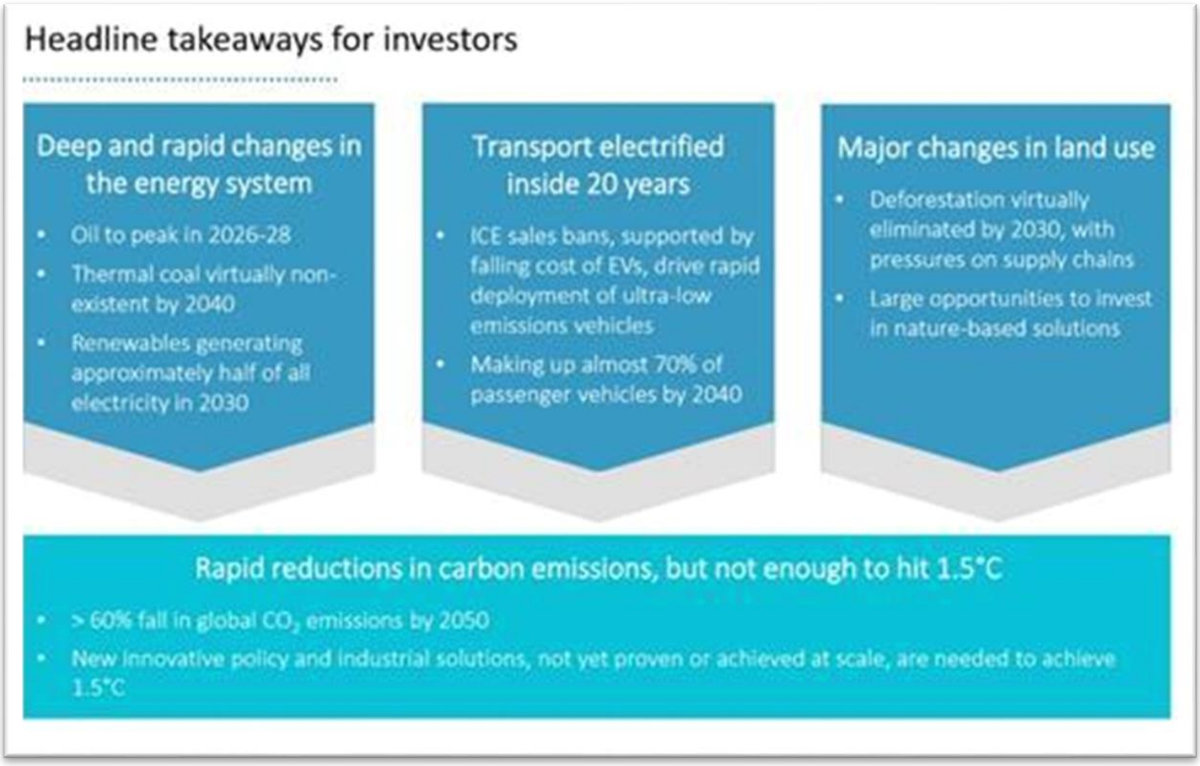
*Policy announcements are expected to accelerate in 2023-2025*

**Figure 4: The global stocktake and third round of climate pledges could catalyse the inevitable policy response.**
**Source: Carbon Brief**



*https://www.unpri.org/inevitable-policy-response/forecast-policy-scenario-macroeconomic-results/4879.article*

*https://www.mainstreamingclimate.org/publication/the-inevitable-policy-response-act-now/*



## Headline takeaways for investors

**Deep and rapid changes in the energy system**

- Oil to peak in 2026-28
- Thermal coal virtually non-existent by 2040
- Renewables generating approximately half of all electricity in 2030

**Transport electrified inside 20 years**

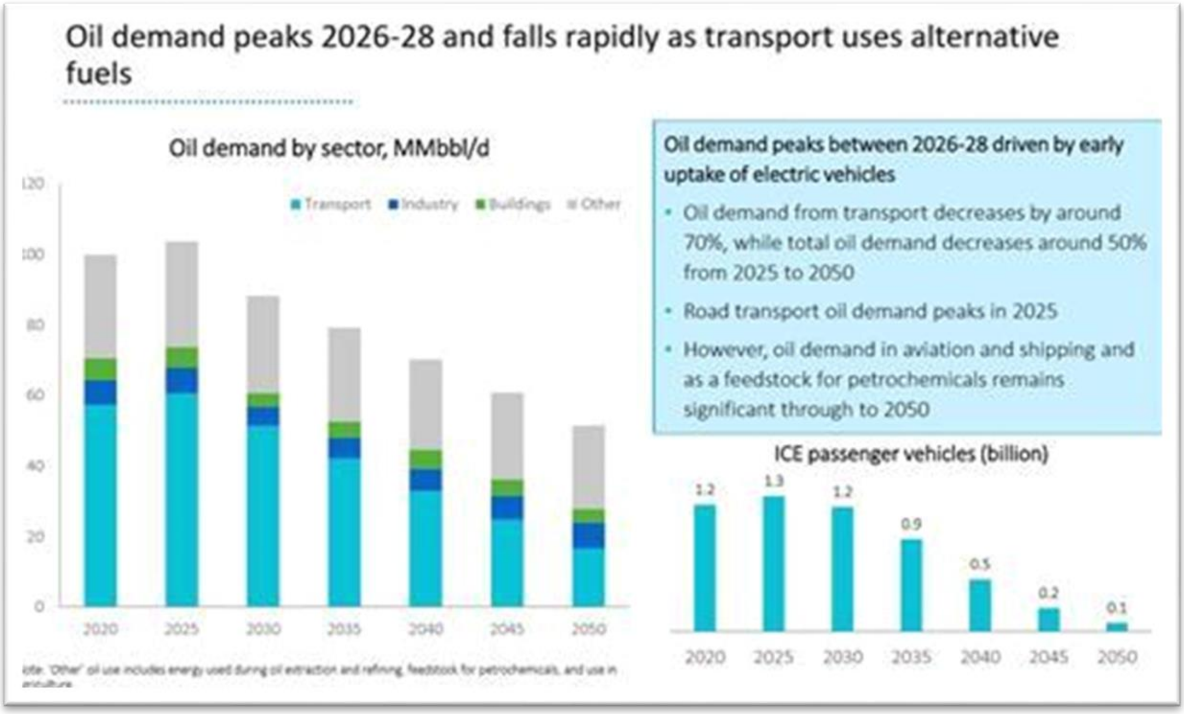
- ICE sales bans, supported by falling cost of EVs, drive rapid deployment of ultra-low emissions vehicles
- Making up almost 70% of passenger vehicles by 2040

**Major changes in land use**

- Deforestation virtually eliminated by 2030, with pressures on supply chains
- Large opportunities to invest in nature-based solutions

**Rapid reductions in carbon emissions, but not enough to hit 1.5°C**

- > 60% fall in global $CO_2$ emissions by 2050
- New innovative policy and industrial solutions, not yet proven or achieved at scale, are needed to achieve 1.5°C



## Oil demand peaks 2026-28 and falls rapidly as transport uses alternative fuels

**Oil demand peaks between 2026-28 driven by early uptake of electric vehicles**

- Oil demand from transport decreases by around 70%, while total oil demand decreases around 50% from 2025 to 2050
- Road transport oil demand peaks in 2025
- However, oil demand in aviation and shipping and as a feedstock for petrochemicals remains significant through to 2050

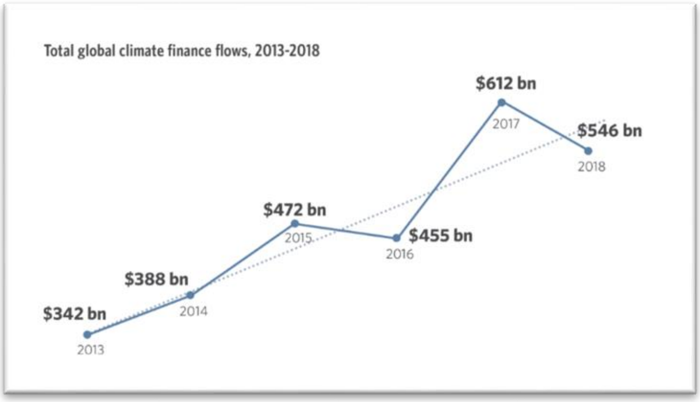
ote: 'Other' oil use includes energy used during oil extraction and refining, feedstock for petrochemicals, and use in agriculture.

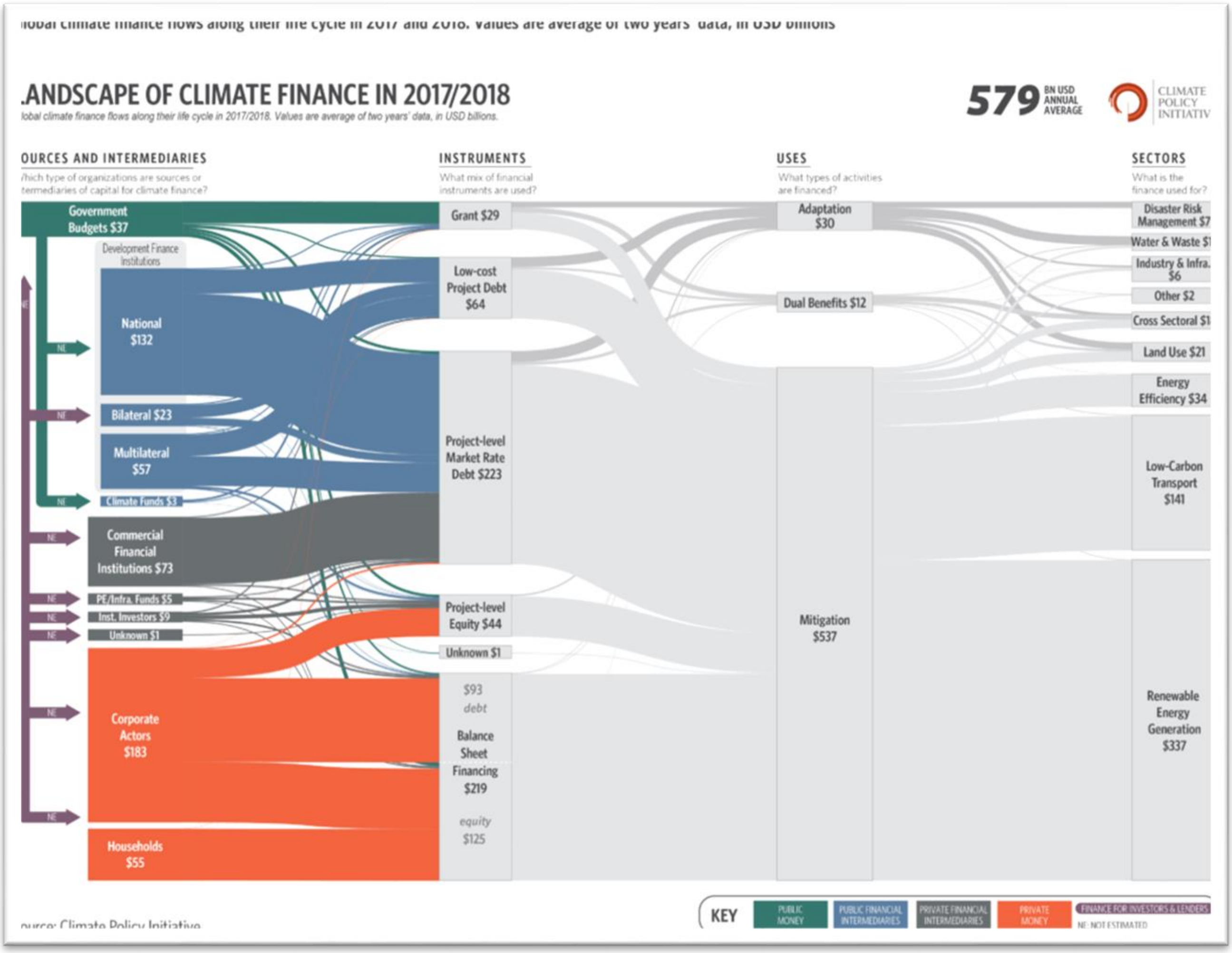
## Summary of results

| Sectors | Statkraft Low Emissions Scenario (2018) | IRENA Remap (2018) | IEA Stated Policies Scenario (STEPS) (2019) | IEA Sustainable Development Scenario (SDS) (2019) | Shell Sky Scenario (2018) | BP ET (2018) | IPR FPS (2019) |
|---|---|---|---|---|---|---|---|
| $CO_2$ emissions | | | | | | | |
| Global energy-related $CO_2$ emissions ($GtCO_2$) in 2040 | 23.4 | 15 | 35.6 | 15.8 | 28.7 | 35.9 | **18** |
| Primary energy | | | | | | | |
| Average annual primary energy demand growth 2015-2040 | 0.5% | -0.1% (to 2050) | 1.0%<br>(2018-2040) | -0.3%<br>(2018-2040) | 1.1% | 1.3% (2010 -2040) | **-0.3%**<br>(2017-2040) |
| Oil consumption: annual average growth 2015-40 | -0.80% | n/a | 0.4%<br>(2018-2040) | -1.8%<br>(2018-2040) | -0.1% | 0.5% (2010 -2040) | **-1.4%**<br>(2017-2040) |
| Gas consumption: annual average growth 2015-40 | 6% | n/a | 1.4%<br>(2018-2040) | -0.2%<br>(2018-2040) | 0.8% | 1.8% (2010 -2040) | **0.7%**<br>(2017-2040) |
| Coal consumption: annual average growth 2015-40 | -2.60% | n/a | -0.10%<br>(2018-2040) | -4.3%<br>(2018-2040) | -0.9% | 0.0% (2010 -2040) | **-6.4%**<br>(2017-2040) |
| Transport sector | | | | | | | |
| Oil share (final, 2040) | 70% | 33% (2050) | 82% | 60% | 91% | 86% | **73%** |
| % Electric vehicle (EV+PHEV) share of new vehicle sales | 77% by 2040 | n/a | 13% by 2030 | 14.5% by 2030 | n/a | n/a | **90% by 2040** |
| Power sector | | | | | | | |
| Demand (annual average growth, 2015-2040) | 2.4% | 2.0% | 2.0%<br>(2018-2040) | 1.7%<br>(2018-2040) | 3.5% | n/a | **2.2%**<br>(2017-2040) |
| Wind power (annual average growth, 2015-2040) | 8.0% | 9.0% | 6.7%<br>(2018-2040) | 8.9%<br>(2018-2040) | 10.2% | n/a | **11.2%**<br>(2017-2040) |
| Solar power (annual average growth, 2015-2040) | 15.0% | 11.3% | 9.9%<br>(2018-2040) | 12.0%<br>(2018-2040) | 17.5% | n/a | **14.7%**<br>(2017-2040) |
| Hydropower (annual average growth, 2015-2040) | 2.1% | 1.1% | 1.7%<br>(2018-2040) | 2.3%<br>(2018-2040) | 1% | n/a | **1.7%**<br>(2017-2040) |
| Fossil fuel share in power (% of total 2040) | 21% | 18% | 48% | 21% | 29% | n/a | **18%**<br>(2017-2040) |

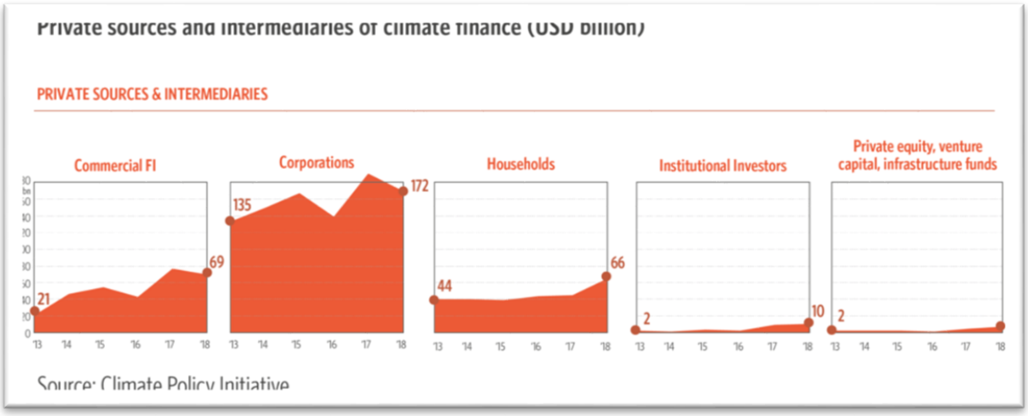
## Climate Policy Initiative

*https://www.climatepolicyinitiative.org/publication/global-climate-finance-an-updated-view-2018/*

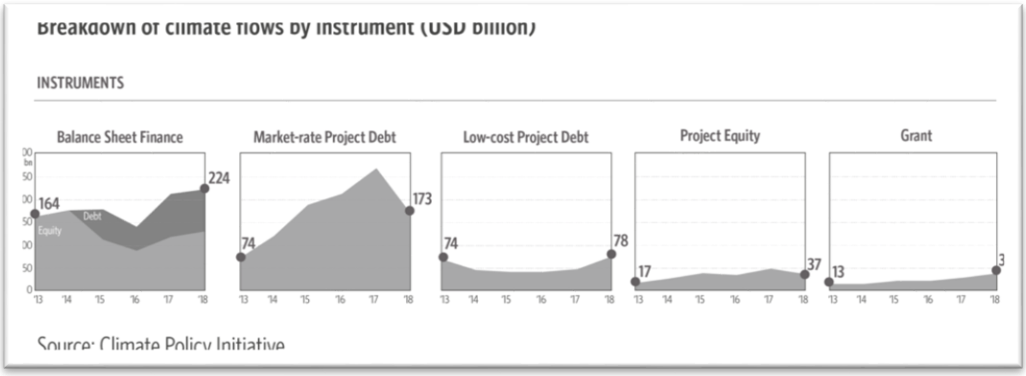


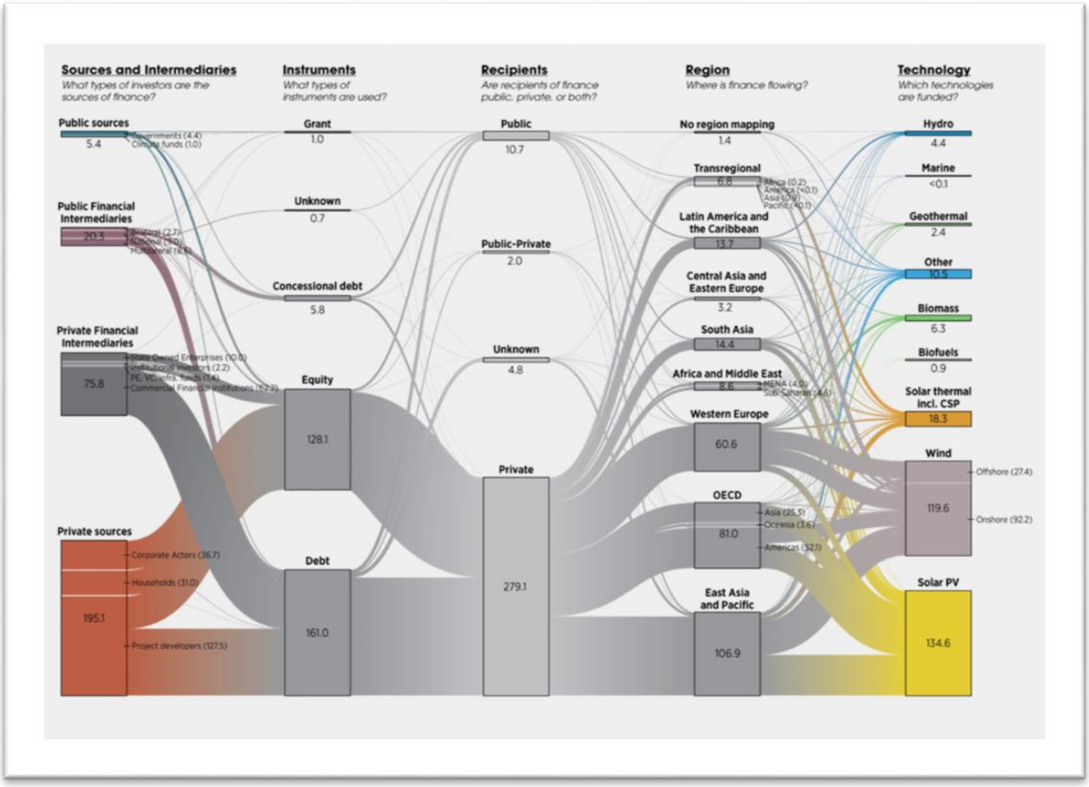


ource: Climate Policy Initiative

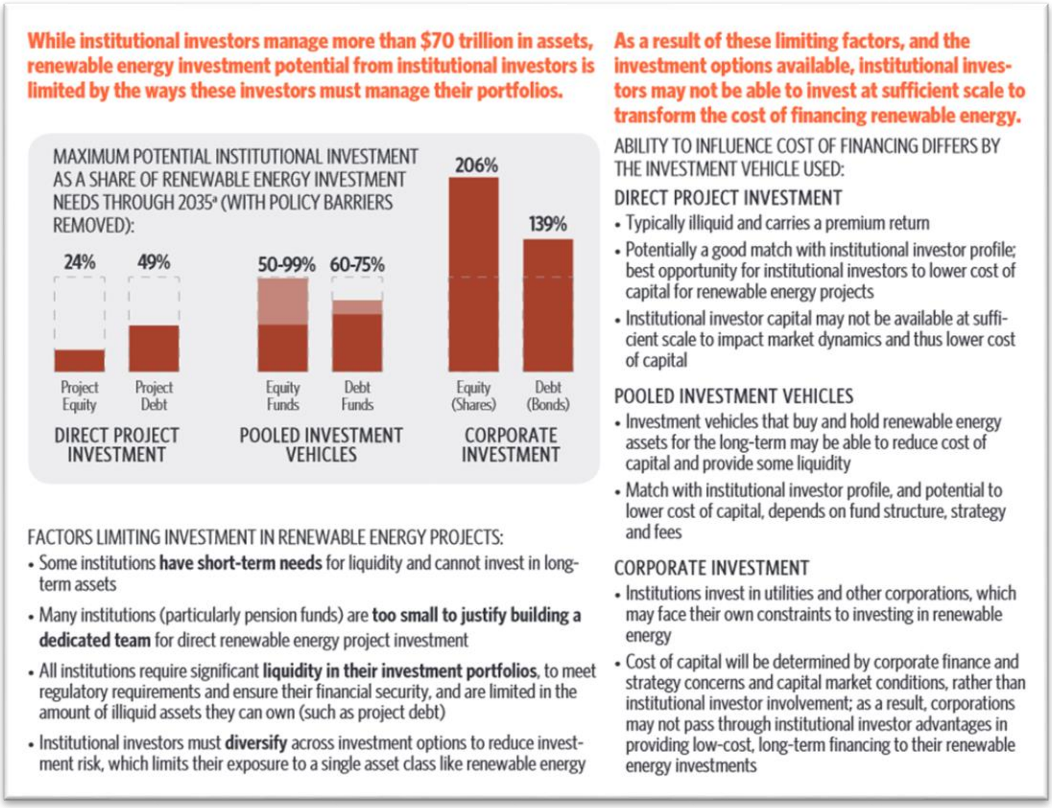


Source: Climate Policy Initiative





*https://www.climatepolicyinitiative.org/publication/global-landscape-renewable-energy-finance-2018/*



**While institutional investors manage more than $70 trillion in assets, renewable energy investment potential from institutional investors is limited by the ways these investors must manage their portfolios.**

MAXIMUM POTENTIAL INSTITUTIONAL INVESTMENT AS A SHARE OF RENEWABLE ENERGY INVESTMENT NEEDS THROUGH 2035[a] (WITH POLICY BARRIERS REMOVED):

FACTORS LIMITING INVESTMENT IN RENEWABLE ENERGY PROJECTS:

- Some institutions **have short-term needs** for liquidity and cannot invest in long-term assets
- Many institutions (particularly pension funds) are **too small to justify building a dedicated team** for direct renewable energy project investment
- All institutions require significant **liquidity in their investment portfolios**, to meet regulatory requirements and ensure their financial security, and are limited in the amount of illiquid assets they can own (such as project debt)
- Institutional investors must **diversify** across investment options to reduce investment risk, which limits their exposure to a single asset class like renewable energy

**As a result of these limiting factors, and the investment options available, institutional investors may not be able to invest at sufficient scale to transform the cost of financing renewable energy.**

ABILITY TO INFLUENCE COST OF FINANCING DIFFERS BY THE INVESTMENT VEHICLE USED:

DIRECT PROJECT INVESTMENT

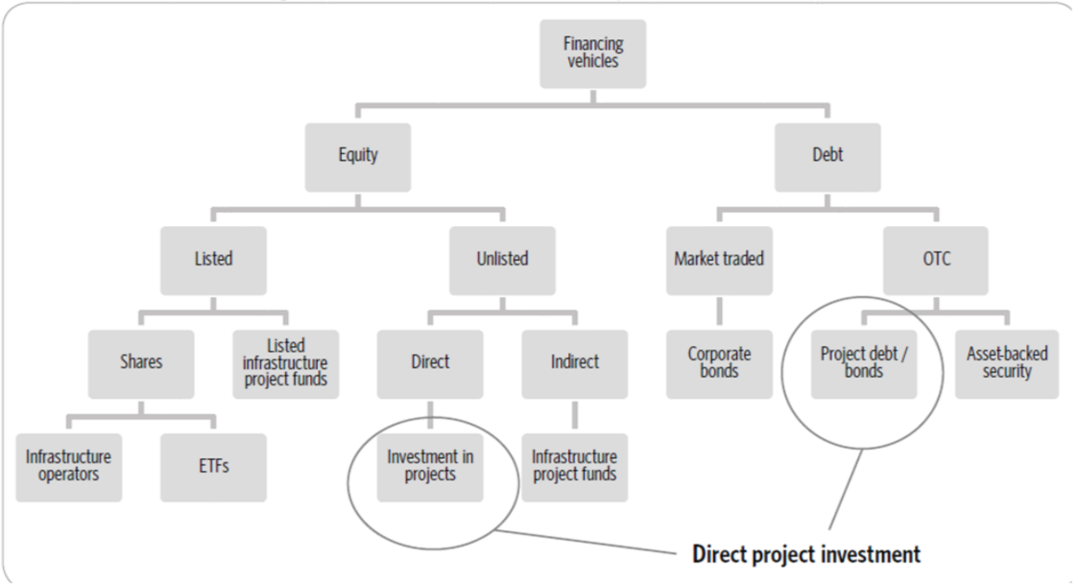
- Typically illiquid and carries a premium return
- Potentially a good match with institutional investor profile; best opportunity for institutional investors to lower cost of capital for renewable energy projects
- Institutional investor capital may not be available at sufficient scale to impact market dynamics and thus lower cost of capital

POOLED INVESTMENT VEHICLES

- Investment vehicles that buy and hold renewable energy assets for the long-term may be able to reduce cost of capital and provide some liquidity
- Match with institutional investor profile, and potential to lower cost of capital, depends on fund structure, strategy and fees

CORPORATE INVESTMENT

- Institutions invest in utilities and other corporations, which may face their own constraints to investing in renewable energy
- Cost of capital will be determined by corporate finance and strategy concerns and capital market conditions, rather than institutional investor involvement; as a result, corporations may not pass through institutional investor advantages in providing low-cost, long-term financing to their renewable energy investments



Main institutional investors' financing vehicles for infrastructure investment (adapted from Kaminker and Stewart (2012))

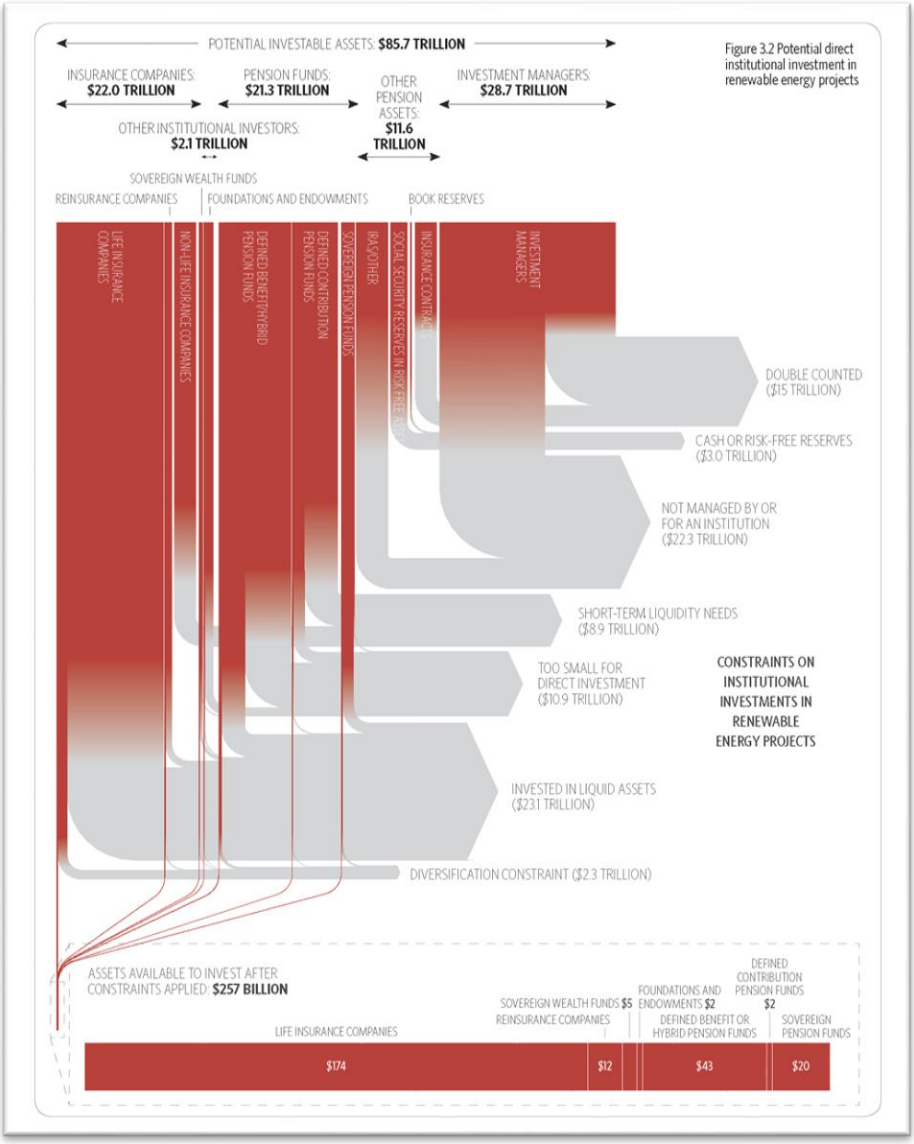


Figure 3.2 Potential direct institutional investment in renewable energy projects

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Roger Bentley has a BSc in Physics and Chemistry from Manchester University, an MASc in Industrial Engineering from Toronto University, and a PhD in solar energy from the University of Reading. His research covers global hydrocarbon depletion, solar energy, and broader energy issues. From 2015 to 2017 he was editor of the academic journal '*The Oil Age*', and earlier was a member of the University of Reading's *ad hoc* 'Oil Resources Group', giving presentations on oil depletion to governments, industry, research institutions and academia. In 2001/2002 Dr. Bentley was Co-ordinator of the Oil Depletion Analysis Centre, London, and is a past-Secretary of the Association for the Study of Peak Oil and Gas (ASPO). Other positions have included Head of Research, Whitfield Solar Ltd; Senior Research Fellow, Department of Cybernetics, University of Reading; Modelling Analyst, Thames Water Utilities; Financial Analyst, Esso Chemicals; and Programmer-Analyst, Imperial Oil. Dr. Bentley has published some 50 academic papers and two books, including *Introduction to Peak Oil*, Springer, 2016.

## Richard Miller

Richard Miller gained a PhD from the University of Alberta in uranium metallogeny. He worked for BP for many years, and while there developed a detailed by-field bottom-up model of global oil supply that informed senior management decisions. Since leaving BP he has continued to follow the topic closely, including as co-author of the 2009 UKERC *Global Oil Depletion* study (Sorrell et al., 2009), and lead author of a Royal Society paper on the subject (Miller and Sorrell, 2014).

## Richard O'Rourke

Richard O'Rourke gained an honours degree in Industrial Chemistry from the University of Limerick in 1996. While an undergraduate he secured a year's experience with Loctite R&D (now Henkel) in Ireland and the US. After graduation Richard spent two years in Taiwan as a product and process development engineer with General Semiconductor (now Vishay), and then a year at the Swiss Polytechnic EPFL carrying out research into Solid Oxide Fuel Cells. In 2000 Richard co-founded Kinematik and became its CEO. Later he became an independent consultant specialising in technology commercialisation and start-up fundraising, based primarily in New York. Since 2006 Richard has shifted his focus back to energy, gaining a Master's degree in Sustainable Energy from University College Cork, and another in Environmental Policy from the London School of Economics. In 2010 Richard joined EnerNOC in a business development role with its UK team. In 2012 Richard joined MITIE Asset Management (MAM), and in 2014 he completed an MBA in Global Energy at Warwick Business School, where his dissertation focused on green infrastructure finance and the securitisation of energy efficiency and distributed generation projects. After graduation, Richard contracted to Pure Leapfrog, a UK-based charity focused on developing the community energy sector, and went on to establish its award-winning trading subsidiary Leapfrog Finance, becoming its managing director. Most recently, Richard has set up and become director of Kinetik NRG, a climate advisory organisation.

### Simon Ratcliffe

Simon Ratcliffe has an MSc in Urban Development Planning from University College London and an MBA from Warwick University and brings urban development, energy and climate change experience to development programmes. Simon has developmental and technological research experience, has led teams that have delivered a wide range of multi-disciplinary projects, and is a provider of innovative thought leadership on cities and the circular economy.

As the climate advisor on the Cities for Infrastructure and Growth programme in Myanmar, Simon is developing guidelines to aid secondary cities integrate climate change into their planning. Simon was until recently an energy and cities advisor at the Department for International Development (DFID) advocated the sustainable cities agenda. He commissioned the Future Proofing Cities report, which helped shift DFID's focus towards cities.

For six years Simon was a board member of an international educational organisation, that delivers leadership trainings and became a life-coach. He has mentored MBA students at the Warwick Business School.