Stopping Climate Change in Ten Years with Little Hardship

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Abstract

The evidence for the warming of the earth's climate due to pollution of atmosphere with, mainly, carbon dioxide arising from burning fossil fuels is *unequivocal*. To lessen the damaging consequences of the *climate change* induced by humans, governments, institutions and enterprises are gradually endorsing a plan for human activity to become *carbon neutral* by 2050 and thereby limit global warming to 1.5° C. However, the observed progress of global warming indicates that the deadline for human activity becoming carbon neutral by 2050 is too late for limiting warming to 1.5°. The analysis of world energy consumption described in this article shows that it is feasible to reach *carbon neutrality* in a much shorter time without severe reduction in economic activity.

1 Introduction

The evidence for the warming of the world's climate is piling up. Extensive research over the last two decades has shown that the warming comes, from the rising CO_2 pollution of the atmosphere mediated by the Greenhouse effect. In turn the CO_2 pollution comes from the burning of fossil fuels to energise our economy and our life style.

It has also become clear that the consequences of this global warming will be very damaging to humanity's current way of life. Despite the ample publicity received by the unsettling predictions about what humanity is to face in the near future, we have been unwilling to take preventive action.

In 2015 representatives of 197 nations, almost all countries of the world, signed the Paris Accord pledging to become *carbon neutral* by 2050 and thereby limit the global temperature rise to $1.5°C$. Carbon neutral means: zero net addition of carbon dioxide to the atmosphere. The reality is that four years later, by the end of 2019, yearly global CO_2 emissions had risen yet again by another 3.3% to 36.44 billion metric tonnes (Gt) a year from its 2015 value of 35.21 Gt. It was only because of the Corona virus pandemic of 2020 that the yearly global emissions dropped temporarily by 6.5% to $34.07\ Gt$. Once the economic activity returns to pre-pandemic level, The CO_2 emissions will start to grow again because nothing has been done in the meantime to reduce them. Recent research (Luderer 2018) shows that achieving the aim of the Paris Accord is turning out ever more unlikely, aggravated by the delay in taking the agreed actions.

It seems that the signatories of the Paris Accord hoped that by pushing the deadline for carbon neutrality 35 years into the future to 2050, they would strike a balance between the amount of global warming and the economic hardship inflicted by weaning humankind from fossil fuels. This *timid* approach is turning out as nothing more than wishful thinking. Since the Accord we have not made any headway and in the six years since the future outlook is becoming ever bleaker. While we spend our time arguing about how to slow down global warming with the least possible reduction of our affluent lifestyle, the pollution of the atmosphere with CO_2 continues and global warming marches on. The time for procrastination is over, we are in an emergency and drastic action is due now. The threat is global and the action to confront it has to be global too.

Recorded data indicates, and climate models confirm (Masson-Delmotte 2021), that here is a direct relation between the mean global temperature and the content of CO_2 in the atmosphere. The more CO_2 in the atmosphere the warmer the climate. The CO_2 accumulates in the atmosphere because its natural removal is very slow. This fact makes the action to take patently clear, as unpalatable as it may be: If we want the earth's mean surface temperature to stop rising, then we simply must stop right now with burning fossil fuels to generate energy.

The affluent lifestyle of the people living the industrial economies depends on the availability of cheap energy. Statistical data confirm that a country's affluence, measured by per capita GDP, grows hand in hand with per capita energy consumption. The higher the GDP the higher the energy consumption. In 2019, 84.3% of the world energy consumption was met by burning fossil fuels[1]. Thus, less than 20% of our energy consumption is supplied from non CO_2 producing sources. Refraining from burning fossil fuels from now on would reduce our available energy to less than a $1/5$-th of what we are currently using. Clearly this action poses an existential threat to our lifestyle and there seems little hope that we will commit ourselves to such a drastic action. Yet, in the face of the threat posed by global

[1]The year 2019 serves as a reference because it was the year before the corona virus pandemic that caused an anomalous drop in energy consumption

warming, our choices are few:

1. To continue to procrastinate and fiddle around the edges hoping for somehow achieving a *soft landing* while risking a temperature increase of more than $2°C$ by 2050. Justifying this behaviour is the increasingly promoted naive belief that we may correct our mistakes later by finding a way to remove the CO_2 we pumped into the atmosphere.

2. To stop CO_2 pollution right now by limiting our energy consumption to the energy currently available from *carbon free* sources and in return accept a drastic drop in comfort until we build up the *carbon free* energy generation capacity needed to restore our life style.

3. To make an all out effort to build up, in the short time of, say, ten years, the capacity for *carbon free* energy generation to the point of making fossil fuels superfluous and stop CO_2 pollution. The climate would then stabilise at the optimistic target of $1.5°C$ and we would avoid a big drop in affluence.

This article assesses the technical feasibility and the monetary and socio-economic cost of the third option, henceforth called the *Fast Track* (FT) energy transition. This assessment does not require complicated modelling. By relating some simple facts based on easily accessible data one can obtain a first overall understanding of the merits of the FT energy transition option. The result of the assessment is that a FT energy transition is feasible because there are no fundamental barriers to it.

2 Carbon-free energy sources

Before embarking in the analysis of the *Fast Track* option, we must take stock of the various ways available for carbon-free energy generation that can be scaled up quickly?

The answer is that currently there are only two candidates that are free of CO_2 emission and that are technically mature for fast large scale deployment. These are nuclear energy and solar energy.

2.1 Nuclear power

Commercial nuclear power generation has been with us since 1957. It is a mature technology but suffers from disabeling drawbacks.

1. Despite the claims by the nuclear power industry that modern nuclear power plants are safe, there have been severe accidents in the past that have undermined public confidence.

Total incident solar irradiation	$5.38\ 10^6$ EJ	$1.361 kW/m^2$
Solar irradiation reaching the earth's surface	$3.958\ 10^6$ EJ	$1 kW/m^2$
2019 world energy consumption	583.9 EJ	
2019 world fossil fuel energy consumption	492.38 EJ	

Table 1: Available solar energy and human energy consumption (in ExaJoules).

2. Nuclear power plants depend on a supply of fissile material (fuel),[2] which is of limited availability.

3. Nuclear fission produces waste that remains radioactive for thousands of years. Safe, long term storage of the radioactive waste is yet an unsolved problem.

An analysis by D. Abbott (Abbott 2011) confirms that nuclear power generation cannot be scaled up to meet current world energy consumption. Thus, for the time being, capturing the energy from the sun is our only choice.

2.2 Solar energy

Solar energy comprises hydroelectric power, photovoltaic and thermal solar panels, and wind turbines. The first question here is: Is there enough solar energy for our needs? The answer is yes; energy from the sun is abundant. The earth intercepts solar irradiation amounting to $1.361kW/m^2$, measured above the atmosphere. When multiplied by the apparent area of the earth (the area of the earth's shadow), over the duration of one year this amounts to a total energy of 5.38 million Exajoules per year (1 Exajoule = 10^{18} joules). Even though only about $1kW/m^2$ reaches the earth's surface at normal incidence, it still leaves us with 3.95 million Exajoules per year. This is 6765 (nearly seven thousand) times the world energy consumption of $583.9EJ$ per year in 2019.

Having established that there is abundant and sufficient energy coming in from the sun, the next question is: How can we capture enough of this energy? Solar energy can be captured by letting the sun heat up matter, for example water, as in thermal solar panels, or by heating up the atmosphere and using the resulting air currents (wind) to drive electricity generators. Solar energy is also captured by plants through photosynthesis (chemical means). Some of the energy captured by plants is stored over time in fossil fuels, which is what we are mostly using. In addition, we have invented Photovoltaic (PV) solar cells that convert solar radiation directly into electricity. The direct conversion of solar radiation into electricity is the available and proven way for meeting our energy demand.

[2] matter whose atomic nuclei can be split releasing energy (nuclear fission)

3 Photovoltaic solar panels

Electricity generation with photovoltaic solar panels is already a mature technology. Solar panels can be spread out geographically in many small installations, or they can be concentrated in large scale power generation plants.

State of the art (2020) solar panels can convert about 18% of the incident solar radiation into electric energy. At vertical solar radiation incidence, one square meter of solar panel will give us a peak power output of $180\ Wp$ (Watt peak). With an average number of daily sunshine hours as, for example, occurring in Rome, such a panel will produce $3\ MJ$ per day. The world daily fossil fuel energy consumption in 2019 was $492.38\ EJ/365 = 1.349\ EJ$ per day. If one square meters of solar panel produces on average $3\ MJ$ per day, how many square meters of solar panels do we need to produce 1.349 EJ per day?

3.1 How much space will it take?

Allowing for some additional area around the panels for supporting structures and service access we find that if we allocate an area of $1.25m^2$ to each square meter of solar panel then covering an area of $562,000\ km^2$ of the earth's surface with solar panels would suffice. This is slightly less than the area of France, or about 7% of the area of Australia or about 0.38% of the earth's land surface. This estimate assumes an 18% efficiency for the solar panels and an average number of daily sunshine hours as occurring in Rome. That area can be split into patches all over the world. A relatively easy and convenient way is to use rooftop spce. Rooftop space is available in all urban areas. About 4% of the world's land area is estimated to be built-up and we need only 0.38% of the world land area for solar panels. Even though the whole urban space cannot be covered in solar panels, it shows that the required area for the solar panels will be spread out and will not be overly intrusive. In conclusion, the energy and the space are available for scaling up solar photovoltaic (PV) electricity generation to meet world energy consumption. The question that remains is: Can we produce and install $562,000km^2$ of solar panels in ten years?

3.2 What will it cost?

We know how much energy we need to generate. If we find the cost of solar panels per unit energy we can estimate the cost, at current prices, of installing enough solar panels to generate as much energy as was consumed world wide by burning fossil fuels in 2019.

The cost of solar panels is quoted as dollars per peak power. Therefore we first need to express our energy demand in terms of peak generating capacity. Above we calculated that a panel rated at $180\ Wp$ will give us about $3\ MJ$ per day. Converting to daily energy per kWp we get

$$\frac{3MJ}{0.18\ kWp} = 16.7\ MJ/kWp \tag{1}$$

and the total nominal peak power needed to generate the daily 2019 world fossil fuel energy consumption of $492.38EJ/365days = 1.349EJ/day$ is

$$\frac{1.349\ 10^{18}\ J}{16.7\ 10^{6}J/kWp} = 0.0808\ 10^{12}kWp = 81\ TWp \tag{2}$$

Data from the U.S National Renewable Energy Laboratory (NREL) indicate that in 2020 the average (across domestic, commercial and utility installations) price per watt peak ($\$/Wp$) is around USD 1.50. According to this estimate the installation of $81TWp$ would cost

$$81\ 10^{12}Wp \times 1.5\$/Wp = 121\ 10^{12}\ USD \tag{3}$$

For comparison the world GDP for 2019 was $87.6\ 10^{12}$ (87.6 trillion) USD. The cost of installing $81\ TWp$ of solar panels is about 1.38 times the world's 2019 GDP. If spread over 10 years that would be 13.8% of GDP per year. If every country on earth would dedicate 14% of its GDP to the installation of PV solar cells, in 10 years every person on earth would have, including the already existing capacity in 2019, $76.7GJ$ (the yearly 2019 per capita energy consumption) of carbon-free electric energy and world CO_2 emissions would be zero!

3.3 How to pay for it?

Committing 14% of yearly GDP to a single purpose is a high but not impossible financial burden on any nation. What first comes to mind is to collect this money by the much talked about, and partially already implemented, price (tax) on carbon (CO_2) emission. What the price on carbon should be is currently a contentious issue. The existing carbon pricing is intended to increase the cost of fossil energy in order to give the *renewable* energy a competitive advantage. Currently, the money raised by carbon pricing is not earmarked for a specific purpose. Instead of seeing carbon pricing as a *disincentive* tax it could be turned in a *constructive* tax where the money raised is dedicated exclusively to pay for the installation of the solar panels needed to replace fossil fuels. This approach immediately sets the *carbon price*.

The accepted figure for the amount of CO_2 released per unit energy from burning crude oil is $73.3kg/GJ$. Global CO_2 emission for 2019 were $36.44Gt$ (billion tonnes). The amount collected globally from the carbon tax per year has to cover $1/10th$ of the total cost of 121 trillion dollars. That makes 12.1 trillion dollars a year, spread over $36.44Gt$

$$\frac{12.1\ 10^{12}}{36.44\ 10^{9}t} = 332\ USD/t \quad (4)$$

In 2021 the effective carbon prices around the world were under the EUR 60/tonne benchmark. A starting price of 332 USD/tonne is 5.5 times that. As a starting point this price could be justified to kick off the solar panel installation program.

The problem with this pricing scheme is that, as the installation of the panels progresses, the yearly CO_2 emissions will shrink, while the yearly cost of the solar panel installation will remain the same. Therefore the carbon price will have to increase every year. Hypothetically after the first year the new solar panel installations will add enough solar electricity generation to reduce global emissions by one tenth. Therefore the carbon price for the following year would increase by 11% from 332 USD to 369 UDS. In the third year emission would have reduced further by one tenth and the carbon price will rise by 12.5% to $415\ USD$. If the installation cost diminishes somewhat due to economy of scale and technological improvements, the carbon price may not have to increase as much. Even if a starting price of 332 USD/tcould be justified, it is unlikely that the continually rising carbon prices will be accepted.

If a carbon tax is made to pay for the installation of solar electricity generation capacity then there is no need to recover costs by selling electricity. The cost of solar electricity cold be kept very low. For all practical purposes electricity would be free. The alternative for funding the solar panel installation is to make the solar panel installation pay for itself trough charging for the electricity generated.

In the end, it is irrelevant for the consumer whether energy cost increases because of a tax or by charging for energy use. Once the decision has been made to build up solar electricity generation capacity at a steady rate over ten years to make fossil fuels superfluous, a disincentive tax such as a carbon price is no longer relevant. It becomes just a question of how to rise the money for the project; be it through consumer pricing, taxation, taking on public debt, money printing or any combination of those.

3.4 How to share the cost

Above we looked at the cost of the FT energy transition from a global perspective. Total and per-capita energy consumption varies greatly among countries, therefore the cost of replacing the fossil energy consumption with solar energy will also vary widely. A global agreement is required for putting such a large infrastructure project into practice. To reach such an agreement resolving the question of who pays how much will undoubtedly be a key point in negotiations. Table 2 shows the

Country	Energy consumption per capita (GJ)	% fossil fuels	PV needed per capita (kWp)	Yearly investment as % of per capita GDP
USA	287.6	83.3	39.28	9.0
Australia	254.3	91.4	38.13	10.4
Germany	157.3	77.4	19.97	6.5
China	98.8	85.1	13.80	20.2
India	24.9	91.0	3.72	26.5
World	75.7	84.3	10.47	13.7

Table 2: Cost of PV power needed to replace 2019 fossil fuel consumption expressed as percentage of the nations per capita GDP, for selected countries

cost, expressed as percentage of the nations GDP, of replacing the 2019 fossil fuel consumption, for selected countries. The high energy consumers are wealthy and with a cost per year of less than 10% of per capita GDP they can well afford the investment. Whereas countries with lower per capita energy consumption, even though they would have to install less per capita PV power capacity, they would struggle to afford it. Therefore the higher energy consuming nations will have to subsidise the lower energy consuming nations. This can be achieved by each nation being required to invest the world average 13.7% of GDP, with the excess of their needs being distributed to nations that are required to invest a greater fraction of their GDP.

3.4.1 Impact of carbon tax on fossil fuel cost

Burning one litre of gasoline produces $2.3kg$ of CO_2. At a carbon cost of 312 USD/t this contributes $2.3kg/l \times 0.312USD/kg = 0.72USD/l$ to the cost of petrol at the pumps. The typical car owner who drives around $15000km/year$ with a fuel efficiency of $12l/100km$ will burn $1800l/year$. The carbon price cost for this will be about $USD\ 1300/year$. This is not a heavy burden considering that current petrol prices are at least 2.5 times the carbon cost. But when compared with the almost zero electricity cost for an electric car the motivation for switching becomes stronger.

3.4.2 Make solar electricity pay for itself

The installation cost of 12.1 trillion USD for $49.24EJ = 13.68\ 10^{12}kWh$ (one tenth of 2019 fossil fuel energy consumption) result in a cost of $0.88USD/kWh$. This is about three times the 2019 domestic electricity cost in most countries.

3.5 Solar energy storage

The above solar energy generation capacity estimate is based on yearly averages. Solar irradiation is only available during day time, subject to weather conditions. Therefore solar energy generation capacity does not match consumption most of the time and there is need for short term energy storage to even out the generation capacity fluctuations. Available and technically mature storage means are batteries, pumped hydroelectricity and clean burning fuel production such as hydrogen and ammonia). The need for storage adds costs to the PV electricity generation that were not yet included in the production cost estimates above.

3.6 Solar electricity utilisation

One thing is to offer the solar energy generation capacity, another thing is to make people use it. Switching from fossil fuel consumption to solar electricity consumption in itself involves a cost for the consumer. That cost will be added to the solar panel installation cost that the consumer is forced to bear in the end. The uptake of solar electricity utilisation only becomes an issue if the consumer is left with a choice of using the solar energy of fossil fuel energy. With an emergency solar energy capacity building program agreed among the nations, the consumer will not have such a choice. The consumer will have certainty the at the end of the program, fossil fuel energy will no longer be available.

3.6.1 Conversion cost to solar electricity

For people to be able to make use of low cost electricity they need to have the means to do it. For industry it means replacing or adapting existing machinery from kerosene/petrol/diesel to electricity. The whole economy must be *electrified* in 10 years. Some sectors of the economy are easy to electrify. Others not so. Domestic electrification is already well advanced although natural gas is still widely used in cooking heating. Suitable replacements by electrical induction hot plates exist. Domestic hot water is already electrified in many places of the world. In cold climates where coal and oil boilers are still common for room heating these can be replaced by heat pumps where the installation cost can be recouped in short time due to the much lower running costs. Thermal solar energy is also an option in many places.

The technology for the electrification of personal transport in the form of electric automotive vehicles is is mature for large scale deployment but will require substantial investment. All petrol passenger cars will have to be replaced by electric cars within 10 years. An accurate number for the total number of passenger cars in circulation is hard to come by, but it is estimated that in 2020 the world wide fleet of passenger cars was in the vicinity of 1.4 billion vehicles. Out of these only about 4 million were electric cars or hybrids, meaning that we still need to replace basically the whole fleet of 1.4 billion of existing passenger cars in 10 years. At an average cost of USD 30,000 per electric vehicle this requires an investment of $1.4\ 10^9 \times 3\ 10^4 = 42$ trillion dollars. This is about half of the worlds GDP for 2019. When split over 10 years this is about 5% of world GDP. Not an exorbitant cost. To this we have to add the cost of disposing the 1.4 billion petrol passenger cars on the road today.

The average combustion engine car weighs about 1.5 tonnes and contains around 65% steel and iron. If 80% percent of that can be recycled then we obtain about 0.8 tons of steel from each car. Scrapping the whole petrol passenger car fleet would yield $1,4\ 10^6 \times 0.8 = 1.12$ billion tonnes of steel. The yearly world steel production in 2020 was 1.86 billion tonnes. The yearly scrap steel from car recycling would be 112 million tonnes which is about 6% of yearly steel production.

The maritime shipping industry is more difficult to electrify. Batteries are insufficient to store the energy to propel ocean going vessels for their typically week-long voyages. An alternatives to batteries for storing large amounts of solar energy for later use is the production of clean burning fuels. Hydrogen, ammonia and even methanol are appropriate fuels. Hydrogen can be produced by electrolysis of water using solar electricity. Hydrogen is difficult to handle due to its low density and flammability. However hydrogen can be used for the production of ammonia or methanol that are easier to handle. Engines that burn ammonia instead of diesel fuel could be used for powering cargo ships.

The shipping industry is already building vessels that can run with both diesel and methanol. However methanol produces CO_2 when burnt, but it is still acceptable however because it is considered carbon-neutral. This means that the CO_2 released was previously bound in the methane production. Ammonia is preferable because its combustion produces nitrogen and water but no CO_2.

in the long haul air transport industry the replacement of fossil fuels is still problematic. We do not yet have a mature technological alternative to jet-fuel (kerosene) powered jet turbines. Although hydrogen powered aircraft have been demonstrated, much research and development is still needed for large scale deployment. Replacement of the whole long haul aircraft fleet whiting 10 year seems very unlikely for now. The aviation industry contributes around 2.5% to global CO_2 emissions. The 2019 energy consumption of the commercial aviation industry was $12.6EJ$ or 2.56% of world fossil fuel consumption. If the aviation industry cannot switch to solar electricity, or its derivative fuels, then it would have to remove its pollution by direct CO_2 capture from the atmosphere. For the quantity just short of 1 Giga tonne ($0.93Gt$) of CO_2 released by the industry during 2019 this may be technically feasible. The air passengers and cargo will have pay for

Type	Consumption	Average price (USD)	Cost (trillion USD)
Coal	157.86 EJ	70/tonne	0.368
Crude oil	35.38 10^9barrels	60/barrel	2.123
Natural gas	3.9292 $10^{12} m^3$	6/mBtu	0.804
All fossil fuels			**3.295**

Table 3: Estimated raw fossil fuel wholesale costs for 2019

the cost of it. The cost of such a direct carbon capture process is yet unknown. If instead the aviation industry were charged a carbon price of $332 USD/t$ then it would have to pay 310 billion USD per year. This is 37% of the 838 billion USD dollar revenue of the aviation industry in 2019. Passengers would face a nearly 40% increase in airfares. This increase would not be catastrophic for the aviation industry and the tourism industry, but it will surely dampen the passenger and freight volume with the consequent reduction in CO_2 emissions.

4 The demise of the fossil fuel industry

During 2019 fossil fuels made up 84% of total world wide energy consumption. The fossil fuel industry penetrates all parts of the economy. It starts with prospecting for new deposits, continues with coal mining, oil and natural gas extraction, oil refining, transport and distribution of all fossil fuel products, and finally, retailing and marketing. On the path from extraction to the end consumer there is additional economic activity. By phasing out fossil fuel consumption all this the economic activity will gradually wind down. How big is that part? Despite the overwhelming dependency of the world economy on fossil fuels a figure for how much the fossil fuel industry contributes to the overall economy is hard to come by. The wide ramifications of the fossil fuel industry makes it difficult to keep track of the global fossil fuel value chain.

The BP Statistical Review of World Energy (British 2019) collects data of the raw (unprocessed) coal, oil and gas consumption, as well as their prices and their ups and downs over the year. From there on it is very laborious to track the final volumes and consumer prices of fossil fuel products at the end of their value chain. Nevertheless we will endeavour to obtain a rough estimate of how much the fossil fuel industry contributes to world GDP.

As a first step let us estimate the yearly value of raw fossil fuel consumption by multiplying the raw consumption volumes by an estimated average price. Table 3 shows the results.

To estimate the total contribution of the fossil fuel industry to world GDP we need to add the value created along the value chain for all fossil fuel products.

The value of the crude oil extraction industry is about 64% of the total value of unprocessed (raw) fossil fuel industry, which we estimate at around 3.3 trillion dollars. To get an idea of the value added to crude oil along the value chain we may compare the retail price of electricity with the bulk price of crude oil. The reason for picking the electricity retail price is that electricity prices are not so much subject to vastly different taxation and subsidies around the world as are, for example, petrol prices.

Spot prices for crude oil fluctuate considerably, nevertheless an average price of 60 USD/barrel for 2019 may not be too far off the mark. At the meter we pay domestic electricity per kilowatt. Looking at domestic electricity retail prices around the world (statista.com) the average may be somewhere around 0.20 to 0.25 USD/kWh. Let's work with an average price of 0.25 USD/kWh. Crude oil prices are quoted in US dollars per barrel. To compare domestic electricity retail prices with the crude oil spot price we need to calculate how much energy there is in a barrel of crude oil. The energy content of crude oil varies somewhat across the various kinds of crude oil. For comparison purposes the International Energy Agency has defined the *tonne of oil equivalent (toe)* energy to be $41.87GJ$, which is the energy obtained from burning one tonne of crude oil. One barrel is 159 litres. How many barrels make a tonne of crude oil? The density of crude oil is $790kg/m^3$, therefore a barrel weighs $0.79kg/l \times 159l = 125.6kg$. That makes $7.96barrels/tonne$. At 60 USD/barrel the cost of one tonne of oil equivalent (toe) costs $7.96barrels/tonne \times 60USD/barrel = 477.60USD/tonne$. Thus one tonne of crude oil produces $41.87GJ$ of energy at a of cost 477.60 dollars. When converted from GJ to kWh we obtain a price of 0.041USD/kWh. The electricity retail price of 0.25 USD/kwh is 6.1 times the price paid for the same amount of energy in its unprocessed form. The price gets multiplied by 6.1 along the value chain. When we apply this factor to the value of the annual crude oil consumption of 2.123 trillion USD we get 12.944 $\approx$13 trillion USD. In terms of world GDP for 2019 (87.6 trillion USD) it represents 15% of world GDP. By using the domestic electricity price we are likely to have overestimated the increase in value along the value chain. Industrial consumers get lower prices. Many power stations use natural gas which reduces the cost relative to oil. If we allow for this by applying an average factor of 4, instead of 6, to the total value of raw fossil fuels from Table 3 we get $4 \times 3.3 = 13.2$ trillion dollars or 15% of world GDP. Thus we will settle on 15% of world GDP as an estimate for the value of the fossil fuel industry. As the fossil fuel industry winds down over a 10 period its contribution to world GDP will shrink year by year. If the shrinkage is linear then it will be about 1.5$\%$ of GDP per year. The cost of 13$\%$ of GDP of installing solar panels, which remains nearly constant over the ten years, will largely outweigh the loss of economic activity from the fossil fuel sector.

4.1 Geopolitical consequences

While the average loss of economic activity from the fossil fuel industry seems moderate it will be unevenly distributed over the world. The majority of countries have to buy most of their consumption from a small number of producer countries, which are heavily dependent on the income generated from the sale of fossil fuels. The demise of fossil fuels will drastically reduce the income for these countries and they urgently need to reduce the dependence of their economies on the sale of fossil fuels. Some of the big oil producers have large unused open spaces, mostly deserts, with high incidence of solar radiation. Therefore it has been suggested that they transform themselves in solar energy producers. However this idea has a fundamental flaw. Namely, in a solar energy world economy, most countries will be energy self sufficient or nearly self sufficient. The inequality in the distribution of energy resources, characteristic of the fossil fuel era, will be much reduced. Therefore the big fossil energy exporting countries that contemplate becoming solar energy exporters will find that they will have a much smaller market. It is inevitable that their economies will go into a dramatic decline. The loss of political relevance of some of the previously dominant fossil fuel producers will have profound consequences for the existing world order. Last but no least, as nuclear power generation loses relevance it will no longer serve to cover up the nuclear weapons aspirations of some countries.

4.2 Carbon Dioxide Removal

The fossil fuel industry pins its hopes of long term survival on the capture of the CO_2 emissions at the source by so called Carbon Capture and Storage (CCS) and on the carbon dioxide removal (CDR) from the atmosphere once the emissions have been dispersed. CCS would be used where large quantities of CO_2 are produced at one location, such as electric power plants or energy intensive petrochemical, steel and cement production plants. The CO_2 is captured at the exhaust and pumped underground for long term storage. For CDR a variety of methods have been proposed ranging from blowing air through CO_2 extraction devices to using the CO_2 binding ability of vegetation. The Bioenergy Carbon Capture and Storage scheme (BECCS) uses large scale plantations of fast growing vegetation that would be harvested and burnt. The released CO_2 is then captured and stored. There are large uncertainties about the capabilities of CCS and CDR techniques regarding the feasibility of upscaling to the rquired capacity removing several tens of Gigatonnes per year. In 2020 only 40 Megatonnes of CO_2 were captured (Page 2021). This amounts to 0.1 $\%$ of the $36.44Gt$ emitted in 2019. In the case of BECCS there are concerns about the sustainability of large areas of monoculture plantations. We do not have to delve any deeper into the potential of these schemes, in order to say that it is surely much better to avoid the pollution in the first place than relying on a questionable clean-up afterwards.

5 Conclusion

The worlds climate is warming at an alarming rate. In its 2021 report the IPCC states that the warming is *unequivocally* caused by human activity, mainly by the release of carbon dioxide from burning of fossil fuels. In 2019, 84% of the world's energy consumption was supplied by burning fossil fuels. As the burning of fossil fuels continues unabated, the window of opportunity for avoiding severe disruption of the human living environment is closing fast. Urgent action is mandatory. A close look at the basic facts shows that the only option for a fast replacement of fossil fuel energy by non CO_2 polluting energy sources is direct capture of solar energy because:

- Solar energy is abundant. The energy available is almost 7,000 times the 2019 world energy consumption.
- At the current efficiency of 18%, covering 0.38$\%$ (562,000km^2) of the earths land area with PV solar panels would provide enough solar energy to replace 2019 world consumption of fossil fuels.
- By spending 13.8$\%$ of world GDP every year for ten years could install the needed area of PV solar panels to produce as much energy per year as the world consumed from fossil fuels during 2019.

The assessment of the FT energy transition made here does consider any changes in how energy is used nor any growth in world energy consumption. Grubler et al. (Grubler 2018) have shown that by efficiency improvements and changes in the way energy is used the world energy demand could be reduced by about half without reduction in economic activity. Consequently, there seems to be ample room for growth and improvement in living conditions.

In summary, this analysis indicates that a FT energy transition is feasible, although it will require a large concerted global effort. This effort is still small price to pay when compared with the consequences of the other alternatives. Success could limit global warming to the aspirational $1.5°C$ with only small cut-backs to the prosperous life style of the people in the richer nations while also leaving open a path to increased prosperity for those living in the less affluent nations.

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