HALFWAY BETWEEN KYOTO AND 2050:
ZERO CARBON IS A HIGHLY UNLIKELY OUTCOME

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Few terms have become as common during the first half of the 2020s as energy transition, decarbonization, and net zero by 2050, all conveying that grand global goal of eliminating fossil fuel combustion, and the attendant emissions of CO_2, by the middle of the 21st century -- and hence preventing further undesirable increases of tropospheric temperature.[1] Net, the zero qualifier, is a hedge considering the possibility of continued reliance on some fossil inputs whose emissions would be captured from the atmosphere and sequestered, resulting in no additions of anthropogenic CO_2.[2] **Unless emission can be decoupled from combustion, severing modern civilization's reliance on fossil fuels is a desirable long-term goal but one that (for many reasons) cannot be accomplished either rapidly or inexpensively.**

Globally, coal and oil surpassed wood as the leading energy sources just before the end of the 19th century, and hence for the past 125 years we have been a predominantly fossil-fueled civilization.[3] In mass terms, we will never run out of fossil fuels: enormous quantities of coal and hydrocarbons will remain in the ground after we end their use because it would be too expensive to extract them. Although the world of the early 2020s is in no imminent danger of running out of fossil fuels, in the long run they would have to replaced even in the absence of any connections to global warming. Their conversions made the modern civilization possible, but their production, processing and transportation are often environmentally disruptive, with impacts ranging from land dereliction to water pollution; their combustion generates not only CO_2 but also such pollutants as CO, nitrogen (NO, NO_2) and sulfur (SO_2 and SO_3) oxides and particulate matter; their highly uneven distribution contributes to worldwide economic inequalities, and the quest for secure fossil fuel supplies has led to many detrimental policies and contributed to recurrent conflicts.

Non-carbon alternatives have been making inroads for the past 140 years: the world's first hydroelectric station began to operate in 1882, the same year as Edison's first two coal-fired power plants. The first commercial nuclear fission reactor was commissioned in 1956, and in 2022 those two modes of electricity generation supplied nearly a quarter of the world's demand.[4] Geothermal generation also goes back more than a century but (for many reasons) it has never really taken off, while relatively large-scale production of biofuels (above all plant-derived ethanol) has been limited to the USA and Brazil. We remain a fossil-fueled civilization and this brief review demonstrates the high degree of our dependence and low probability, if not impossibility, of energizing the world's economy without any fossil carbon by 2050.

Carbon in the biosphere The Earth is made hospitable for photosynthesis and habitable for all higher organisms thanks to the regulation of its atmospheric temperature by several naturally occurring trace gases -- above all by carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone (O_3). Without their presence the planet's surface would be permanently frozen at about -18^oC, but by absorbing a small share of the outgoing (infrared) radiation these trace gases keep the mean tropospheric temperature at about 15^oC or 33^oC higher than in their absence.[5]

There is nothing new about the realization that these trace gases could affect climate. In 1861 John Tyndall concluded that variation of atmospheric CO_2 "must produce a change in climate."[6] In 1896 Svante Arrhenius explained that exponential rise of CO_2 would result in a nearly arithmetic rise of surface temperatures and that the doubling of pre-industrial CO_2 levels might raise the Earth's temperature by $5-6^oC$.[7] In 1957 Roger Revelle and Hans Suess concluded that the civilization has embarked on a large-scale *"geophysical experiment of a kind that could not have happened in the past nor be reproduced in the future."*[8] Just a year later US scientists began to measure CO_2 concentrations at Mauna Loa observatory in Hawai'i which demonstrated their steady annual rise.[9]

Remarkably, accumulated understanding had no effect on our actions and policies, and global warming began to receive wider public attention only since

1988 when the UN General Assembly endorsed the establishment of the Intergovernmental Panel on Climate Change (IPCC).[10]

Adoption of the UN's Framework Convention on Climate change followed in 1992, and the establishment of its supreme decision-making body, Conference of Parties (COP), in 1995, and Kyoto Protocol, committing the signatory countries to cut greenhouse gases to "a level that would prevent dangerous anthropogenic interference with the climate system" was adopted in 1997.[11] Since that time there has been an exponential rise of attention paid to the global climate change. We have learned a great deal, and although uncertainties remain, basic facts are indisputable. The best available summaries of global CO_2 emissions show that their increased 19-fold between 1900 and 2022, and that this steady rise was interrupted (for up to three years) fewer than 20 times across the 122-year span (Fig. 1).[12]

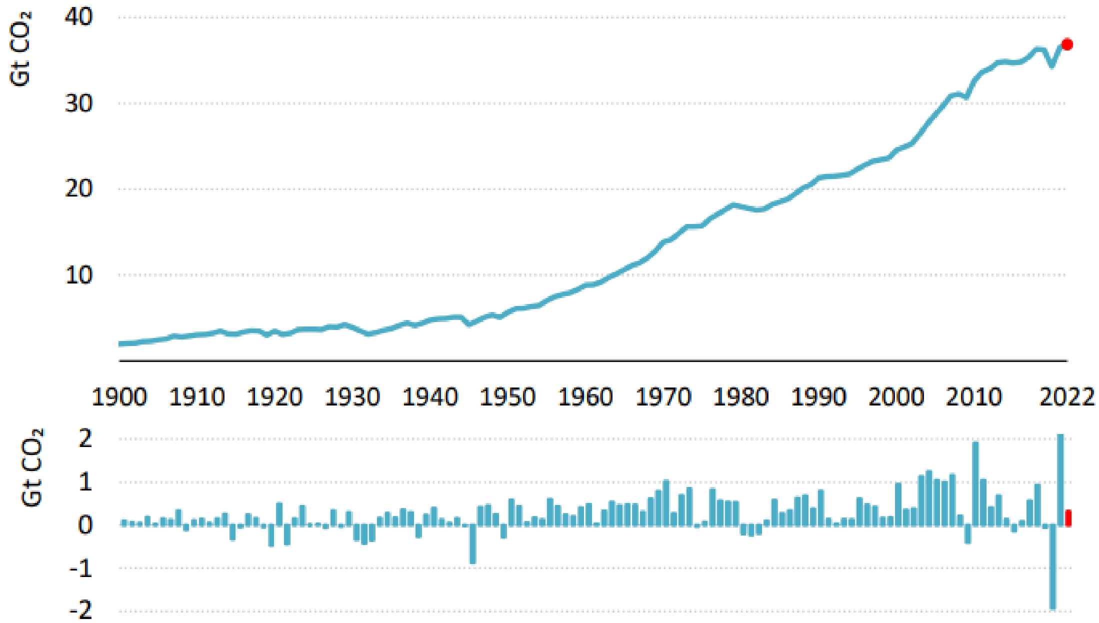

Figure 1: Global CO_2 emissions from energy combustion and industrial processes and their annual change, 1900-2022

Fig.1. Global CO_2 emissions from fossil fuel combustion rose 19-fold between 1900 and 2022. Source: CO2 Emissions in 2022 – Analysis - IEA

Ice core analyses show the CO_2 levels close to 270 parts per million (ppm) by volume during the preindustrial era; in 1958 (when the Mauna Loa monitoring began) they reached 313 ppm; by the year 2000 they were at 370 ppm and by the end of 2023 they reached 420 ppm, that is more than 50% above the late 18th-century level (Fig. 2).[13] **Notice that the post-1958 rise has been uninterrupted: average annual concentrations show a steady rise that continued even during the years when global CO_2 emissions had temporarily declined: even in the year 2020 when the Covid restrictions cut the emissions by 2% the Mauna Loa level rose by 2.56 ppm.**

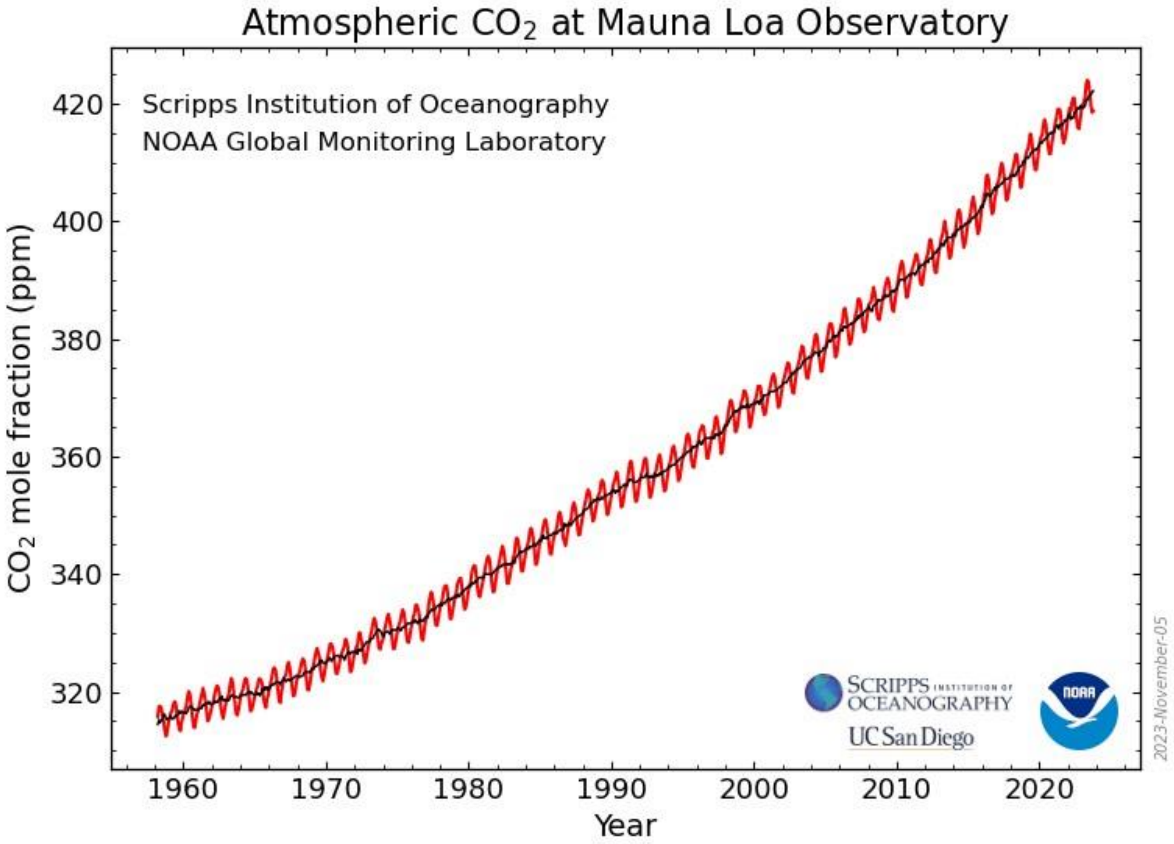

Fig. 2. Average annual CO_2 concentrations measured at Mauna Loa rose by 34% between 1958 and 2023. Source: Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases (noaa.gov)

This rise (together with contributions by CH_4 and N_2O) has translated to about 1° C of global warming compared to the 19th-century mean. All continents have been affected, recent decadal warming gains have been steadily rising and the eight years between 2015 and 2022 were the warmest years on record since 1850.[14] Complex interactions of the atmosphere, hydrosphere and biosphere and unknown levels of future greenhouse gas emissions make it impossible to pinpoint the degree of global warming that will be experienced by 2050, and this brief assessment does not revisit any of these, by now widely covered, uncertainties and controversies. Instead, it concentrates on the realities. modalities and probabilities of accomplishing the most important action that is now advocated to keep the global mean temperature rise to acceptable maximum: on the elimination of fossil fuel combustion, that is a complete decarbonization of the global energy supply, by 2050.

Genesis of this goal goes to the Paris Agreement of 2015 (COP 21) which stated that the world must "achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century".[15] The now common term “net zero” and the year of 2050 were used for the first time in the IPCC’s Special Report on a Global Warming of 1.5°C in 2018: in order to limit the warming to 1.5°C, global net anthropogenic CO_2 emissions must “decline by about 45% from 2010 levels by 2030 . . . reaching net zero around 2050.”[16] (Fig. 3)

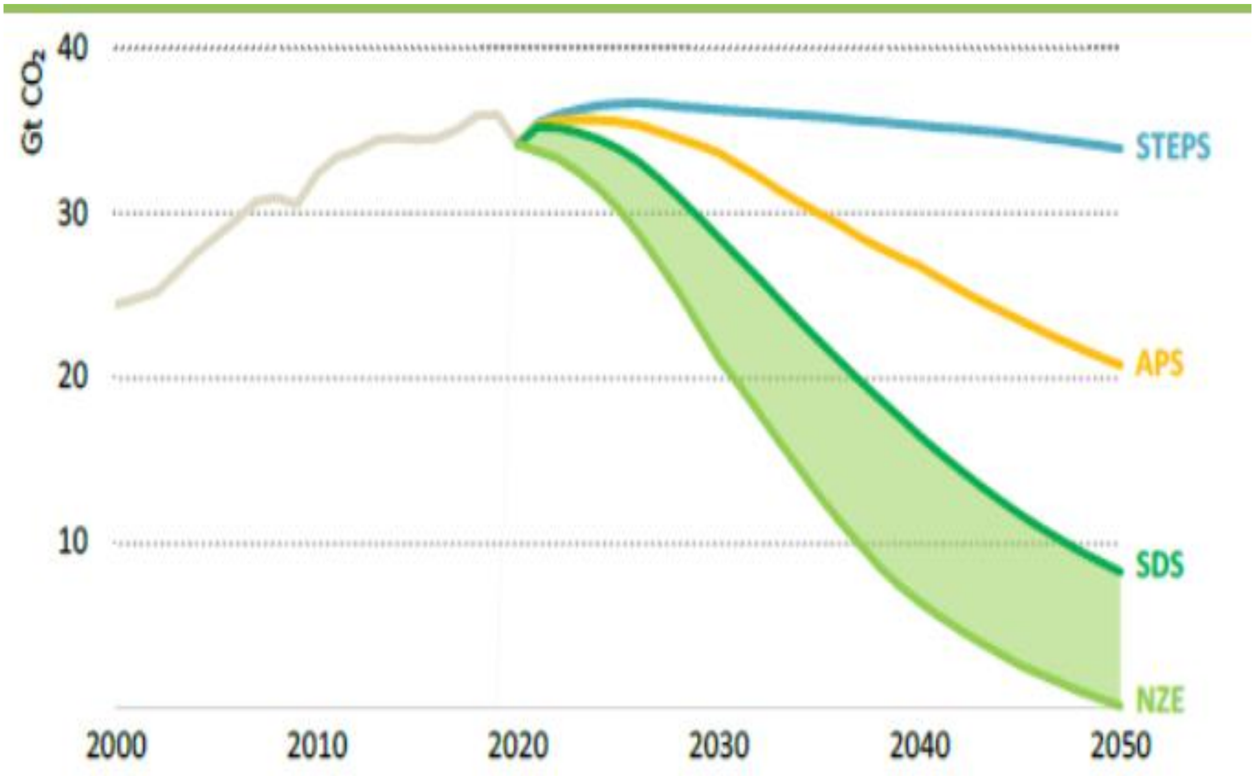

Fig. 3. CO_2 emissions according to IEA's scenarios. STEPS = Stated Policies Scenario; APS = Announced Pledges Scenario; SDS = Sustainable Development Scenario; NZE = Net Zero Emissions by 2050. After two centuries of rise, fossil fuel combustion is to experience a sudden and steep drop to zero by 2050. Source: World Energy Outlook 2021 – Analysis - IEA

Energy transitions This goal is to be achieved by energy transition whose speed, scale, and modalities (technical, economic, social, political) would be historically unprecedented -- and I will show why the accomplishment of such a transformation, no matter how desirable it might be, is highly unlikely during the prescribed period. What is particularly clear that (in the absence of an unprecedented and prolonged global economic downturn) **the world will remain far from reducing energy-related CO_2 emissions by 45% from the 2010 level by 2030: for that we would have to cut the emissions by nearly 16 billion tons between 2023 and 2030 -- or eliminating nearly as much fossil carbon as the combined emissions of the two largest energy consumers, China and the USA.** [17]

The combination of scale and speed is the foremost enormity that makes the unfolding transition so taxing. Miniaturization and relative dematerialization are two qualities admired in modern society enjoying the benefits of solid-state microelectronics -- but in aggregate terms mass will always matter. When the world began to undergo the first energy transition during the 19th century it had to replace about 1.5 billion tons of (mostly locally cut and burned) wood by coal and (after 1860s) also by hydrocarbons.[18] In 2022 the world produced nearly 8.2 billion tons of coal, almost 4.5 billion tons of crude oil and 2.8 billion tons of natural gas, all extracted very efficiently and mostly in highly concentrated manner from large mines and from enormous hydrocarbon fields on every continent.

In terms of their final uses this means that we would have to replace more than 4 TW of electricity-generating capacity now installed in large coal- and gas-fired stations by non-carbon conversion; to substitute nearly 1.5 billion combustion (gasoline and diesel) engines in road and off-road vehicles;

to convert all agricultural and crop processing machinery (including about 50 million tractors and more than 100 million irrigation pumps) to electric drive or to non-fossil fuels; to find new sources of heat, hot air and hot water used in a wide variety of industrial processes (from iron smelting and cement and glass making to chemical syntheses and food preservation) that now consume close to 30% of all final uses; to replace more than half a billion natural gas furnaces now heating houses and industrial, institutional and commercial places by heat pumps or other sources of heat; and to find new ways to power nearly 120,000 merchant fleet vessels (bulk carrier of ores, cement, fertilizers, wood and grain and container ships, the largest one with capacities of some 24,000 units, now running mostly on heavy fuel oil and diesel fuel) and nearly 25,000 active jetliners that form the foundation of global long-distance transportation (fueled by kerosene).[19]

On the face of it, and even without performing any informed technical and economic analyses, this seems to be an impossible task given that: we have only a single generation (about 25 years) to do it; that we have not even reached the peak of global consumption of fossil carbon; that the peak will not be followed by precipitous declines; that we still have not deployed any zero-carbon large-scale commercial processes to produce essential materials; and that the electrification has, by the end of 2022, converted only about 2% of passenger vehicles (more than 26 million) to different varieties of battery-powered cars and that decarbonization is yet to affect heavy road transport, shipping and flying.[20] **None of this comes as a surprise to students of energy history as global energy transitions have been always protracted affairs.**

Coal surpassed global wood combustion only in 1900, and its share of energy supply peaked only in the mid-1960s; oil began to supply more than 25% of all fossil fuels only during the late 1950s, nearly a century after its first modern commercial extraction, and natural gas began to contribute more than 25% of fossil energy supply just before the end of the 20th century, after some 130 years of the industry's development.[21] **Moreover, even the first grand energy transition still has not been completed more than two centuries after it began: nearly 3 billion people (in Africa, monsoonal Asia, and Latin America) still depend, mainly for cooking, some also for heating, on traditional biomass energies: fuel wood (and charcoal made from it), straw and dried dung still supplied about 5% of the world's primary energy in 2020.**[22]

International Energy Agency's *World Energy Oulook 2023* illustrates both the widely misunderstood realities and the likely outcomes of the unfolding transition. The outcome of its scenario based on the stated national policies (that is on policies already adopted by individual states to reach the intended decarbonization goals) was called something that "has never previously been seen" because each of the three fossil fuel was projected to reach a peak by 2030, the peak in energy-related CO_2 emissions is to take place by 2025, and afterwards the demand for fossil fuels is to decline by average of 3 EJ/year until 2050.[23] Those who read just the media reports listing these changes and emphasizing this historic “turning point” were left with the impression of an imminent astounding shift -- but that would be a fundamental misunderstanding of the process as consumption peaks on the large-scale level (globally and for populous nations, not necessarily for small countries that can shift faster) are followed by long periods of decline.

Indeed, the accompanying figure from the IEA’s outlook would have returned the consumers of media headlines back to reality. By 2050 even coal consumption, after an unprecedented projected decline, would be as high as it was at the beginning of the 21st century; both crude oil and natural gas consumption (yet to peak) would be nearly as high (>95%) as in 2030; **and a steady decline would still leave the fossil fuel consumption at about 85% of the current level (Fig. 4). That is, of course, very far from any zero carbon scenarios.**

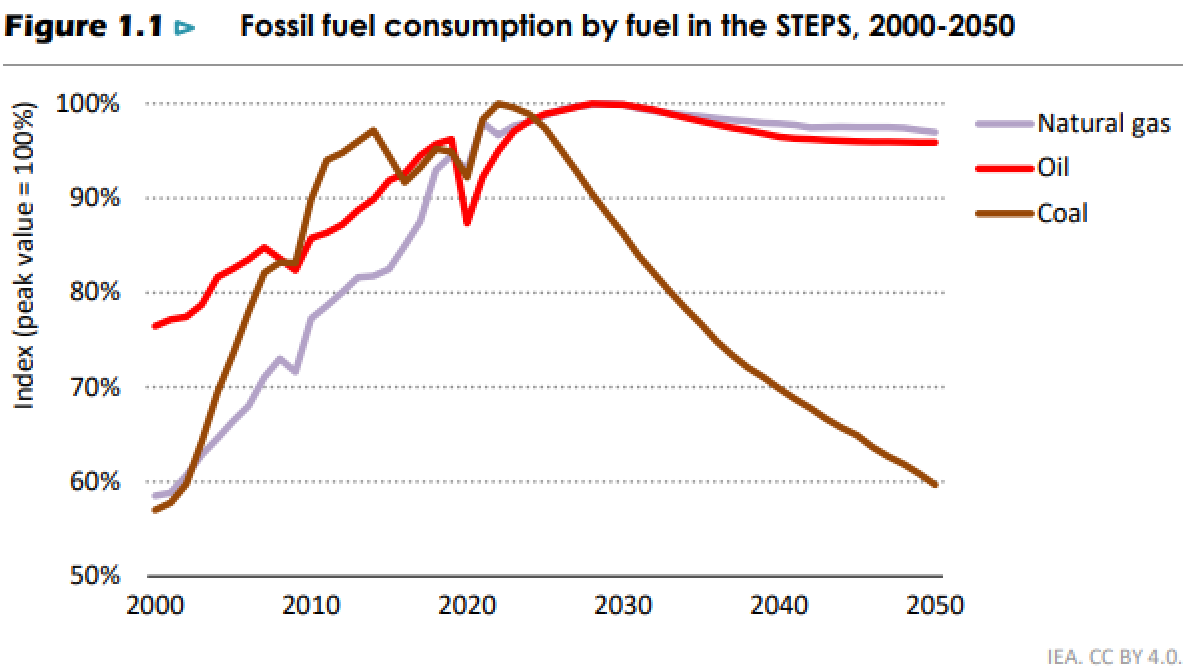

Fig. 4. IEA's global turning points followed by long and substantial presence of fossil fuels in the Stated Policies Scenario. Source: World Energy Outlook 2023 (windows.net)

The gradual nature of energy transitions is an inevitable consequence of the fact that none of them have been just a simple replacement of converters. To believe a common (but completely misplaced) phone analogy -- we have largely switched from landlines to mobile phones in (depending how you define the process) only two to three decades, so why not to get rid of fossil fuels on a similarly short time scale -- is to commit a serious category mistake, a logical fallacy that compares (confuses) an extraordinarily complex system of securing reliable and affordable global supply (variety of final energy uses) with just one type of user assembly (most recently the 5G network).

These networks are complex, their establishment and operation require constant maintenance and upgrading, and their costs are considerable, but they are only one of many parts making up the vastly more complex global energy system. **That is why global energy transitions are complicated, multifaceted, protracted and in their details rather unpredictable system changes which require mass-scale development, adoption and massive scaling-up of new techniques (be they large-scale "green" hydrogen electrolysis or extensive multiplication of small modular fission reactors), construction of new extraction, processing, and distribution networks (to produce large quantities of basic materials, metals, synthetic compounds and automated controls), all requiring decades of steady, high-level investments and political commitments that will result in major economic and social changes.**

In the past, replacing wood stoves by coal stoves, waterwheels and wind mills by steam engines, horse teams by diesel engines and oil and gas lamps by electric lights required new, extensive and complicated infrastructures needed to extract (coal mines, oil and gas fields, dams), prepare (coal sorting and cleaning, crude oil refining, natural gas processing), transport (railways, pipelines, ships, trucks, high-voltage transmission lines) and convert (steam engines, steam and gas turbines, furnaces, boilers, turbogenerators, transformers, electric motors) new forms of energy, and the invention and mass production of new converters ranging from light bulbs and toasters to engines able to operate with high efficiency and astonishing reliability aloft or under water.

The unfolding energy transition requires not just very large numbers of new wind turbines and photovoltaic panels to generate “green” electricity. Renewable generation also needs expanded high-voltage transmission (overhead wires and undersea cables from offshore wind sites) to bring the electricity from the windiest and sunniest places to often distant cities and industrial areas. As it ramps up it will also need capacious electricity storage, such as batteries (or other mechanical, thermal, or chemical arrangements) large enough to cope with the intermittency of wind and solar radiation: this need will become imperative if these sources become dominant generators of electricity and if there would not be, complemented, as they are today, by base-load nuclear or fossil fueled generation or by near-instant deployment of gas turbines.

Moreover, there are many final energy conversions (ranging from heavy ocean shipping and long-distance commercial aviation to key industrial processes, above all continuous chemical syntheses) that cannot be readily electrified, and we would need substantial quantities of solid and liquid fossil carbon even in the zero-carbon world for paving (asphalt) and for industrial and commercial lubricants.[24] Producing what I have called the four pillars of modern civilization -- cement, primary iron, plastics, and ammonia -- now depends on fossil fuels, and replacing them with alternatives will require the development of new mass-scale industries and distribution networks ranging from green hydrogen (made by electrolysis of water by green electricity) and ethanol to new synthetic fuels.[25]

Costs can alleviate or aggravate the challenges of complexity. If more complex innovations are cheaper than the established ways, or if their higher cost are outweighed by higher quality, efficiency and convenience, then the transitions can proceed rapidly. Examples include black vs. color TV, reciprocating engines vs. jet engines in long-distance commercial aviation, landlines vs. mobile phones, high-efficiency natural gas furnaces vs. coal stoves. In contrast, renewable conversions start with the inherent disadvantages of low power density and intermittency, and hence their full costs (with service comparable to the on-demand supply and reliability of fossil fuel converters) are considerably higher than the marginal cost of purchasing and installing new PV panels or wind turbines.[26]

Differences have been narrowing but the latest comparisons of levelized costs of electricity generation in the US indicate the overall cost of solar PV (capacity factor of 28%) entering service in 2027 will be only 9% lower than the cost of combined cycle gas turbine (CCGT, capacity factor 85%), that onshore wind will have the same overall cost but offshore wind as well as battery storage will be still more than three times as expensive.[27] The promise of low-cost nuclear generation remains just that: by 2027 advanced nuclear generation is still expected to cost at least twice as much as CCGT, unsubsidized electric cars remain more expensive than comparable gasoline-powered vehicles, and the cost of green hydrogen, now in the earliest stages of development, remains uncertain.[28] The unfolding transition thus relies on techniques that are not (as yet) compellingly and across the board cheaper, more reliable and more than the conversion they are replacing. Moreover, some of them (above all new reactors and mass-scale electricity storage) will require a great deal of further expensive development.[29]

Our record so far The most obvious way to start assessing the progress of the required energy transition is to look at what has been accomplished during the past generation when the concerns about global decarbonization assumed new urgency and prominence. Contrary to common impression, there has been no absolute worldwide decarbonization -- just the very opposite as the world has become much more reliant on fossil carbon (even as its relative share declined a bit). We are now halfway between 1997 (27 years ago) when delegates of nearly 200 nations met in Kyoto to agree on commitments to limit the emissions of greenhouse gases, and 2050, with 27 years left to achieve the goal of decarbonizing the global energy system, a momentous divide to judge the progress, or the lack of it.

Numbers are clear. All we had managed to do halfway through the intended grand global energy transition is a small relative decline of fossil fuel's share in the world's primary energy consumption, from nearly 86% in 1997 to about 82% in 2022. But this marginal relative retreat has been

accompanied by a massive absolute increase of fossil fuel combustion: in 2022 the world consumed nearly 55% more energy locked in fossil carbon than it did in the year 1997 (Fig. 5).[30]

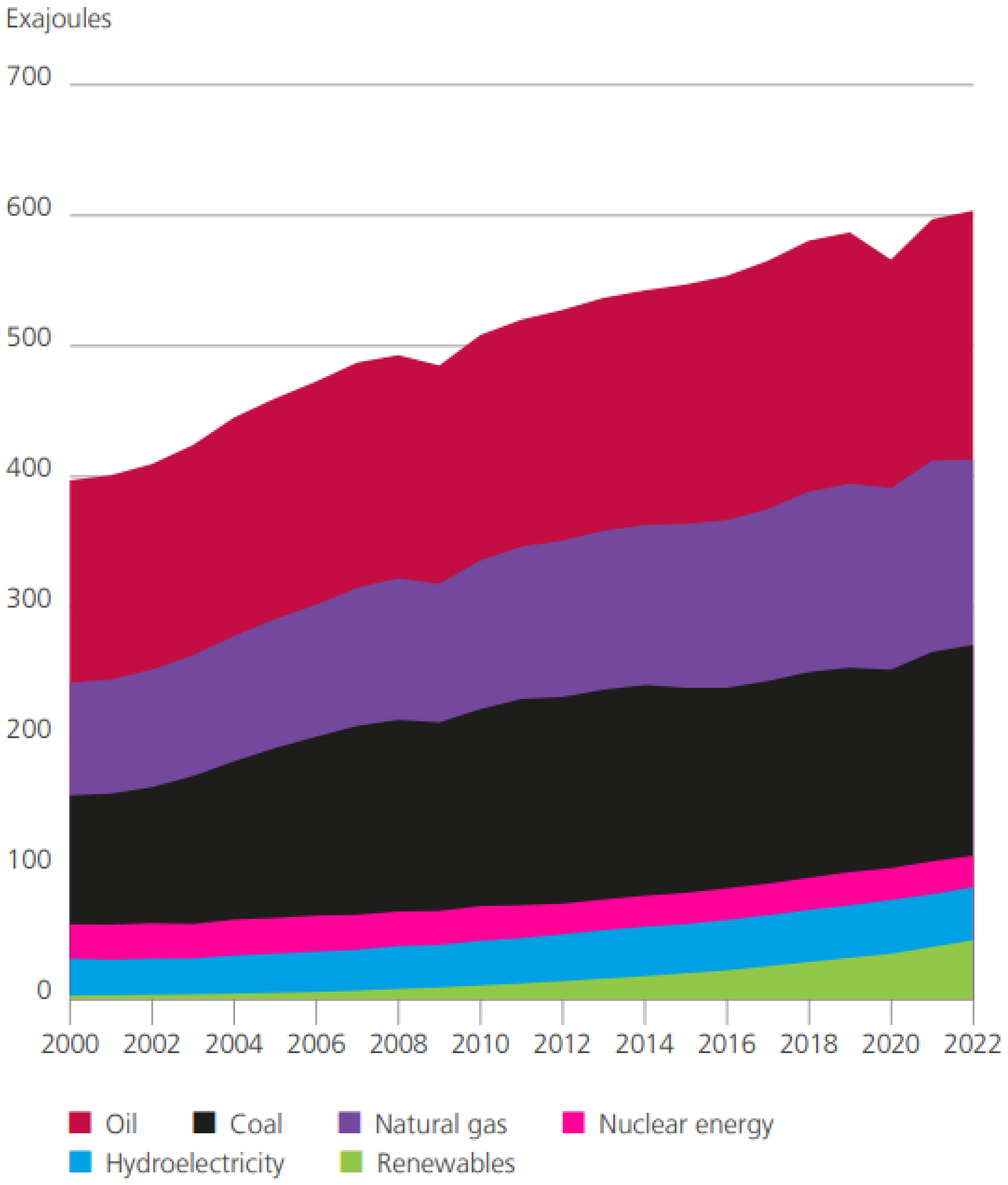

Fig. 5. Global dependence on fossil fuels has continued to rise in the 21st century. Source: Home | Statistical Review of World Energy (energyinst.org)

Absolute cuts in carbon emissions that took place in such large economies as the EU (-23%) and the US (-9%) were far surpassed by massive absolute gains in the world's two largest industrializing nations -- China's emissions rose 3.3 times, India's three times -- as well as in the Middle Eastern hydrocarbon producers (Saudi emissions rose 2.3 times) and among other smaller emitters.

The conclusion is unequivocal: by 2023, after a quarter century of targeted energy transition, there was no absolute global decarbonization of energy supply, just the opposite as the world had substantially increased its dependence on fossil carbon. This is a fundamental point: changes in global average atmospheric temperature respond to changes in the total atmospheric burden of radiation-absorbing gases, not to any local or national declines. Between 1997 and 2022 annual emissions of CO_2 from the fossil fuel energy sector (CO_2 from fuel combustion and processing, CO_2 equivalent of CH_4 from extraction, flaring and pipeline leakage) rose from about 25.5 billion tons CO_2e to about 39.3 billion tons (54% rise).[31]

As a result of complex interchanges within the global biogeochemical carbon cycle, only a fraction of these anthropogenic emissions remains in the atmosphere as most of them are absorbed by the oceans and by vegetation, resulting in increasing concentration of the gas in ocean water (and hence in its acidification) and in the greening of the biosphere (expansion of plant cover). Consequently, the total atmospheric burden of CO_2 (including the emissions from other sectors) rose from 2.85 trillion tons in 1997 to 3.27 trillion tons in the year 2022, corresponding to the increase of the mean Mauna Loa concentration from 364 ppm to nearly 420 parts per million (up by more than 15%).

What it would take Given these realities, what are the chances of not only decisively reversing the past emission trend and starting global decarbonization but eliminating the generation of carbon from fossil fuel combustion by 2050? After cutting our relative dependence on fossil fuels by just 4% during the first half of the prescribed post-Kyoto period, we would have to (even if there would no further increase in CO_2 emissions) cut it by 82% by 2050. **In absolute terms it would mean cutting the energy-related emissions by an average of 1.45 billion tons a year (compared to average annual rise of nearly half a billion tons since 1995) -- and that would be like eliminating every year the equivalent of two years of Saudi emissions or nearly half of India's 2022 total.**

Obviously, any postponement of these annual cuts would then require higher cuts during the later years of the remaining period. Another revealing way of viewing the daunting magnitude of this challenge is to look at the cuts that would have to be made by G20 economies to meet the interim 2030 goals: for nearly all major economies the shares cluster around halving the 2020 emissions, with cuts of 45% for Canada and 46% for Saudi Arabia to 55% for EU, 56% for the US and 63% for China.[32] Only an unprecedented economic collapse could bring such cuts during the next seven years.

To reach zero carbon in 2050 we would have to eliminate, after increasing our dependence on fossil fuels by almost 180 EJ since 1997, almost 500 EJ (that is equivalent to about 12 billion tons of crude oil) even if there were no further consumption increases. But the real need for non-carbon energies would be much larger: they would have to replace not only all of today's carbon fuels but also cover all additional increase of global energy use anticipated by 2050. **As expected, long-range forecasts differ but global energy demand (reduced by higher conversion efficiencies) is set to grow by at least 10-15% by 2050, and that would require the total of close to 700 EJ of new, non-carbon energies by 2050.[33] In the carbon-free world, these needs would have to be met by a combination of renewably generated electricity, green hydrogen, and green fuels.**

The task ahead: zero carbon electricity and hydrogen Hydroelectricity now supplies about 15% of the world's primary energy consumption, followed by about 10% generated by nuclear fission.[34] New renewables, wind and solar, have grown rapidly during the past three decades and in 2022 they supplied

12% of all electricity generation, still less than half generated by the two old carbon-free techniques. **Moreover, primary electricity (hydro, nuclear, wind, solar and a small contribution by geothermal plants) accounted for no more than about 18% of the world's primary energy consumption, which means that wind and solar generation provided only about 7% of the world's primary energy supply in 2022**. This comes as a surprise to people unfamiliar with global energy statistics: endless announcement of new wind farms and large areas covered by PV cells make most people believe that we have gone much further toward renewably electrifying everything!

The ultimate extent of that task depends on the (yet unknowable) contributions of other generation methods and the eventual extent and modes of electrification. Fission's fate is perhaps the main uncertainty. Despite the decades of promising an imminent arrival of large numbers of small modular reactors (SMRs, up to 300 MW) that would bring the resurrection of stagnating electricity generation by nuclear fission, and despite some 80 different designs, in 2023 not a single SMR was operating anywhere in the West, and China had only a single test prototype.[35] Proponents of geothermal generation stress its enormous potential, but practical advances have been slow.

And the eventual need for renewably generated electricity will depend on the extent of direct and indirect uses of electricity, the choice exemplified in transportation by Tesla vs. Toyota: what market shares will eventually be claimed by battery-powered vehicles and fuel cell vehicles (with hydrogen fuel made by electrolysis of water)? Further along the transition road, will it be airplanes using much improved (yet unavailable high-power density) batteries, burning hydrogen directly, using fuel cells for electric drive? What is clear is that the total addition of zero carbon electricity will have to go far beyond just replacing today's fossil-fueled generation, that is about 62% of the total of more than 29 quadrillion watthours (PWh) in 2022. **Electricity demand will continue to grow: the International Energy Agency forecasts annual growth of 3.3% until 2050 and that would raise the 2022 total nearly 2.5-fold to just over 72 PWh.**[36]

Even if hydro and nuclear were to cover 20% of that total, wind and solar would have to reach about 58 PWh in 2050, about 17 times their 2022 output and almost exactly twice the 2022 electricity generation from all sources (and their inherent intermittency would require further substantial investments in mass-scale storage and HV transmission to ensure interrupted supply). That would require sustained annual growth of about 10.5%, a rate that looks quite manageable compared to actual annual growth of about 29% for solar and 15% for wind between 2012 and 2022 -- but that will be, as in the case of any long-term growth, harder to sustain as the absolute annual totals become an order of magnitude higher (already, the respective 2017-2022 rates declined to 22% and 12%).

And besides the electrification trends already underway (passenger cars, heating, some industrial processes) large shares of non-carbon generation will be needed for electrifying, to the maximum extent possible, all those industries that now rely on coal, oil, and gas. While further expansion of wind and solar generations rests on scaling up well-known, mature conversion techniques, decarbonizing many industrial processes will require the development of new processes, first testing their prototypes and then deploying them commercially around the world. Two key examples show the challenges of such unprecedented efforts.

Steel is, and it will remain, the modern civilization’s dominant metal, indispensable for all infrastructures, housing, transportation, agriculture, and industrial production.[37] Roughly 30% of the world’s steel is made by recycling scrap metal: this is done in electric arc furnaces (EAF) and hence this effort can be totally energized by green electricity. But 70% of the world’s steel came from basic oxygen furnaces (BOF) using cast (pig) iron smelted in blast furnaces (BF) fueled with coke (made from coking coal), coal dust and natural gas. In 2022 output of this primary BF-BOF steel reached 1.4 billion tons and forecasts are for no less than 2.6 billion tons of the metal needed in 2050; that would, even with raising the EAF steel share to 35%, require roughly 1.7 billion tons of green iron.[38] Instead of reducing iron ores with carbon (and emitting CO_2), in the zero-carbon world we would have to reduce them with hydrogen ($Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$). **This means that by 2050 the annual output of 1.7 billion tons of green steel would need about 91 million tons of green hydrogen (Fig. 6).**

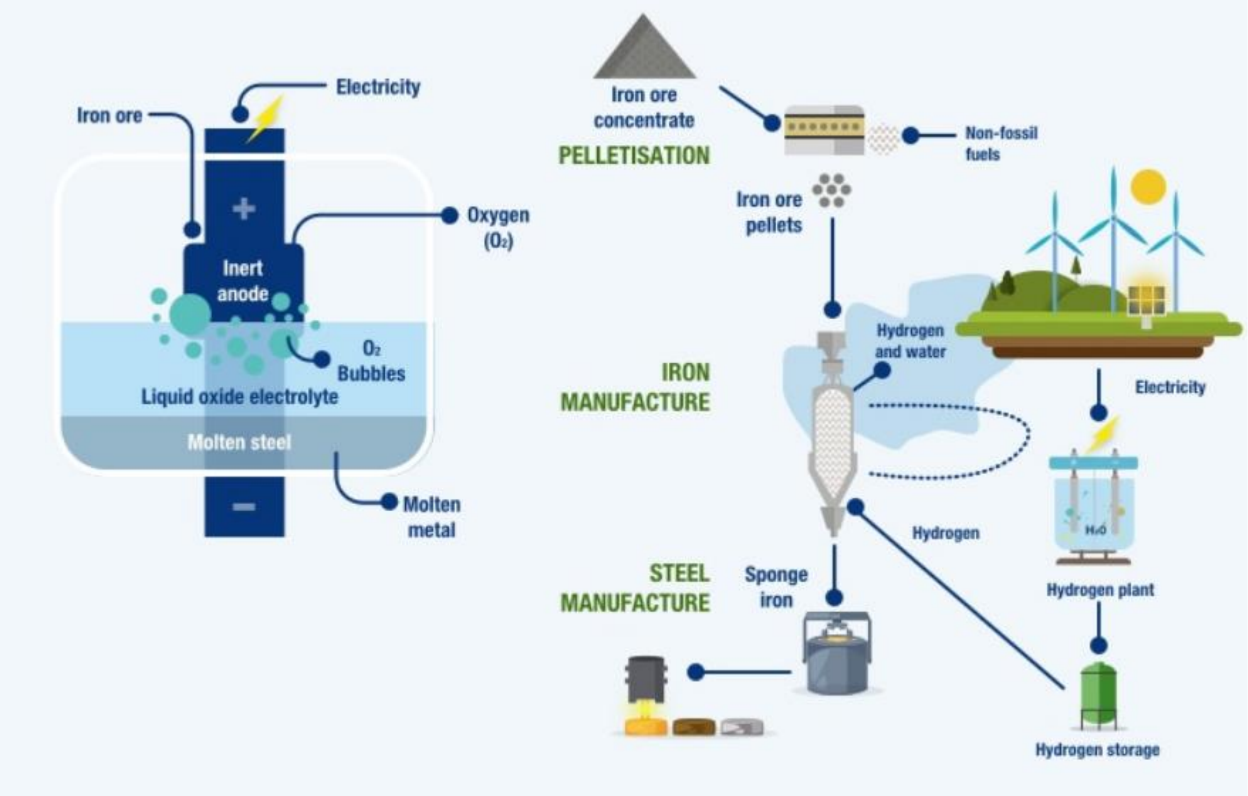

Fig. 6 Primary green ironmaking: set-ups such as this one, non-existent in 2023, would need to produce more than 1.5 billion tons of metal by 2050. Source: Green steel, the material that will transform the steel industry – Iberdrola

Ammonia is an even more important products: about 85% of its annual production is used to make synthetic nitrogenous fertilizers without whose continuing applications about half of today's world population could not survive.[39] Ammonia is now synthesized with nitrogen taken from air and hydrogen produced by shift reaction from natural gas, coal, and liquid hydrocarbons ($N_2 + 3H_2 \rightarrow 2NH_3$), with less than 5% coming from electrolysis of water (green hydrogen). In 2022 annual output of ammonia reached about 150 million tons and forecasts are for at least 200 million tons by 2050. **Fossil carbon-free Haber-Bosch ammonia synthesis process would need about 44 million tons of green hydrogen by 2050.**

The two key material processes, making of steel and ammonia, would need annual production capacity of some 135 million tons of green hydrogen by 2050 -- but depending on additional needs for transportation, heating, industries (from glassmaking to food preservation), and peak electricity generation, the total demand for green hydrogen could be easily as high as 500 million tons by 2050 (that would be the equivalent of 65 EJ, less than 10% of the expected primary energy need by 2050). Electrolytic production of green hydrogen needs about 50 MWh/ton: making 500 million tons of green hydrogen by 2050 would thus require about 25 PWh of green electricity, the total equal to about 86% of the 2022 global use.[40] To repeat, this renewably generated electricity would be for green hydrogen alone! How fast can we get there? In 2023 IEA review estimated that in 2030 the global output of green hydrogen could reach 38 Mt -- but only if all intended projects for electrolytical process (or from fossil fuels with carbon capture) were completed.[41]

But half of these potential output comes from projects that were still undergoing feasibility studies or were at early stages of realization, while the projects under construction or those that received final investment decision made up only 4% of all announcements. Production targets by HyDeal España are an excellent example of this uncertain state. In 2021 the International Renewable Energy Agency welcomed its announcement as “the world’s largest renewable hydrogen giga-project” -- but in September 2023 the company more than halved its 2030 target for electrolyser capacity from 7.4 GW to 3.3 GW, as it announced a new goal of producing 150,000 tons of green hydrogen by 2031.[42] And the “giga” label should be put into practical perspective. Annual output of 150,000 tons of green hydrogen would be enough to synthesize 700,000 tons of ammonia, and that would supply about 0.65% of nitrogen now applied every year to the world’s crops. Conversely that means we would need more than 150 of equally sized “giga” projects to cover today’s global demand for the most important plant macronutrient.

As for the green steel, the first steel plant smelting iron ore with hydrogen produced by renewably-generated electricity is now under construction in Boden, in northern Sweden: the plan is to make 1 Mt of steel in 2026 and then to ramp it up to 5 Mt by 2030.[43] Annual output of 1 Mt is an equivalent of 0.07% of the world’s 2022 primary steel production and to make all primary steel (1.7 Gt) green by 2050 the world would need open 340 Boden-like (5 Mt/year) plants between 2030 and 2050, that is one every three weeks during that 20-year period, preferably with co-located (or nearby) green hydrogen electrolytic plants and with plants producing pelleted or briquetted iron without any fossil fuel.

This pace of required hydrogen and steel plant additions illustrates another fundamental factor that is likely to affect the unfolding global energy transition: every one of its components will generate unprecedented demand for materials and the challenge is made more difficult both by higher material intensities of some new techniques and by complicated access to many essential resources.[44] Wind turbines are perhaps the best illustration of the former reality. While gas turbines -- today's dominant on-demand generator of electricity are highly efficient (>60%) and compact machines -- need less than 10 tons of materials per installed MW, and no more than 30 t/MW when adding all associated structures, large wind turbines need typically about 500 t/MW.[45] Reinforced concrete for foundations dominates, followed by steel for tall towers, epoxy resins, balsa and carbon fibers for blades, plastics, copper, aluminum, ceramics for the nacelle and two rare metals, neodymium, and praseodymium, for permanent magnets.

Materials for electric vehicles fit into both categories of concern. Typical electric vehicle contains more than five times of copper (80 vs. 15 kg) than an internal combustion engine car and replacing today's 1.35 billion light-duty gasoline and diesel vehicles by EVs and supplying the expanded market (2.2 billion cars by 2050) would thus require nearly 150 million tons of additional copper during the next 27 years, that is an equivalent of more than seven years of today's annual copper extraction for all of the metal's many industrial and commercial uses.[46] In addition, the IEA estimates that, compared to 2020, by

2040 the take-over by EVs would need more than 40 times as much lithium and up to 25 times graphite, cobalt, and nickel.[47] Cumulative demand for total decarbonization by 2050 has been estimated (to list just the three largest items) at about 5 billion tons for steel, nearly a billion tons for aluminum and more than 600 million tons of copper, and such massive mineral needs bring not only technical and financial concerns, but they also have environmental and political implications.[48]

Copper offers a stunning example of these environmental externalities. Metal content of exploited Chilean copper ores, the world's leading source of the metal, has declined from 1.41% in 1999 to 0.6% in 2023, and further quality deterioration is inevitable.[49] (Fig. 7).

Fig. 7. Declining quality of Chilean copper resources. Source: Copper: Most Important Metal Were Running Short Of (streetwisereports.com)

Using the mean richness of 0.6% means that the extraction of additional 600 million tons of metal would require the removal, processing, and deposition of nearly 100 billion tons of waste rock (mining and processing spoils), that is about twice as much as the annual total of global material extraction including harvested biomass, all fossil fuels, ores and industrial minerals and all bulk construction materials.[50] Extracting and dumping such enormous masses of waste material exacts a very high energy and environmental price as it puts new, supposedly "green" energy uses even further from the goal of maximized material recycling. Moreover, copper's production is dominated by just a few countries (Chile, Peru, China, Congo) and China alone refines 40% of the world's supply. China processes even more of other minerals require for green energy conversion: nearly 60% of lithium, 65% of cobalt and close to 90% of rare earths.[51] That makes OPEC's grip on crude oil (now 40% of global production) a relatively restrained affair!

And when countries from Canada to Germany find it impossible to construct enough basic housing it is obvious that any accelerated installation of green energy projects and infrastructures will be restricted by shortages of experienced labor. Germany, thanks to its *Energiewende* the EU's leader in the pursuit of greenness, is already affected: in 2023 the country lacked about 216,000 skilled workers to expand solar and wind power, and now mandatory heat pumps installations would need another 80,000 technicians.[52] Similarly, the US is finding that labor shortages will slow-down any radical plans for green energy transitions.[53]

Costs, politics and demand We do not know either the eventual magnitudes and shares of specific energies that would enable the carbon-free world or the extent of their global infrastructures: these realities cannot be determined decades ahead, they will be formed gradually and, to a significant degree, unpredictably. This makes any overall cost estimates questionable. We also need to interpret properly the trend of decreasing cost of newly installed wind and solar capacities. As is common with most new conversion techniques undergoing large-scale commercialization, these declines per unit of installed capacity have been substantial, but during the next quarter century they cannot be expected to continue at rates similar to those that experienced since the year 2000 and, more importantly, those two renewable, and hence intermittent (variable), modes of generation need back-up when nights, cloudiness, and calm (or winds too strong to operate wind turbines) intervene.[54]

As long as solar and wind supply relatively low shares of total electricity generation, such needs are readily covered by existing base-load coal-fired or nuclear generation, by near-instantly available gas turbines or by imports from neighboring countries.[55] Once the intermittent sources become dominant, and all gas-turbines are gone, they will need either extensive high-voltage interconnections to bring electricity from more distant regions or substantial capacities of longer term of electricity storage. Construction of much-needed high-voltage lines has been notoriously behind the anticipated completion dates (with causes ranging from vigorous NIMBY opposition to high cost of new links), be in the US (interior to coasts) or Germany (north-south) -- while the IEA estimated that meeting the national decarbonization goals would require adding or refurbishing more 80 million kilometres of transmission grids by 2040, that is the equivalent of the entire existing global grid in 2023 and one predicated on further mass-scale mobilization of steel, aluminum, copper and cement.[56]

And, so far, only pumped hydro storage (requiring specific terrain configuration and impossible in lowlands) can provide as much as gigawatts of power for many consecutive hours. But renewably electrified megacities of the 2040s in monsoonal Asia might need (during a typhoon day) storage of many gigawatts (5-20 GW) for 10-20 hours (rating up to 400 GWh), while today's largest Li-ion battery energy storage (Moss Landing in California) is rated at 750 MW/3 GWh, two orders of magnitude lower.[57] Obviously, costs of these necessary transmission or storage arrangements (back-ups) will have to be added to the cost of wind turbines and PV panels in all systems dominated by intermittent generation.

Another category mistake involving costs is to hope that the global energy transition to zero fossil carbon can be achieved by embarking on an equivalent of dedicated targeted development so famously exemplified by the construction of first nuclear bombs (Manhattan Project) or putting men on the Moon (Project Apollo). We have comprehensive data about the cost of those two endeavors and after converting them to 2022 monies they look, when see from the spending perspective of the 2020s, like extraordinary bargains: Manhattan Project (1943-1945) cost just $(2022) 33 billion or 0.3% of GDP for those years, while the Project Apollo (1961-1972) came to $207 billion or 0.2% of GDP for those 12 years.[58]

Nobody can offer a reliable estimate of the eventual cost of worldwide energy transition by 2050 though a recent (and almost certainly highly conservative) total suggested by McKinsey Global Institute's makes it clear that comparing this effort to any former dedicated government-funded projects is another serious category mistake. The estimate of $275 trillion between 2021 and 2050 prorates to $9.2 trillion a year, compared to the 2022 global economic product of $101 trillion, implying annual expenditure on the order of 10% of the total economic product for three decades, rather than 0.2 or 0.3% for a few years.[59]

But, for two reasons, the real burden would be far higher. First, it cannot be expected that low-income countries could sustain such a diversion of their limited resources, and hence this global endeavor could not succeed unless the world's high-income nations would spend annually sums equal to 15-20% of their economic product. **More importantly, this ultimate global transformation project would face enormous cost overruns. As the world's most**

comprehensive study of cost overruns (more than 16,000 projects in 16 countries and in 20 categories, from airports to nuclear stations) shows, 91.5% of projects worth more than $1 billion have run over the initial estimate, with the mean overrun of 62%.[60] Applying 60% correction would raise McKinsey's estimate of global decarbonization cost to $440 trillion or nearly $15 trillion a year for three decades, requiring affluent economies to spend 20-25% of their annual GDP on the transition. Only once in history did the US (and Russia) spent higher shares of their annual economic product, and they did so for less than five years they needed to win World War II.[61] Is any country seriously contemplating similar, but now decades-long, commitments?

In 2023, political implications and complications of eliminating carbon emissions by 2050 are self-evident. Global warming is a global problem and decarbonization cannot be achieved without worldwide participation, with most of the burden carried by a small group of the largest emitters. China is now responsible for 31% of global emissions from energy use, US for 14%, EU for 11%, India for 8%, Russia for 4% and Saudi Arabia and Indonesia each for about 2%. What are the chances that this Big Seven will move harmoniously and steadfastly for the next 27 years toward the common goal of zero carbon by 2050?

What incentives does Russia have -- being in *de facto* state of war with EU/US in Ukraine -- to join the West in decarbonizing when hydrocarbon exports are the foundation of its otherwise weak economy? How eager will

China be to work with India (there is still no peace treaty between the two nations) and with the US bent on newly embraced decoupling? Why would India, now trying to replicate (at least to some degree) China's post-1990 economic ascent, forgo the use of its coal when China had quadrupled its extraction during the past 30 years? Not surprisingly, we see headlines such as "India May Boost Coal Power Fleet 25% by 2030 Amid Rising Demand".[62] Moreover, as recent numbers indicate, China is far from done with its massive use of fossil fuel: its coal output reached a new record in 2022 and the country approved the construction of 106 gigawatts of new coal-fired power, the highest capacity since 2015.[63]

And then we must consider the poorest continent whose population will grow from 1.2 to 2.5 billion by 2050. Africa has seen how China became relatively rich during the past generation by quadrupling its combustion of fossil carbon and becoming the world's largest producer of cement, steel, plastics, and ammonia. Affluent countries themselves have no large-scale non-fossil alternatives that could be transferred to Africa and enable the continent to pursue green development. That is why "African nations tell COP27 fossil fuels will tackle poverty."[64]

And the need for energy and associated infrastructures is immense. Sub-Saharan Africa's (excepting the RSA) per capita energy use is less than 10 GJ/year, compared to India's 26 GJ and China's 112 GJ (Canada is nearly 370 GJ): no wonder that African politicians demand the development fossil fuel resources to lift the living standards perhaps at least to the Indian level! Development of some large natural gas reservoirs looks particularly appealing as the liquefied fuel can be readily exported worldwide, and new gas fields are now under development in Senegal, Ghana, Nigeria, Cameroon, Angola, Mozambique, and Tanzania -- and they will not start producing before 2030 only to be shut down a decade or two later.[65]

And let us not forget that it was not any accelerated production of wind or solar electricity, nor any green hydrogen, but the diversion of liquefied natural gas from the US, Qatar, and Nigeria that prevented crippling supply shortages in the EU following the Russia's invasion of Ukraine in 2022 and 2023, and that large-scale natural gas exports, not any construction of PV cells, are the foundation of Russia-China alliance.[66] And the demand for fossil-fueled machines remains high everywhere. Post-Covid airlines are placing record orders for large new jetliners: 2022 United Airlines ordered 200 jets, in 2023 Indigo (India's largest airline) ordered 500 and Air India 470 jets -- and the latest forecast by Airbus sees the need for more than 40,000 new jetliners between 2023 and 2042 – and these kerosene-fueled machines typically operate for up to 30 years.[67] (Fig. 8).

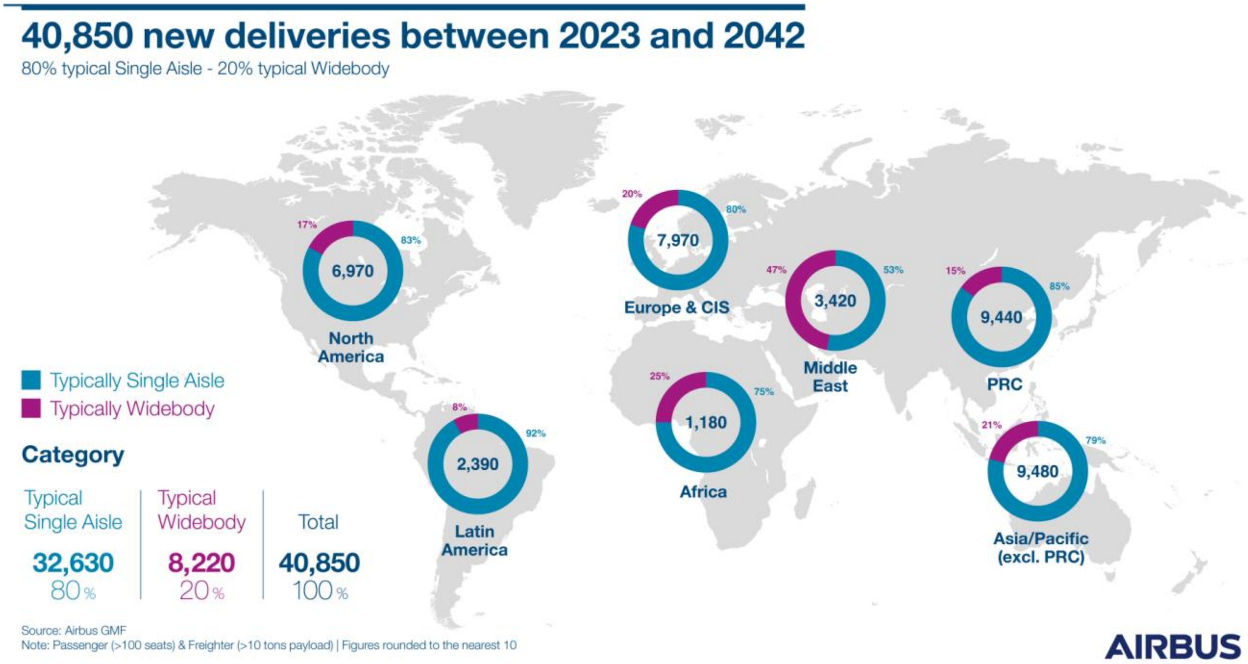

Fig. 8 Forecast of new airplane deliveries between 2023 and 2042. Source: Global Market Forecast | Airbus

Orders for massive diesel-powered cruise ships reached 56 new vessels by August 2023 and, again, they will not be launched before 2030 with the intent of sailing for just a few years.[68] Too many realities point to the same conclusion: there will not be any near-50% fossil carbon cut by 2030, no zero carbon by 2050.

Realities vs. wishful thinking Since we began to focus on the need to end the combustion of fossil fuels, we have not made a slightest progress in the absolute global decarbonization: emission declines in many affluent countries were far smaller than increased consumption of coal and hydrocarbons in the rest of the world, a trend that has also reflected the continuing deindustrialization in Europe and North America and the rising shares of carbon-intensive industrial production originating in Asia. As a result, by 2023 the absolute reliance on fossil carbon rose by 54% since the Kyoto commitment. Moreover, a significant part of emission declines in many affluent countries has been due to their deindustrialization, to transferring some of their carbon-intensive industries abroad, above all to China.

Denmark, with half of its electricity now coming from wind, is often pointed out as a particular decarbonization success: since 1995 it cut its energy-related emissions by 56% (compared to EU's average of about 22%) -- but (unlike its neighbors) the country does not produce any major metals (aluminum, copper, iron and steel), it does not make any float glass and paper, does not synthesize any ammonia, it does not even assemble any cars. These are all energy-intensive products, and transferring the emissions associated with their production to other countries creates an undeservedly green reputation.

Given the fact that we have yet to reach the global carbon emission peak (or a plateau) and considering the necessarily gradual progress of several key technical solutions (from large-scale electricity storage to mass-scale hydrogen use), we cannot expect the world economy to become carbon-free by 2050: the goal may be desirable, but it remains unrealistic. The latest International Energy Agency *World Outlook* report confirms that conclusion. While it projects that

energy-related CO_2 emissions will peak in 2025, and that the demand for all fossil fuels will peak by 2030, it also anticipates that only coal consumption will decline significantly by 2050 (but that it will still be about half of the 2023 level), and that the demand for crude oil and natural gas will see only marginal changes by 2050, with oil still close to 100 million barrels a day and gas still above 4 trillion cubic meters.[69]

Wishful thinking, claiming otherwise, should not be used, and defended, by saying that it represents aspirational goals. Responsible analyses must acknowledge existing energy, material, engineering, managerial, economic, and political realities. Their impartial assessment makes it extremely unlikely that the global energy system will be rid of all fossil carbon by 2050: sensible policies and their vigorous pursuit will determine the actual degree of that dissociation that might be as high as 60% or 65%. Recognition of these realities, as opposed to that incessant stream of miraculously downward bending decarbonization scenarios so dear to demand modelers, is rising.

Long-term global energy forecasts offering numbers for overall demand or supply and for shares contributed by specific sources or conversions are beyond our capability: the system is too complex and too open to unforeseen but profound perturbations -- but skepticism in constructing long-term estimates will lessen the extent of inevitable errors. Here is an example of a realistic 2023 forecast done by DNV, a Norwegian risk management company, that has been recently echoed by other realistic assessments. After noting that global energy-related emissions are still climbing (but might peak in 2024 when the transition would effectively begin) it concludes that by 2050 we will move from the present roughly 80% fossil 20% non-fossil split to a 48%:52% by 2050, with primary energy from fossil fuels declining by nearly two thirds but still remaining at about 314 EJ by 2050, that is about as high as it was in 1995.[70]

Again, that is as expected by any serious student of global energy transitions: individual components change at different speeds and notably rapid transformations are possible -- but the overall historical pattern quantified in terms of primary energies is one of gradual changes. Unfortunately, modern forecasting in general, and the anticipation of energy advances in particular, have an unmistakable tendency toward excessive optimism, exaggeration, and outright hype.[71] During the 1970s many people believed that by the year 2000 all electricity will come not just from fission, but from fast breeder reactors, and soon afterwards came the promises of "soft energy" taking over.[72]

Beliefs in near-miraculous tomorrows never go away: now we can read declarations claiming that the world can rely solely on wind and PV by 2030.[73] And then there are those repeated claims of all energy needs (from airplanes to smelting steel) to be supplied by cheap green hydrogen or by affordable nuclear fusion. What does this all accomplish besides filling print and screens with unrealizable claims? Instead, we should devote our efforts to chart realistic futures that consider our technical capabilities, our material supplies, our economic possibilities, and our social necessities -- and then devise practical ways to achieve them. We can always strive to surpass them, a far better goal than setting ourselves for repeated failures by clinging to unrealistic targets and to impractical visions.

Failing to reach an unrealistic goal of complete global decarbonization by 2050 means failing to limit average global warming to 1.5°C. How much higher the temperature might rise will not depend only on our continued efforts to decarbonize global energy supply but also on our success in limiting CO_2 and other greenhouse gases generated by agriculture, animal husbandry, deforestation, land use changes and waste disposal. After all, those contributions account for at least a quarter of global anthropogenic emissions but, so far, we have been almost exclusively focused on CO_2 from fossil fuel combustion. But that would be a topic for another inquiry.

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I will close with a simple historical comparison. I used the best available statistics to reconstruct the post-1800 changes of the global primary energy supply.[74] The quality of data improves as we move into the second half of the 19th century, but uncertainties regarding many Asian and African data persist until after 1950. With that in mind we can trace how the traditional biomass fuels (wood, charcoal, crop residues, dried dung) receded from supplying about

98% of all primary energy in 1800 to 52% a century later (when coal provided 47% and crude oil about 1%), to about 12% in the year 2000 and to no more than about 7% in 2020. Conversely, this means that the new sources of primary energy (fossil fuels and later also hydro and nuclear electricity) rose from just 2% in 1800 to 95% in 2020, implying an average annual market share gain of 0.42%.

New renewables reached 2% of the modern global primary energy supply (the total excluding the traditional biomass fuels) in 2010 and to reach 100% in 2050 their average annual market gain would have to be 2.45%, roughly six times faster than the pace of the first grand global energy transition. Comparison of this simple, relative measure of transition progress is a very revealing indicator as it subsumes the necessary extraction of energies of energies and the development and diffusion of their converters -- but with an important difference: past transitions unfolded gradually as they were largely governed by economic opportunities taking advantage of new technical advances, while much of the unfolding transition is due to government mandates and subsidies whose, often arbitrary, targets tend to be frequently ahead of the technical solutions that are ready for mass adoption.

The quest to eliminate fossil fuel by 2050 would, with 2010 as the starting point, imply the 2022 share of renewables in the primary energy supply at about 29% -- but the actual share was 7.5%: in the first 12 years of the race the adoption speed was only about a quarter of the desired pace. By 2030 we

should be close to 50% but at the beginning of 2024 it seems highly unlikely that we could accelerate our retreat from fossil so suddenly. But if not, then the deficit would grow and to meet the zero 2050 target we would need substantially higher annual additions of wind, solar and biofuels capacities: what are the chances that we could manage annual gains of 4%, or during the 2040s even 5%, to close the gap?

I must stress that the comparison of the two transitions is not done either to offer the first one as a template of the present one or to suggest that such processes are likely to unfold at a similar pace. The juxtaposition is done just as a reminder that the unfolding transition is only the second such fundamentally transformative event in history, and that these two events share a similar goal: a complete change of energy foundations of the entire civilization. In comparison to today's technical achievements and options, the first grand transition began to unfold with rudimentary technical capabilities -- but it also needed less to accomplish: even after the first century of its progress it had to deliver primary energy supply that was an order of magnitude smaller than today's global needs. Eventually, the first transition had certainly surpassed the initial expectations as it created new affluent, high-energy societies.

Even though we are technically far better equipped than we were 150-200 years ago, that task presented by the second energy transition has not got any easier, in fact it appears to be even more challenging. So far, and despite our superior technical capabilities, we have done no better than roughly matching the earlier transition's pace: going from 2% in 2010 to 7.5% renewables in primary energy supply in 2022 implies an average annual market gain of 0.45%, less than a fifth of the pace needed for zero carbon in 2050. This highly inadequate speed of energy transition may be also used to confirm the previously adjusted estimate of the total cost of reaching zero carbon by 2050. Just before the end of 2023 the International Energy Agency published its estimate of global investment in "clean energy", that is essentially the annual cost of energy transition: in 2023 it was close to $2.2 trillion.[75]

If the spending of $2.2 trillion bought us roughly 0.5% of the ultimately needed decarbonization total, then the remainder of the process -- with some 92% to go by the end of 2023 -- would come (even in the absence of any major escalation of costs) to about $405 trillion, and excellent confirmation of the previously calculated cost of zero carbon by 2050. No natural laws bar us from making even such enormous investments needed to achieve such massive annual gains: we could resort to an unprecedented, decades-long, and civilization-wide existential mobilization of constructive and transformative efforts or, conversely, we could deliberately reduce our energy use by lowering our standard of living and keeping it low to make it easier to displace all fossil carbon.

In the absence of these two radical choices, we should not ignore the experience of the past grand energy transition (from traditional biomass

energies to fossil fuels) and we should not underestimate the concatenation of challenges presented by practical engineering, material, organizational, social, political, and environmental requirements of the unfolding transition to a fossil carbon-free world that have been, partially, reviewed in this essay. When we do so, we must conclude that the world free of fossil carbon by 2050 is highly unlikely.

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