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NOTE AND COMMENT

Towards net zero CO_2 emissions without relying on massive carbon dioxide removal

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Abstract

Current emission scenarios that allow keeping the global temperature increase below 2 °C or even 1.5 °C—as foreseen by the Paris Agreement—are based on very optimistic assumptions, including enormous volumes of carbon dioxide removal (CDR). A closer look at the globally most important emission sectors—power, transport and industry—shows manifold barriers for very ambitious mitigation. A new policy guideline called "Net Zero CO_2 Emissions without relying on massive CDR" and promotion of technological research, in addition to economic incentives and other policy measures, would help to overcome the often simplistic demands for positive modelling results and refocus climate policy on tackling the enormous barriers in key emitting sectors. Such an approach is more aligned with the Paris Agreement's bottom-up logic and therefore more appropriate to make the transformational project of global decarbonization a success.

Keywords CO_2 zero emissions · Massive CDR · Actionable policy guideline · Sector specific technologies · Major emitting sectors

Introduction

The fact that the Paris Agreement came into force within less than a year after its adoption in December 2015 was hailed as a major success. However, it remains unclear how the parties to the United Nations Framework Convention on Climate Change (UNFCCC) will deal with the enormous task of delivering what they have agreed to—holding the global average temperature increase to well below 2 °C above pre-industrial levels and pursuing efforts to achieve even 1.5 °C. Currently, the aggregated nationally determined contributions (NDC) are not ambitious enough to achieve these temperature targets. Even optimistically assuming that current pledges will be met by 2030 (Victor et al. 2017), the temperature increase would likely reach 3 °C or more by 2100 (Rogelj et al. 2016; IPCC 2018). Almost all of the mitigation pathways that would limit warming to 2 °C or less rely on massive amounts of carbon dioxide removal (CDR). There are several existing and potential CDR methods, including bio-energy with carbon capture and storage (BECCS), afforestation, land restoration and soil carbon sequestration, direct air carbon capture and storage (DACCS), enhanced weathering and ocean alkalinization (Williamson 2016; Fuss et al. 2018). To date, only a few published emission reduction pathways include CDR methods other than afforestation and BECCS (IPCC 2018), and among these two, the removal levels generated by BECCS are much higher than those generated by afforestation (Anderson and Peters 2016; IPCC 2018). To achieve a 2 °C target, cumulative CDR volumes of about 600 gigatonnes (Gt) CO_2 would need to be reached by 2100 (Luderer et al. 2018). For 1.5 °C, 730 Gt would be necessary (IPCC 2018). Although negative emissions have been part of mitigation pathways for more than a decade now (Pielke 2018), the development of such technologies is still in its infancy (Nemet et al. 2018). No country has yet committed to a CDR strategy (Peters and Geden 2017) and that there are serious concerns about the enormous requirements for land and trade-offs with biodiversity, food production, energy demand and water supply (Smith et al. 2016; Newbold et al. 2015).

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Table 1 Examples of sector-specific zero-emissions technologies

Major sectors	Zero-emission technologies	Issues to be overcome
Power generation	Renewables	1. Demand–supply gap; battery cost
	Hydro, geothermal	
	Solar, wind	2. Frequency instability due to lack of inertia
	Biomass	
	Nuclear	Nuclear waste disposal, etc
Transport	Electricity (automobiles, light trucks)	Need for large capacity batteries
	Biofuels (heavy trucks, ships and planes)	1. Large-scale production of cellulose-based biofuels
		2. Lowering cost
Industries		
Iron and steel	Electrolysis	1. Lowering cost
	Direct reduction by hydrogen	2. Large-scale use of carbon-free power
Cement	CCS	Reduction in CCS cost

To achieve the agreed temperature goal of 1.5–2 °C, the Paris Agreement also stipulates that a balance between greenhouse gas (GHG) emissions by sources and removals by sinks should be achieved in the second half of this century. However, such a target does not actually tell any country, economic sector or individual company what exactly it would need to achieve in the long-term to comply with a global climate stabilization target (Geden 2016). Furthermore, net zero target years derived from emission scenarios often rely on hidden and questionable assumptions about the long-term feasibility of net negative emissions to reverse a temporary temperature overshoot (Geden and Löschel 2017). In cost-optimization scenarios, this usually leads to massive CDR deployment late in the century (Obersteiner et al. 2018), with the annual deployment of more than 15 Gt towards 2100 (IPCC 2018). We, therefore, need a new and more actionable policy guideline that clearly signals to all key actors what they need to do—"Net Zero CO_2 Emissions of all sectors without relying on massive CDR" ($NZCO_2Es$).

Obviously, following a zero-emissions target will not mean eliminating every single ton of GHG emissions, since there will be 'residual' emissions too difficult, too expensive or even impossible to mitigate (Luderer et al. 2018). Minimized residual emissions will have to be offset by CDR.

Since CO_2 is the most important GHG, we focus here on CO_2 and especially on energy-related CO_2 emissions, which represent roughly 85% of global CO_2 emissions. While fossil fuels' share of the global energy mix is still at 85.2% in 2017 (BP 2018) and CO_2 emissions have continued to rise since the Paris climate summit (Le Quere et al. 2018), the recent IPCC Special Report assumes that to achieve the Paris goal of 1.5–2 °C, CO_2 emissions would have to reach net-zero between 2045 and 2080 (IPCC 2018).

To attain net zero emissions in the future, it will certainly be necessary to conduct country-specific assessments for reaching $NZCO_2Es$—as currently undertaken in Sweden, the United Kingdom, the European Union (EU), and California—and also to explore sector and technology-based global solutions. We, therefore, propose to shift the primary focus of climate-change mitigation debates away from globally aggregated emissions pathways to a more tangible perspective. How can $NZCO_2Es$ actually be achieved in key economic sectors? What barriers must be overcome? We illustrate this approach by briefly looking at power generation, transport and industry sectors, all being major emitters of energy-related CO_2.

For policymakers, this means that they should encourage research and development (R&D) investments both public and private, especially focusing on overcoming barriers in major emitting sectors illustrated in Table 1. Another approach would be to encourage key sectors to set specific global roadmaps towards net zero CO_2 emissions, with intermediate benchmarks for 2030 and 2050. Information sharing on technology development between governments and related sectors is indispensable, and in setting and continuously updating these roadmaps political and economic considerations must also be taken into account.[1]

Power generation

Global CO_2 emissions from electric power systems currently represent around 40% of total energy-related CO_2 emissions and this share may rise in the future due to the electrification of industrial activities, development of electric vehicles, and electrification of other sectors. In this sense, the most

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[1] The authors note that any mitigation approach should be accompanied by adaptive actions to enhance resilience to climate change. Since this papers' focus is on emission reductions it will not further discuss this issue.

important measure to achieve $NZCO_2Es$ is to decarbonize power systems. The International Energy Agency (IEA) has already published a scenario of zero-emission power generation by about 2060 in its 'Energy Technology Perspectives' (International Energy Agency 2017a). In its Below 2 Degree Scenario (B2DS) the structure of power generation (in kWh) is as follows: nuclear 15%, fossil fuel plants with CCS 7%, hydropower 17%, photovoltaics (PV) 17%, wind 20%, concentrated solar power (CSP) 10%, and other renewables 15%. Among renewables, wind and PV (variable renewables, VREs) should be viewed cautiously as VREs pose two serious problems in power-systems operation. One is the intermittency of outputs, and the other is their inertialess character. To balance power supply and demand under high levels of intermittent VREs would require huge amounts of power storage. In the past, mainly pumped hydroelectric storage was utilized for this purpose, but the physical potential for new stations is very limited in most countries. Therefore, a huge battery bank is needed as future power storage for VREs. However, one of the serious problems with batteries is their high price. In the IEA's zero-emissions power scenario in 2060, the total required battery amount is about 3600 GWh globally, whereas the present costs are around \$300/kWh (International Energy Agency 2017a). At today's battery prices, total costs would reach \$1000 billion, almost 6% of the present GDP of the United States. Therefore, much effort is needed to reduce battery cost through R&D and mass production. It seems too early to discuss the use of hydrogen storage of electric power, as comparative economic analysis shows that battery storage is much more advantageous than hydrogen at the present stage (Zhang et al. 2016).

Another, equally challenging problem is the fact that VREs are power sources of non-synchronous generators without any inertia. Since the frequency of power systems depends heavily on the rotational speed of synchronous generators with significant inertia, the introduction of large amounts of VREs without inertia has a serious negative impact on the frequency stability of power systems (O'Sullivan et al. 2014). For example, a severe blackout of power systems in South Australia in September 2016 originated from a decrease in the total inertia of synchronous generators due to an increase in wind generators within the power system (Australian Energy Market Operator 2017). The most straightforward way to preserve the frequency stability of the power system is to limit the share of non-synchronous generators (such as VREs) in overall power generation. Ireland power (ErGrid) once suffered also from this issue and developed the criterion for avoiding serious impacts of low inertia of VREs on the power system, called system non-synchronous penetration (SNSP) (ErGrid and Soni 2017). In a power system without any flow to and from the outer system, SNSP is defined as the size of VREs (in kWh) against the whole demand of the system. According to ErGrid, the safe zone of SNSP for the frequency stability is 50% and it is now trying to introduce technologies for increasing the limit of SNSP to around 70%. In the case of the above-mentioned IEA B2DS scenario, the share of VREs in the world electricity demand is 37% (17% for PV and 20% for wind), much smaller than 50%. Since there are many independent power systems in the world, SNSP for each system should be calculated independently, but the above number suggests that in most of these systems SNSP will be smaller than 50%. In other words, if the IEA scenario's power generation mix is considered to be plausible, most power systems in the world may have sufficient frequency stabilities. However, since some power systems may approach SNSP values higher than 50%, there is a need to develop technological measures for improving the stability of such systems. Presently a more drastic approach of designing controllers of inverters of VREs to regulate the frequency of the power system supported by relatively few synchronous generators is under investigation, for example in the EU Horizon 2020 project Migrate (Denis et al. 2018).

Transport

25% of global energy-related CO_2 emissions come from the transport sector, mainly through the consumption of petroleum products as fuels. CCS is clearly not an option here. Zero CO_2 emissions, therefore, should be achieved by use of either carbon-free electric power or biofuels. Electrification is already a global trend for passenger cars and light trucks but hardly applicable to heavy trucks, marine and aviation transport (non-light vehicles), mainly due to the need for huge batteries, which are much heavier than fuel oil. At present, the maximum density of batteries is 0.2 kWh/kg while the energy intensity of petroleum is 12 kWh/kg, around 60 times greater. This leads to the conclusion that biofuels are almost the only alternative for non-light vehicles (International Energy Agency 2017b). Beyond the disputes about the ecological sustainability of biofuel production (Elshout et al. 2015; Newbold et al. 2015) there are currently also-significant economic problems. One is the enormous gap between biofuel supply and demand. World production of biofuels stands at 70–80 Megatonnes per year (Araújo et al. 2017), less than one-tenth of the present demand for petroleum fuels for non-light vehicles. Therefore, tremendous efforts would be necessary to produce far more biofuels, and to do so in a sustainable way. The other difficulty is the huge price gap between present biofuels and petroleum fuels for non-light vehicles. A possible solution is to expand the innovative production of less expensive cellulosic biofuels. Cellulosic biofuels are still in development; great efforts will be needed for large-scale production of cellulosic fuels at a lower cost. A typical example for this kind of efforts are those by the Japanese New Energy and Industrial Technology Development Organization (NEDO), which conducts a R&D project for cellulosic biofuels with the cost target of 70 Japanese Yen (60 US Dollar cents) per liter.

Industry

The industry currently generates about 20% of global energy-related CO_2 emissions. Within its huge variety of products and processes, the biggest emitter is the iron and steel sector. Most iron and steel manufacturers now use blast furnaces and basic oxygen furnaces to make steel from iron ore. Coal is the basic reduction material in this process, and CO_2 is inevitably emitted from the furnaces. At present, Japanese steel companies are conducting a project called COURSE 50 in which CO_2 in the flue gas of blast furnaces is captured and stored in geological reservoirs. The total reduction rate of CO_2 is, however, only 30%, and for a deep decarbonization of steel production, the introduction of other processes will be required. Three processes have been proposed for a much deeper level of decarbonization. These are hydrogen direct reduction of iron ore—where the hydrogen is obtained either by gasification of biomass or by electrolysis of water—and electrolysis of iron ore (Philibert 2017; Fischedick et al. 2014). Let us briefly examine these three processes in terms of energy demand and economic profitability: (1a) hydrogen direct reduction by use of biomass gasification, (1b) hydrogen direct reduction by use of water electrolysis with carbon-free power, and (2) electrolysis of iron ore.

In terms of energy demand, process 2 fares best. We calculate that for process 1a—assuming a gasification efficiency of 50% −3.6 MWh per ton of steel would be needed. According to Philibert (2017), the energy required for process 1b is also 3.6 MWh per ton and 2.6 MWh for process 2. In other words, electrolysis of iron ore is more energy efficient than both hydrogen direct reduction processes. Regarding the economics, it seems that all the processes could be profitable under the assumption of steadily increasing carbon prices in the future, with process 1b being the most promising one (Fischedick et al. 2014). But taking into account that process 2, electrolysis of iron ore, is still at the level of laboratory experiments, it may be appropriate to promote either process 1a or 1b, i.e., hydrogen direct reduction, at least for now.

However, looking at the respective resource bases of the hydrogen pathways processes 1a and 1b bring severe constraints into perspective. Suppose that the entire global steel production would be fully based on either process 1a or 1b. The energy needed for process 1a would amount to 6.1 PWh/year (3.6 MWh × 1.7 Gton/year of steel, the present global production), while the current energetic use of biomass amounts to 15.7 PWh/year globally. In other words, more than one-third of the global biomass had to be spent for a decarbonized global steel production. Since future non-light vehicles will require a huge amount of biofuels, global bioenergy production would have to be expanded enormously to satisfy demands from both the transport and the steel sector in a sustainable way. A similar calculation can be made for process 1b, which would lead to an additional power consumption of 6.5 PWh/year, a little more than one-fourth of today's global power supply of 22 PWh/year. Since power for water electrolysis has to be carbon-free to contribute to a deeply decarbonized steel production, this would increase heavily the above-mentioned challenges in the power sector. The realization of zero-emission steel production is obviously not an easy task. Therefore, efforts need to be made for utilizing steel as efficiently as possible to limit the total global steel demand.

Another significant CO_2 emitter is the cement industry. About half of the CO_2 in this sector comes from fuel combustion and the other half from processing the raw material (i.e., limestone). There may be two ways for drastically reducing CO_2 emissions in the cement industry. Both ways need first to capture CO_2 originating from the cement production process. One could then either store this CO_2 underground (CCS) or make concrete absorb the CO_2 (Galan et al. 2011; Yoshioka et al. 2013). The process of capturing CO_2 from the cement production process is common in both cases, and its cost represents more than half of the total cost in both cases. If one takes the cost for the CCS case, for example, which is about \$100/ton CO_2 (Irlam 2017). Then removing the entire CO_2 emissions from Japanese cement production would amount to an extra cost of about Yen700B/year (US\$6B/year), almost equaling the total sales of the entire Japanese cement industry. Hence, the introduction of CCS to reach zero CO_2 emissions would lead to almost a doubling of cement product prices. It is doubtful whether customers will accept such a price hike. Efforts towards reducing CCS costs are therefore indispensable for the cement industry.

Conclusions

The above are some examples of the manifold challenges in achieving $NZCO_2Es$ in the most weighty economic sectors (Davis et al. 2018). They highlight that the decarbonization assumed by the Paris Agreement will depend on overcoming specific engineering and economic challenges, including carbon pricing. Recent literature argues that by developing a low energy demand society, decarbonization without relying on CDR options except for a limited contribution of net removals from agriculture, forestry and land-use would theoretically be possible (Grubler et al. 2018). But even in this case, the above efforts towards net zero CO_2 emissions in all sectors are indispensable. Concentrating on these more practical issues means shifting the focus from often simplistic demands for positive modelling results to fulfill a grand policy design (often presupposing speculative and immense amounts of CDR) to what can be achieved in the real world. By extending such a bottom-up approach to all emitting sectors, accompanied by economic and social feasibility studies, we will be able to ascertain when sectors can realistically be expected to reach net zero CO_2 emissions, based on which technologies, and on which volumes of CDR to offset 'residual emissions' that are too expensive or even technically impossible to mitigate. This would be much more in line with the bottom-up character of the Paris Agreement and make greater use of engineering skills to make the transformational project of global decarbonization a success.

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