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Perspective

Six bold steps towards net-zero industry

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ABSTRACT

The rapid and deep decarbonization of global industry is key to reaching climate policy targets, yet it remains an incredibly difficult challenge. We propose six bold steps for accelerating progress on achieving net-zero industrial carbon emissions by mid-century with a focus on lessons learned and emerging analysis from both the Global North and Global South, the latter of which we consider as low or middle income countries primarily located in Africa, Asia and Latin America. These steps are (1) quintupling financing, (2) expediting technology transfer, (3) investing in human resources, (4) setting binding targets, (5) steering social acceptance and (6) enacting a new global treaty and shaping climate clubs. Perhaps surprisingly, there are more than thirty effective historical and contemporary initiatives to learn from, showcasing a rich tapestry of previous efforts and templates to build on and to inform net-zero decarbonization efforts.

1. Introduction

Reaching "net-zero" for climate change is becoming one of the most salient economic and political challenges of the modern era. Realizing this goal means decarbonizing all parts of the economy with speed [1]. In a very small number of sectors, such as electricity or buildings, pathways to net-zero may be well understood and even cost-effective, but these are the exceptions, not the norm. Industry stands out as particularly difficult.

The global industrial sector accounted for 38 % of total final energy use in 2020 [2]. Industry is also the sector with the fastest growing carbon dioxide emissions and is the single largest source of global greenhouse emissions (more than one-third) when one accounts for related electricity consumption and heat generation [3]. To date, progress on decarbonizing industry, especially energy intensive sectors such as chemicals, iron and steel, cement and concrete, and oil refining— has been stunted at best with industrial direct emissions needing to decline by nearly 25 % by 2030, or roughly 3 % annually, to align with net-zero 2050 aspirations [2]. Such industries have long been sheltered from strong energy and climate policies over concerns about job losses, national competitiveness, and cross-border carbon leakage.

There are effective, transformative, and promising innovations for industrial decarbonization, such as direct reduced iron for the steel industry based on low and zero-carbon hydrogen [4], or pursuit of a clusters approach to decarbonization that cuts across technologies, industrial sectors, and places, such as in the United Kingdom [5] [6] or Australia [7]. In addition, measures to mitigate other potent greenhouse gases, particularly methane, nitrous oxide and fluorinated gases, are underway in an effort to achieve net-zero greenhouse gas emissions across industrial sectors [8].

However, applying transformative innovations globally is difficult because not all countries are in the position to rapidly adopt them. Although the war in Ukraine that began in 2022 has disrupted energy markets to the extent that a global clean energy transition may have been pulled forward as much 10 years [9], it is mainly countries in the Global North that stand to benefit from measures taken to address sharpened energy security and economic concerns. The United States, as one example, has committed nearly $80 billion in annual climate spending for the period 2022 to 2027 via the Inflation Reduction Act, CHIPS and Science Act and Infrastructure Investment and Jobs Act [10] [11] with impact spanning fundamental science to commercial clean technology deployment. Fig. 1 shows that the Inflation Reduction Act is expected to direct more than $114 billion into renewable energy investments by 2031 through a diverse set of programs that include

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government loans, government loan guarantees and tax credits to corporate and industrial stakeholders, tax credits to end users and consumers and grants to state and local governments. These types of investments and programs are projected to lower carbon emissions in the United States by as much as 40 % by 2030 relative to 2005 levels.

Developing countries, on the other hand, face enormous social, political and economic barriers that hinder adoption of decarbonization interventions. Hence, financial barriers, insufficient infrastructure, lack of required labor force skills, lock-in effects, and political economy considerations are global challenges that need solutions tailored to context [12]. To address these concerns, we propose a roadmap of six steps to reach net-zero industry by 2050.

2. Quintuple financing

It is true that the net-zero challenge begins—though does not end—with money. Scaling up international financial support for industrial decarbonization, particularly in developing countries, is critical. Annual spending on industrial decarbonization interventions globally needs to increase more than 7-fold by 2030 relative to the level of investments made in the five years between 2016 and 2021 [13]. Various direct transfer mechanisms exist to support countries financially, such as up-front grants and funding during operation, and these are complimented by mechanisms to facilitate access to financing, such as risk coverage, loans and equity investments [14].

These financial mechanisms could focus on facilitating adoption of cross-cutting solutions like electrification, material efficiency and the use of carbon capture and hydrogen to decarbonize the most carbon-intensive industries, which include iron and steel and chemicals [15] [16] [17]. Chemicals, for example, are responsible for 13.3 % of industrial emissions, but could be significantly decarbonized using zero-carbon hydrogen in the production of ammonia and methanol. Chemicals such as benzene, butadiene, propylene and ethylene, which are important for the production of plastics and many other products, can also benefit from zero-carbon hydrogen but require further consideration of oil refinery decarbonization [18]. Given that the chemicals industry is so challenging to decarbonize [19], net-zero approaches such as Circular Carbon Economy (CCE) and Extended Producer Responsibility (EPR) may be required. We discuss both frameworks later in the context of social acceptance and social license to operate.

Decarbonization options, such as carbon capture and hydrogen are particularly important for sectors with significant embodied feedstock carbon emissions and/or direct carbon emissions from production processes, such as oil refining, chemicals, iron and steel, and cement and concrete. These options, however, are almost nonexistent, particularly in the Global South. Hence, bolstering their deployment by new modes of finance that have shown effectiveness in other sectors is essential. For instance, Africa needs to invest at least $15.7 billion in oil refineries alone to curtail emissions sufficiently to achieve the continent's climate change ambitions [20]. Such sectors can benefit from direct support in the form of loans and credit guarantees, such as those that have strongly steered the development of rail, waterways, and multi-modal terminals to facilitate the decarbonization of long-haul freight transport in Brazil

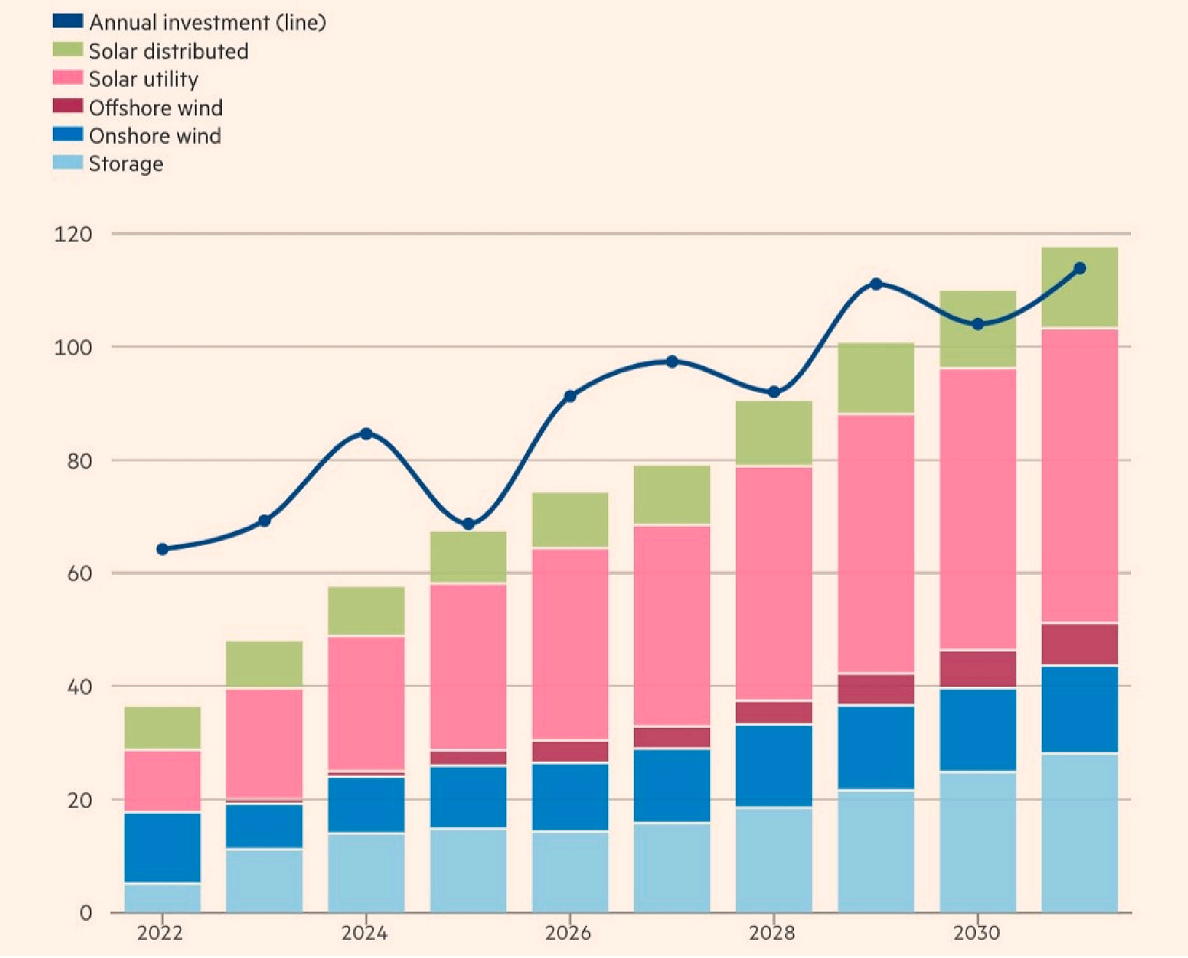

Fig. 1. Expected capacity additions for renewable energy in the United States, 2022–2031 ($bn).
Source: Financial Times data.

[21]. Similarly, indirect support in the form of grants or credit guarantees to local agencies has stimulated renewable energy supply for rural communities in Ghana [22].

Industrial decarbonization via hydrogen is a particularly good opportunity for countries in the Global South as many possess the natural resources to produce low and/or zero-carbon hydrogen at low cost. Chile's Corporación de Fomento de la Producción (Production Development Corporation) has already implemented a grant program to support renewable hydrogen projects and Brazil has begun a tax incentive program for low-emission projects, including hydrogen, in Ceará state. Rio de Janeiro and Pernambuco states are soon to follow. Brazil's effort is further complimented by the allocation of funding to establish hydrogen hubs in the country. While such efforts to promote hydrogen adoption are widely seen in the Global North [23], it is imperative that countries in the Global South move quickly with such measures to avoid being left behind as hydrogen adoption for industrial decarbonization gains traction. Catalyzing clean hydrogen production and consumption in the Global North could thus stimulate the Global South's hydrogen economy and present an opportunity for new cooperation models.

Despite such potential benefits, we recognize that production of hydrogen using renewable electricity requires careful consideration of the electricity source, which is context dependent. Balancing of electricity grids with very-high shares of intermittent renewables, which is required to produce "green" hydrogen from grid electricity, can be both technically and economically challenging. Likewise, production of hydrogen from captive power generation facilities or clusters, which avoids issues with grid balancing, can be technically, socially, politically

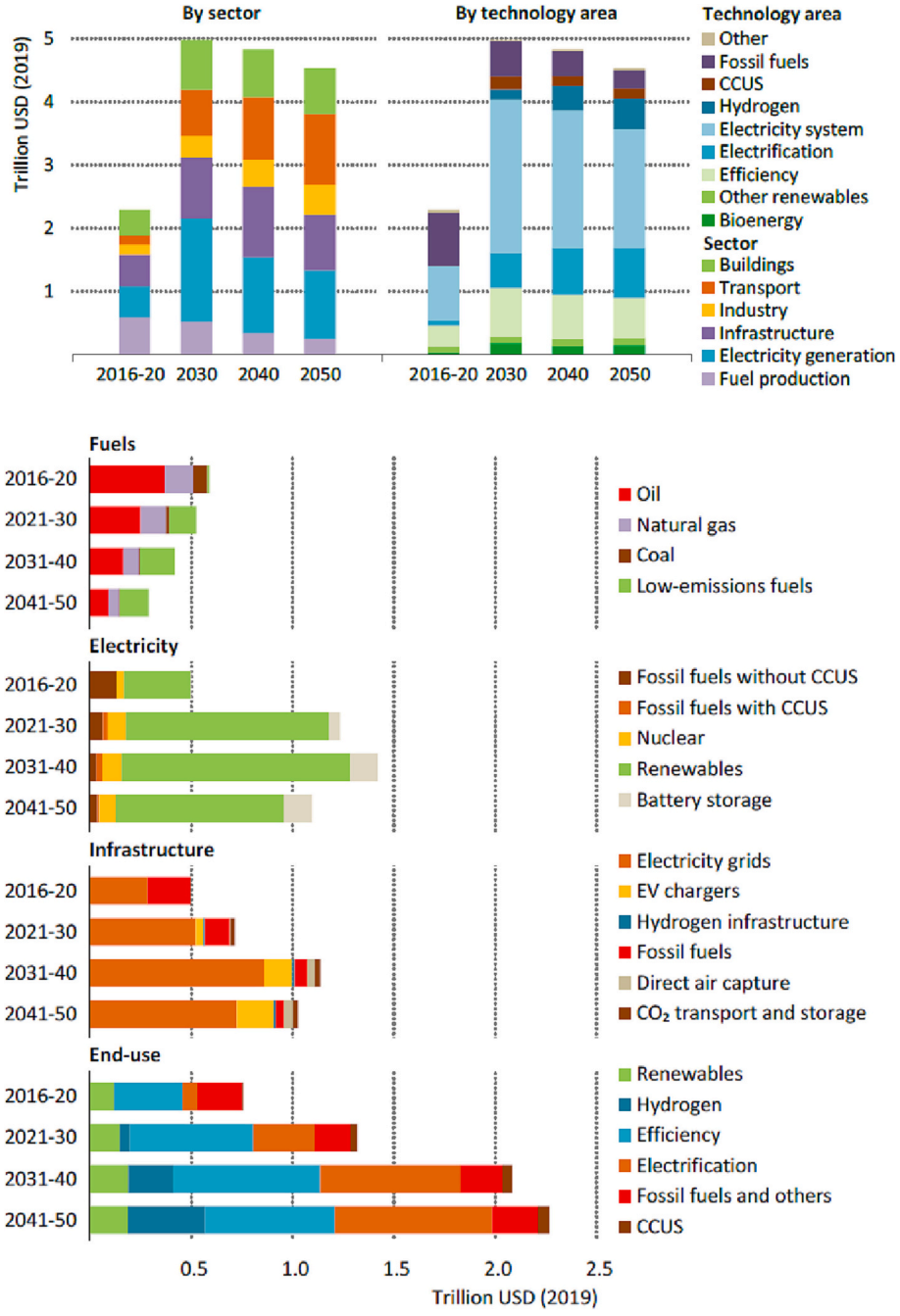

Fig. 2. Projections of annual average capital investment in net-zero energy infrastructure by sector and technology area.
Source: Data redrawn from the International Energy Agency. CCUS = carbon capture utilization and storage.

or economically not viable in certain contexts. Hence, we do not position hydrogen as a silver bullet for industrial decarbonization but rather an important opportunity that should have as much opportunity for impact in the Global South as in the Global North.

The financing mechanisms already described can be adapted and configured to stimulate the deployment of net-zero industrial infrastructure. While the scaling needs for global net-zero deployment would be vast, with the International Energy Agency projecting capital investment needs of more than $100 trillion (total) by 2050 across all sectors (see Fig. 2), the increase in finance needed for industrial decarbonization specifically is even more daunting. Some projections suggest as much as a ten-fold increase is needed in average annual spending on industrial decarbonization globally by 2030 if net-zero ambitions are to be achieved [24]. The Global South needs to be prioritized in such spending since this is where industrial energy demand, and related carbon emissions, are expected to grow most strongly.

3. Expedite technology transfer to developing countries

Ensuring adequate financing is a necessary, but by no means sufficient, condition to ensure global industries decarbonize, especially in developing countries in the Global South. Developing countries are critically important given that by mid-century under current policy projections, a majority of industrial emissions will come from ten emerging economies, including China, Brazil, India, and South Africa (see Fig. 3).

Recent net-zero modeling scenarios project that the industrial sector as a whole will maintain a level of annual residual direct emissions by 2050 (see blue bars in Fig. 4, showing a range of 9–18 % on a global scale, with regional differences between 0 %–45 %) [25]. Although this makes meeting global climate targets difficult, some regions, notably North America and in particular the United States, are projected to meet their zero emissions marks sooner than others. If so, then it will be essential for such net-zero regions to accelerate technology transfer to the rest of the world, especially Africa, Asia, and Latin America. This builds on the prior discussion of countries in the Global North having an advantaged status with regard to political and economic support required to move towards net-zero 2050.

Many tools exist that can accelerate the diffusion of low-carbon industrial technologies to countries in the Global South. From 2011 to 2020, the United States and China managed a joint "Clean Energy Research Center", which acted as a research consortium for work on carbon capture, energy efficiency, and nuclear energy. The United Nations Framework Convention on Climate Change also has utilized a technology transfer mechanism called the Climate Technology Centre and Network (CTCN). The CTCN has completed 155 projects, and was reviewing, designing and implementing more than 200 project requests as of Q3 2022. The Renewable Energy and Energy Efficiency Partnership (REEEP) similarly coordinates technology transfer to the Global South, with example projects that include the promotion of solar water heaters in Uganda, energy efficient lighting in India, rural biomass development in China, renewable energy financing in Mexico, and regulatory framework assessment for renewable energy in Argentina. Since its establishment in 2002, REEEP has managed almost 200 projects in 56 countries with a combined worth of $490 million, most of which was supported through private equity financing with REEEP serving as a matchmaker. All three examples provide general models that could be expanded or adapted to support energy transitions in countries with large and growing industrial sectors.

Other, more novel technology transfer options include patent pools and common access to critical technologies. While such mechanisms have been leveraged in response to the COVID-19 pandemic [26], they have yet to gain wide adoption in the energy and climate domain. When adopted, however, they can help overcome intellectual property barriers related to carbon capture and storage technologies, fuel cells, efficiency upgrades to industrial processes and other such decarbonization levers. One classic example of an effective patent pool was the creation of the Manufacturers Aircraft Association to license patents necessary for the production of airplanes but that had previously been controlled separately by scores of smaller companies. More recent examples the international community can learn from include the Eco-Patent Commons (created in January 2008 and focused on electronics and mobile phones), open-source software (computing), and the Medicines Patent Pool (public health).

As a promising sign, Brazil, Mauritania, and South Africa (among other Global South countries) are already using ample solar photovoltaic, wind, and hydroelectric electricity that can be directed towards making hydrogen for iron and steel manufacturing while also piloting electric arc furnaces with technology developed in the Global North [27]. In June 2021, there was a Clean Energy Ministerial agreement backed by the United Nations Industrial Development Organization (UNIDO) to pursue steel and cement decarbonization in the Global South. This was the first time steel and cement decarbonization has seen this level of political commitment [27]. Moreover, targeted research and development funding and technology accelerator programs are beginning to open technology transfer opportunities with some funding shared by governments and firms globally (e.g., the EU Ultra Low Carbon Steel (ULCOS) program, the UK Offshore Wind Accelerator, and recent US DOE ARPA-E steel initiatives) [27].

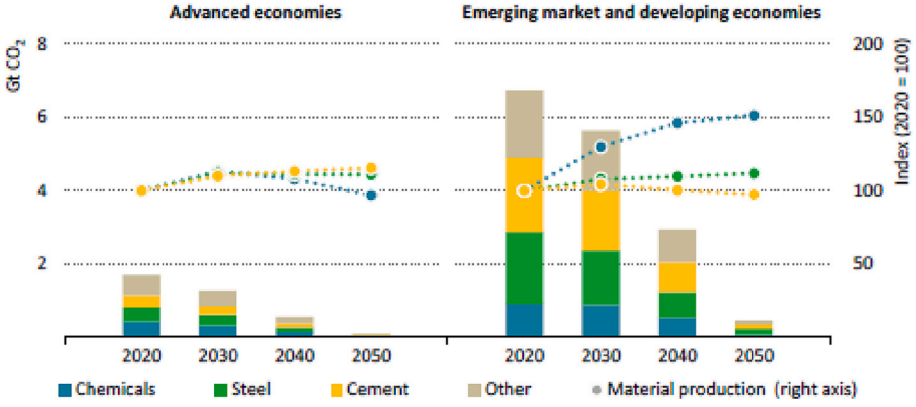

Fig. 3. Global carbon emissions from industry, 2020–2050.
Source: International Energy Agency, based on their net-zero economy pathway. Note that "other" includes emissions from aluminum, paper and pulp, non-metallic metals, non-ferrous metals, and light industry.

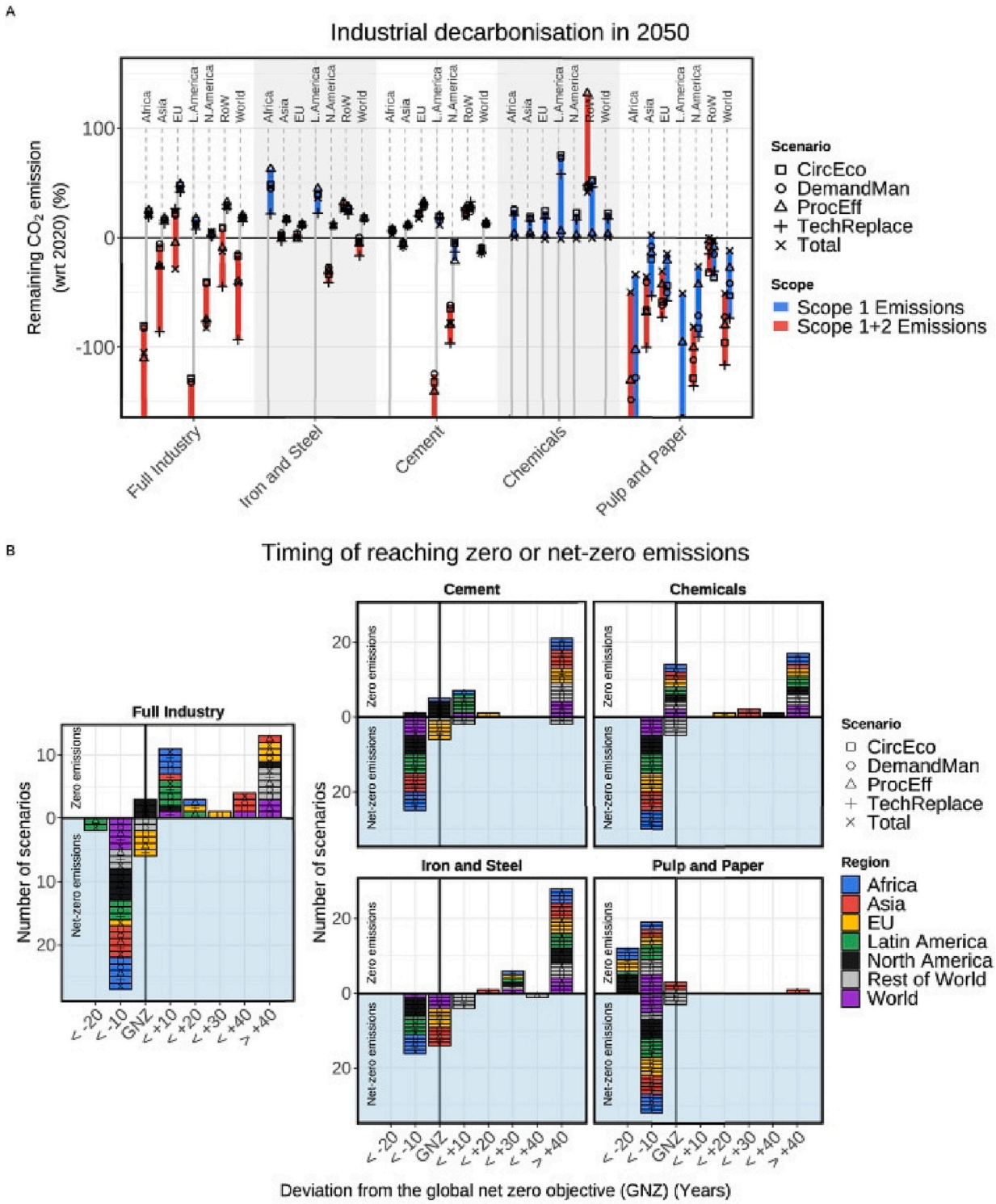

Fig. 4. Overview of net and direct carbon emissions from the global industrial sector in 2050.
Source [25]: The dotted line in (A) represents the drift from 2020 values; the solid line represents the drift among the zero and net-zero interpretations. Sub-plot (B) represents the difference in timing of when the industry sector itself is projected to reach the zero (direct, scope 1) emissions and net-zero emissions (direct+indirect, or scope 1 + 2) mark compared to the global net-zero objective (GNZ). EU: European Union, L. America: Latin America, N. America: North America, RoW: Rest of World (Russia and Central Asia)

4. Invest in human resources and capacity

A third challenge is neither financial nor technological, but rather social. There is a huge skills shortage looming that is positioned to hinder the attainment of net-zero industry. This shortage encompasses near-term workforce demands, such as for skilled welders, civil engineers, machinists, as well as workforce development and talent recruitment for the future workforce. The latter includes developing and attracting a workforce with the digital skills required for the increasing levels of industrial automation, which will play an increasingly critical

role in industrial energy efficiency. Training is further needed in rapidly evolving areas like refining and fuel processing where products and business models are necessarily changing to accommodate net-zero motives [28].

Some nascent examples of successful skills training for net-zero are emerging in the Global North and these could be applied to the Global South as well. In the United Kingdom, the Hynet Academy has been created to help support Hynet Northwest in England [29]. The Academy will train workers in advanced hydrogen and carbon capture, utilization and storage techniques, with skills including those needed to ensure that hydrogen is safely blended into the existing natural gas grid and piped into local industrial parks. In the EU, the Digital Skills and Jobs Platform and Digital Education Action Plan have been launched in response to the fact that 70 % of EU businesses see lack of digital skills as a barrier to technology investment [30].

Within the Global South, South Africa has created a Presidential Climate Commission to coordinate and oversee the transition towards a low-carbon society with a focus on human capacity and skills development. Moreover, South Africa manages an Industrial Energy Efficiency program that seeks to optimize energy systems in companies by advanced training in energy audits and ways of reducing energy consumption for manufacturing. China is also making substantial investments in human capacity for net-zero by significantly increasing funding for higher education in strategic science, technology, engineering and math (STEM) sectors and by cultivating human capital in selected sectors such as steel and refining. Thailand established the Climate Change International Technical and Training Center in 2014, an official program monitored by the UN Office for South-South Cooperation, to build capacity and train human resources for climate change and greenhouse gas management in Southeast Asian countries.

5. Harness sub-national actors and industry coalitions

Increasingly, a traditional climate governance system centered on nation-states and intergovernmental organizations is proving inadequate for addressing some of the most pressing and urgent climate change and net-zero challenges, particularly challenges that necessitate transboundary cooperation [31] [32] [33].

A broad range of companies across industries are adopting renewable energy, implementing energy efficiency, pursuing negative emissions (particularly via forestry), and investing in alternative fuels infrastructure, often on a voluntary basis, and with an emphasis in the developing world. The Science Based Targets initiative (SBTi), a global coalition of organizations focused on driving sustainability, exemplifies the type of effort required for such companies to catalyze industrial contribution to net-zero industry.

SBTi targets are independently validated and monitored to ensure compliance, and the companies committed to cut emissions in line with climate science now represent approximately $38 trillion of global economy. In India, for example, UltraTech Cement is committed to SBTi targets as it aims to reduce by 2032 operational emissions by 27 % relative to 2017 levels. The diverse mechanisms employed are carbon pricing, energy efficiency measures, use of alternate fuel sources, waste heat recovery and renewable energy. Similarly, Proctor and Gamble has already achieved a 50 % reduction in emissions relative to 2010 levels by investing in geothermal, wind, solar, hydroelectric, and biomass with projects taking place across North America, South America, Asia, and Europe.

Similarly, the Super-Efficient Equipment and Appliance Deployment (SEAD) Initiative focuses on energy efficiency standards and best practices across industries in the developing world. The Apparel Impact Institute, which originated from the Clean by Design program, demonstrates decarbonization collective action in the apparel and textile industry (particularly in China and ASEAN countries) through energy and resource efficiency. The Low Carbon Technology Partnership initiative (LCTPi) Climate Smart Agriculture program targets reduced emissions from the agriculture, food, and beverages sectors (especially in countries such as Brazil and China), and the Zero Routine Flaring Initiative is seeking to end the flaring of natural gas in the oil and gas sector (with an emphasis on countries like Russia that account for the majority of gas flaring globally). Lastly, India and the United States both manage a Joint Clean Energy Research and Development Centre (JCERDC), which offers industry partnering Ignition Grants for “Innovations for Net Zero”. Recent projects focus on next generation renewable energy, energy storage, and carbon sequestration.

6. Steer social acceptance and a social license to operate

Social acceptance and public opinion are core elements of successful net-zero transitions, especially in an industrial context. This is particularly important for communities where the industrial transition can have significant socio-economic impacts. Hence, it is critical to establish programs and policies that are visible and aimed at supporting those impacted.

The Just Transition concept has become an anchor for interconnecting trade unions, social movements, and industrial incumbents to ensure that equity is better accounted for in low-carbon energy transitions, especially those that need consensus and political support [34]. Examples include the National Economic Transition Platform to support coal communities in the United States and the EU’s Just Transition Platform, which is the interface for EU citizens to engage the Just Transition Mechanism that the EU established to help ensure net-zero ambitions are achieved with the whole of society in mind [35].

Numerous Just Transition commissions and frameworks are emerging in the Global South. South Africa has its National Planning Just Transition Dialogue as well as The One Million Climate Jobs Campaign. Ghana has a National Dialogue on Decent Work and Just Transition to a Sustainable Economy and Society. Costa Rica has a National Decarbonization Plan 2018–2050. Slovakia has a Transformation Action Plan of coal region Upper Nitra, and Greece has established the National Just Transition Fund for Lignite areas. All seek to promote equity principles and protect industrial competitiveness and

Box 1
Selected organizations and movements supporting a Just Transition (with Global South initiatives in bold).

Asian Pacific Forum on Women, Law and Development (Asia Pacific)	Kentuckians for the Commonwealth (US)
Blue Green Alliance (US)	Labor Network for Sustainability (US)
Beyond Coal campaign (US)	Latrobe Valley Authority (Australia)
Central Única dos Trabalhadores (Brazil)	Movement Generation (US)
Climate Action Network (global)	NAACP (US)
Climate Justice Alliance (US)	**National Union of Mineworkers of South Africa (South Africa)**
Cooperation Jackson (US)	**Pan African Climate Justice Alliance (Africa)**
Dejusticia (Colombia)	**Post Petroleum Transitions Roundtable (Mesa de Transición Post Petrolera) (Argentina)**
Deutscher Gewerkschaftsbund (German Trade Union Confederation) (Germany)	**Powering Past Coal Alliance (global)**
DiEM25 (pan-European)	Right to the City Alliance (US)
European Trade Union Confederation (EU)	Sierra Club (US)
Grassroots Global Justice (US)	Sunrise Movement (US)
IndustriALL Global Union (global)	The Leap Manifesto (Canada)
Indigenous Environmental Network (US)	**The Trade Unions for Energy Democracy Initiative (Global)**
International Labor Organization (global)	**Trade Union Confederation of the Americas (TUCA) ITUC’s regional branch (Americas)**
International Trade Union Confederation-affiliated Just Transition Centre (Global)	Transitions Town Movement (UK)
Just Transition Alliance (US)	**Women’s Environment and Development Organization (Global)**
Just Transition Centre (global)	**350.org (Global)**
Just Transition Fund (US)	

Source: Most recent IPCC (2022) data, used with permission.

employment as countries, and their heavy industries, decarbonize. Box 1 illustrates more than 40 other active Just Transition organizations or movements active as of 2022, all aimed a making decarbonization efforts more socially acceptable. Notably, 15 of the listed organizations and movements have a focus on the Global South or operate worldwide and include Global South members [36]. Many of these frameworks have begun implementation in an industrial context [37], although mostly in the extractive industries that supply energy resources to the industrial sector, rather than sectors such as steel, chemicals, or oil refining themselves.

When considering social protections associated with industrial transition in the Global South, context is critically important. Specifically, social, political and economic barriers may prevent some industries and countries from moving away quickly from hydrocarbon resources for industrial energy and feedstock purposes. Hence, a concept like the Circular Carbon Economy (CCE), which was proposed by the Saudi Arabia G20 Presidency and subsequently endorsed by G20 members, may be fitting for countries in the Global South where transitioning away from fossil energy sources will be particularly challenging. The CCE framework supports the reduction of carbon emissions from fossil fuels via renewable energy and energy efficiency, but also endorses the recycle, reuse and removal of carbon emissions via carbon capture. Similarly, the principle of Extended Producer Responsibility (EPR) has been proposed as a net-zero emissions mechanism that would leverage geologic carbon dioxide storage and nature based carbon storage solutions as an alternative to eradication of fossil fuel production and consumption [38]. Just Industrial Transitions for countries in the Global South are likely to require flexible mechanisms like CCE and EPR as countries define pathways for industrial decarbonization that are most aligned with local contexts. Pursuit of these mechanisms in parallel to more commonly discussed net-zero approaches also mitigates some of the inherent risk involved with complete reliance on a global energy transition that requires massive clean electricity generation, transmission, distribution and storage for buildings, industry, transportation and clean hydrogen production.

7. Enact a new global treaty and foster climate clubs

Our last recommeded bold step is a new global treaty to expressly address the insidious global governance issues that arise with coordinating net-zero industry decarbonization. A new institution, or a far-reaching reform of existing institutions, to provide international rule-setting and set in place globally accepted certifications and standards for low and zero-carbon industrial products is likely needed [39]. More specifically, a mechanism is needed for achieving a rapid and coordinated sectoral approach to mobilizing sufficient resources and avoiding unfair competition and carbon leakage as net-zero industry is pursued [40].

Although some commentators point to the Kyoto Protocol and Paris Agreement as templates on which to build, we believe that the Montreal Protocol and Nuclear Non-Proliferation Treaty (NPT) offer better examples of relevant international policy architecture for net-zero. Developing countries have agreed to the binding agreements of the Montreal Protocol, which is an international treaty designed to phase out production and consumption of ozone-depleting substances, in exchange for financing from the Multilateral Fund, which is governed by a committee of seven developed and seven developing country parties with a history of operating by consensus [41]. The Protocol is special insofar as every United Nations member state is a party. This means that this is the only environmental treaty with universal membership and every party in full compliance (with temporary exemptions for some developing countries). Given this universal membership and compliance, one study notes that “The Montreal Protocol is widely considered the most successful environmental treaty.” [42]

The NPT was negotiated between 1965 and 1968, came into force about 50 years ago, and has been signed by 191 states. The NPT is seen as a historic success in terms of arms control [43]. Similar to the NPT, a Fossil Fuel Non-Proliferation Treaty for net-zero industry could operate according to the three pillars of non-proliferation, global disarmament, and peaceful use [44]. The non-proliferation element could involve preventing the exploitation of new fossil fuel reserves, based on estimations such as those provided by McGlade and Elkins [45], and revised in light of new knowledge and advances in technology, as well as new discoveries by the fossil fuel industry. The disarmament element would be to not only coordinate, manage, and accelerate the decline of fossil fuel infrastructures, but also to stimulate low-carbon alternatives across buildings, energy supply, manufacturing, and industrial supply chains. The peaceful use element would involve reorienting fossil fuel subsidies to massively expand efforts to decarbonize least developed and developing countries, ensuring that they can access the technology needed to reach net-zero energy systems.

Climate clubs focused on industrial sectors may also be necessary to achieve rapid industrial decarbonization at the global scale given the myriad technical, social, economic and political challenges that must be jointly overcome. The climate club concept [46] would bring together both developed and developing countries to coherently undertake industrial deep decarbonization in sectors such as iron and steel [47]. This would be achieved through incentivized and enforceable coordination on the key policies, standards and regulations that underpin the decarbonization interventions necessary.

8. Conclusion

Reaching net-zero industry by 2050, paramount in importance to meeting global climate targets and part of many national climate policies, will not happen without focused global attention and particular efforts in the Global South. Achieving this does, however, face pernicious barriers. One recent assessment from UNIDO identified four such interconnected barriers common to developing countries: a strong reliance on fossil fuels within industrial sectors; renewable energy’s historic inability to produce the high temperature heat required by many industrial processes; lack of carbon pricing, carbon emissions trading and carbon border adjustment taxes; and weak policy environments [48].

Due to these barriers, global decarbonization of industry will not occur without concerted action from governments, private sector entities, and even civil society and members of the public. We thus propose a blueprint consisting of the six bold steps, summarized in Table 1, with numerous historical examples from other programs, sectors, and policies where such efforts have succeeded. Perhaps surprisingly, there are more than thirty effective historical and contemporary initiatives to learn from, showcasing a rich tapestry of previous efforts and templates to build on and to inform net-zero decarbonization efforts across the Global North and Global South, and across countries rich in renewable energy resources as well as those rich in fossil fuels, such as China, India, Russia, the United States and Saudi Arabia, to name just a few.

As Table 1 also indicates, successful decarbonization will require more money, jobs, technology transfer, and coordination of sub-national and non-traditional actors, as well as shaping patterns of social acceptance and implementing new modes of global climate governance. The Montreal Protocol and NPT are apt here as examples of best-practice global coordination mechanisms. Harnessing novel configurations of patent pools and public information campaigns, similar to what has been observed in other sectors like healthcare, open-source software and aviation, should also be leveraged.

Critically, all six of our bold steps will need to be pursued as part of an integrated whole with careful consideration of the Global South context, which as we’ve highlighted is rather different from that of the Global North. Furthermore, even though we call our required actions steps, they are not sequential and actually should be pursued simultaneously, starting immediately. Undertaking these actions now would transform the largest single source of total final energy demand, and the fastest growing segment of greenhouse gas emissions—industry—from a

Table 1
Bold steps towards global net-zero industry.

Step	Description	Historical and contemporary examples from which to learn
Quintuple financing	Scaling up international financial support for industrial decarbonization, particularly in the Global South	1. Loans, credit guarantees, and tax incentives in Brazil 2. Grants and credit guarantees in Ghana 3. Chile's Corporación de Fomento de la Producción (Production Development Corporation)
Expedite technology transfer to developing countries	Accelerating the diffusion of low-carbon industrial decarbonization technologies worldwide	4. China and the United States Clean Energy Research Center 5. The United Nation's Climate Technology Centre and Network 6. The Renewable Energy and Energy Efficiency Partnership (REEEP) 7. Patent pools and common access to critical technologies (similar to the Manufacturers Aircraft Association, Eco-Patent Commons, open-source software, the Medicines Patent Pool) 8. Clean Energy Ministerial on steel and cement 9. EU Ultra Low Carbon Steel (ULCOS) program 10. UK Offshore Wind Accelerator 11. US DOE ARPA-E steel initiative
Invest in human resources and capacity	Building industrial net-zero skills and training regimes	12. The Hynet Academy in England 13. Digital Skills and Jobs Platform and Digital Education Action Plan in the European Union 14. South Africa's Presidential Climate Commission and Industrial Energy Efficiency program 15. China's strategic plan for higher education in strategic STEM sectors 16. Thailand's Climate Change International Technical and Training Center
Harness sub-national actors and industry coalitions	Encouraging cities, private sector firms, and other non-state actors to adopt renewable energy, implement energy efficiency, pursue negative emissions (particularly via forestry), and invest in alternative fuels infrastructure	17. Science Based Targets initiative (SBTi) 18. Super-Efficient Equipment and Appliance Deployment (SEAD) Initiative 19. The Apparel Impact Institute 20. LCTPi Climate Smart Agriculture 21. Zero Routine Flaring Initiative 22. US-India Joint Clean Energy Research and Development Centre (JCERDC)'s Ignition Grants for "Innovations for Net Zero"
Steer social acceptance and a social license to operate	Establishing programs and policies that build social support and are aimed at ensuring a just and equitable transition	23. The National Economic Transition Platform in the United States 24. The European Union's Just Transition Platform 25. South Africa's National Planning Just Transition Dialogue and One million Climate Jobs Campaign 26. Ghana's National Dialogue on Decent Work and 'Just Transition" to a Sustainable Economy and Society 27. Costa Rica's National Decarbonization Plan 2018–2050 28. Slovakia's Transformation Action Plan of coal region Upper Nitra 29. Greece's National Just Transition Fund for Lignite areas 30. G20's Circular Carbon Economy (CCE)
Enact a new global treaty and foster climate clubs	Implementing a new global treaty to expressly address the insidious global governance issues that arise with coordinating net-zero industry decarbonization	31. Kyoto Protocol 32. Paris Accord 33. Montreal Protocol 34. Nuclear Non-Proliferation Treaty (NPT) 35. Fossil Fuel Non-Proliferation Treaty 36. Climate Clubs

Source: Authors.

nagging problem into a compelling solution, a leverage point that deeply embeds net-zero infrastructure and practice into our climate future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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