Emissions from fossil feedstocks are partly responsible for global warming and are driving unprecedented efforts to reduce the carbon intensity of products and processes. The intention to move away from carbon-based energy has triggered the transition to renewable sources and encouraged setting carbon targets to mitigate climate changes. The transition to a low carbon economy is a journey whose timeframe depends on climate action goals, geopolitics, and their macroeconomic effects, besides socioeconomic issues. The energy industry holds the top carbon intensity position and is thus the workhorse of change. National and global decisions on energy planning propagate to other sectors proportionally to their energy intensity. Achieving the goal of Net-Zero Emissions (NZE) in a couple of decades requires a coordinated innovation effort utilizing multiple energy sources, large-scale carbon management technologies, and electrification.

The main governing factors of a nation’s CO2 emissions from energy are the per capita GDP, the economy’s energy intensity, and the carbon intensity of its energy grid. Combined, they provide the carbon intensity of the economy:

\[
\frac{CO_2}{GDP} \left( \frac{\text{kg CO}_2}{\$} \right) = \frac{\text{Energy}}{GDP} \left( \frac{\text{kWh}}{\$} \right) \times \frac{CO_2}{\text{Energy}} \left( \frac{\text{kg CO}_2}{\text{kWh}} \right)
\]

Decarbonization strategies target first improving energy efficiency to reduce \(\frac{\text{Energy}}{GDP} \left( \frac{\text{kWh}}{\$} \right)\). A second strategy is deep-electrification of production processes with low-carbon energy, which increases the economy’s energy intensity. A third approach is to offset carbon emissions through Carbon Capture and Utilization (CCU), Carbon Capture and Storage (CCS). Following these decarbonization steps, CDR (Carbon Dioxide Reduction) is the remaining alternative, inevitably the most expensive. Reduction of CO2 in the atmosphere requires technologies or procedures to achieve negative emissions, which are: (a) Direct Air Capture with Carbon Storage (DACC); (b) Forestation; and (c) Bioenergy with Carbon Capture and Storage (BECCS). The technology decision should be guided by Marginal Abatement Cost (MAC) Curves, comparing their leveraged cost of mitigating emissions.

In targeting reduction of carbon intensity, two Sustainable Development Goals (SDGs) are prioritized: #7—Affordable Clean Energy (mostly Clean than Affordable), and #13—Climate Action. Accounting for underprioritized SDGs is a must-do: water intensity under water scarcity (#6, Clean Water and Sanitation), land use (#15, Life on Land) facing their use for food production (#2, Zero Hunger), and eradication of poverty (#1, No poverty). Also, planning the energy transition must recognize the well-being of populations of developing economies (#8, Decent Work and Economic Growth; #3, Good Health and Well-Being). Transitioning energy systems push a cascade of companion transitions proportionally to their capital intensity. Policymakers must minimize the risk of the energy transition creating spiraling price pressures across the economy—“carbon inflation”, while acting on mitigating climate changes which, thorough droughts and floodings, to cite a couple, impact the economy—“climate inflation”.

One might argue that the UN’s SDGs is a political document for shifting societies’ mindset to a long-term way of thinking, while clean energy production and mitigation of carbon emissions are dominated by technology, mastered by pragmatic engineering minds. Progress towards attaining SDGs is monitored by 231 indicators spread across 169 targets, some being physically measurable or inferred. For instance, remote sensing provides Earth observation data for 30 of these indicators (Ronald 2020). Ament and coworkers (2020) have shown empirically that nearly 70% of SDGs indicators status is positively associated with GDP per capita. A point of relevance in the perception of SDGs effects is that large-scale technology deployments are capital-intensive, and SDGs have built pressure on the financial system to mobilize resources for sustainable development (United Nations 2021). The macroeconomic aspects of the transition to a low-carbon economy have been named “sustainomics” (Munasinghe 2019) to explain the economic response...
to SDGs. These goals also orient regulatory frameworks to address social and environmental risks, changing technologies’ outcomes, thus posing business risks.

The energy transition mainly affects the fossil-resources-based industries, pushed by the need to accelerate the mitigation of carbon emissions. Also, deep decarbonization of energy-intensive industries is necessary to meet climate targets (Åhman et al. 2017). Interestingly, those are the industries most fitted to undertake large-scale and capital-intensive endeavors. They have been protagonists of milestone transitions in energy feedstocks, from coal to oil to gas. Those transitions did not occur because of depletion of the feedstock but from externalities, and the energy transition is no exception. For instance, pressure on oil prices from “sustainability” and climate targets (e.g., limit temperature increase to 2 °C) might render oil reserves at risk of not being developed. New oil and gas reserves are needed to supply the increasing energy demand while affordable large-scale energy alternatives are being developed.

Although fossil fuels have traditionally low marginal cost of supply, exploration of new reserves has become more capital intensive. Agostinho and Weijermars (2017) analysis suggests that the major oil companies increased significantly on CAPEX investments, while cash flow from operations (CFO) did not grow proportionally. High oil and gas prices increase CFO and net income, which facilitating investment spending. High world oil and gas prices, as in the post-COVID19 pandemics and the Russia-Ukraine war, are stimulating investments by the oil and gas industry. The intensity of capital investment in fossil installations builds technology resilience, incentifying oil operators to undertake more investment. This scenario intensifies technology lock-in, though fossil-reserves exploration costs have been increasing due to the intensification of climate targets. In fact, the extent of new oil reserves (e.g., in Latin America) becoming stranded assets results from their investment break-even point.

The nations worldwide recognize climate changes and the need to act to mitigate their effects while moving toward renewable sources. Europe leads in actions and rules to accelerate the transition, but the specificities of other economic blocks and nations frustrate policymakers’ expectations. Some relevant issues counterbalance the plans and time expectations. First, the Russia-Ukraine war has exposed the fragility of the renewable-fossil energy strategies of the European nations and the European Parliament backed EU rules labeling investments in gas and nuclear power plants as climate-friendly (Abnett 2022). Secondly, the developing countries (many of them with substantial fossil reserves) will account for nearly 60% of world GDP by 2030. OECD’s wishful perspective is that the economic and financial crisis is accelerating the longer-term structural transformation in the global economy, relying on natural gas as the “transition fuel” (OCDE 2020). Those nations must highly prioritize affordable energy (SDG #8) and economic development (SDG #8), as well as SDG #1 (No poverty) and SDG #2 (Zero hunger).

It is pointless to forge reforms for which a society is not yet ready. Policymakers need to assess “the nature of the current social contract, and all the possible social contracts into which it might conceivably be transformed by pushing on whatever levers of power are currently available” (Bimore 2006). The world is not uniformly ready to undertake a homogeneous transition, as it would not be equitably sustainable. Solving the global warming problem by a simplistic diagnostic-action decision, i.e., “the carbon is in the air,” so “leave carbon in the ground,” ignores the liability of past emissions from the developed economies. A reasonable approach would be for the developed nations to erase their previous contribution to the atmospheric carbon inventory with Carbon Dioxide Removal (CDR) technologies and allow the developing nations to develop their fossil assets while transitioning to a low-carbon economy.

Last and most importantly, geopolitics differs among nations, folded by resource availability and opportunities to overtake the scene. Specific challenges and opportunities exist for both the demand and supply-side of industries, governments, regions, and individuals. Although these forces are mostly known, gains and losses are sizable and must drive policy objectives to shape the future. Decarbonization has several realization paths and impacts, and a needed goal for society to embrace is adopting just and equitable paths. Transition to a low-carbon economy is a complex and capital-intensive journey that by no means must be faced by a scalar function to optimize — “minimum carbon” — but rather a multi-objective to be searched in a large-dimensional space. The UN SDGs bring to scene directions that seek advancements beyond climate actions, such as (i) Increasing energy safety and resilience to extreme events — health (e.g., COVID-19 pandemics), political (e.g., the Russia-Ukraine war) and climate (O’Driscoll 2021) (e.g., the hurricane Katrina, which cost US$ 185 billion (Weather and Change 2022)); (ii) Minimizing the occurrence of “carbon inflation” and “green inflation” (Schnabel 2022); and (iii) Investing in innovative large-scale decarbonization technologies (Holmes et al. 2021) while expanding energy supply by renewable sources.

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Declarations

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