"TAKE IT SLOWLY WITH THE PROCESSION, FOR THE SAINT IS MADE OF CLAY"[1]

Contemporary society often reduces complex topics to viral, bite-sized content. The nuanced discussion surrounding energy transition is weakened in this context, since it involves multiple dimensions of human behavior. While society recognizes the effect of carbon concentration in the atmosphere and its severe implications for climate imbalance, it is unable to renounce the gains in well-being provided by harnessing such energy. The collective distraction in recognizing such dependence of our development journey on energy availability is astonishing. It recalls the story of two young fish that bump into an older fish that greets them with a "Good morning boys, how's the water?" After a while swimming, the young fish look at each other and ask, "What the hell is water?!" Look around. If you set eyes on a non-biological object, it is likely a product, directly or indirectly, of fossil hydrocarbons.

Discussions insist on top-down slogans: "humanity can no longer burn fossil fuels," or "the world must transition to a clean energy matrix." They hide in the abstract, forgetting that humanity arises from the interactions of billions of individuals arbitrating daily decisions based on their own survival. And no one is willing to make personal sacrifices. It is the attachment to narrative battling stark reality. Not to mention the amount of individuals burning carbon to convince the world to use less carbon[2]. A textbook case of tragicomedy.

Efforts to reduce emissions and mitigate humanity's imminent risks can only be sustained by addressing the intertwined dynamics of pricing and geopolitics. The number of COP meetings we organize is irrelevant if the proposed alternatives fail to provide business competitiveness or sovereignty. Inconclusive analysis will continue to overshadow decisive actions.

The reduction of greenhouse gas (GHG) emissions in recent decades has primarily been driven by a reduction in the use of coal for electricity generation. In the U.S., between 2007 and 2023, GHG emissions in the energy sector declined by more than 20% despite rising electricity consumption, representing half of all emissions reductions by OECD countries[3]. This reduction was the result of large-scale exploitation of shale gas through hydraulic fracturing, more commonly known as fracking. The most significant event in the world of energy and geopolitics since the oil crisis of the 1970s.

[1] Brazilian proverb conveying the risks of speeding into conclusions.

[2] More than 80 thousand people traveled to COP 28 in Dubai to discuss, inside air-conditioned rooms in the middle of the desert, how to reduce greenhouse gas emissions.

[3] The greenhouse gas emissions data of OECD countries should be analyzed with caution since a significant part of manufacturing has gradually been outsourced to other countries, especially China. The per capita energy use in developed countries, when adjusted for the energy intensity of imported goods, is 30% higher [Thunder Said Energy - Global energy demand: false ceiling?].

This crisis was a landmark for countries that were not self-sufficient in oil. The International Energy Agency (IEA) was established at the time to assist OECD countries in coordinating energy security measures and collective action, serving as a counterbalance to OPEC. The period is marked by incentives for local oil production as well as a boom in nuclear energy, which jumped from 1% of the European energy matrix in 1973 to just over 10% in 1989. In this context, Japan initiated the first global project to promote solar energy, accounting for half of all installations worldwide by 1999. In Brazil, we responded with the construction of large hydroelectric plants, accounting for 20% of all global hydropower generation added in the decade following the first oil crisis. Additionally, we created the National Alcohol Program, developing the sugarcane ethanol industry and establishing ourselves as leaders in biofuels — by 1990, Brazil represented 80% of global production. The U.S. only surpassed Brazil in 2005 with the creation of the Renewable Fuel Standards (RFS) program[4]. RFS was a response to the renewed increase in oil prices in the early 2000s amid a sharp decline in domestic oil production, which in 2005 fell to 70% of the peak level seen 20 years earlier.

Subsequently, with the boom in American shale production, the U.S. reshuffled global geopolitics. The country reduced its historical dependence on energy imports, challenged Russia's dominance in the natural gas market, and diminished the Middle East's influence on U.S. foreign policy. Meanwhile, on the other side of the Atlantic, a fragile Europe watched the excitement around renewables and the vilification of certain energy sources cause harm to society and cloud the geopolitical landscape. The green policies of Germany's Social Democratic Party symbolize this naive pursuit of one-dimensional goals. By reducing nuclear generation, it became a voluntary hostage to imported gas, creating dependence on a country historically distant from Western values. The German government as a result relinquished part of its sovereignty[5] and has since been enduring the consequences. Today, to reduce its dependence on Russia, Europe relies on importing liquefied natural gas (LNG) from foreign countries. Therefore the largest global exporter — post-shale U.S. — gains undeniable influence while Germany's energy-intensive industry, responsible for about 6% of GDP and 8 million jobs, has become vulnerable.

In this backdrop, the question arises as to what role Brazil will play. Our media prominence is indisputable as we are an aspiring energy transition celebrity. We represent only 2% of global energy consumption but produce 8% of all clean energy. In the last five years, we have been the third country to install the most wind power capacity, the fifth in solar power capacity[6], and the third in marginal biofuel production. This helped to disseminate the belief that the energy transition is Brazil's bridge to the future. However, this is only part of the story. Our relevance is not limited to renewables since we are also among the top 10 oil producers in the world. A dilemma therefore arises. How should we deal with the tension between continuing to produce hydrocarbons while evolving into a green energy powerhouse? Should the idea of exploring oil in new frontiers or expanding our reserves through hydraulic fracturing be abandoned in the name of our ambition

[4] The RFS is a federal program in the United States that establishes annual targets for blending renewable fuels, such as ethanol and biodiesel, into diesel and gasoline. Refineries and fossil fuel importers must accumulate credits called Renewable Identification Numbers (RINs), which can be generated by blending biofuels or purchased from third parties.

[5] The European Union produced two-thirds of all energy consumed in 1990, primarily from coal, natural gas, and nuclear sources. Fast forward a little over 30 years and the picture is far from encouraging. Even with renewable sources already accounting for 10% of energy demand, the bloc now produces only 43% of what it consumes.

[6] When we look at the energy actually generated, we move up one position in the ranking due to Germany's dismal solar capacity factor, ranking fourth in terms of installed capacity during this period but twelfth in terms of actual generation.

to be at the environmental forefront? Is the rest of the world willing to pay a premium for our green attributes? Does it make sense to direct our efforts towards offshore wind power, green hydrogen, or sustainable aviation fuel?

As the capital allocated today will be instrumental in the success of this journey, selecting competitive and viable energy sources while respecting regional idiosyncrasies becomes an indispensable reflective investigation for Brazil. Choosing appropriate energy policies is not straightforward. We cannot abide by comfortable narratives that lead to serious adverse effects to be borne by future generations.

“WAIT SITTING DOWN / OR YOU’LL GET TIRED / FOR WAITING NEVER PAYS OFF"[7]

Brazil's clean energy matrix was not intentionally designed with its carbon footprint in mind. Our remarkable hydropower potential stems from a blessed geography. A happy coincidence. Similarly, our reliance on sugarcane cultivation originates from our favorable climate and the economic priorities of the colonial era. A mere historical accident. Carbon considerations have never influenced decision making; the ultimate goal has always been to expand energy supply and secure sovereignty, particularly after the oil crises of the 1970s highlighted the risks of external energy dependence. To achieve self-sufficiency, the country invested heavily in developing hydropower and biofuels while simultaneously pioneering offshore oil exploration. This effort doubled domestic production during a challenging decade and established the foundation for Brazil's emergence as a leader in deep-water exploration.

In the current *zeitgeist* of decarbonization, this energy matrix becomes a source of pride. It is the basis through which we seek the role of leaders in the energy transition and aim to enhance our economic and geopolitical relevance. But just as we arrived here without focusing on carbon, it seems naive to believe that other countries would be willing to pay a premium for our renewable attributes without this being reflected in directly quantifiable benefits.

The issue is that this topic often receives an excessively superficial treatment. The clichés repeated *ad nauseam* ignore countless challenges and narrow the scope of the debate. The energy matrix of a modern society is its supporting pillar; reconstructing it is a fundamentally disruptive and complex activity. A diligent analysis of these potential avenues is invariably technical, producing content that can be dry and unpleasant to read. With this in mind, we chose to share in this letter the analysis of only two topics: solar energy and green hydrogen.

Solar energy is an undeniable success story. It operates within the binomial of price and sovereignty. Its decentralized nature ensures energy independence and its low cost provides competitiveness. It is no coincidence that it is the fastest-growing energy source in history[8]. In Brazil, photovoltaic energy represented

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[7] Excerpt from the song "Bom Conselho" by Chico Buarque.
[8] Carbon Brief - Wind and solar are ‘fastest-growing electricity sources in history’

two-thirds of our marginal installed capacity in the last five years, establishing itself as the second-largest source of energy in terms of capacity, only behind hydropower[9]. To understand the causes and consequences of these impressive results, we will dive deeper into this story and point out the inevitable challenges that arise from its own success.

"I FEAR NOT THE MAN WHO HAS PRACTICED 10,000 KICKS ONCE, BUT I FEAR THE MAN WHO HAS PRACTICED ONE KICK 10,000 TIMES"[10]

The accumulation of knowledge through repetition is the fundamental element that allows for cost reduction in an industrial process. The rule is clear: the more you iterate, the more you learn, and the cheaper it gets. Between 1975 and 2010, the price of solar panels dropped by 98%. In the following decade, it fell by another 90%[11]. It is the energy source with the greatest cost reduction for each doubling of capacity in history[12]. Its industrial process consists of continuously building scores of practically identical small modules. This modular nature enhances the learning curve.

An overlooked aspect when recounting the virtuous journey of solar competitiveness is its symbiotic relationship with the semiconductor industry. Hyper-purified silicon cut into thin wafers and doped with chemical elements to create interfaces between positive and negative sides allows for controlling the flow of electrons as desired in each of the applications. Thus, both industrial chains share not only the central raw material but also part of the manufacturing techniques, in addition to benefiting from massive investments in R&D. The river really does flow to the sea.

Many countries have wholeheartedly embraced the solar energy adventure. Japan's initiatives to reduce its reliance on imported oil in the 1970s resulted in the country possessing nearly half of the world's photovoltaic generation capacity by 1999. A number that at first glance sounds impressive, but represented only 0.02% of the country's electricity consumption[13]. Staying true to the classic Japanese proverb of renowned patience: "Great things often have small beginnings." In the 1990s, it was Germany's turn to push generous incentives for the solar industry - partly driven by the anti-nuclear movement that gained momentum after the Chernobyl disaster. Germany soon replaced Japan in the race, representing almost half of the global installed capacity by 2005. However, just a few years later the incentives were terminated and the industry collapsed, culminating in the bankruptcy of some of the most notable German companies in the sector[14]. Spain also acted eagerly. Their federal public debt increased by more than 10% of GDP due to a policy of solar energy incentives. A few years later Spain retroactively removed the subsidies, and thus still ranks at the top of the

[9] This comparison is not entirely fair due to the capacity factor of solar energy. The actual power delivered only matches the nominal power for a short part of the day.
[10] Bruce Lee.
[11] From when we started writing this letter until it was published, the price of solar panels in China fell by 60%.
[12] A review of learning rates for electricity supply technologies, Rubin et al., 2015.
[13] Which, in turn, represented only 17.5% of all energy consumed.
[14] The most notorious example is Q-Cells, the former flagship of the German energy transition, which went from being the world's largest producer of solar panels to bankruptcy just a few years later. This fate was shared by several other German companies in the sector: Solon, Solarhybrid, Odersun, Centrotherm…

list of European countries with accumulated debt for non-compliance with trade agreements. Without competitiveness, there is no sustainability.

Finally, European myopia was replaced by a Chinese industrial policy obsessed about scale, which ultimately succeeded in reducing costs to the point of granting competitiveness to solar energy. Along this path, China became the country with the largest installed capacity in the world as early as 2015, later reaching 40% of total installations. In the year 2023 alone, it was responsible for installing solar generation capacity 10% greater than the combined total of Japan, Germany, and Spain over the past five decades.

Such achievement of industrial dominance came at a cost, but the game theory in geopolitics can help understand why it made sense. Over the past three years, China consumed an average of 15.5 million barrels of oil per day, of which it produced only 4.1 million. The average cost of this deficit at market prices would be approximately $340 billion per year, by far the largest offender to the country's current account balance. This number would be even greater if photovoltaic modules had not generated an energy equivalent to 2.7 million barrels in 2023. By solidifying its position as the most relevant player in the solar energy production chain[15], China simultaneously reduces its dependence on imported oil, increases its export portfolio, reduces its marginal energy production cost, and gains prominence in any global discussion related to the energy transition.

Today, solar is the most competitive source for additional energy capacity[16]. This does not mean that other sources are doomed to irrelevance, or that a future with 100% renewable grids is possible. Integrating this type of energy into the system is far from trivial. Its attributes require planning and a degree of caution.

"THERE ARE NO SOLUTIONS, ONLY TRADE-OFFS"[17]

Electricity's production and consumption must occur simultaneously. Until recently, operating an electrical system meant ensuring that there was enough generation to meet demand at every moment. The equation was simple — if consumption decreases, generate less; if consumption increases, generate more. Intermittent energy sources follow a different logic since they cannot be dispatched on demand. They are equivalent to competent employees who only show up at the office when they feel like it. They can be good team members, but it is hard to rely exclusively on them. When intermittent generation decreases, the new equilibrium can occur in two ways: either we increase generation from other sources or we reduce consumption until it matches generation. Supply-side adjustments require maintaining sufficient reserves of dependable energy sources to accommodate potential fluctuations. It is no coincidence that while China was setting records in renewable capacity additions, it was also installing unprecedented amounts of coal-fired

[15] In 2021, China held 72% of the world's polysilicon manufacturing capacity, 98% of ingots, 97% of wafers, 81% of cells, and 77% of modules [US DOE - Solar Photovoltaics Supply Chain Deep Dive Assessment].
[16] With the exception of geographies that do not have such a constant presence of the sun.
[17] Thomas Sowell.

power plants. Without sufficient dispatchable generation capacity[18], the alternative is to adjust through consumption — resulting in blackouts. When intermittent generation increases and there is excess supply, three new possible equilibriums emerge: we either reduce generation from dispatchable sources[19], increase consumption[20], or prevent intermittent generation from injecting power into the grid in a phenomenon known as curtailment. In plain terms: "throwing energy away."

When generation capacity exceeds transmission or consumption capacity at that moment, there is no alternative but to restrict energy injection into the grid. In Brazil, we already see curtailments of up to 80% on Sunday mornings, when demand cannot absorb the intermittent renewable supply. At that moment, that energy is five times more expensive since the cost is fixed and much of it goes to waste. Curtailment is therefore the key variable to understand the penetration limit for renewable sources. A theoretical model without transmission restrictions[21] and without storage, with a 30% capacity factor and 35% solar penetration, translates to an average curtailment of only 2%[22]. Expanding this penetration from 35% to 40% increases that average restriction from 2% to 15%. However, more relevant than the average is the marginal curtailment of the added capacity, which would already be around 56%. The higher we raise this penetration, the more pronounced this effect becomes. To increase solar from 40% to 42.5% of the grid, the marginal curtailment jumps to 83%. This means that the additional energy must cost almost six times more just to achieve the same level of financial return. For every new unit of energy, it is as if every day were Sunday.

Batteries are natural candidates to solve part of this puzzle. By adding a few hours of storage, we can smoothen the solar generation curve and avoid energy waste. But the economic reality is complex. Although the cost of batteries has fallen more than 80% in the last decade, the absolute investment needed to balance systems at this scale is still significant. Setting aside the issue of seasonality[23], delivering energy consistently throughout the day implies at least doubling the cost in a typical Brazilian solar park[24]. This equation may change if the trend of falling prices continues. Unfortunately, this is still a scenario fraught with uncertainties. The cost decline observed so far has predominantly occurred in the industrial component. Manufacturing costs, which accounted for about 90% of the total in 2012, now represent less than 30%. Continued

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[18] Sufficient not only from a physical standpoint, but also economic and technical, considering transmission limitations, ramp-up speed, etc.

[19] This is not always possible for various reasons. In Brazil's case, for example, hydroelectric plants have a significant inflexible component due to the multiple uses of water. Shutting down a hydroelectric plant often means interrupting the flow of a river and, consequently, the entire economy that depends on it.

[20] The electrical grid as we know it was born from Edison's insight to design advantageous pricing to attract industrial consumers to the system during periods of excess generation.

[21] In Brazil, electrical and reliability restrictions currently represent a volume three times greater than the energy restrictions we are describing in this theoretical example.

[22] The model assumes a 30% capacity factor, such that achieving a 35% penetration requires building generation capacity exceeding the load. As a result, at peak generation times we necessarily need to discard some electricity.

[23] A battery operating in hourly modulation is activated for about 16 hours a day with low or no solar intensity, whereas a battery aiming to handle seasonality, if dispatched for a week, would be activated for 168 hours. Over a year, this represents a difference of about 35 times, making the investment in seasonal batteries very difficult to amortize, rarely being more competitive than other supply alternatives.

[24] An exercise considering the average hourly generation curve of a solar park, which means adding slightly less than 4x the park's capacity in batteries for a flat average delivery. In this configuration, the park cannot deliver energy for about 15% of the time, remaining exposed to the short-term market. The battery cost to ensure delivery 95% of the time is prohibitive (reason listed in the footnote above), multiplying the price by another four times.

reductions in cost therefore increasingly depend on commodity prices or chemical innovations in battery composition.

The challenges toward increasing the penetration of renewable sources are not limited to the realm of time. Besides dealing with the problem of "when" energy is generated, we must also address the "where." The combination of available land and the abundance of renewable resources exists far from consumption centers. We have 82% of the installed wind and solar capacity in the northeast of Brazil, but only 16% of electricity demand resides there. For this excess energy to reliably reach where it is needed, we must invest in transmission infrastructure[25]. And since we size the infrastructure for peak generation instances, we will inevitably build partially idle assets. As in any high fixed cost business, greater idleness translates into higher unit prices. The paradox becomes evident: adding cheaper capacity may result in more expensive energy to the end consumer.

Distributed Generation (DG) is, in theory, a good solution to the "where" problem, as generation is installed at the point of consumption. However, in practice this energy source brings more problems than solutions. The rampant expansion seen in recent years was facilitated by consumers who continued buying energy from distributors. Those with sufficient capital and space to install solar panels benefited from net metering, which is nothing more than the right not to pay all the other components of the tariff: back up electricity sources, remuneration for distributors and transmission assets, various sectoral charges, and taxes[26]. This unpaid amount is distributed among the remaining consumers, increasing rates and thus creating an even greater incentive for migration to DG. The infamous "death spiral" or reverse Robin Hood policy. This enhanced incentive structure amplified the effects of falling photovoltaic module costs and removed any risk of curtailment and price modulation. Thus, despite Brazil's struggling industrial sector and high capital costs, the country accounted for 4% of global installations over the last five years while only consuming 2.3% of global electricity.

"BY FAILING TO PREPARE, YOU ARE PREPARING TO FAIL"[27]

The 3 million solar DG projects generate up to 30% of all the electricity in the country at noon. And since the sun inevitably sets, it is up to the National System Operator (NSO) to replenish this electricity with energy from other sources. The abundance of intermittency therefore inevitably demands greater flexibility. Hydropower plants, our historical supporting backbone, are limited by hydrological cycles and multiple uses of water[28]. Without additional controllable power, we will struggle to supply the necessary energy to meet the

[25] Brazil contracted just over R$74 billion in investments in the sector over the last three years, adding a cost to the system of around R$9 billion per year, a 5% increase in total costs.
[26] In the upside-down world of distributed generation, even tax increases generate additional investment returns.
[27] Benjamin Franklin.
[28] Increasing the generation of a hydropower plant means increasing the flow of the river upstream of the plant, which has collateral effects on the entire biological and social dynamics in the surrounding area. These adjustments of flow speed restrictions are not part of the system operation model (DESSEM), resulting in various distortions that must be manually adjusted in a process called “post-DESSEM.”

ramp down of solar sources. The NSO assesses this risk of power supply failure in its Energy Operation Plan (EOP). In the last published version, we will exceed what is deemed acceptable levels[29] as early as 2025, a timeframe insufficient to respond responsibly. In the following years, the situation only worsens. Ultimately, we will rely on natural gas to manage this abundance of solar energy, a topic we will explore in more detail in the next letter.

Some conclusions become inescapable when studying electrical systems that have undergone similar integrations of renewable sources. The first is the importance of price signals. In California, with the locational marginal pricing (LMP) model, it is common to see negative prices[30] at various points throughout the day, with significant dispersion between different consumption and generation points. This is the absolute cue for rebalancing the market, which must invest in generation where it lacks, in consumption where there is surplus, or in batteries to transport energy over time. Texas, the oil capital of the U.S., is also noteworthy because, unlike California, it did not design explicit incentives for the renewable sector yet still emerged as the leading state in wind and solar installations and ranks second in battery capacity. This demonstrates that the price signal acts as a north star for investments.

In Brazil, our hourly PLD[31] is the result of complex stochastic calculations with limited scope, followed by manual adjustments due to unspecified restrictions in the mathematical models. It resists fulfilling the classic function of the price variable—balancing supply and demand. Additionally, artificial floors and ceilings reduce its effective signaling power. In recent months, hourly pricing has finally begun to incorporate some volatility from the system, but it is still common to see demand response programs, energy imports, and thermal dispatch at variable costs higher than those implied in the PLD. That said, recent signals are already sufficient to caution solar generators: in October 2024, the effective price for solar in the northeast was about R$80/MWh lower than the linear average[32], a reduction of at least one-third in project revenue. If the generator sold the energy under a flat contract that delivers the same amount every hour of the day, those projects will certainly struggle to generate the expected return. This compromises future expansions. Meanwhile, the implicit selling price for DG is independent of any system conditions. We pay exorbitant prices even when we don't need the generated energy, which amplifies the negative effect for centralized generators[33].

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[29] Resolution 29 introduced in 2019 by the CNPE assigns the MME the responsibility for defining maximum limits and confidence levels for metrics of adequacy risk for power and energy.
[30] Prices consistently turn negative to compensate for any public incentives aimed at actually reducing unwanted generation.
[31] The PLD is calculated by the Electric Energy Commercialization Chamber (EECC) using data distinct from those that guide the actual operation of the system. Although the NSO and EECC run the same mathematical models, the input data is not uniform and the model results undergo manual adjustments during real-time operation that are not reflected in the price formation stage. It is a variable that confuses more than clarifies.
[32] Explaining the exercise: a theoretical plant with a capacity of 100 MW and a 30% capacity factor has 30 MW available to sell. The generator that closes a contract with linear delivery must handle an inevitable temporal mismatch since the sun does not shine 24 hours a day: at noon the plant produces 100 MW, and when the sun sets it produces zero. Thus, the generator has a surplus of 70 MW at noon and a deficit of 30 MW at night. This adjustment at market prices represented a cost of R$80/MWh for solar generators in the Northeast during October.
[33] If DG were part of the generation cuts due to lack of demand (energy curtailment), the impact on centralized renewable generators would be about 20% less.

Another commonly overlooked aspect of the energy transition is the wide range of invisible products that are fundamental for the full operation of an electrical system. Attributes such as power, flexibility, frequency regulation, inertia, black start, ramp rate, etc. Hydropower plants, historical pillars of our matrix, provided all these ancillary services for free. Such scenario changes in a grid with a higher penetration of intermittent renewables. The regulatory challenge is to create mechanisms that encourage the development of these necessary attributes, a burdensome task in the current institutional context of the electricity sector in the country[34]. In California, ancillary services are explicitly defined, planned, and contracted, ensuring grid reliability and maintaining sufficient generation capacity to meet current and future demand at stable voltage and frequency levels. In Brazil, however, the definition, contracting, and remuneration of these ancillary services are conducted indirectly through auction requirements, resulting in a confusion of the products involved.

In the end, the significant decline in costs of photovoltaic components and the extensive subsidy policy through net metering have elevated solar energy to a prominent role in Brazil's energy landscape. While this fact may initially seem like a positive development, reinforcing our image as a green power, we are beginning to encounter the challenges posed by a less stable grid. Ironically, the very success of solar energy may hinder its future expansion. In this context, green hydrogen emerges as a potential solution—a versatile element that functions as a long-term battery, a medium for transporting renewable energy, and a means to enhance our standing in global geopolitics. We nevertheless remain skeptical. This brings us to the second topic we aim to address in this letter.

"FOR A SUCCESSFUL TECHNOLOGY, REALITY MUST TAKE PRECEDENCE OVER PUBLIC RELATIONS, FOR NATURE CANNOT BE FOOLED"[35]

Hydrogen has captured the imagination of techno-optimists for over a century. In the 1875 book "The Mysterious Island," the protagonist of Jules Verne states: "Water will one day be employed as fuel, that hydrogen and oxygen which constitute it, used singly or together, will furnish an inexhaustible source of heat and light, of an intensity of which coal is not capable." One of the pioneers of the science fiction genre had a certain obsession with humanity's struggle to tame the elements of nature. In 1923, British scientist J.B.S. Haldane described a future in which the energy challenges of the United Kingdom would be overcome with wind turbines combined with hydrogen for seasonal storage[36]. In 1970, nuclear physicist Lawrence W. Jones from the University of Michigan wrote an article[37] concluding that the use of liquid hydrogen as fuel would not only be feasible but desirable and perhaps inevitable — an obvious substitute for hydrocarbons in the

[34] We are witnessing a relentless weakening of the once-respected technical institutions in the country: Aneel, EECC, EPE, NSO—none have remained unscathed by the recklessness of those who dangerously blur the line between technical matters and politics. The legislature, which occasionally reassures us by acting as a moderating force, fails to offer any relief in this context—quite the opposite. And the judiciary, which is meant to uphold the rules and provide stability, has shamelessly intervened in complex regulatory matters to the benefit of private agents.

[35] Richard Feynman.

[36] http://bactra.org/Daedalus.html.

[37] Toward a Liquid Hydrogen Fuel Economy.

21st century. The hype faded with the fall in oil prices in the 1980s, later returning during the tech bubble of the 2000s[38]. In 2002, the book "The Hydrogen Economy" by Jeremy Rifkin projected a future with decentralized production of this miraculous fuel, potentially overturning the global geopolitical landscape and ending the fossil fuel era. With the Green Deal in the European Union in 2020 and the Inflation Reduction Act in the U.S. in 2022, hydrogen has returned to the spotlight, ready to save us from the threat of global warming and this time propelled by the continuous drop in renewable energy prices.

Today, we globally consume about 100 million tons of hydrogen, entirely sourced from fossil fuels[39]. It is primarily used as a raw material in industrial processes, from fertilizer production[40] to desulfurization in refineries[41]. But to help humanity tackle its decarbonization challenge, hydrogen needs to be produced differently. Green hydrogen emerges as an alternative: using renewable electrical energy, we break the bonds between hydrogen and oxygen atoms in water through a process called electrolysis. Eureka! We isolate an element that burns at the same temperature as traditional natural gas, but carries almost three times more energy per kilogram and produces no greenhouse gas emissions. Yet what seems like a magical solution to all our woes becomes deceptively complex upon investigation.

With only one proton in its nucleus, hydrogen is the lightest element in the periodic table. While one cubic meter of LNG weighs around 450 kg, the same volume of hydrogen weighs only 70 kg. However, in current transportation logistics systems, gravimetric density — the amount of energy per mass — becomes less relevant than volumetric density — the amount of energy per volume. This cubic meter of hydrogen carries only 40% of the energy that the same volume of LNG does. This means that to transport the same amount of energy on a ship, 2.5 times more trips are required given there are physical bottlenecks that do not allow for simply enlarging the vessels, such as artificial channels and natural straits. Additionally, hydrogen becomes liquid at -253°C (20 Kelvin[42]), compared to -161°C (111 Kelvin) for methane. The energy required to lower the temperature grows exponentially as we approach absolute zero, which translates into lower energy efficiency during the liquefaction process. 100 kWh of gaseous hydrogen becomes only 60-70 kWh of liquid hydrogen. The second law of thermodynamics prevails. Furthermore, maintaining such low temperatures during transport is far from trivial. The ingress of unwanted heat and the tiny radius of the hydrogen molecule[43] lead to high boil-off rates, causing hydrogen to escape into the atmosphere[44]. This hydrogen in turn acts as a greenhouse gas[45] with a global warming potential (GWP-100) 11 times worse than CO2.

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[38] Hydrogen companies like Ballard, Plug, and Fuel Cell reached a collective valuation of tens of billion dollars. Naturally, none of them could deliver on the expectations embedded in their valuations.

[39] The main method is steam methane (CH4) reforming. When methane is combined with water vapor (H2O) and heated, it transforms into one molecule of carbon monoxide (CO) and three molecules of hydrogen (H2). Subsequently, the carbon monoxide reacts with water, forming carbon dioxide and one more molecule of hydrogen.

[40] Through the famous Haber-Bosch process, hydrogen is combined with nitrogen from the environment to produce ammonia (NH3).

[41] An essential process in oil refining, used to remove sulfur compounds from fossil fuels, reducing the emission of pollutants such as sulfur dioxide (SO_2) and improving the quality of refined products.

[42] Using the Kelvin scale is essential as it accurately reflects absolute temperature differences.

[43] The radius of an H2 molecule is 3 times smaller than that of a CH4 molecule.

[44] As heat is transferred to liquid hydrogen, some of it turns into gas through vaporization. This gas must be released or recaptured to prevent an increase in pressure in the tank.

[45] Technically, the H2 molecule is not a greenhouse gas since its diatomic configuration (H-H) does not absorb infrared radiation. However, as these bonds break, H2 increases the warming potential of other molecules.

To avoid the inescapable difficulties of handling hydrogen in its liquid form, using ammonia as a carrier is an option. Still, the problem with this type of solution is once again the efficiency of the process from start to finish. The Haber-Bosch process[46] consumes between 7-10 GJ for each ton of ammonia due to the high pressures and temperatures required to combine hydrogen and nitrogen, not to mention the energy needed for nitrogen production that would add around 1 GJ to the equation. If your final product is ammonia itself, fine. But if your goal is to convert ammonia into hydrogen and then generate clean electricity, the industrial competitiveness in the destination country will be severely compromised. The remaining energy after generating renewable electricity, producing hydrogen, producing ammonia, transporting ammonia, separating the hydrogen, and burning it to generate electricity at the destination amounts to just under 20% of the original energy. This means that the destination country has an electricity cost at least 5 times higher than that of the producing country.

The only viable option left then is to consume green hydrogen where it is produced. The theoretical maximum efficiency of the electrolysis process consumes 40 kWh for each kg of hydrogen. With an efficiency of 73%[47] and purchasing electricity at R$220/MWh, the associated cost for each kg of hydrogen is $2.10 plus an additional $1.20 for transmission costs[48]. The H2 molecule thus has an operational cost of at least $3.30/kg, which translates to a natural gas cost of $29/MMBTU — a price level only seen briefly during the European panic following Russia's supply restrictions after the invasion of Ukraine. Natural gas at Henry Hub in Louisiana, USA, costs 10 times less. The implicit cost of avoided carbon — assuming zero emissions over the hydrogen's life cycle — is around $500 per ton. Such a price would render a barrel of oil four times more expensive. This exercise considers only the operational cost of the acquired electricity, ignoring the capex of the electrolyzer as well as the capital needed to install and operate it. It is hard to find any appetite for balancing this math.

Brazil, with its abundant natural resources, has not remained immune to the promises of hydrogen. Over $30 billion in announced projects are already in progress, leaving major players in the energy sector confident in asserting that "low-carbon H2 will be the main driver of electricity demand growth in Brazil." The political class is eager to do its part in this race, having designed incentive programs and subsidies to boost the industry fearing a loss of competitiveness compared to other potential producers. In the Low-Carbon Hydrogen Development Program (LCHDP), there are more than R$18 billion in tax credits to be granted between 2028 and 2032.

"THERE IS ONLY ONE BOSS. THE CUSTOMER. AND HE CAN FIRE EVERYBODY IN THE COMPANY FROM THE CHAIRMAN ON DOWN, SIMPLY BY SPENDING HIS MONEY SOMEWHERE ELSE"[49]

[46] Ammonia (NH_3) production from nitrogen and hydrogen ($N_2 + 3H_2 \rightarrow 2NH_3$).
[47] Average efficiency of electrolyzers in the market today.
[48] The cost of R$220/MWh used in this exercise refers to energy consumed on the grid. A project with non-intermittent renewable energy would not incur transmission costs but would need to add batteries or run idle.
[49] Sam Walton.

Ultimately, what will define whether Brazil can attract incremental energy demand, and therefore additional investments, is price competitiveness. More specifically, the relative price of Brazil compared to alternative energy solutions around the world. The most important question is how much does this abundant renewable energy cost in Brazil.

The cost of new renewable energy[50], whether solar or wind, is determined by four factors: capex, cost of capital, capacity factor, and subsidies/public incentives. Due to investment decisions in China, discussed in the previous section, capex has reached competitive levels[51]. But this does not set us apart from the rest of the world[52]. Brazil stands out in studies from renowned consulting firms for having an exceptional capacity factor. However, this factor alone doesn't translate to lower energy prices. The excess energy produced by our enviable capacity factor is insufficient to counterbalance the disproportionately high cost of capital in comparison to developed markets. The sum of these vectors does not reduce energy prices.

On the matter of subsidies and incentives, we cannot compete, as our electricity bill is already filled with add-ons and our federal budget is completely constrained. The situation the country faces is curious: the best subsidy the government could provide to encourage capital-intensive projects would not be through increased public spending, but rather through less spending. A credible trajectory of spending reduction that allows the country to reach a lower equilibrium interest rate[53]—a counter-cyclical fiscal contraction.

Many of the potential avenues in this energy transition journey depend on greater upfront investment that is compensated by a lower marginal operating cost. More capex with less opex. This is the case for renewable energy generation, for example. Other routes depend on cheap energy as an input for less efficient processes, such as electrolysis for hydrogen production. Bad news for the narrative of Brazil as a green power. A country with a high cost of capital believing that it will be saved by investments that depend on a low cost of capital to materialize.

"THE GREAT ENEMY OF THE TRUTH IS VERY OFTEN NOT THE LIE—DELIBERATE, CONTRIVED AND DISHONEST—BUT THE MYTH—PERSISTENT, PERSUASIVE AND UNREALISTIC"[54]

We examine two interconnected, yet distinct, aspects of the energy transition. It is crucial to recognize that the success of one aspect doesn't guarantee the success of the other. Hydrogen's physical reality is inescapable. Even if a significant gain in industrial productivity reduces the cost of manufacturing electrolyzers, the commercial viability of green hydrogen at the factory level will depend on a substantial

[50] Even existing energy should have its price converging to the marginal cost of expansion over long periods; that is why we focus the discussion around new energy.
[51] With the notable exception of offshore wind. Depending on the support technology, this source demands prices between 4 and 8 times higher than solar energy to be viable. A premium sufficient to warrant no more than a footnote in this letter.
[52] With the exception of the U.S., which imposes tariffs on products imported from China.
[53] It is important to highlight for those nostalgic of Alexandre Tombini's central bank mandate (if they exist) that the relevant interest rate is the long-term interest rate; voluntaristic rate cuts in the Selic serve no practical purpose and are counterproductive as they merely steepen the curve.
[54] John F. Kennedy.

reduction in the price of electricity[55], which in turn would transform electricity itself into a fierce competitor in the markets contested by hydrogen. The snake would bite its own tail. The plan to export the molecule for consumption in distant geographies without access to clean and cheap electricity runs into the "unsustainable lightness"[56] of the molecule. Transporting it around the world is physically possible but commercially unviable. Some kind of state policy with mandates and specific budgets might be sufficient to cover the cost difference to encourage this market, but it lacks economic sustainability over time. For example, what incentive does Germany have to buy a Brazilian green product priced higher than alternatives and without geopolitical concessions? How would such a decision improve the life of the average German or their energy-intensive industry? If this question cannot produce a direct and easily comprehended answer, can we be confident that this policy will survive future electoral cycles? Formulations on energy transition that neglect the connection between sustainability and sovereignty are at risk of becoming mere aspirations disguised as predictions.

These considerations should take priority in any planning agenda, focusing on our energy needs and the possible alternatives to address them. Observing the circumstances and nuances of a global system already organized under certain premises, instead of romantically throwing ourselves into fanciful utopias. Although oil and gas are momentary villains, our intrinsic dependence is clearer than the sun that fuels our photovoltaic panels. And on the horizon, we already see a Brazilian decline in oil production starting in 2030, with no equivalent decrease in energy demand. The status quo would therefore lead us to a dependence on imports to satisfy our consumption, affecting our current account balance and exposing us to supply risks in periods of global imbalance. Less energy, less sovereignty and less resilience. This discussion triggered debates around oil exploration on the Equatorial Margin, an exploratory bet that gained notoriety after significant discoveries in Guyana, and about unconventional exploration with hydraulic fracturing. Actors rightly concerned with the global need for decarbonization position themselves against the exploration of these resources. They envision supply restriction as the solution to the problem. However, on the other side of the equation, demand proves so resilient and inelastic that supply constraints only lead to significant price increases. Previously uncompetitive green alternatives begin to stand out as oil prices rise, making this pathway a possible route for emission reductions at least in theory. The analytical failure in this reasoning manifests itself through second-order effects arising from the negative consequences that higher prices produce in our social organization systems, as evidenced by the Yellow Vest movement in France or the American political reaction to the ESG movement.

The history of our civilization is inherently linked to the history of energy. Development comes to those who consume it, and power flows to those who produce it. Geopolitical architecture, as well as the distribution of global wealth, respects all these dimensions.

The last letter of this trilogy details how we translate this worldview into practical investment decisions.

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[55] It is important to remember that panels currently represent a small portion of the cost. Even if their prices fell by another 50% from the current value, total capex would only fall by about 10-15%.

[56] Reference to the article "The Unbearable Lightness of Hydrogen" by Michael Liebreich, founder of Bloomberg New Energy Finance.