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Managing Decarbonization, Economics and Innovation in the Energy Sector

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Abstract - **The world is currently experiencing the third energy revolution of traditional energy from fossil fuels to new energy sources. The energy revolution led to the industrial revolution and also promoted the development of social productivity and human civilization. However, the contradictions between economic growth, resource consumption and ecological balance pose new challenges to energy use. The construction of a global energy network and the rapid development of decarbonization technology are effective ways to solve the problem of irrational energy exploitation. Accurate matching and optimal allocation of resources in the new relationship between energy demand, supply and emissions are the necessary conditions to achieve a win-win situation for energy, the economy and the environment. There are various economic phenomena such as markets, prices, supply and demand in the process of energy development and use. In turn, economic markets are inextricably linked to energy markets in terms of policy making, development planning, commodity trading, economic activity and decarbonization.**

Keywords – **decarbonization, energy conservation, emission reduction, innovation, economics, energy sector**

I. INTRODUCTION

The world seems to be on the brink of a precipice, heading towards an unsustainable level of carbon emissions, which is accelerating the pace of climate change, a factor that threatens our economic prosperity and even our very existence. Despite the best intentions, the technologies, policies, and financial instruments of the twentieth century have failed to address the challenges, positioning climate change mitigation as a Faustian bargain between the economy and sustainability. While there is a broad scientific consensus on the serious impact that climate change will have globally, the motivation for meaningful and immediate action is limited. This is because there has so far been no direct short-term incentive for decision-makers to solve the problem, and because all future costs and impacts of taking no action today can be socialized and transferred to future generations (who are not here to fight for their rights).

As intelligent, educated, and rational beings, we understand the urgency of the situation and believe that we would do anything to solve the problem – except perhaps change our own behavior and jeopardize our personal financial future, especially when we personally have not caused the problem. Or perhaps we worry that the various groups with which we identify – our nations, professions, generations, etc. – have not caused the problem and we have the right to reach a level of prosperity enjoyed by others before we start correcting our paths. Or perhaps we are producers of fossil fuels and believe that the link between climate change and carbon is at best weak (after all, the world has gone through many cycles of climate change in the past, cycles that have not been associated with anthropogenic carbon emissions) and that it would be foolish to compromise our livelihood and economic growth in response to uncertain and unforeseeable scenarios. Or perhaps we have built global businesses that have brought prosperity to the world and believe that we should protect our investors, workers, and customers and that there is no way unproven new disruptive solutions can fulfill their promise in a timely manner without causing economic chaos.

And we would all be right – in our own way. After all, we have spent decades building our personal worldview and area of expertise, and we feel that we have an economically and morally defensible perspective. As a result, we believe that others might not be seeing the important elements in this picture. We believe strongly in our point of view and consider as fact only those points that support our opinions and which are then spread through the internet, social media and print media in waves that ignite passion at all levels. Maligning our partners on this sustainability journey is perhaps the worst way to align our goals and make progress. And yet, that's where we often find ourselves, in opposing camps: the haves versus the have-nots; developed versus emerging nations; advocates of carbon mitigation versus proponents of economic growth; academic idealists versus practical doers. In such a deeply divided world, how do we come to alignment, to rapprochement?[1]

Since 1992, when the IPCC report raised early questions about anthropogenic carbon emissions and their potential impact on humanity (the planet will do well, its people might not), we, as a society have struggled with how to respond. Each subsequent global summit (with the most recent being COP 27 in Cairo and COP 28 in Dubai) has attempted to bring all nations together – very challenging given the multitude of issues to be addressed and the extremely tumultuous political and policy process that it swings like a yo-yo depending on who is in power. Decarbonization targets are set each time, but with poor compliance mechanisms and no real accountability at the national level (in any case, changing political realities can completely change the short-term strategy, for example as we saw for the US during the transition from the Obama administration to the Trump and then the Biden administration).

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At a fundamental level, energy is at the heart of this challenge called 'decarbonisation' - directly accounting for up to 75% of all carbon emissions when electricity generation, heating and cooling, industry and transport are taken into account. We cannot reduce carbon emissions without solving the energy problem. But the world will not function without access to as much affordable, reliable and safe energy as it needs – that must be a priority. To get to zero carbon emissions, we must either stop emitting CO 2 (carbon dioxide) and other greenhouse gases (GHGs), or we must remove them from the atmosphere.[2]

On the other hand, the level of improvement in people's living standards that access to energy and technology has brought about over the past 100+ years is incredible and sets a gold standard that must be preserved. Despite all the advances, 700 million people still live off the grid and 3 billion live in energy poverty so extreme that it affects their ability to make a living. It is clear that the benefits of energy as it is available today are not equitably distributed, and we must ensure that any future we move towards resolves, not exacerbates, this inequality. We strongly believe that most people are not opposed to clean and sustainable energy. Their main concern is that they do not want to return to an era where energy costs are high and reliability is low, compromising the economic gains made over the last century.

This is the puzzle we have to unravel. Can the proverb "the wolf is full and the lamb is whole" be fulfilled? Can we sustain our economies and move towards global prosperity while meeting decarbonisation targets and better positioning ourselves to manage the impacts of climate change? Can this process be fair, bringing the economically disadvantaged on par with the rest of the world? Or are we doomed to repeat history – a battle between the haves and the have-nots, a story of dominance by a few with geopolitical or economic influence and growing inequality in a world with limited resources? Here are some proposals with promising results and a wide range of application in society, economy and management.[3]

II. EXPOSITION

A. *Photovoltaics*

The most disruptive breakthrough occurs around photovoltaic solar energy (wind may reach limits on how long it can continue along the steep learning curve, although it should be noted that it is already significantly below the cost of traditional fossil fuel-based production and may continue to gain market share). There are many new technologies being developed for the next generation of solar cells, including cells based on perovskites (calcium titanium oxide), as well as organic solar cells. Perovskites are thin-layer devices built with layers of materials that can be deposited on cheap substrates using printing, coating, or vacuum deposition techniques. By converting more of the incoming solar energy, they can also achieve higher efficiencies than silicon, with reported efficiencies of ~25%. Tandem cells with perovskite on silicon have also been built with efficiencies >33%, with even higher levels possible. Even lower costs can be achieved with organic solar cells, where a wide range of non-toxic organic materials can be sprayed onto a substrate such as paper or glass to achieve ultra-low cost.

Over the past ten years, the efficiency of organic cells has increased from ~3% to over 17%, with continued increases expected. Additional developments, such as building-integrated photovoltaics and "solar paint," point to ongoing efforts to further reduce the cost of available solar power. Over the next 20 years and more, it seems very likely that photovoltaics will continue to progress along a steep learning curve, potentially driving down costs to a point where solar energy becomes abundant and cheap. An ambitious levelized cost of energy (LCOE) target of <$10/MWh for utility-scale installations and a vision of solar as abundant and ubiquitous certainly seem achievable in the next 20, maybe even 10 years.

While the potential of abundant, almost free, solar energy dazzles our imaginations, we also need to understand the challenges ahead. Being able to produce high-efficiency, large-area thin-film cells and ensuring that they can last a target lifetime of 20+ years presents major challenges (whether they should last 20 years with steep learning curves is a whole different discussion). With the exploding market comes the question of the circular economy, something that can only come from politics and mandates. The research community, systematically supported by grants and other institutions in Europe, the US, China and other nations, is constantly moving the ball forward on all these issues. As the PV disruption driven by rapidly developing technologies is already underway, there is less resistance from manufacturers who are now actively seeking new technologies to ensure they can maintain or take the lead in proven and fast growing market. [4]

Much of the production of solar cells and panels has moved to China, with few European manufacturers remaining. This leads to geopolitical vulnerabilities of a different kind than oil and gas, but also creates situations that need to be addressed. On the other hand, as the price of photovoltaic cells continues to decrease, the costs of transporting the panels and assembling them on site will become a larger part of the total cost and make local production more favorable. Also, since this technology is developing rapidly, one can always build PV panels using different or slightly older technologies (with roughly a 1% efficiency fee) and still make a profit because PV panels are much more cheaper than other alternatives. This dramatically reduces geopolitical vulnerability because, unlike oil, we always have other viable options - which should encourage offshore solutions to remain competitive and reduce geopolitical vulnerability.

B. *Energy storage*

Existing lithium-ion chemistries include NMC (lithium-nickel, manganese, and cobalt oxide cathode) and LFP (lithium-iron phosphate cathode) with graphite anodes, which have an energy density of around 250 Wh/kg and a lifespan of 1500-3000 charge/discharge cycles. Using silicon anodes can increase storage capacity by 20-40%, while the advent of solid-state batteries may allow for faster charging/discharging and reduce the risk of fire by enabling batteries to operate at higher temperatures. New battery chemistries like lithium-sulfur (Li-S) and lithium-air offer even higher energy densities, with a theoretical density for lithium-air of 13,000 Wh/kg, 50 times more than what we can achieve today with lithium-ion. And finally, various batteries such as sodium-ion batteries operate with abundant materials and are now commercially available, while gold nanowire batteries promise over 200,000 charge/discharge cycles — virtually endless life! Again, as with photovoltaic solar cells, there are significant markets with strong growth serviced by batteries at prices and performance points that are already competitive in many large-scale use cases, with further market expansion as prices continue to decrease. This demand fuels further research to overcome key performance, cost, and safety gaps, with systematic development and sustainable steep learning curves ensuring that advanced batteries can meet the needs of the electric vehicle industry for decades to come. Electric vehicle battery demand alone is expected to rise to 1200 GWh by 2040 with battery prices at $76/kWh and lower.

Grid-scale storage for 2–8 hour durations appears to be a much smaller market than electric vehicles at the moment. Automotive batteries are offered at low prices and used for grid storage, with good returns in some cases. 125 million electric vehicles in Europe by 2035 will represent 9,000 GWh of energy storage (compared to 600 GWh forecasted globally as grid storage demand) and 25,000 GW inverter capacity (compared to 1000 GW energy generation capacity in Europe today), often grid connected. The ability to realize value from electric vehicles using vehicle-to-grid (V2G), vehicle-to-home (V2H), and other applications can provide significant value in terms of grid support, emergency backup power, and community resilience. The need for high levels of energy storage drives further innovations, including companies like Form Energy with iron-air batteries promising long-duration energy storage at ~$20/kWh, as well as gravitational batteries that move vast amounts of material to convert potential energy into electricity. [5]

C. Generation with dispatchable zero emissions

While we look beyond short-term storage, there is also a need for medium-term (1 day to 1 month) and long-term (many months) storage. They are critical to grid operation and may also be important for high-energy applications such as heavy trucks, ships, locomotives, and aircraft. For the grid, the need for long-term dispatchable generation with zero greenhouse gas (GHG) emissions can be met in many ways, including hydropower, geothermal power, nuclear power through the deployment of small modular reactors and microreactors, and the use of green hydrogen or blue hydrogen from natural gas, but with permanent carbon capture, all of which were discussed in a previous chapter. Geothermal energy is limited by location, but can be an attractive option when available. For fission-based nuclear power, spent fuel management, proliferation risk, accident hazard, and community pushback continue to hold back widespread deployment. Nuclear fusion, on the other hand, looks attractive (especially with the recent announcement of the first break-even energy reaction), but remains a longer-term goal. Although much progress has been made, the first viable commercial-scale fusion plant is not feasible before 2040.

We have already seen that hydropower provides a very good balancing resource to offset the variability of PEP (Distributed Energy Resources), including the ability to run continuously for weeks and months when needed. Converting existing hydro plants to pumped hydro plants offers another opportunity to provide the flexibility grid operators need to balance the system. Where possible, existing hydro plants can be converted into hybrid plants, where they are also combined with deployed solar or wind photovoltaics. Such plants can provide the required energy >90% of the time from PEP, using hydroelectric power primarily as a dynamic balancing resource, conserving water for human consumption and environmental purposes, while retaining the ability to use it for continuous emergency power generation. Grid integration costs are also low because the substations and transmission needed to connect PV/wind to the grid already exist. Similarly, co-locating PV with an existing depreciated gas generation plant can eliminate the need for new transmission, reduce emissions by 90% and still deliver the reliability and long-term backup that the grid needs. Such a hybrid approach can provide a good transition strategy. [6]

Of all these solutions, perhaps the one that has the potential for steep learning rates and is extremely promising is green hydrogen. Ongoing major projects to couple photovoltaic solar generation with hydrogen electrolysis point the way to a price of less than $1/kg for green hydrogen, enough to unlock a $100 billion/year market by 2030. Key Innovations to reduce the capital cost of the electrolyzer from $700/kW today to below $200/kW in a few years includes replacing precious metal catalysts with cheaper, more readily available minerals, photoelectrolysis of water, generating hydrogen directly from seawater, solid oxide electrolysis cells (SOEC) and reversible fuel cells that can convert electricity to hydrogen and back again in the same device, thus greatly simplifying the overall system. Taken in conjunction with declining PV solar prices, the path to $1/kg green hydrogen appears clear, as evidenced by the more than 250 GW global green hydrogen projects already in the pipeline. Green hydrogen can not only serve as a generating resource for electrical energy, but can also replace fossil fuel-based heating for industrial processes, commercial buildings and heavy transportation.

The other approach using blue hydrogen with permanent carbon capture is to take natural gas (which is abundant) and use microwave plasma pyrolysis or another similar technique to generate hydrogen and solid carbon in the form of graphene or other organic feedstock. Carbon chain products permanently sequester carbon and allow hydrogen to be used as a carbon-free fuel (fuels produced with this technique still result in carbon emissions). Since energy is required to release the hydrogen atoms, the net energy realized by this multistep process is not so favorable. However, the value of carbon products such as graphene may allow for a much lower price for carbon-free hydrogen. It should also be noted that each ton of hydrogen generates 17 – 20 tons of carbon-based products, which may provide high economic value initially, but may become a challenge once the market for graphene or carbon products becomes saturated. On the other hand, using the carbon in the carbon capture and utilization (CCU) process to generate much-needed chemicals and raw materials can provide longer-term sustainability.

D. Commercial and residential applications

Finally, we should not overlook the need for new solutions in commercial and residential spaces—especially solutions that mitigate or adapt to climate change and global warming. The solutions needed include personal transportation (including personal mobility and mass transit), cooking, water, cooling/heating buildings, and resilience that allows us to continue living our lives in the face of HILF (High Impact Low Frequency Events) events. This is also a big challenge, as the life of buildings is usually 30 – 60 years, which makes it a challenge to renew the infrastructure. There is a wide range of new technologies targeting buildings, including building-integrated photovoltaics, thermal energy storage using structural elements and occupancy-based lighting and cooling, and 3D printing methods to reduce construction costs and the time for new buildings. Cooking lends itself to electrification and can be addressed by the availability of cheap electricity as well as by city regulations that increasingly ban gas cooking for new homes.

The biggest challenge is probably the air conditioning and cooling of the premises. Along with cheap energy, this also requires refrigerants with low ozone-depleting potential (ODP). New technologies such as metal organic framework (MOF) use interstitial spaces to manage humidity, reducing the energy requirement for a given level of cooling by 75%. Likewise, another new approach, also using new materials, applies hydrophobic (water-repellent) ceramics to highly water-absorbing ceramics to create a highly efficient heat exchanger. Even more exotic cooling systems are available that work on thermoacoustic and thermoelectric principles, now appearing in the form of cheap beer coolers! Although these technologies are slightly less efficient than conventional air conditioners and coolers, they do not use refrigerants and may have a very attractive future in a world where solar PV can be almost free when abundant. With heating, ventilation and cooling (HVAC) units set to increase from 1.6 billion today to over 5 billion by 2030, this is a very serious problem that needs “out of the box” solutions.

As these new solutions based on low-cost solar PV become available, developing markets will gain the most, as lower energy costs and new "smart" functionality will allow them to leapfrog developed nations and achieve high standard of living without the high level of energy consumption required today to maintain it. [7]

CONCLUSION

As we have seen, this is a complex question. We can all agree that change is coming at us like a freight train driven by rapidly developing technologies with exponential growth and falling prices. As these technologies connect to the grid, we must also agree that something needs to be done at the grid level if potential chaos is to be avoided. But because there are so many groups that would like to maintain the status quo, and because they stand to lose billions of dollars in the process, the transition will be challenging.

The rapid pace of change is difficult to keep up with, given the limited scope and range of state regulations, widely varying regional regulations, and the challenge, both in terms of policy and timing, of implementing all the necessary changes. On top of this are issues of global politics, the geopolitics of raw materials and supply chains, equity, consumer preferences, regional economic and workforce development and, of course, climate change and decarbonization. All these forces simultaneously vying for resources and acceptance create a high level of uncertainty about how the system will evolve, for how long, and what new solutions will be needed. How do we navigate this complex maze?

I consider the best way to cut through the mess is to elevate the discussion to a point where we can all agree on an aspirational vision of what an ideal future energy system should look like for us and our children. In short: we want an energy ecosystem that is fueled by clean, abundant, emission-free energy that is also sustainable, economical, flexible, reliable, durable, and equitable, that meets the needs of the rapidly evolving sources and loads it serves, and that does not trample on the rights of future generations. [8]

> *"We want an energy ecosystem that is fueled by clean, abundant, emission-free energy that is also sustainable, economical, flexible, reliable, durable and equitable, that meets the needs of the fast-growing sources and loads it serves, and that does not trample the rights of future generations."*

Such a vision can serve as our North Star, a guide to shape our decisions and actions and help clear up confusion and ambiguities. Armed with this guidance, we can derive what solutions need to be developed, solutions that are green and flexible and can be used in multiple potential pathways, including any regional differences that may exist. We will look at the various players in the power sector to see what, if anything, can be done to achieve the desired alignment.

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