On the emergence of the energy transition

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The Energy Transition: A reliance on technology alone ultimately leads to a bet on Solar Fuels

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"The Energy Transition: A reliance on technology alone ultimately leads to a bet on Solar Fuels", under review at *Joule*.

Abstract

Today the energy transition progresses with the build-out of electric renewables and increased electrification of end-use. However, significant demand for hydrocarbon fuels will persist. That demand could be met by capturing and storing fossil fuel emissions and balancing remaining emissions with negative emissions by deploying existing technologies. This requires active government involvement to orchestrate and support the transition. A radical alternative exists in the form of Solar Fuels, carbon-neutral fuels produced from renewable electricity, water and the circular use of CO2. If and when Solar Fuels could be produced at affordable cost and scaled, their market introduction could be market-led needing no more than price-protection in the form of a carbon price. We give a specific target for the future viability of solar hydrocarbon fuels of 200 US$ per barrel. While this is potentially achievable in the long run, policy reliance on it is a significant bet.

Keywords

Energy transition, Energy scenario, Solar fuels, Collective action.

3.1 The choice at the heart of the energy transition

The task to build-out and reshape the world's energy system is central to two of the greatest challenges for the 21st century: fulfilling the economic aspirations of a growing world population while drastically reducing CO_2 emissions to limit global warming. Since 2000, the world has tried to make progress on these challenges by the rapid deployment of "new renewables", notably solar PV and wind [175]. This expansion appears likely to continue apace as costs continue to fall and decarbonisation efforts increase under the pressure of "Paris" [5]. Any future scenario therefore includes large-scale electrification with significant contributions of solar PV and wind electricity, which will continue to be the workhorses of energy-sector CO_2 mitigation in the decades ahead. There is no alternative. Even when electrification is pushed to its limits, however, demand for fuels will persist – often in the form of hydrocarbons. How these fuels will be supplied while committing to climate targets is a societal choice for which the world has yet to make up its mind.

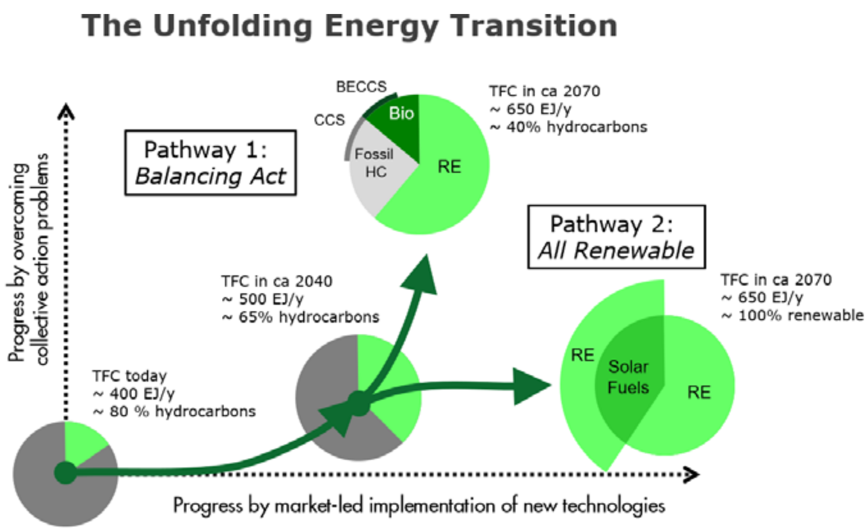

Figure 3.1 – A paradigm for the two dimensions of progress in the energy transition. Second circle in Pathway 2 shows energy going into solar fuel production process (580 EJ/y). The 2070 date given is consistent with the Paris Agreement. Total Final consumption (TFC), Fossil hydrocarbons (Fossil HC), Renewable, non-hydrocarbon-based electricity (RE), Bio-Energy with CCS (BECCS).

In our view, two fundamental directions in the pursuit of 'progress' are possible, see Figure 3.1. One is progress that requires overcoming co-ordination and planning hurdles, such as through active government involvement This pathway, *Balancing Act*, has several aspects. It requires orchestrating the roll-out of new infrastructure: long-distance electricity transmission, hydrogen distribution networks and the deployment of carbon capture and storage (CCS). It also requires coherent policy actions across countries, for bio-energy to grow to its full potential in an environmentally responsible manner.

Many commentators are sceptical that we can overcome these collective action problems. Instead, they put their faith in the possibility of developing new technology [176] with just a limited government role just to get the ball rolling. This leads us to Pathway 2, *All Renewable*, that relies on unpredictable technical progress. Most of the progress we see today is of this type: renewable technologies (wind, solar), vehicle electrification and efficiency measures, helped initially and when needed by substantial subsidies or mandates, but eventually becoming completely market-led once their costs are competitive. Taken to its logical conclusion, this ultimately will become a bet on solar fuels: the making of everyday hydrocarbon fuels like methane, gasoline and jet fuel from solar and wind energy, water, and the circular use of CO_2.

Balancing Act and *All Renewable* differ in one other crucial manner. *Balancing Act*'s reliance on biomass and carbon storage will eventually constrain the world's total fuel supply, which may eventually raise difficult questions around lifestyle-change and limits to growth [20]. *All Renewable* with its reliance on solar and wind, at least in theory, offers scope for an unlimited supply of renewable fuels. As history time and again shows, this is an enduring aspiration, see box [177].

> ***"[I]t would be highly desirable to have an efficient and economical way of directly converting and storing solar energy as a chemical fuel".***
>
> **J. Bolton - Science (1978)**

3.2 Current and future energy demand

Our current energy system, responsible for 70% of all greenhouse gas (GHG) emissions, has an annual take-in of 590 EJ primary energy. 80% is of fossil origin, a percentage that has hardly changed since the 1960s. Another 10% is biomass (most of it traditional), hence a full 90% of the world's energy supply is hydrocarbon-based. After conversion losses two-thirds of this primary energy reaches the end-user, with some 20% in the form of electricity. Fuels and chemicals feedstock account for 70%, while biomass and heat make up the remaining 10% of consumption by end-users [31].

A recent Shell scenario, Sky [7], depicts a transition pathway that is consistent with the Paris agreement but at the same time acknowledges that energy demand will grow as the non-OECD develops and billions more enter the global middle class. In this world the demand for energy services (lighting, heating, transport kilometres, tonnes of steel produced, etc) will grow substantially. Even under optimistic assumptions that energy efficiency will improve (by a factor of between two and six in the Sky scenario, across different sectors), total final energy will increase by 60% to 2100. This would equate to around 650 EJ / year, or 65 GJ / person / year, half the level of demand per person in the OECD today.

How can the broad range of energy services be met with net-zero CO_2 emissions? What are our options to meet Paris? In what follows we will follow the logic of Figure 3.1; electrification pushed to its inevitable limits leading to a branching point of how to deal with the remaining fuel demand.

3.3 Renewable electricity and electrification: immediate push to inevitable limits

Since the beginning of the century, we have seen that solar PV and wind industries have grown from insignificance to US$ 300 billion per year, adding 150 GW every year [178, 179]. Yet such is the scale of the world's energy system, that between them they still comprise less than 1% of the global energy supply today and so further very substantial growth will be needed. In the coming decades these technologies will increasingly have to be paired with storage and ongoing electrification of sectors which traditionally relied on fuels, specifically transport (by introducing electric vehicles) and heating of the built environment (by applying heat pumps). In short, the transition is gathering pace and the list of near-term options for change is impressive. But at the same time, it is one-sided, heavily leaning on electric renewables, electrification of demand and strong efficiency improvement. It leaves the fuels half of the energy transition still to be done.

This includes industrial sectors where GHG emissions are inherently difficult to strip from the production process such as in steel and cement making. Also, while recognising the electrification potential of passenger road transport, the decarbonisation of the heavy-duty transport (ships, aeroplanes, lorries) will be limited. These sectors must be expected to remain significant reliant on energy-dense, portable fuels for a long time. Another critical aspect is that at least 15% of the total energy demand, 100 EJ / year, will need to meet feedstock needs for the chemical and materials industry. This "non-energy use" is dominated by oil and natural gas today, and may have increasing shares of coal or biomass, but it fundamentally relies on carbon.

Hydrogen is the natural – one might say preferred – fuel in a decarbonised world, for it contains no carbon. But the slow progress over the last decades makes clear how great the infrastructural challenges are. There can be no doubt that hydrogen will play a role, but only in regions and sectors where the infrastructure challenge can be overcome. This is specifically the case in large industrial clusters. Transport and the built environment are sectors where the hurdle for introduction is much greater, and hydrogen's future in those sectors is both uncertain and globally limited. This leads us to the view that also in a net-zero emissions-world, hydrocarbons are likely to continue to be the mainstay of fuel provision.

Our best estimate, in line with Sky, is that at least a third of the energy supply will require some sort of carbon-based 'fuel', or some 225 EJ per year.[1] This will lead societies to a choice as to how to proceed to make these fuels carbon-neutral: to face up to the difficult organisational challenges (as in *Balancing Act*) or to bet on uncertain technological advances (as in *All Renewable*).

3.4 The orthodox energy transition for fuels: efficiency, bio-energy and offsets

Pathway 1, *Balancing Act*, would seek to deliver the 225 EJ of fuel through a combination of bio-energy and fossil fuels, and is similar to Sky Scenario assumptions. Following the current views on the sustainable resource base for biomass, between 100 and 200 EJ primary energy could be supplied by biomass as feedstock for biofuels and bioplastics [181]. After converting the woody biomass, we could expect biofuels to deliver up to 80 EJ / y of final energy. This would leave 145 EJ, or 25% of the system, relying on fossil resources.

The use of fossil fuels however entails emissions. To get to a balance of "sources and removals by sinks" [5], the ubiquitous use of CCS will be essential, but those emissions that cannot be captured and sequestrated centrally (such as from the transport sector) will need to be offset by negative emissions. To attain these negative emissions, most major long-term outlooks [182] including Sky rely on the capturing and sequestration of point sources bio-energy emissions currently seen as the most promising option to deliver negative emissions at the required scale.[2]

None of this requires transformational technological breakthroughs. The

[1] This is in line with experts that showed that a mid-century, low-cost 100% decarbonisation scenario for the energy system using only electric renewables is in-feasible. [180]

[2] Importantly, this calculation relies on the hydrocarbons (fossil and biomass) that are used to make materials being properly disposed of after use. If waste plastics, for example, cannot be recycled, and if they are burnt to provide electricity and heat, then those emissions in turn will need to be captured with CCS.

technologies exist today and large-scale CCS projects have already stored more than 200 million tonnes of CO_2 [183]. At a long-term cost of 50 US$/t$CO_2$ [183], CCS would add about 3 US$ / GJ to the average energy costs of a mix of coal, gas, oil, and biomass combined, giving a total of 15 US$ / GJ (of which CCS is 20%). Further deployment will bring CCS cost down, but further deployment will need better alignment of incentives. Societal support for strong policy signals will be required to trigger the appropriate investments, alongside a clear legislative framework and a planning of co_2 infrastructure. Only by overcoming these coordination hurdles will large scale deployment of CCS arise.

3.5 The technology leap: what one needs to believe for solar fuels

Pathway 2, *All Renewable*, by contrast, supplies the demand for hydrocarbon fuels with a new, carbon neutral fuel, a Solar Fuel, produced by capturing co_2 directly from air. Such fuels have recently gained much attention under the headings of Power-to-X (X being gas, liquid or product) and electricity-based fuels [184, 185, 186, 187, 188, 189].

Production of these solar fuels banks on the integration of a suite of technologies, that individually need both greatly improved performance and cost reductions to make it into an economic and scalable option. But when hydrocarbon fuels can be synthesised at an affordable cost from renewables and co_2 in circular use from the atmosphere, the prospect offers a practically unlimited supply of carbon-neutral (high energy density) fuels.

Although in both pathways the energy industry would be completely transformed, what sets *All Renewable* apart from *Balancing Act* is that, though the technology challenges are harder, the public policy challenge may be a great deal easier. Consumers can continue using energy exactly as they do today, but without affecting the climate as any consumption would simply be returning co_2 to the atmosphere that had been drawn from it to make the fuels. Starting with R&D incentives, the transition would proceed by entrepreneurs and large companies making use of market mechanisms, since they do not need to rely on any new infrastructure. In addition, the resource base for all practical needs is unconstrained and most countries could choose to produce solar fuels locally if they wished. Therefore, *All Renewable* depends on the ability to develop and deploy key technologies well beyond their current pilot stage but thereafter only on its affordability.

We suggest a reasonable target to be 200 US$ / barrel (bbl). The cost of crude oil has typically ranged between 50 and 100 US$ / bbl in recent years, but solar fuels are in the form of useable fuels, for which retail prices can be much higher. For example, gasoline in Germany typically sells for the equivalent of 250 US$ / bbl today. As such, this does suppose societies are willing to pay a premium for one or all of the attractions above. Yet it would still be affordable, particularly in time and as economies grow. In our outline assessment here, we find that when assumptions from technology experts in different fields are combined, and optimistic yet plausible values are used, an overall cost of around 200 US$ / bbl comes into sight. Although some elements are only at pilot stage today, a first order indication is that the cost today could be around 850 US$ / bbl. With regards to the energetic and economic costs, what do we need to believe in order for solar fuel to become reality?

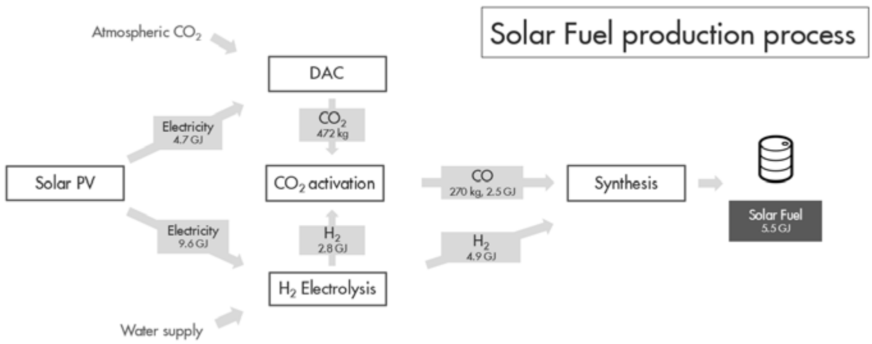

Figure 3.2 – The five principal elements of solar fuels production: Solar Photovoltaics (Solar PV), Direct Air Capture of CO_2 (DAC), Hydrogen (H2), Activation of CO_2 to CO, and Synthesis (e.g. via Fischer-Tropsch) of the fuels.

Using an engineering process that we can conceive today, there are five principal elements to manufacturing solar fuels, see Figure 3.2. A barrel of fuel products, like gasoline or diesel, contains 5.5 GJ of energy, with a little over 100 kg of embedded carbon. As such, the production process of a barrel of solar fuel would need to draw about 0.5 tonne of CO_2 from the atmosphere.[3] Around 5 GJ would be needed to run this Direct Air Capture (DAC)process [191] and an additional 9.6 GJ would be required to produce hydrogen and upgrade the captured CO_2 to CO [192]. Together with the produced hydrogen, this CO can be synthesised to a fuel. As such, the energy efficiency could be close to 40%, requiring 14.3 GJ of electricity to produce 5.5 GJ of solar fuel. Based on current projections [193, 194], it is reasonable to expect that in favourable locations, the cost of solar PV (or other renewable) electricity can fall from typical values of

[3]Some scientists have put forward work on artificial photosynthesis as an alternative, but the theory as well as the technology is at an earlier and more speculative stage [190].

around 50 US$ / MWh today [195] to 15 US$ / MWh. This would equate to 60 US$ / bbl for the electricity costs. Recently, engineers have put forward a pathway for developing DAC at a cost of 100 US$ / t CO_2 [196, 197, 198]. As a result, this contributes nearly 50 US$ for the cost of our barrel. Previously, the comprehensive analysis by the American Physical Society in 2011 [199] estimated a cost of 600 US$ / t CO_2. This is the greatest contribution to the change in the economics of solar fuels from today.

Electrolysis of water to produce hydrogen is established but limited in scale. IEA estimate [200] the current cost of electrolysers at around 1200 US$ / kW (input electricity). There are substantial efforts to reduce the cost from today, targeting 300 US$ / kW [201]. At that level, the equipment would add around 50US$ to the tally.

Finally, the Fischer-Tropsch process for synthesis is used in full-scale industrial production today for converting natural gas or coal to liquid fuels. Here it would take the activated CO_2 as carbon feedstock. The costs of this activation - for which several alternative technologies exist[4] [203] - are still speculative but let us assume it could be done for 10 US$ / bbl. With further development and economies of scale of these processes, the final Fischer - Tropsch synthesis would cost around 20 US$ per barrel [204].

There would inevitably be other costs for processes such as the water handling and gas transport, and for other equipment such as the hydrogen storage tanks. If the combined cost of these could be no more than 5% of the total costs, then alongside the other progress, the 200 US$ target could be realised (see Figure 3.3 for summary of the calculation).

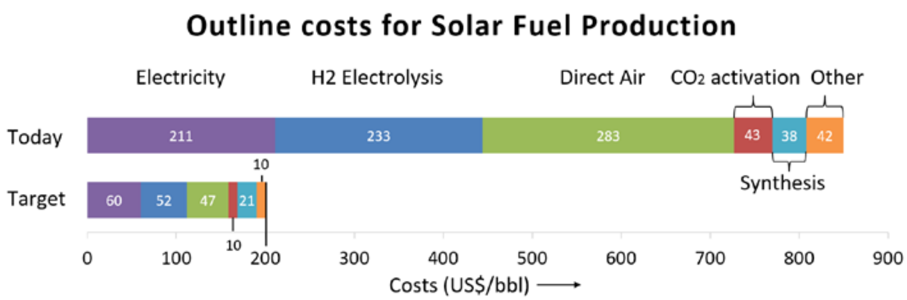

Figure 3.3 – Outline costs for solar fuels production

[4]The leading options for converting CO_2 to CO are the reverse water-gas shift reaction [202] or electrolysis of CO_2 [203]

3.6 Conclusion

A fifty percent increase in energy consumption in about 50 years, combined with increasing environmental stresses will bring the world to uncharted territory. Even if wind and solar PV succeed in replacing half of the existing energy system, as well as meeting the significant demand growth in the decades ahead, they will run into the systems limits of electrification. Close to a half of the energy system will need a fuel from one source or another. That is where the path forks.

The world can either choose to rely on the policy and infrastructure coordination, necessary to bring CCS, bioenergy and BECCS to the required scale. This is the path of *Balancing Act*, a development trajectory for which the technologies are ready to be scaled. However, for decades now, nations have hesitated to make a start, as with CCS, or have struggled with the governance and co-ordination, as with biofuels. Nevertheless, the Paris Agreement may offer a resilient global architecture and it remains a plausible approach.

However, the scepticism over the world's ability to overcome these collective action problems and the reluctance to embrace technologies such as CCS and BECCS [205, 191], has created space for an alternative narrative. In turn, that relies on technologies that are at a lower level of readiness, but that offer the promise of less hindrance from the problems that have held back the deployment of CCS and biofuels. This narrative, *All Renewable*, explores the rapid technological progress to make solar fuels affordable and scalable over an unprecedentedly short time period [123]. It presents a daunting technical challenge. While affordable, *All Renewable* is still a significantly more expensive route than *Balancing Act*. Furthermore, *Balancing Act* is more resilient: *All Renewable* will only work if all its five components make great technological advances. Yet if solving the co-ordination problems of *Balancing Act* proves insurmountable, the world may be forced to commit to *All Renewable* to address climate change, whether it wants to or not.

In order to avoid postponing action and hence making a late, risky bet on *All Renewable* by default, we recommend that it would be prudent policy to stimulate developments along both pathways simultaneously. And if only some of the elements of *All Renewable* prove successful, then they are likely to benefit *Balancing Act* anyway.

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