Green Chemistry

Cutting-edge research for a greener sustainable future

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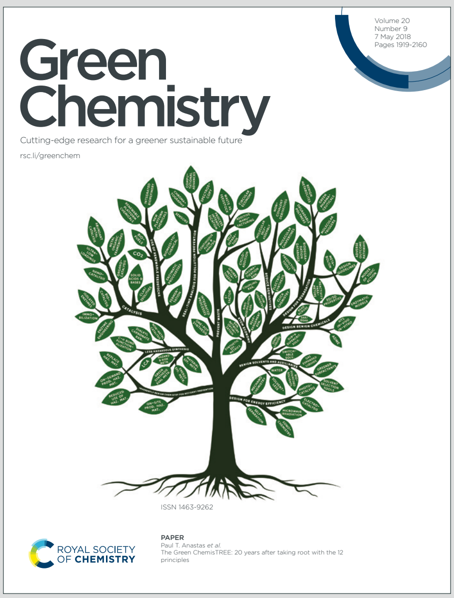

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1. What advances in green chemistry have been discussed?

The paper provides a systemic perspective on the carbon transition, i.e. the defossilisation of fuels and chemcials. It does it by critically discussing feedstock, technology, deployment hurdles and enablers, addressing technological as well as societal aspects of the transition.

2. What makes the area of study of significant wider interest?

The switch from fossil to renewable feedstock is essential to alleviate the broad climate impact of fuels and chemicals. It is also an excellent opportunity to address other environmental challenges such as transitioning to non-persitent chemicals. It addresses the technological as well as societal dimensions of the defossilisation transition.

3. What will the future of this field hold, and how will the insight in your review help shape green chemistry science?

The defossilisation of fuels and chemicals is inevitable. The broad and systemic discussion presented here should help practisioners of green chemistry to understnad the bigger picture and, thereby, focus their research such that it also addresses the deployment hurdles.

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Defossilising fuels and chemicals - a systemic analysis from feedstock and technology, to hurdles and enablers.

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Abstract

Climate change will force society to abandon the fossil feedstocks, which were so far invaluable for energy, fuels and chemicals, and will force it to switch to renewable feedstocks. Much of the defossilisation will be achieved by switching to renewable electricity. But heavy duty fuels and chemicals will resist electrification. They will largely switch to renewable carbon instead. This paper presents a systemic perspective on the carbon transition. It will review the applications that will still rely on renewable carbon, estimate the size of the carbon demand by 2100 and discuss the renewable carbon sources in terms of availability, acceptability and affordability. The paper will then discuss the technologies that are available for valorising these resources. Systemic hurdles to deployments will then be considered, e.g. politic/public resistance, costs, pain of technology maturation and infrastructure lock-in. Finally, the paper will discuss a few systemic enablers, e.g. the value of local resources and existing infrastructure, the adjustment of product portfolio to the new feedstocks, approaches to gain public acceptance and the need to revisit our economic model.

1 Introduction

The exploitation of fossil resources has provided unprecedented wealth in most part of the world by powering machines that replace human and animal work with much higher power and lower costs. However, this progress also destabilized the fragile planet's equilibrium in various ways, most critically by influencing the global climate through the release of CO_2. From the Club of Rome (1968) to Kyoto protocol (1997), six reports from the International Panel for Climate Change (IPPC), the Paris (2015) and Dubai (2023) agreements, and the advisory opinion of the International Court of Justice (2025), virtually all states are working at limiting the global warming by defossilising their energy system and offsetting the remaining use of fossil resources by capturing and sequestering CO_2. Much of this defossilisation can be achieved by transitioning to renewable electricity. But some applications will resist electrification and will have to transition to renewable carbon, namely to CO_2, biomass and waste. Several authoritative papers discuss various facets of this carbon transition.[1-3] . But none seem to address its full systemic breath.

This paper presents a systemic perspective of this carbon transition, addressing not only the energy sector but also the chemical and material sectors, which spun off the fossil industry. The perspective starts by sketching the present state of the fossil industry, then reviews the potential sources of renewable carbons with their global availability, environmental acceptability and affordability. The

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paper then discusses the various technologies available to convert these resources, covering waste valorisation (e.g. plastic recycling), biorefining and CO_2 utilization technologies. The paper then analyses several systemic hurdles, namely political and public resistances, costs and pain of technology maturation. It finally considers systemic enablers such as local resources, existing industrial infrastructure, broadening of product portfolio, building public support and reimagining our economic model.

This perspective will show that we have the feedstock and technologies to make the carbon transition. It will also make technical recommendations for various choices to be made, e.g. on feedstock, technology, products and favourable combinations of all three. It will also argue that the carbon transition is now limited by societal developments. The carbon transition needs now profound systemic changes. Such systemic changes are so complex that one may not see the forest for the trees. The perspective will try to mitigate that by audaciously simplifying the discussion down to the few major factors that impact the technical and societal aspects of the transition, leaving the many important nuances to more specialised literature. Accordingly, the discussion will use approximative numbers and simplified calcula By prioritising transparency over completeness, the perspective will limit the literature references to about 80 illustrative ones, trusting these will help and encourage readers to look for more in the abundant and very broad literature.

Interested readers may also appreciate to know that a multi-author book is being prepared and will be published by the RSC, to cover the scope if this perspective in much more depth, throughout 30 chapters written by specialists, and hopefully to fill a number of gaps left open by this perspective.

2 Demand for renewable carbon

Society is presently consuming about 10 Gt of fossil carbon per annum, mainly as energy source for industry, transport and building, and to a smaller extend, as feedstock for chemicals and materials (Figure 1, top [4]). Many energy applications can be defossilised by switching to renewable electricity. This particularly applies to light-duty applications such as light machinery, personal transportation and lightening / heating of buildings. Heavy-duty applications are much more difficult to electrify, however. The heavy industry needs very large amounts of energy - up to 1 GW or the output of a world-scale power plant - to power a single manufacturing site and use much of it to deliver high temperatures (>600 ºC) that are challenging to reach at scale with electrical heating.[2] Similarly, the heavy-duty transport such as aviation, marine, long-haul trucks and off-road machines need to carry large amount of energy in a very compact manner. Batteries fall short by a factor of ~50, compared to hydrocarbon fuels.[5] Consequently, many high-duty applications will likely keep using fuels, preferably fuels based on carbon that don’t suffer from the low energy-density and/or the high hazard of H_2 and NH_3 fuels. Finally the chemical and material sectors will indisputably keep needing carbon as versatile basis for their products.

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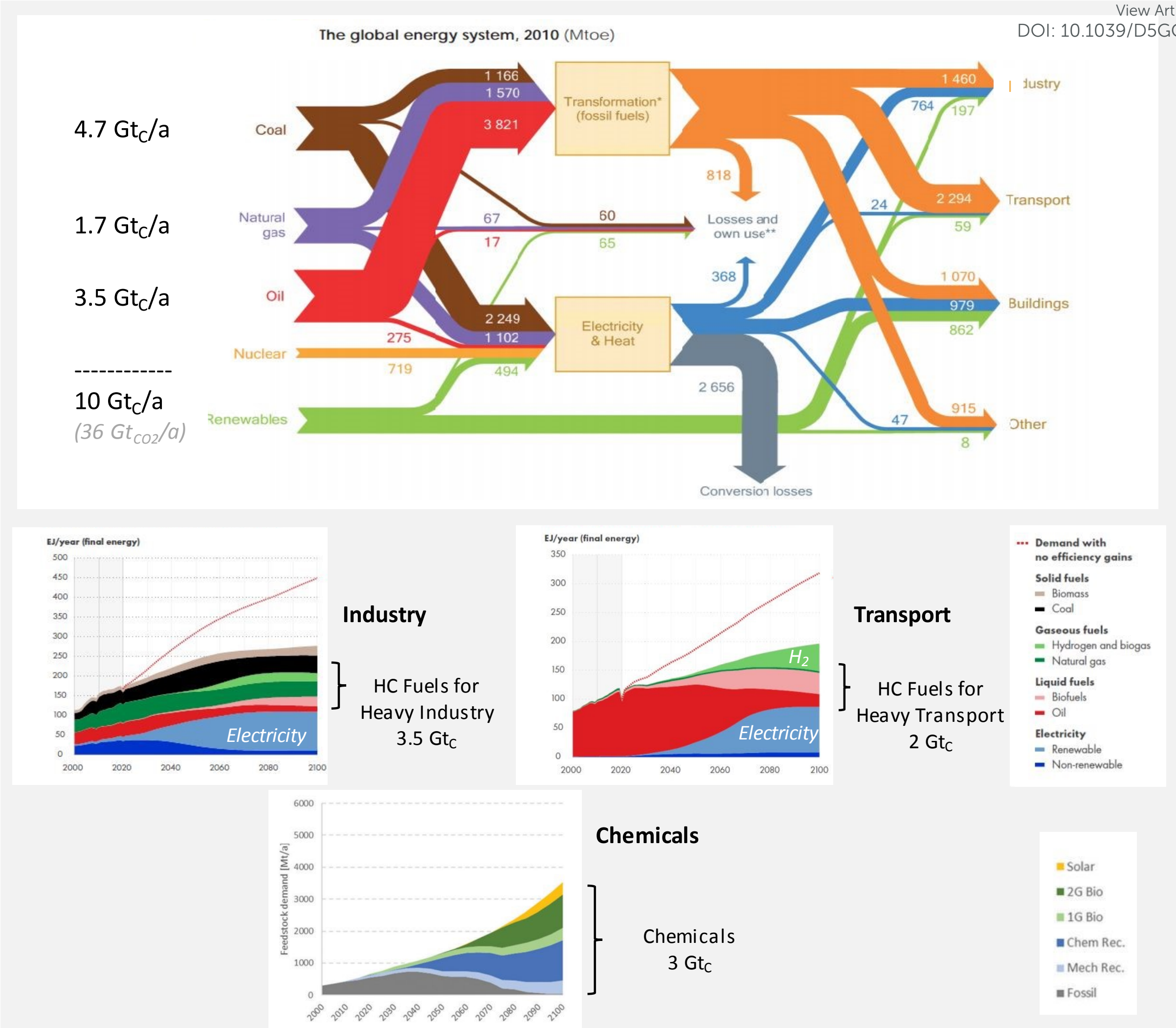

Figure 1 - Present (top[6]) and future (middle [4] and bottom[2]) demand for carbon (top is adapter from IEA copyright 2012, middle is adapted from Shell, copyright 2021)

Different scenarios estimate different rates of defossilisation, electrification and complementary need for carbon-based fuels. For the sake of illustration rather than prediction, this perspective will focus on one aggressive scenario that aims at limiting the global warming to +1.5°C. Such scenario is the Shell's SKY1.5 scenario [6] that estimates a demand for carbon of ~5.5 Gt per annum by 2100, i.e. about 3.5 Gt/a for the heavy industry, and 2 Gt/a for the heavy transport (Figure 1, midden; [6]). But one also needs to add the growing demand for chemicals and materials, which could rise to ~3 Gt/a (Figure 1, bottom; [2]). Different scenarios developed by the International Energy Agency (IEA) estimate a demand of 2.5-6.5 Gt of carbon for fuels, i.e. without including the chemical feedstock.[7] These evolution of carbon demand eventually result from a balance between decreasing fuel demand due to electrification and the increasing chemical demand. Being for 5 or 10 Gt_C/a, society will need to shift its carbon feedstock from fossil to renewable carbon to supply the growing demand for high-duty fuels and chemicals while limiting the global warming to +1.5ºC.

3 Feedstock for renewable carbon

Where will society finds 5-10 Gt/a of renewable carbon? The ultimate form of renewable carbon is arguably the CO_2 present in the atmosphere and the oceans. There are two main routes to valorise it (Figure 2, routes 1 and 2). The first one is based on biomass, letting nature capturing CO_2 from the

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atmosphere and converting it to usable forms such as sugars through photosynthesis. The second approach relies on human technologies to capture CO_2 from the atmosphere and converting it with renewable electricity and water. Beyond CO_2, there is another source of 'renewable' carbon, the carbon that is imbedded in our products and eventually ends up in our waste (Figure 2, route 3).

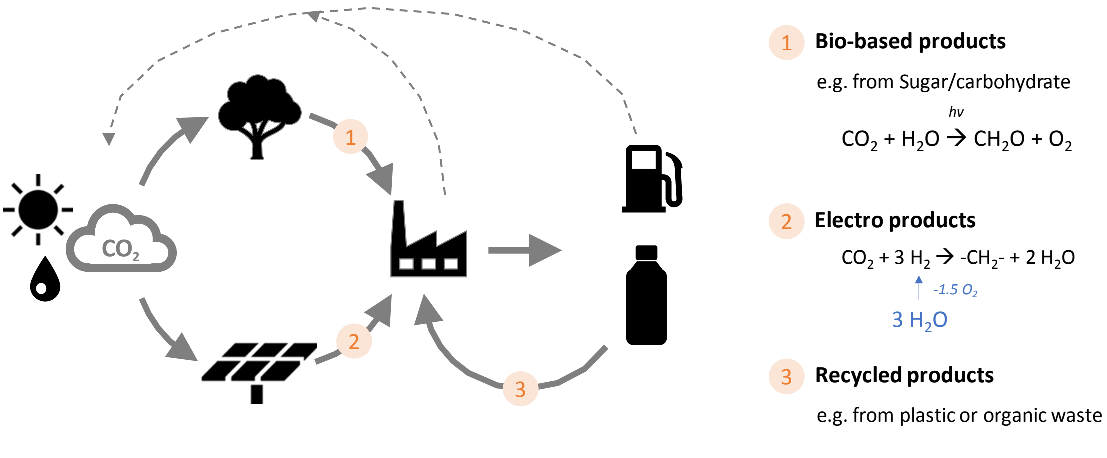

Figure 2 – Potential reserves of renewable carbon

These feedstocks have their own strengths and weaknesses, which can be expressed in terms of Availability, Acceptability and Affordability, i.e. in terms of their *triple-A potential*. These aspects, which are summarized in Table 1, will be discussed one by one in the following sections, and then combined in a triple-A potential in section 3.4 and in Figure 4. The readers can choose to jump directly to the combined analysis in section 3.4, and come back to the sections 3.1-3.3 thereafter, e.g. to understand the basis of the combined analysis. The numbers reported in Table 1 represent a selection from the literature, which is deemed sufficient for the illustrative purpose of this perspective.

Table 1 – Premises on approximative availability, acceptability and affordability of renewable carbon feedstock (see main text for justification and sources)

	Potential volume (Gt_C/a)	CO_2 emissions (t_{CO2}/t_C)	Price ($/$t_C$)	Conversion Yield (C%)
Fossil	*5-10*	*1*	*550*	*90%*
Waste	5	-2,5	-100	50%
Sugars	0,2	-1	500	65%
Bio-Residues	5	-2,5	150	50%
Atm. CO_2 (+H_2)	1	-2	1900[b]	95%
waste-CO_2 (+H_2) [a]	5,1	-3	1100[b]	95%

(a) waste-CO_2 corresponds to the C lost during conversion of waste, sugars and bio-residues;
(b) based on CO_2 captured optimistically at +\$100/t from atmosphere and at -\$100/t (avoided emission) from waste and on renewable H_2 optimistically priced at \$3/kg.

3.1 Availability

The largest reserve of renewable carbon is indisputably the **CO_2** that is present in the atmosphere and the oceans. The atmospheric CO_2 alone has been estimated to 900 Gt_C [8], i.e. 100 times the annual demand of renewable carbon estimated above. Humanity could run a century on it. But capturing atmospheric CO_2 at a rate of 1 Gt_C/a, i.e. ~10% of the present emission of CO_2, would

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already be an gigantic task. It would also require us to produce about 0.5 Gt/a of renewable H_2 to reduce the captured CO_2 to hydrocarbon, which corresponds to using 1/3 of today's global energy consumption in the form of renewable electricity to split water to H_2; an equally gigantic task.

More convenient is to let nature capturing CO_2 for us. The earth is estimated to support about 450 Gt_C of **plant biomass**.[9] But only a small fraction is being harvested. Food and feed crops are growing at the scale of about 2 Gt_C/a,[10] from which we could reasonably divert ~10% for valorisation to fuels and chemicals. But crops are accompanied by a comparable amount (~2 Gt_C/a) of lignocellulosic residues,[11] that could be used as feedstock. The same holds for forestry that produces as much lignocellulosic residues as round wood and other wood products.[12] We could therefore count on having ~5 Gt_C/a of lignocellulosic residues for manufacturing fuels and chemicals. This is consistent with the 100 EJ/a (5.9 Gt/a) that is reported as sustainable biomass in the literature. This potential could further increase with improvements in agriculture, with reduction in biomass losses and with reduction in meat consumption that would free crops or land for growing more biomass.

Much smaller is the availability of carbon in **waste**, about 0.5 Gt_C/a that is split about equally among plastic waste and organic waste such as paper, cardboard and wood.[13] But the growing global wealth and the correlated growing demand for chemical products will also result in a growing supply of waste to valorise. The 10x increase in chemicals proposed in Figure 1 (bottom) by 2100 would raise the availability of waste carbon to some 5 Gt_C/a.

These resources add up to about 10 Gt_C/a of renewable carbon, which compares favourably with the 5-10 Gt_C/a that we may need by 2100. But this does not mean they could deliver 10 Gt_C/a of renewable products, for a significant fraction will be lost during conversion, mainly as CO_2. Assuming overall valorisation efficiencies of 50 C% for waste (e.g. by gasification or pyrolysis [14,15]), ~65 C% for crops (e.g. sugar to ethanol) and 95 C% for CO_2, we could expect the 10 Gt/a of renewable carbon to produce some 5 Gt_C/a of products and discard 5 Gt_C/a as waste-CO_2. This waste-CO_2 could be captured and valorised to fuel and chemicals as well, with the assistance of 2.5 Gt/a of renewable H_2. Notice that this waste-CO_2 is more promising than atmospheric CO_2, forit is generally produced at much higher concentration for capture. Moreover, a significant fraction will likely be produced during gasification, e.g. of waste or biomass, and may be valorised directly by injecting H_2 into the gasification unit, bypassing thereby the need for CO_2 capture.

3.2 Acceptability

The discussion of acceptability will focus on environmental acceptability, starting with climate impact and then broadening to other planet boundaries. But it will also recognize the importance of social acceptability.

Climate impact: Many extensive Life Cycle Analyses (LCA) have been devoted to assessing their overall saving in CO_2 emissions of renewable and waste-based products vs. the present fossil routes.[10,16] These calculations are based on a plethora of parameters, assumptions and boundary conditions that are often hidden in the supplementary materials. But much of the conclusions can be drawn in a simpler way by focusing the discussion on the CO_2 footprint of the feedstock, leaving aside the emissions of converting the feedstock to final product that, by experience, appear toshow much less differentiation. We will use naphtha as fossil reference, which is produced with an emission of ~1 kg CO_2 per kg C of naphtha.[17] The discussion below is not meant to provide accurate savings in CO_2 emissions but to illustrate the main origin of the savings.

The capture of atmospheric CO_2 as well as the production of biomass removes ~3.6 kg CO_2 per kg C from the atmosphere, but reemits a small fraction during harvest and transport. By experience, this

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results in overall emissions of about -1.5 kg_{CO2}/kg_C for crops, -3 kg_{CO2}/kg_C for bio-residues and -2.5 kg_{CO2}/kg_C for atmospheric CO_2/H_2 (CCU). The moderate final savings of crops and CCU results from the sizable emissions of making/using fertilizers or producing H_2. Notice that the CO_2 fixed by biomass is a conservative figure that only considers the carbon harvested and excludes the CO_2 fixed underground in the root system and the microbial life that feeds it.

The CO_2 footprint of waste is more complex to treat, for it depends on the alternative disposal of the waste that would have been chosen if the waste was not valorised. Mixed waste that is diverted from landfill starts with zero CO_2 footprint, to which one needs to add the modest emissions of sorting and washing prior to recycling. The emissions of waste collection should not be considered here since one must collect the waste, even for landfill. Mixed waste that is diverted from incineration starts with saving of -3.6 kg_{CO2}/kg_C by omitting incineration, to which one needs to add the marginal emissions of sorting and cleaning for recycling. Consequently, waste feedstock show a CO_2 footprint that could vary from about +0.5 to -3 kg_{CO2}/kg_C, when diverting waste from landfill or incineration, respectively.

Broader environmental footprint: Beyond CO_2 emissions, one needs to consider other environmental stresses to spare, e.g. water use / contamination, land use / degradation and pressure on biodiversity. Importantly, however, these are local environmental factors and no global ones as is CO_2 emission. Hence, they need to be assessed for their local impact, at the project location and size. Nevertheless, some general considerations can still be made.

The broader footprint of CO_2 / H_2 will arguably be dominated by its demand for renewable energy and by the land needed to collect this energy, which is has been estimated to ~1000 $km^2/(t_{H2}/a)$ for a balanced combination of PV and wind farms.[18]

Biomass is often claimed to have a broad environmental impact in terms of land use/degradation, water use/contamination, air contamination and pressure on biodiversity. These impacts are mainly due to intensive agriculture that produces food and feed with generous use of fertilizers, herbicides/pesticides and forced irrigation. However, agricultural residues such as straw are co-produced at a rate of about 1 ton residue per ton grain without additional environmental impact. [11] The same applies to forestry residues that also come at a rate of about 1 ton residue per ton round wood needed e.g. for construction.[12] For a general perspective, it is therefore reasonable to assign all environmental burden to the priority products (e.g. food and wood) and none to their residues. Some Life-Cycle analysts argue that the residues need to bare part of the overall environmental impact of growing crops and wood. But this is a purely human bookkeeping activity that has no impact on the environment but only on eventual credits defined by regulators.

Diverting waste from landfill is bound to be environmentally favourable since it avoids contamination of land, air and water. Diverting waste from incineration is reducing local emissions (beyond CO_2), particularly where incineration would be done without exhaust gases cleaning.

Social acceptability: The switch to renewable feedstock can also impact social structures and functioning, both in constructive and destructive ways.[19] On the constructive side, it can contribute to the local economy by monetising local feedstock and providing labour and incomes. It can also reduce the risks of food shortage by increasing the production of crops to supply industry, while still prioritising food use in case of shortage. But a poor governance could also allow negative side-effects to develop. For instance, land could be taken away from local people to be sold to international companies. The demand for low-qualification manual jobs e.g. for harvesting biomass

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or for collecting and sorting waste, could lead to exploitation, child labour or abuse of work immigrants.

3.3 Affordability

From experience, the costs of feedstock – normalised for its carbon content – increases from mixed waste with negative costs (i.e. positive income) of about -\$100/t_C, to well-sorted waste and biomass residue at ~\$100/t_C, to naphtha and carbohydrate at ~\$500/t_C, to CO_2/H_2 at ~\$1200-1700/t_C. The latter is a very optimistic figure based on -\$100 or +\$100/t_{CO2} for not emitting CO_2 at point-source or for capturing it from atmosphere, and based on renewable H_2 priced at \$3/kg [20]). These feedstock prices are largely determined by the homogeneity and reactivity of the feedstock, as illustrated in Figure 3 (orange triangles) that uses an approximate and arbitrary estimate of feedstock homogeneity. Homogeneity and reactivity indeed determine the ease of valorisation and the alternative use these feedstocks.

But feedstock affordability should also consider conversion efficiency, which increases the overall costs of the feedstock per ton of C in the product (Figure 3, blue circles). Finally, the product affordability should also consider the costs of valorising the feedstock, which can be very significant, particularly for cheap, inhomogeneous and/or poorly reactive feedstock that need extensive processing. We will not discuss this matter here, in the section on feedstock, but will postpone it to section 5.3.

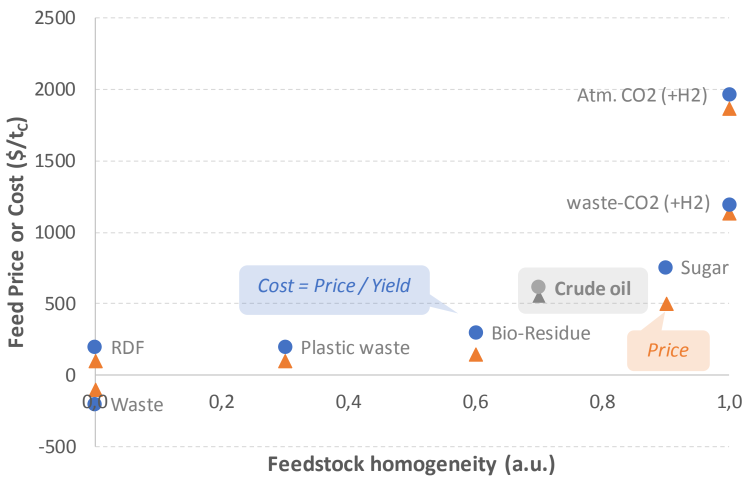

Figure 3 – Approximate prices (triangles) and costs (Spheres) of renewable feedstock increase with homogeneity.

3.4 Triple-A potential

The various A's discussed above can now be combined in Figure 4 for a comparative analysis. Accordingly, no single source seems capable to deliver the 5-10 Gt_C/a that we expect to need for our fuels and chemicals by 2100 (Figure 4, top). Together, however, they may suffice as they add up to 11 Gt_C/a: 1 Gt_C/a from atmospheric CO_2, 5 Gt_C/a from residual biomass and 5 Gt_C/a from mixed waste. The mixed waste and bio-residues will arguably be the most attractive feedstocks, considering their availability (5 Gt_C/a each), their acceptability (-2.5 t_{CO2}/t_C each) and their affordability (-\$100 and +\$150/t_C, respectively). Crop and atmospheric CO_2 are expected to play a much smaller role due to their limited availability (0.2 and 1 Gt/a, respectively), but also due to the modest acceptability of crops and the unaffordability of CO_2/H_2.

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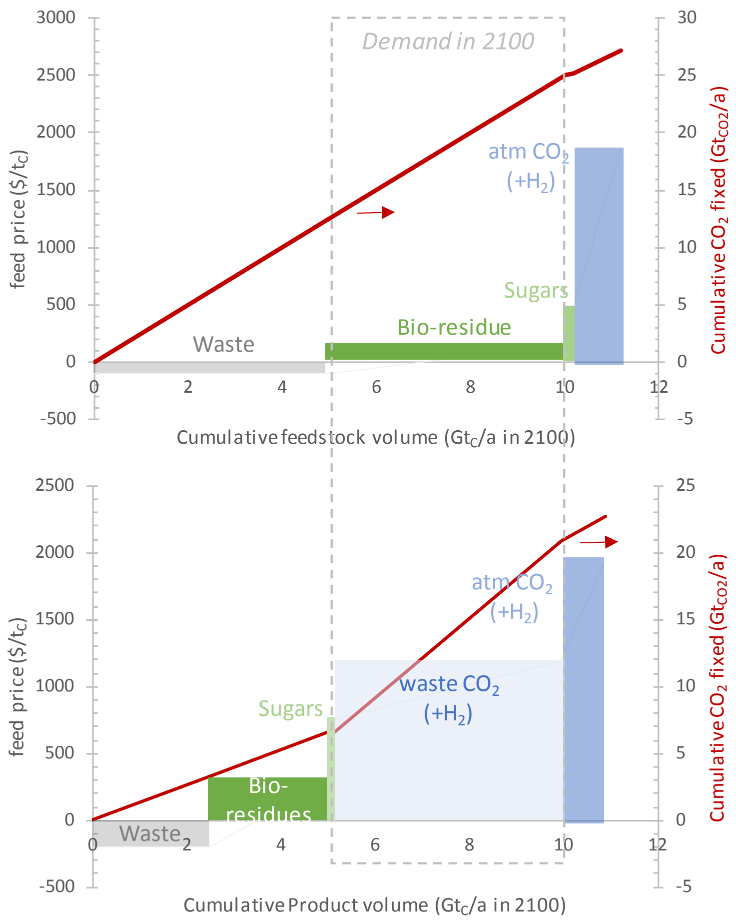

Figure 4 - Potential volume, costs and GHG emissions of renewable carbon feedstock (top) and their derived products (bottom) after correction for conversion yields. The carbon lost during conversion of waste, sugar and biomass forms the waste-CO_2 feedstock (premises are detailed in the text)

This analysis changes significantly when including the conversion efficiency to visualize the potential of the products made from these feedstock (Figure 4, bottom). The conversion efficiency indeed reduces the amount of carbon that truly ends up in the product, and concentrates the costs and footprint of the feedstock onto a smaller product volume. Specifically, about half of the carbon contained in waste and bio-residue (5 Gt_C /a) can be directly converted to products, which bare the full costs and emissions of the feedstock. The other half will be lost during conversion, largely as waste-CO_2. Interestingly, however, the waste-CO_2 now represents the third most promising feedstock for renewable carbon when combined with renewable H_2. Waste-CO_2 is indeed more promising than atmospheric CO_2 for its ease of capture and its proximity of conversion facilities. It still needs much renewable H_2, about 0.5 t_{H2}/t_C, and thereby come with high feedstock costs (~\$1100/t_C for CO_2+H_2), though still lower than for atmospheric CO_2 (~\$1900/t_C).

In conclusion, society should have enough renewable carbon to produce the fuels and chemicals it needs by the end of the century, based on the premises discussed above. And this carbon can be harvested sustainably, without competing with priority needs such as food (e.g. crops) and shelter (e.g. wood).

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4 Valorisation technologies

Since we have waste, biomass and CO_2 as potential resource for renewable carbon, we should now consider the technologies we have to valorise them.

4.1 Waste valorisation

Arguably, we should start the defossilisation by valorising our waste, for it also reduces our deterioration of the environment related to landfill, waste dumps or burning. Particular attention should be devoted to plastics that are consumed at high rate, sometimes unnecessarily, and are disposed of without recognizing their value as feedstock. Spent plastics can indeed be reused as such, be recycled by cleaning and remelting (mechanical recycling without or with assistance of solvent) or be converted back to their building block or their feedstock (chemical recycling). These technologies are properly described in the literature [14,21] and will not be discussed in more details here. Importantly, however, these various approaches are not competing with each other but rather complementing one another.[15] Mechanical recycling can process fairly pure and clean waste streams with high efficiency. Chemical recycling can process mixed and contaminated streams that are unsuitable for mechanical recycling. However, they do it at much lower efficiency and much higher costs. For instance, pyrolysis and gasification recycle about 50% of the carbon to the chemical industry and discard the other half as fuel product (gas and char for pyrolysis) or CO_2 (gasification). They could thereby be seen as half-recycling and half-incineration, which is not ideal but still better than incineration. When combining them in a cascade, as shown in Figure 5, these various technologies could displace up to 70% of the fossil feedstock otherwise needed to feed the chemical industry [15]. Note that a minimal cascade consisting of the two extremes, i.e. mechanical recycling and gasification, could already displace some 60% of the fossil feedstock of the industry [15].

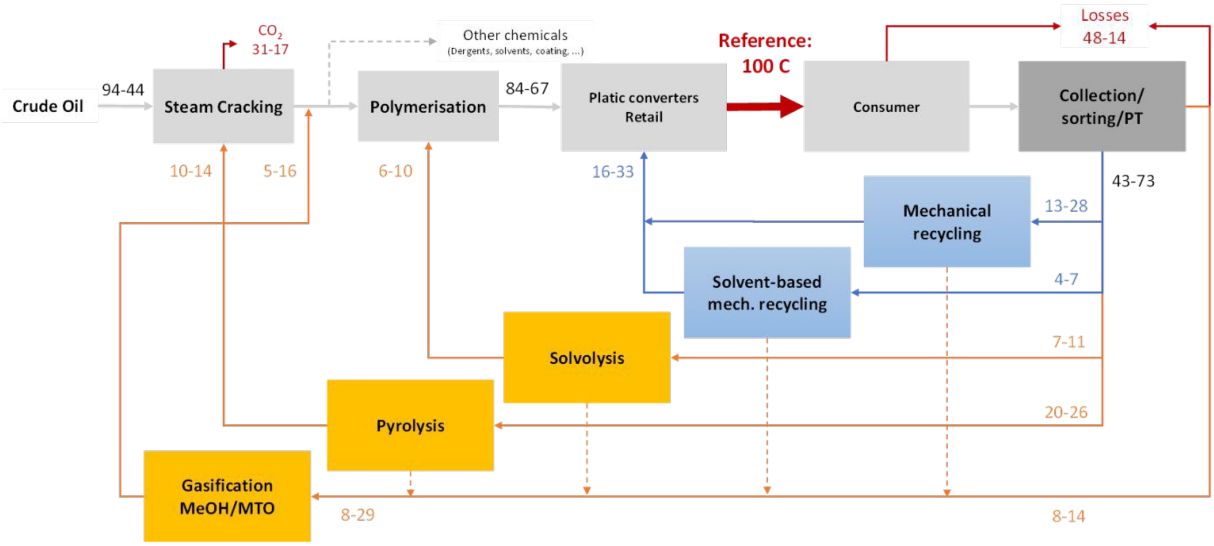

Figure 5 – Plastic recycling technologies are best placed in cascade to maximize the substitution of fossil carbon with recycled carbon. The numbers represent normalized carbon flows according to realistic and futuristic sorting scenarios [15]

But the waste streams contain other carbon sources than spent plastics. They also contain organic carbon in the form of spent paper, cardboard, wood as well as food and plant waste. This organic carbon, which accounts for as much carbon as the spent plastic [22], could also be valorised after proper sorting. Well-segregated paper and cardboard are presently recycled at rate of some 50% while segregated organic waste can be used for composting or for fermentation to biogas. Regrettably, a significant fraction of the organic waste is not properly sorted and, eventually, ends

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up with unsorted plastic in a residual fraction that is called refused-derived fuel (RDF) that is burned e.g. to generate electricity or heat. This unsorted fraction could be recycled by means of gasification, instead. The organic carbon present in the gasification feed could help the recycling cascade to displace more than 70% of the fossil chemical feedstock mentioned above, and possibly replace it all. Consequently, gasification is the inevitable corner stone of the recycling cascade.

4.2 Biomass valorisation

Plants have evolved to convert CO_2 and water to carbohydrates, more widely known as sugars. The majority of the carbohydrates is used as structural elements of the plant, e.g. in wood and straw of trees and crops, while a smaller fraction is used as energy storage in the form of starch in grains and tubers. Of course, plants also contain proteins, oils and other components worth valorising. But their amounts are dwarfed by that of carbohydrates and by the 5-10 Gt_C that we will need for fuel and chemicals by the end of the century. Hence, these feedstocks will not be considered further here.

Humanity has learned to use these carbohydrates, particularly the well-digestible 'storage' ones, to produce a large variety of chemical intermediates; some via fermentation and others via hydrogenation or acid catalysis (Figure 6).[23,24] These intermediates generally exhibit alcohol and/or acid functionalities. They are thereby well suited for producing polyesters and related condensation polymers. The most common today is polylactic acid (PLA) but others are coming to maturation, e.g. polyhydroxybutyrate (PHB), polybutylsuccinate (PBS) or polyethylfuranoate (PEF). These and other polymers show a variety of properties that may allow competition with the traditional polymers such as polyolefins, polyesters and polyamides (Figure 7).[25] One differentiating properties that is gaining attention is the natural degradation of bio-based polyesters when released in the environment, which could reduce the accumulation of plastic and microplastics that are threatening the environment and human health.[26,27]

With a bit more chemistry, the bio-based intermediates can also be converted to the existing fossil intermediates such as olefins and aromatics.[28,29] Carbohydrates can thereby also deliver today's polymers, although in a more expensive way, as we will discuss later.

The bio-intermediates can also lead to fuel components, by being directly used as blending components, as done with ethanol at the scale of >90 Mt/a,[30] or by being converted to hydrocarbons for use as diesel or aviation fuel components. Ethanol and furfural are promising fuel precursors (Figure 6).[31-34]

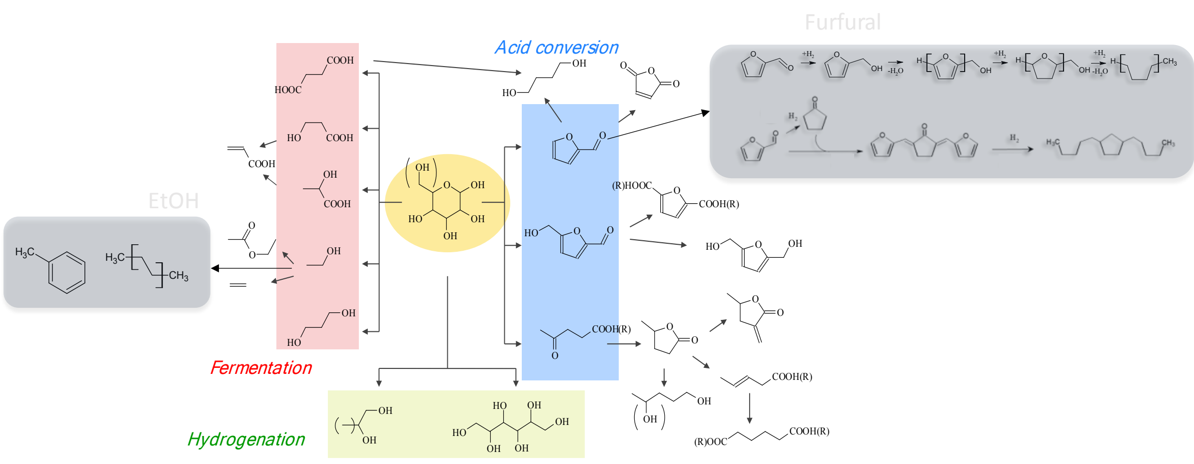

Figure 6 - Sugars can lead to a variety of chemical intermediates and fuels components [adapted from [31,34]].

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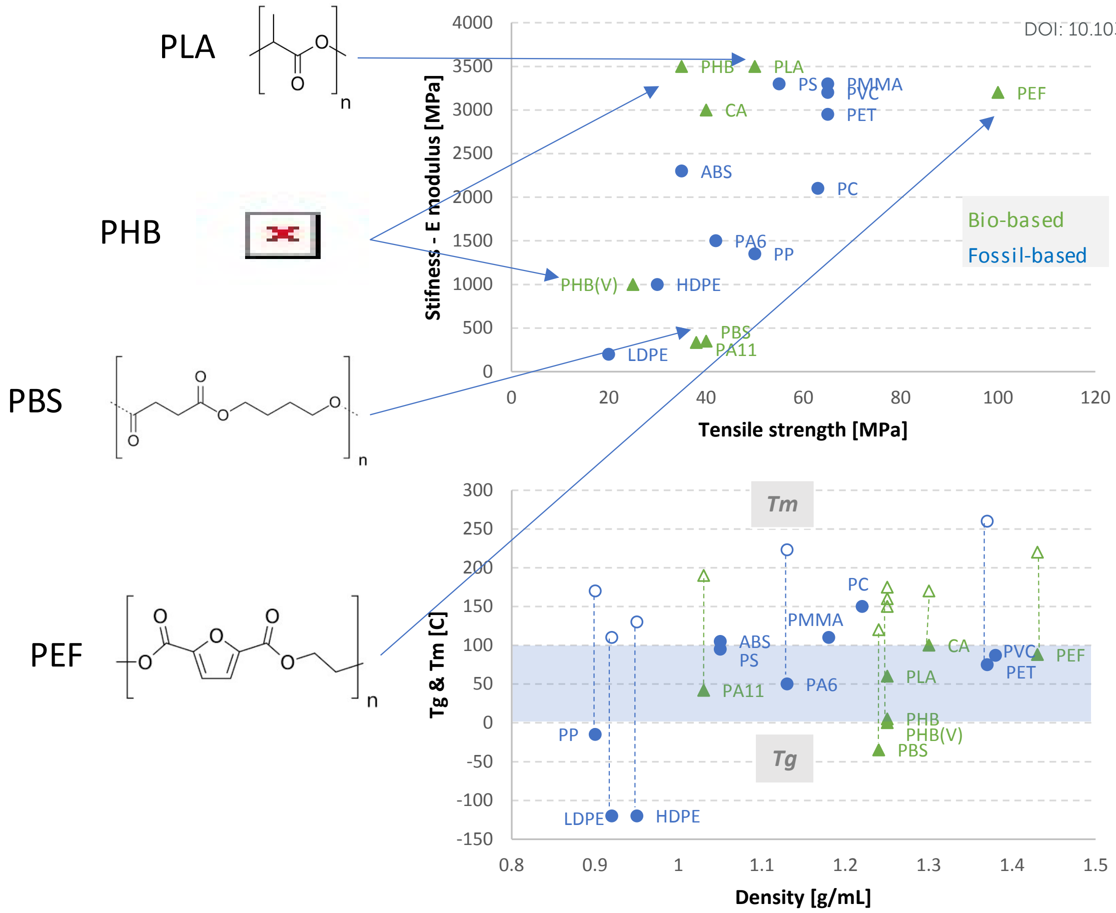

Figure 7 – Sugar-based polymers (green) can provide a variety of properties already offered by today's fossil polymers (blue) (Tg and Tm represent the glass transition and melting temperatures of polymers; adapted from [25])

But the technologies developed for the 'digestible' carbohydrates, the starch and free sugars, is not directly suited for the more abundant 'structural' carbohydrates, the cellulose and hemicellulose hidden in wood, straw and other lignocellulosic materials. Scientists have developed alternative or complementary technologies for them (Figure 8).[35] High-temperature technologies such as pyrolysis (being thermal, catalytic or hydro-pyrolysis), liquefaction and gasification have been developed to convert the complex structural biomass, i.e. the contained carbohydrates and other components such as lignin, to a complex oil or to synthesis gas that can subsequently be upgraded to valuable hydrocarbons.[35-38] However, experience learns that the hydrocarbon yields remains modest, typically 20-25 wt.% of the biomass intake, as the technologies eventually discard all contained oxygen and half the carbon with it.

A more subtle and efficient, though more complex and costlier approach consists of fractionating the biomass into its main constituents, the cellulose, hemicellulose and lignin, and valorise them independently with technologies well-tuned for the various fractions to deliver products at much higher yields.[35,39] The cellulose can be hydrolysed to glucose, which can be processed as digestible carbohydrates using the technologies mentioned earlier. The hemicellulose can be hydrolysed to its constituting carbohydrates and processed with technologies that are derived from those for digestible sugars. A special case is the production furfural from pentoses that are not found in cellulose but only in the hemicellulose of hard wood and grasses.[32,33,40] Finally, the lignin can be used as process fuel or may be upgraded to chemical intermediates or materials by various emerging technologies.[41]

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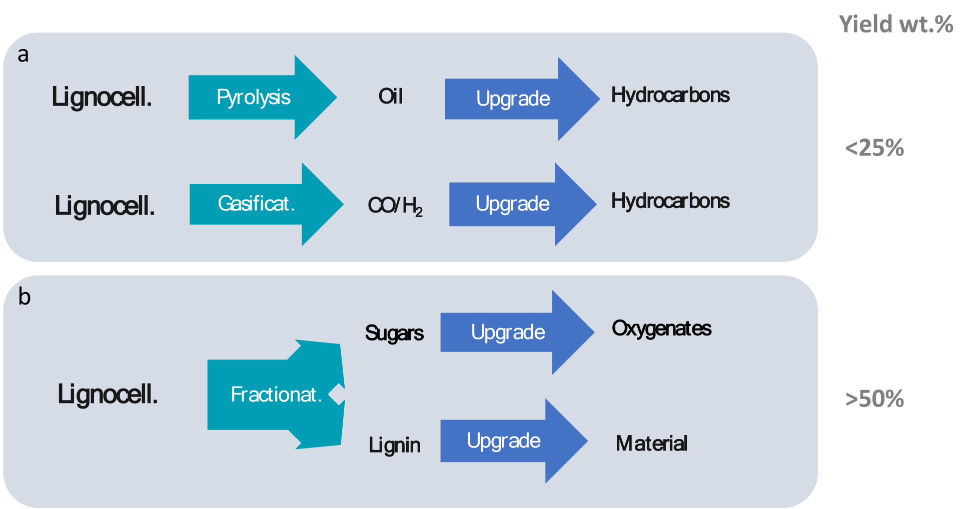

Figure 8 - Valorisation of lignocellulosic biomass via pyrolysis or gasification to hydrocarbons (a), or via fractionation to sugar-based oxygenates and lignin-based materials or fuels (b)

While subject of intense developments over the past two decades, the fractionation approach is not fundamentally novel. It is indeed parented to the pulping processes used for making paper and cardboard.[42] Much development is also being made in making paper and sibling cellulosic products, e.g. cellulosic fibres for textile or nanocellulose for advanced applications.[43] The contribution of this industry to delivering materials should not be underestimated. One should thereby recognize that the paper industry is huge as well, with a global production volume around 400 Mt_C/a of virgin and recycled paper – as large as the chemical industry.[44]

4.3 CO_2 valorisation

Numerous approaches have been developed for using CO_2.[45] As electrophilic molecule, it reacts with various nucleophiles such as epoxides and amines, or with unsaturated molecules to form various chemical intermediates. These reactions promise high economic returns from expensive products. But they may not be very impactful, as these products have a small markets, possibly of a few tens of Mt/a globally or <1% of the 5-10 Gt_C/a that we need.

More impactful is the hydrogenation of CO_2 to synthesis gas and subsequently to methanol or Fischer-Tropsch hydrocarbons.[46,47] This route is of importance because it can lead to the fuels and base chemicals used today at large scale of hundreds to thousands Mt_C/a. However, this route is economically uncompetitive as it requires a lot of expensive renewable hydrogen (0.5 t_{H2}/t_C), as we will discuss in section 5.3.

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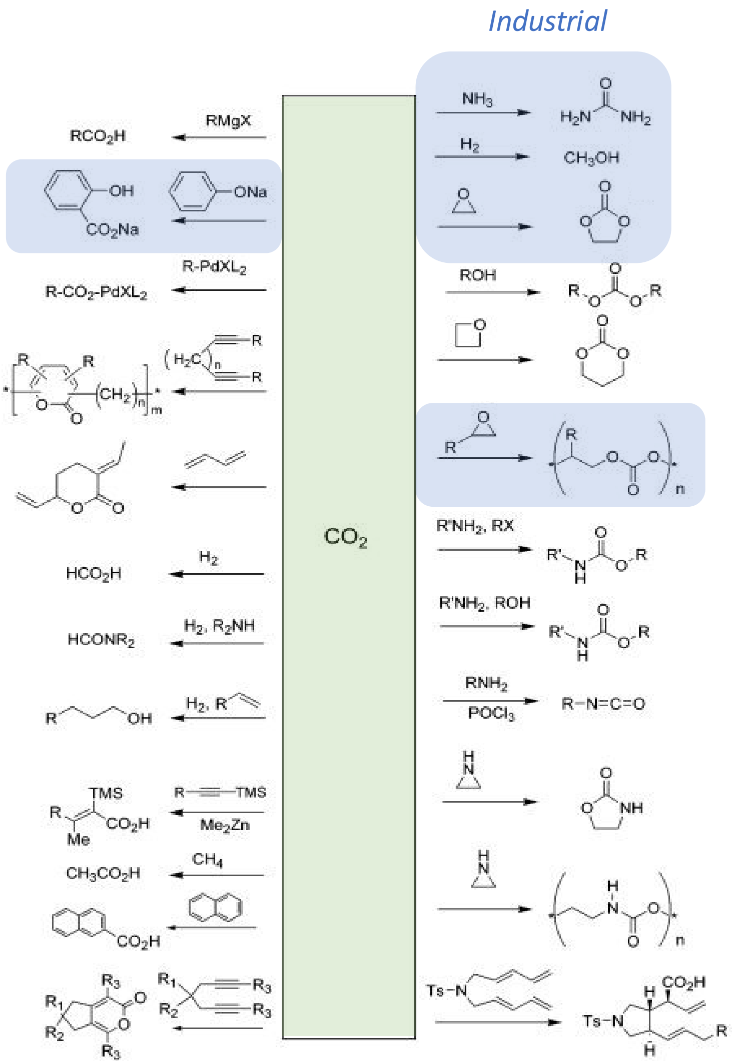

Figure 9 - approaches to CO_2 valorisation (adapted from [45] with permission from Chem. Rev., copyright 2007)

Much research is focusing on the hydrogenation route in attempt to make it more affordable. CO_2 hydrogenation technologies build on a few well-developed technologies, methanol and Fischer-Tropsch synthesis. But CO_2 valorisation also requires a few novel technologies that are well-understood but much too expensive to deploy (Figure 10). CO_2 has to be captured the from the atmosphere and regenerating the absorbent/adsorbent at low costs and low energy demand remains challenging.[46,48] CO_2 valorisation also requires renewable hydrogen, arguably by splitting water.[49,50] Extracting H_2 from biomass or waste seems less sensible, for it rejects carbon that we are just trying to utilize. Other source of renewable H_2 are difficult to imagine. CO_2 hydrogenation to synthesis gas should not be forgotten. The corresponding reverse-water-gas-shift reaction is not really new but still needs further improvement.[46,47] But other new alleys are also being considered, e.g. direct hydrogenation of CO_2 to MeOH or Fischer-Tropsch hydrocarbons, the co-electroreduction of water and CO_2 to synthesis gas, the integration of CO_2 capture with electroreduction or hydrogenation, and a few more.[46,47] Much of these efforts are focused on integrating functionalities. While seemingly attractive, such integration lead to loss of degree of freedom and loss of performance by operating each function away from its optimum conditions. The resulting penalty may offset much if not all the economic benefits targeted .

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Artificial photosynthesis that integrates light absorption, water splitting and CO_2 reduction, is a good example of deep integration that has been presented as the ultimate route to solar fuels and chemicals. But early sceptics flagged the challenges of integrating all the chemical functions and the necessary light, mass and heat transfers into a single device, without excessive compromises. They also wondered about the true technical and economic advantage over separated systems based on PV, water electrolysers and CO_2 hydrogenation discussed above, particularly for producing large-volume and low-cost commodity products such as fuels and commodity chemicals. Since then, much progress has been made but many chemistry and engineering challenges remains.[51]

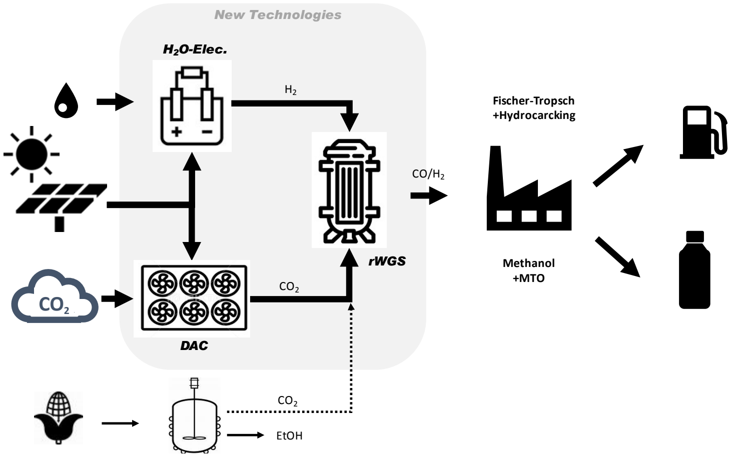

Figure 10 - portfolio of technologies for CO_2 capture and hydrogenation

5 Systemic hurdles

Having the renewable feedstock and the technology to valorise them does not seem enough to defossilise fuels and chemicals, for the energy and carbon transition has started some 25 years ago and has progressed haphazardly since. The progress is even shaming when compared to the penetration of the mobile/smart phones that started around the same time and is now ubiquitous in high and medium income economies. Why is it so much more complicated? What are the hurdles on the way? We will discuss here a few critical ones, namely the political and consumer resistance, the high costs, the pain of technology maturation and the infrastructure lock-in.

5.1 Political priorities - Energy trilemma

The energy system is truly driven by the wealth it delivers. Governments throughout the world are designing their energy system such as to make energy affordable and abundant for all, while securing its supply and, since a few decades, also minimizing its environmental impact. This Balancing act is also known as the *Energy Trilemma*. Eventually, Affordability often claims the highest priority, above Security and Sustainability, as illustrated in Figure 11 for the major economic blocks.[54] This balance is not static but keep changing with time, however. For instance, the long-term criticality of climate change has recently given way to the short-term priorities of security and affordability since the Russian invasion of Ukraine in 2022 and Trump's tariff war in 2025. Indeed, the European Green Deal, an ambitious set environmental policies approved in 2020 to make the EU climate neutral by 2050, sees now elements being challenged, weakened and/or delayed. Similarly, the US Inflation Reduction Act that was signed in 2022, sees its Clean Energy elements challenged by the 2025 legislative order 'Unleashing American Energy'.

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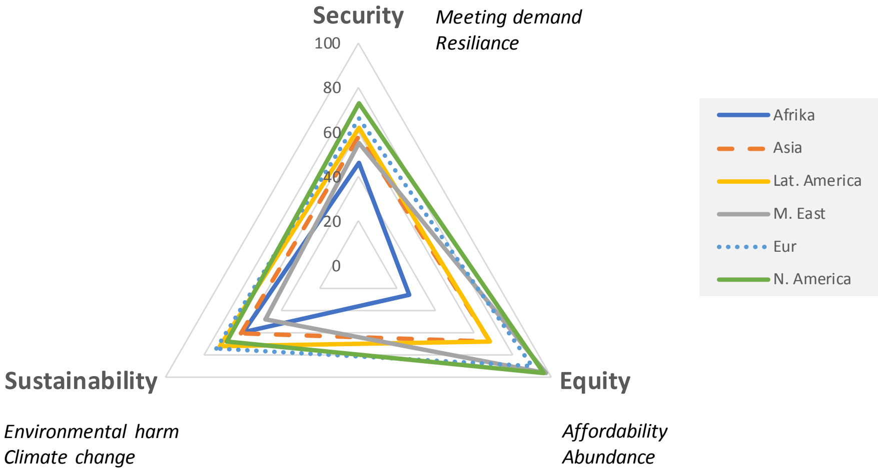

Figure 11 - Energy Trilemma of major economic blocks in 2021 (based on data from [52])

With today's trend of deglobalisation and the growing uncertainty on global trade, governments are considering to apply the trilemma concept to other sectors as well, e.g. to the chemical sector that is of interest here. Here again, Sustainability has recently been deprioritized in attempt to help the industry to face the Chinese competition, particularly in Europe.

Eventually, government's priorities reflects the balance between the priorities of the people in (or aiming to) power– in politic, finance and industry –, and the priorities of the citizens who assign the power in democratic countries. So, let's look at the broader societal and consumer priorities in the next section.

5.2 Societal resistance

Psychology and its new subdiscipline – environmental psychology [53] – teaches us that people are driven by a variety of emotions, e.g. Gain, Pleasure, Pride / Identity, and Belonging, which are themselves influenced by personal values and social norms. New products or services become popular when they free these emotions. The energy and carbon transition seems to miss many of these drivers, much in contrast to the more successful transition to mobile/smart phones. In fact, the energy and carbon transitions are perceived as bringing costs, inconvenience and uncertainties – i.e. less gain and less pleasure – for a vague promise of better livelihood for later generations, often elsewhere in the world – i.e. for a bit of pride and belonging. Indeed, the transition brings costs, inconvenience and uncertainty when needing to change equipment (e.g. PV, heat pumps). It also brings inconvenience when asking for new habits (e.g. washing during sunny hours, using public transportation, driving shorter distance with e-car, lowering heating temperature, flying less). Finally, the transition brings uncertainties on the impact of individual efforts because individual efforts are diluted by collective efforts, can be offset by the behaviour of lifters, and show no visible results before decades.

This resistance is not limited to the citizen but may equally apply to the captains of industry, the shareholders and the politicians. Decision makers are also driven by emotions of Gain, Pleasure, Pride or Identity, Belonging, etc. They also struggle with the costs, inconvenience and uncertainties for them, their customers and/or their voters. Overall, this does not look like a great motivator. Much needs to be done here, as we will discuss later.

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An important needs to be made here. One should carve out renewable fuels and chemicals from the broader energy transition, and particularly from its electrification components. Renewable fuels and chemicals are generally identical or very similar to their fossil siblings. They can be used unnoticed by the consumer and, thereby, avoid much inconvenience and uncertainties. Residual inconveniences may just be limited to the sorting wastes for recycling or the occasional use of less-performant renewable materials such as paper packaging's instead of plastic ones. Hence, the carbon transition is mainly suffering from high costs. So let's talk about costs!

5.3 Costs

Since affordability is top priority in the energy trilemma and is an important cause of consumer resistance, it warrants deeper analysis. So let's look at the economic potential of renewable fuels and chemicals, let's identify which renewable routes are promising, and why the other routes seem unaffordable.

Among the renewable feedstocks, mixed wastes and residual biomass are economically advantaged over fossil feedstocks (section 3.3 and Figure 3). But cheap feedstocks generally require extensive processing, and this may eventually make products to expensive, e.g. when the market prices ignore the societal cost of fossil-based products. This trade-off explains why the expensive crude oil successfully displaced cheaper coal in the previous century and resisted the rise of cheaper natural gas some 40 years ago. This trade-off between feedstock and processing costs warrants a brief discussion of manufacturing economics.

With gross oversimplification, we can relate the manufacturing costs (or minimum selling price) of a product to the feed price, the processing costs and the conversion yield, according to equation 1.[54]

Min. Product price [\$/t_{prod}] = (feed price [\$/t_{feed}] + processing costs [\$/t_{feed}]) / yield [$t_{prod.}$/t_{feed}] (1)

Product and feed prices are available in the literature [55], the processing costs can be crudely related to the number of processing steps and an average step costs (e.g. \$100-300/t_{feed}/step) [54], and the yield can be estimated from laboratory experiments. Figure 12 (top) applied this approach to the valorisation of glucose, CO_2 and polyolefin waste to methanol, ethanol, ethylene or its oligomers as Sustainable Aviation Fuel (SAF) to illustrate the following: To be competitive, the process needs to be simple and proceed with high mass-yield:

- Multistep processes should indeed be avoided as they can lead to processing costs that outweigh the costs of a cheap feedstock, as illustrated by the conversion of glucose and CO_2 to Sustainable Aviation Fuels (SAF) and the valorisation of polyolefin waste to olefins and aromatics (simplified to ethylene here) in Figure 12 (top).
- But it is also imperative to achieve high yield *on weight basis*, i.e. to sell as many tons of product per ton of feedstock as possible, to have a larger product output baring feedstock and processing costs. Biomass and CO_2 are rich in oxygen and should preferably be converted to oxygenated products to achieve high mass-yields.

The impact of both factors is also illustrated with Figure 12 (bottom) that compares the stoichiometric yield of various products made from glucose (left) and CO_2 (right) with minimum yield needed for the product to be affordable.[17] Accordingly, various oxygenated chemicals may be affordable, i.e. by having a target yield that is lower than the stoichiometric yield, while hydrocarbons seem unaffordable with minimum yield exceeding the stoichiometric yield. Notice that the costs of renewable H_2 makes very few CO_2 derivatives affordable, even when we assume to

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make them in a single steps and use optimistically cheap renewable H_2 ($3/kg), as done in Figure 12 (bottom, right).

$$\textbf{Product Price}\ (\$/t_{prod}) > \frac{\textbf{Feed Price}\ (\$/t_{feed}) + \textbf{Proc. Cost}\ (\$/t_{feed})}{\textbf{Yield}\ (t_{feed}/t_{prod})}$$

Reaction	Calculation	Market prices*
$C_6(H_2O)_6 \rightarrow 2\ EtOH + 2\ CO_2$	(300 + 1*200) / 0.5 = $1000/t	$700-900/t (bio)
$C_6(H_2O)_6 \rightarrow (EtOH) \rightarrow 2\ CH_2{=}CH_2 + 2\ H_2O + CO_2$	(300 + 2*200) / 0.3 = $2300/t	$600-1200/t (fossil)
$C_6(H_2O)_6 \rightarrow (EtOH/C_2H_4) \rightarrow -(CH_2)_4- + 2\ H_2O + CO_2$ (SAF)	(300 + 4*200) / 0.3 = $3700/t	$600-1200/t (fossil)
$CO_2 + 3\ H_2 \rightarrow CH_3OH + H_2O$	(±100 (DAC/Waste) + 0.14*3000 + 200) / 0.64 = $800-1100/t	$300-600/t (fossil)
$CO_2 + 3\ H_2 \rightarrow (CH_3OH) \rightarrow -(CH_2)- + 2\ H_2O$ (SAF)	(±100 (DAC/Waste) + 0.14*3000 + 4*200) / 0.28 = $4000-4700/t	$600-1200/t (fossil)
$-(CH_2)- \rightarrow ½C_2H_4 + H_2$ (Plastic waste)	(300 + 3*200) / 0,5 = $1800/t	$600-1200/t (fossil)

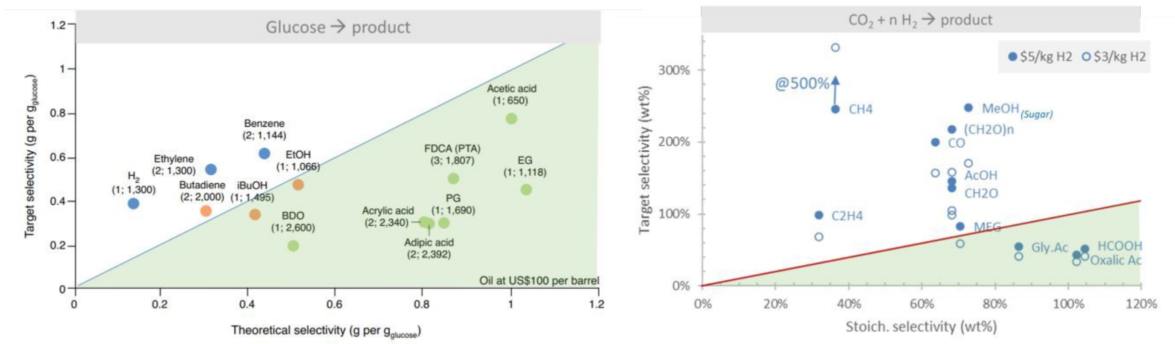

Figure 12 - Screening economics for valorising sugars and CO_2 (premises: Glucose at \$300/t, CO_2 at \$100/t, H_2 at \$3-5/kg; \$200/t/step; multiple steps for Glucose but single step for CO_2; Bottom left comes from [17])

The economic analysis discussed above obviously needs much refinement. A small first step is to recognize that not all steps are really equally expensive, because they differ in scale and/or complexity.

Renewable feedstock are generally more difficult to harvest and transport over long distances than is crude oil. Hence, their conversion processes will likely operate at smaller scale (Figure 13, left). The general scaling laws teach us that a 10-fold decrease in scale leads to only 5-fold decrease in investment costs, i.e. to a doubling of the investment costs per ton of product.

Arguably more important than scale, however, is the complexity of individual process steps. This can be inferred from its energy transfer duty: the higher the heating/cooling/pumping duties, the higher the investment costs (Figure 13, right).[56,57] Water electrolysis is an extreme case of endothermic reaction with prohibitive transfer duty (~180 MJ/kg_{H2}) and, thereby, high investment costs.[58] Thermal cracking of polyolefins waste is also highly endothermic (~3 MJ/kg_{C2H4}). Biomass fractionation and sugar valorisation generally proceed at high dilution in water, which results in high duties for heating/cooling and for product recovery. All these aspects, and a few more, will impact the processing costs of the individual steps and push it to higher or lower level within the range of $100-300/$t_{feed}$/step. Such refinement can be incorporated into the economic equation of Figure 12 (top), and may even become critical when the overall processing costs exceeds the feed costs.

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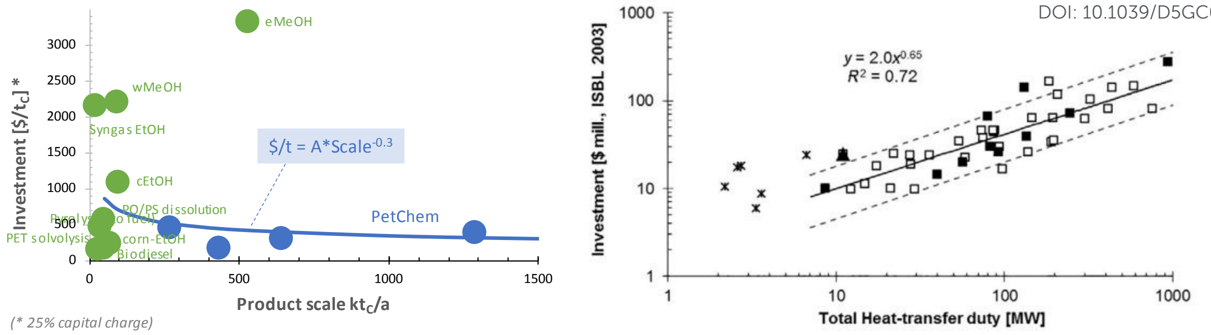

Figure 13 – Process Scale (left) and energy transfer duty (right) largely determine the investment and processing costs (a: data from [59]; b: [57]).

Although oversimplified, this discussion on manufacturing economics clearly shows that renewable hydrocarbons will likely remain more expensive than their fossil equivalent, only slightly when derived from waste plastic waste, more from biomass and prohibitively from CO_2. However, oxygenated intermediates offer better perspectives because they are expensive to make from fossil feedstock, and they valorise the oxygen paid for when purchasing the feedstock.

5.4 Pain of technology maturation

The costs of production are not fixed in time but vary. They fluctuate with the global economy and, importantly, they decrease with technology maturation. The technology maturation warrants some attention, for it greatly improves the competitiveness of emerging technologies over time.

As novel technologies get deployed, they generally get better understood, optimized, more sharply designed and deployed a larger scale. All this usually results in an erosion of conversion costs with time following the well-documented learning curve of equation2[63] because of gradual decrease of processing costs and increase in yield (equation 1). For typical power *m* of -0.3 [63], the costs per unit of product decreases by 20% for every doubling of deployed capacity and by 50% for every 10x increase in deployed capacity (Figure 14, left – with nuclear as notorious exception [63,64]).

$$\text{Costs [\$/t or kW]} = C_o * \text{cumulative capacity}^m \qquad (2)$$

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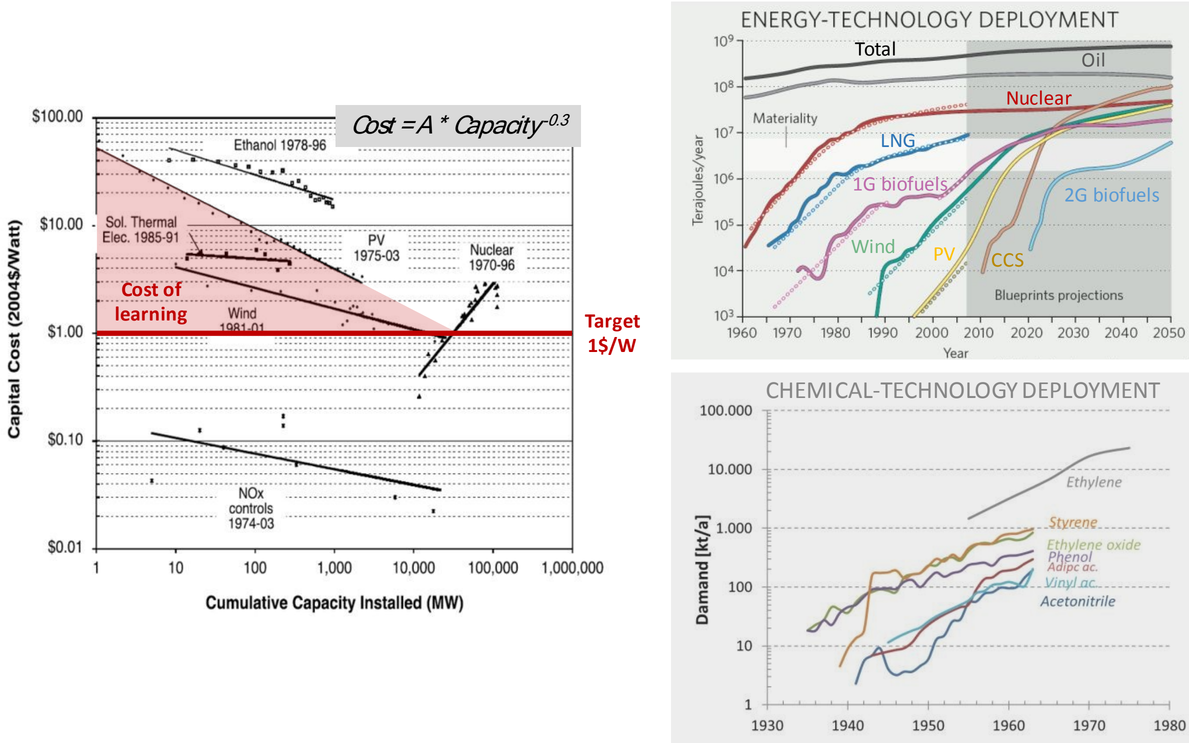

Figure 14 – Technology maturation erodes the manufacturing costs (Left) but takes about half a century to complete (top & bottom right) (Top left and right adapted from [62,65] with permission from Springer, copyright 2007 and 2009; bottom right with data sourced from [63,64])

Junginger et al. report such learning curves for numerous energy technologies, e.g. for wind, PV, concentrated solar power and bioenergy.[61] So one can reasonably expect the conversion costs of renewable fuels and chemicals to also drop by about 50% for every 10-fold increase in cumulative capacity, eventually making the most promising options advantaged over their fossil equivalent and making less promising ones possibly competitive. Interestingly, the learning curve is not limited to the conversion costs but may also apply to the production of energy feedstock, as exemplified for the production of sugar cane and corn,[61] decreasing thereby the feed cost term in equation 1.

The learning curve also provides information on the overall maturation costs of new technologies, which is illustrated by the red area in Figure 14 (top). This maturation costs can be financed by starting with niche markets that can afford the high initial costs, and then gradually targeting larger markets as the costs erodes. But such deployment strategy may require decades to reach maturation, particularly for commodity products such as energy and chemicals. In fact, energy (and chemical) technologies took half a century to mature; taking ~25 years of exponential growth to capture a few percent of market share and ~25 more years of linear growth to mature their share of the market (Figure 14, right).[65]

Accelerating the learning would likely requires the industry to invest with higher risks and at higher costs. This would need support from governments, e.g. in the form of co-investment, investment guarantees, mandates, tax incentives, public purchase commitments, etc. But this would also shift (part of) the learning costs to society and to the consumers, which is no popular measure, as discussed above.

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5.5 Infrastructure Lock-in

So far, the transition could progress thanks to individual players implementing new devices and services. But it has now reached a point where it gets constrained by physical infrastructure and governing institutions, also called '*infrastructure lock-in*'.[66,67] These include sunk costs in the form of money and space, interdependencies between various technologies, legal and political factors often put in place for safety, and social norms and expectations e.g. on availability, quality and reliability of good and services. Further progress now needs deeper and well-coordinated systemic changes. Unlocking the broad infrastructure will require a broad set of strategies at multiple levels, individual, social, institutional, technological and economic levels. For instance, the transition needs new infrastructure to distribute and use the renewable energy and products, while maintaining the present infrastructure of oil and gas products for as long as we use them. This brings e.g. additional cost that will be charged to the consumers, either directly or indirectly.

Interestingly, however, the renewable fuels and chemicals don't need new infrastructure for distribution and use. This has been a major motivation for some companies to favour biofuels over e-mobility or hydrogen fuel.

6 Systemic enablers

The systemic hurdles discussed above are not necessarily show stoppers, for we have some enablers that could help surpassing these hurdles. Renewable carbons produced and valorised locally could contribute to feedstock security while stimulating the local economy. Integrating renewable carbon into the existing infrastructure could lower the costs of manufacturing and distributing renewable products. Focusing on oxygenated products beyond today's hydrocarbons may lower the costs of the carbon transition. A combination of smart nudging, fair financial support and effective regulations may help gaining support from consumers. But all this is arguably not enough. We may need to reimagine our economic model to stimulate innovation and increases wealth while reducing inequality and protecting the environment. Let's discuss these enablers in more depth.

6.1 Exploiting local feedstock

The exploitation of local feedstocks is a promising option for passing some hurdles, for it also reduces the dependency on foreign feedstock, corrects trade imbalance, and reduces public resistance by stimulating the local economy and wealth. Renewable carbons are indeed more equally distributed over the planet than are oil and gas. All countries have access to their own wastes, are growing crops for food/feed which gives access to agro-residues, and may have additional land to grow more biomass or install PV / wind farms to valorise their own waste-CO_2.

The possibilities for each country to meet its demand for fuel and chemicals with local renewable carbon largely depends on its C-demand per km^2, i.e. the product of *population density * C-demand per person,* with the latter generally correlating with the Gross Domestic Product (GDP) per person. For instance, today's areal C-demand for energy and materials increases from ~40 $t_C/km^2/a$ for Brazil to ~200 $t_C/km^2/a$ for the USA and 300-400 $t_C/km^2/a$ for the EU, India and China (see case study in Box 1). Oversimplified assumptions, discussed in Box 1, suggest that waste and agro-residues co-produced with a minimum of food production (arbitrarily set at 5x the UN Reference Food Intake) could cover 10-20% of the carbon demand for USA, EU and China, 27% for Brazil and 50% for India. The remaining land, however, could potentially provide a multi-fold of the carbon demand as biomass (e.g. as energy crop or more food and agro-residue) or as product derived from waste-CO_2 and renewable H_2.

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Box 1 – Case study on local feedstock

We will consider five archetypical 'countries', namely USA, EU, Brazil, China and India, which vary in population density, GDP and energy demand, and we will use data reported by *Our World in Data* and other websites. We will use a simplistic scenario to estimate the amount of waste or renewable carbon they could produce themselves as waste, as agro-residue they are bound to co-produce with (part of) their food, or as biomass or CO_2-product they could produce from their land. The results are summarised in the table below.

The archetypical countries show an energy/carbon demand varying over an order of magnitude, from 0.7 to 5.7 t_C/pers./a, which follows their GDP. They also show variation in the potential production of renewable carbon. The production of total waste, set at 2x that of plastic waste to include organic waste, vary from <0.01 to 0.11 t_C/pers./a. We assume that the various countries produce a minimum fraction of their food, which we set arbitrarily at 5x the Reference Food Intake (8400 kJ/pers./day) and corresponds to 0.36 t_C/pers./a of food and which uses 700 m^2/Cap of land at an average productivity of 500 t_C/km^2/a. The countries thereby co-produce the same amounts of agro-residue to be used. The remaining land, which varies between 1,300 and 39,000 m^2/cap for India and Brazil based on respective population densities, is then used for growing biomass (or food with agro-residues) or for producing renewable electricity to valorise waste-CO_2 to products, with a land productivity set at 500 t_C/pers./a for biomass and at 2000 t_C/pers./a for CO_2 products for all countries, neglecting differences in climate and soil conditions for the sake of simplicity. This leads to 1-20 t_C/pers./a of biomass or 3-75 t_C/pers./a of CO_2 products.

Overall, waste and minimum agro-residues would cover a modest fraction of the carbon demand, but biomass and CO_2 products could cover it all. Obviously, the lower their C-demand per km^2 (demand/pers.*population density), the easier the switch to local renewable carbon. This ease increases here in the order of Brazil > USA > EU~India~China.

Table – Potential for renewable fuels and chemicals for selected countries based on today's population and demand (data source: Our World in data)

	Units	USA	EU	Brazil	China	India
GDP	k$/pers.	75	40	20	13	9
pop density	pers./km^2	38	117	25	150	492
Energy consumption	t_C/pers./a	5,7	2,9	1,7	2,6	0,7
	t_C/km^2/a	218	335	42	387	357
POTENTIAL ren-C PRODUCTION						
Total waste	t_C/pers./a	0,21	0,13	0,11	0,08	0,01
	% demand	*4%*	*4%*	*6%*	*3%*	*1%*
min. ag-residue	t_C/pers./a	0,4	0,4	0,4	0,4	0,4
	% demand	*6%*	*13%*	*21%*	*14%*	*50%*
biomass	t_C/pers./a	13	4	20	3	1
	% demand	*223%*	*137%*	*1156%*	*115%*	*90%*
CO_2 (PV+wind)	t_C/pers./a	49	15	75	11	3
	% demand	*857%*	*524%*	*4433%*	*442%*	*347%*

Premises:, min. agro-residue = min. food = 5x ref. food intake of 70 kg_C/pers./a; tot. waste =2x plastic waste to include organic waste; land productivity is 500 and 2000 t_C/km^2/a for dedicated biomass and for PV+Wind farms needed for CO_2 hydrogenation.

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Hence, there are significant opportunities to produce renewable carbon locally, despite all the oversimplification made for drawing this conclusion. We may want to start with waste and agro-residue, and fill the gap with biomass to benefit from its additional environmental services, and/or with CO_2-based products to use as little land as possible.

6.2 Building on existing industrial infrastructure

The various technologies mentioned above should ideally complement and extend today's industrial infrastructure without replacing it (Figure 15). This is needed to allow the transition to develop gradually and to minimize infrastructure costs. Waste recycling and gasification will require new processes to be implemented upstream of today's refining and chemical sites, to feed them with renewable carbon in the form of plastic recyclates, recycled monomers, pyrolysis oil and syngas products (Figure 15, orange infrastructure). Biomass can also feed today's refineries and chemicals parks, e.g. with bio-naphtha, bio-pyrolysis oil, bio-ethanol or bio-syngas, to lead to renewable hydrocarbons fuels and chemicals (Figure 15, green infrastructure). Biomass may also deliver higher-value intermediates (e.g. furfural, maleic anhydride or butanediol) that are shipped to existing chemical sites for further upgrading to high-value polymers, when it brings benefits from economy of scale and/or from utilities/skills that are not readily available in the biorefinery, e.g. high-pressure H_2. Waste from the refining/chemical site as well as waste-CO_2 (with renewable H_2, Figure 15, blue infrastructure) can also be valorised by co-feeding to the waste gasifier.

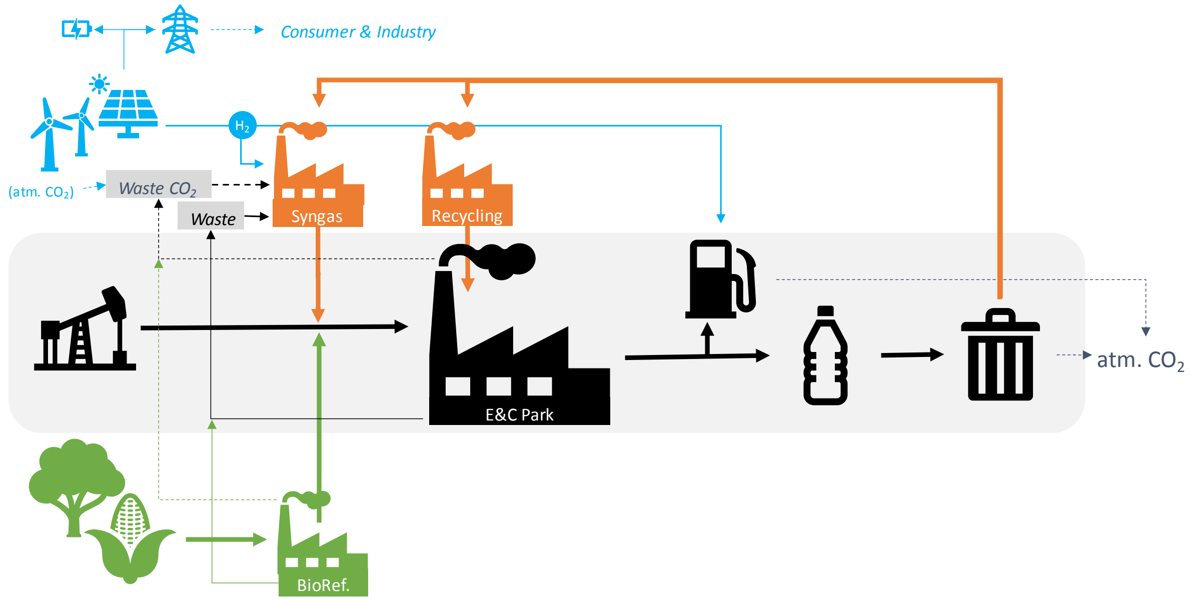

Figure 15 – Renewable carbon economy should be built on the existing industry infrastructure

6.3 Matching the products to its feedstock

Today's product portfolio mainly consists of hydrocarbons that resemble much the feedstock they are made of, for instance crude oil. But the major sources of renewable carbon contain oxygen. Should we therefore consider shifting to more oxygenated products that resemble better the new renewable feedstock?

The economic analysis illustrated in Figure 12 showed that oxygenated intermediates such as ethylene glycol, butane diol, acrylic acid and adipic acids can be made affordably from sugars, while hydrocarbons seem unaffordable. The same applies to the oxygenated intermediates formic and glycolic acids made from CO_2. Focusing our effort to converting the oxygen-rich feedstocks to

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hydrocarbons, as we presently do, promises to displace much larger volumes of fossil resources but with excessive learning costs (Section 5.4) that may get rejected by society. It seems therefore preferable to start the transition by targeting higher-value oxygenated chemicals to prove the new technologies, and then gradually transition to higher-volume and lower-value products such as hydrocarbons.

The initial targets could consist of oxygenated molecules that are identical to today's fossil oxygenates and can be directly fed to today's infrastructure and markets. Such products are named *drop-ins*. But the oxygenates could also consist of new molecules that offer new and hopefully improved properties that could justify higher market prices. However, their market penetration will likely start small and require decades to grow and prove themselves. The bio-based polymer polylactic acid or polylactide, PLA, is a good example of a slow market penetration by growing to ~700 kt/a or ~1% of the well-established fossil polyester PET in 30 years. The *drop-ins* don't need to prove themselves in the market and could therefore grow much more rapidly. In short, drop-ins seem to offer a better balance between affordability and market size.

The similarity between feedstock and products should also be applied for waste. The similarity principle obviously favours mechanical recycling. When not possible, waste streams rich in mixed polyolefins would preferably be pyrolyzed to hydrocarbon fuels or hydrocarbon chemicals (e.g. aromatics and olefins).[15] Mixed wastes containing various plastics and organic wastes, i.e. Refused Derived Fuels (RDF), are clearly more challenging, however. The most robust and mature route consists of gasification that burns part of the carbon to reach the temperature needed for producing synthesis gas.[67,68] Being a partial oxidation process, gasification should target more oxidized products. Acetic acid is a good candidate that relies on well-proven technology. But the equally mature technologies lead to less-oxidized and lower-value products such as MeOH and Fischer-Tropsch hydrocarbons, which need more hydrogen that available in the waste syngas. The process therefore needs to consume expensive renewable H_2 or to reject the excessive carbon. Both options increase the production costs, either via higher feed costs (H_2 addition) or lower yield (C rejection), for a product that is already not competitive. Waste gasification, the arguable cornerstone of the circular economy, will likely require financial support from society.

Finally, various academic groups propose to convert waste and biomass to renewable H_2 via gasification or reforming. Why would we want to discard the valuable renewable carbon that we need for making fuels and chemicals? This obviously increases the C-footprint of the resulting H_2 and of the product that will be made from this H_2. The resulting H_2 would furthermore be quite expensive, as it is manufactured using extensive chemistry and at low mass yield (~10 wt.% H_2 on feed). The low return obtained for sequestering the CO_2 by-product is not expected to help the economics very much. It seems more sensible to convert waste and biomass to fuels and chemicals directly, as discussed above.

6.4 Building public support

By bringing costs, inconvenience and uncertainties, the energy transition is struggling to seduce the mass. Consumers may claim to support green products and services in opinion pools but often choose otherwise in supermarkets. In fact, the energy transition only seduces a small group of people who are appealed by its social/environmental offering or by the exclusivity of specific goods and who can afford the costs and inconvenience. The rise of biological food may be representative of the former, while the early popularity of Tesla cars may illustrate the latter. Building a broader acceptance will likely require a portfolio of stimulations or nudges to pass these hurdles.

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'Soft' nudging of consumer and industry may take various forms.[70] Providing feedback on the progress made would encourage more progress, even more if the feedback helps turning the effort into a game. Creating a community may also help people by sharing experience, encouraging, not feeling alone in the effort, and putting mild peer pressure on eventual lifters. Public choices could be presented with the green option as default and with the possibility to opt out to secure freedom.

But citizens can contribute to such nudging themselves by influencing their co-citizens, the industry and regulators.[71] They can inform and inspire people around them, develop or join sharing or repair networks, boycott or invest in companies, join protests and political decisions, and vote for change.

But harder **financial support** may likely be necessary as well, e.g. through low but progressive taxes on fossil options or waste, and/or high but degressive subsidies on green options, i.e. taxes/subsidies that increase/ decrease with time or with consumption volume. However, care should been taken to ensure that these financial measures are effective, bearable and fair.[53] For instance, subsidies on solar panels have eventually benefited wealthy home owners while increasing the electricity bill of less wealthy home renters. Such measures should not be limited to consumers but also be extended the industry.

But nudges and financial support may not be sufficient either. Hard **regulations** will also be needed, e.g. by mandating green options and/or banning fossil or wasteful ones. But they should be formulated such as to avoid administrative burden that may be unbearable for the small and medium enterprises. For instance, regulations are defined per sectors. This often leads to systemic inconsistencies, biases and flaws, when comparing different sectors. To effectively unlock the pervasive and interrelated energy system, regulations need to adopt a larger, more **holistic, multi-sectorial and coordinated approach** that considers e.g. industry, agriculture, forestry and waste management; an approach that considers fuels and chemicals equally, but also considers other industries such as steel, cement and paper with the same metrics for climate and environmental impact; an approach that focuses on impact (e.g. CO_2 emissions) without preselecting routes to desired impact (e.g. green H_2 vs. green electricity).

Let's dive into one bias that is particularly relevant for the present discussion, namely the **discrimination between fuels and chemicals**. So far, regulators, NGO's and society treat fuels and chemicals separately. For example, renewable fuels - often erroneously called 'low-carbon' fuels - benefit from large incentives in the form of tax breaks or mandates. Renewable chemicals don't enjoy such support and, consequently, can't compete fairly with renewable fuels for accessing renewable feedstocks. As second example, the industry is mandated to use plastic waste for manufacturing circular chemicals but is discouraged to convert it to renewable fuels. Such separation is as artificial as undesirable. The ultimate goal should be to substitute as much fossil carbon as possible to minimize net CO_2 emissions and waste disposal. Society should favour the path with the least and lowest barriers. This could mean e.g. encouraging the industry to pyrolyze mixed polyolefin waste to make renewable kerosene for aviation and renewable diesel for long-haul trucks. It could also mean encouraging the use of sugars for making novel polyesters such as PLA. The separation between fuels and chemicals is even more artificial when one recognizes the synergies that connect the two sectors. Numerous waste or bio-refineries could advantageously co-produce fuels and chemicals or advantageously switch from the one to the other in time. Coming back to the example of plastic pyrolysis, it may be cheaper for society to allow to prove the technology and develop the industry by using the pyrolysis oil for fuels and lubricant blend stock and, only later, tune the technology to make more demanding feedstock for the chemical industry. Similarly, sugar and cellulosic bio-refineries produce fuel ethanol today because it's mandated. But it may be (have

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been) cheaper for society to stimulate them to start with high-value chemicals and gradually move to lower-value but larger volume fuels later.

New regulations also need to look at the world finance that eventually determine where investments are made. They need stronger control and enforcement. Most importantly, they need the become priority for society. This implies that our whole economic model needs to be revisited - the subject of the next section.

6.5 Reimagining Society?

The capitalism has raised wealth by encouraging the deployment of new technologies and the use of fossil energies to deploy work at a scale that was so far unimaginable with human and animal power alone. But this economic model seems to reach its limits by destroying its foundations, namely the environment, the institutions and people equality. These are indeed foundational as they provide the resources, the framework and the stability that capitalism needs to thrive. Today's situation disturbingly resemble that of past human civilizations that eventually collapsed, with the difference of being now at global scale.[72] Like today, past civilizations ignored the threat (environmental and others) for too long, organized themself ineffectively by building internal conflicts in their governance, and reacted too late, too little and at too high costs.[72] Can we learn from these collapses?

Some believe that technology will solve the problem.[73] New technologies that are growing at exponential rate (e.g. Biotech, communication, robotics and 3D printing) promise access to resources that are inaccessible with today's technologies. They promise to help people to meet their fundamental needs for water and food, and thereby, to free time and energy for them to pursue higher level needs such as energy, health, education and freedom. The present climate strategy of 'net Zero by 2050' seems to also blindly rely on technology miracles – developing CO_2 removal at incredible scale and preparing Geo-engineering as last resort.[74] In fact, societal changes were excluded up front, as stated by George H.W. Bush in his opening speech of the earth summit of Rio in 1992: "The American way of life is not negotiable".

But others disagree with G.H.W. Bush and call for attacking the problem at its root cause, 'the way of life' of high-income populations.:

T. Jackson [75] argues that an infinite economic growth, the keystone of capitalism, is neither compatible with a finite planet, nor essential to happiness and prosperity. He therefore advocates for a simpler and less materialistic life, for a shift from consumption to investments (e.g. in environment, assets and infrastructure), and for much more. R. Ares [76] argues that the energy transition will reduce the economic growth anyway: energy saving and renewable energy are more labour and capital intensive than fossil resources; they leave less labour, capital and useful work to feed the economic growth.

K. Raworth [77] extends Jackson's analysis by recommending to redesign the economy to serve not finance but society and the ecosystem that society (and finance) depends on. The economy needs furthermore to be built for resilience rather than efficiency, to better manage its dynamic that is typical for such complex systems. Raworth proposes numerous specific measures towards these goals.[77]

Focusing on industry, R. Henderson [78] warns companies for major risks they are facing, being in supply chains by losing access to quality resources, being in the market through damaging reputation and consumer boycott, or being in finance with early closure of expensive assets or with fines for

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external damages caused. She pleas for companies to change their focus away from *shareholder value* to *purpose for society*, and reorganize themselves around this purpose. They need to rediscover the value of respecting and empowering their employees. They need to identify new financing schemes that support them in their new focus on long-term societal benefits. They need to collaborate with governments to protect the common goods and protect the public institutions that secure law, health and education that society and companies need. In fact, the new capitalism needs to recognize and rebuild the basis it's standing on: a good natural capital as resource, good law for smooth operation and well-distributed wealth as consumers basis.

A. Buller [79] dives further into the world of Finance, particularly of Green Capitalism that attempts to solve today's environmental crises through the forces of free-markets. She demonstrates that four existential premises of green finance are in fact utopias: namely (1) the decoupling of economic growth from the consumption of energy and natural resources - the *Green Growth*, (2) the apolitic definition of environmental capital and environmental services, (3) the apolitic definition of market values for these capital and services, and (4) the effectiveness of the free-market in driving the systemic changes needed.

Supporting Buller, Finance is urged to better recognize and internalize the economic risks that are related to climate change,[80] being damages that are caused by climate change and that will affect the economy, being reserves and assets that may never or insufficiently be exploited, or being companies sued for the impact of their activities. In fact, the European Central bank recently announced to include some of these risks and their evaluation processes and the US Federal Reserve warned about the increasing cost and decreasing availability of property and rental insurance as a result of climate-related risks[81,82]

In short, capitalism is possibly the best we have to drive progress, as it has done for two centuries. But the free market and novel technologies may not be able to unlock the infrastructure lock-in that hinder solving the global environmental crises. The free market may have to be restrained to ensure that critical externalities such as the environment, the institutions and equalities are properly protected in economic decisions. Hence, we may need to consider alternative futures for humanity, futures that address the root cause of the environmental crises, i.e. the consumerism and unlimited economic growth?[83]

7 Conclusions

The defossilisation of our economy will proceed through the electrification of a large part of the energy system. But this will not fully displace the carbon-based economy, for we'll likely keep using carbon-based fuels for high-duty applications and keep using carbon-based products for chemicals and materials. Defossilisation will force to transition from oil and gas to waste, biomass and CO_2.

We argued that society has enough **renewable carbon sources** to supply the expected demand for fuels and chemicals, even for aggressive defossilisation scenario: waste and biomass residues from agriculture and forestry could suffice to meet a demand of 5-10 Gt_C/a carbon. Half of the carbon could be provided directly and the other half indirectly by valorising the waste-CO_2 rejected by these processes. Accordingly, there would be no need for expensive capture and utilization of atmospheric CO_2 nor for the dedicated crops or marine biomass.

We also argue to have enough **technology** capabilities to start using these renewable feedstocks, being mechanical/chemical recycling, waste gasification, chemical/fermentative conversion of sugars, lignocellulose fractionation, or CO_2 hydrogenation/electroreduction.

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But we recommend to broaden our **product portfolio**. Waste and waste-CO_2 are well suited to deliver the hydrocarbon products that form the bulk of our product slate. But residual biomass would be better used for making oxygenated fuels and materials, e.g. fuel-ethanol, polyesters and paper/cardboard products. These would ideally decompose naturally when accidently/inevitably released in the environment. We also recommend to value renewable fuels and chemicals according to their defossilisation merit rather than focusing on CO_2 savings for fuels and on circularity for chemicals.

But having the feedstock and conversion technologies don't seem sufficient to progress the defossilisation of energy and chemicals beyond the point reached today. Several ***systemic hurdles*** need to be recognized and removed. An important hurdle is the public resistance: it brings personal and immediate costs, inconvenience and uncertainty for the vague perspective better livelihood for others in the future. This public resistance naturally leads to a political resistance, which prioritize the *Affordability for all* over *Security of Supply* and *Sustainability* for the energy sector (see Energy Trilemma), i.e. fossil over renewable carbon. But equally important is the combined infrastructure and institutional lock-in that limit further progress. This requires broad and well-coordinated unlocking strategies for systemic change.

Within the broader energy system, renewable fuels and chemicals are peculiar by mainly suffering from high costs, but much less from inconvenience and uncertainty as well as infrastructure lock-in. The renewable feedstocks are indeed harvested at modest scale and require extensive processing, but the renewable products are generally compatible with present infrastructure and behaviours.

But society also has a number of ***systemic enablers*** that can lower the hurdles on costs, inconvenience and uncertainty or provide some valuable compensation for them. Local renewable feedstock can support the local economy and secure the access to feedstocks. Integrating the renewable economy into the present fossil infrastructure can lower the costs, reduce infrastructure lock-in and smoothen the deployment of the novel technologies (Figure 16). Initially prioritizing the affordable products for the feedstock available, e.g. making fuels from plastic waste and oxygenated chemicals from sugar or biomass, could help reducing the maturation costs of the new feedstock and conversion technologies.

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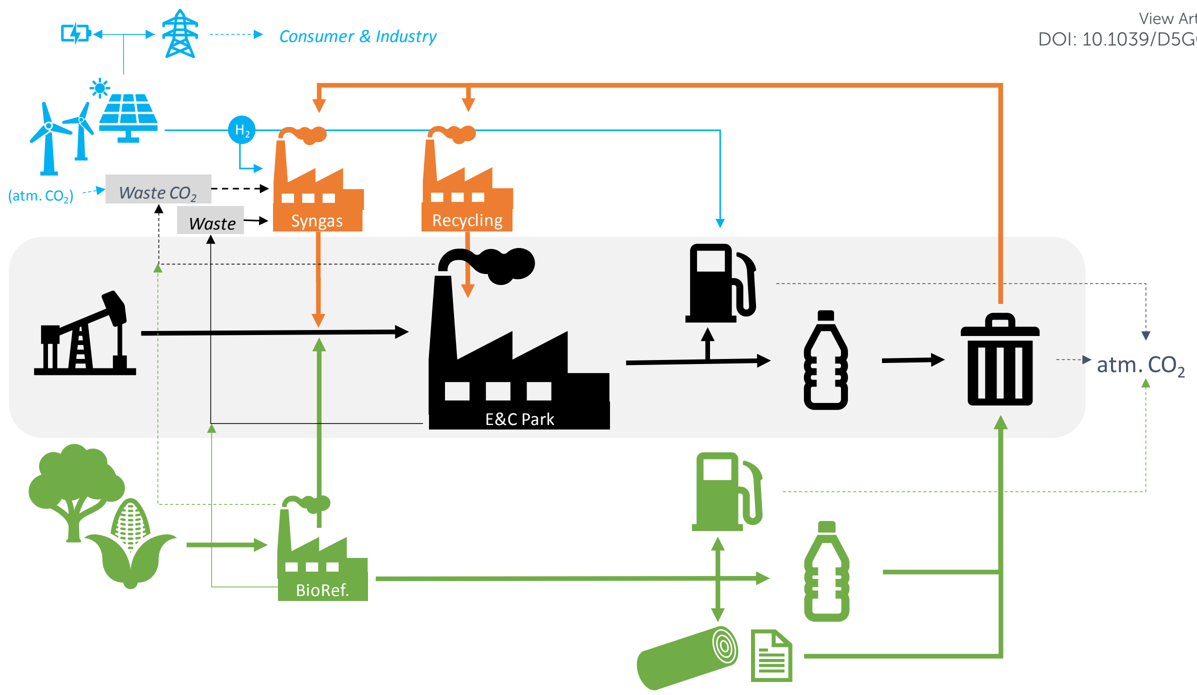

Figure 16 – Integrated network of technologies to transition from fossil products to drop-in and new renewable products

But the defossilisation of our economy will still bring costs, inconvenience and uncertainty. It will therefore need a broader support. It will need soft encouragement or nudging e.g. in the form of information, feedback, fossil-free defaults, peer emulation and gentle peer pressure, fair and affordable regulations, etc. to help society to choose for defossilisation and accept its inevitable burden. All these pressures are eventually challenging the foundation of our economic model that has evolved to serve the economy rather than the society, and that empowered the *free market* to make the arguably best choices. We may need to reimagine our economic model to better serve society and restore its foundations: its environment, its institutions and its equality.

Noted added in print: *The costs considered in this perspective were limited to direct consumer costs. They did not include the external costs to society that result from side-effects such as pollution, chronic accidents (e.g. spills), congestion, climate change, etc. These external costs can be very significant, occasionally higher than the direct costs of energy and fuels (Sovacool, 2021). They should be included to determine the true affordability of renewable energy and products to society.*

*(B.K. Sovacool, J. Kim, M. Yang, Energy Research & Social Science, 2021, **72**, 101885)*

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Data availability statement

The data are reported either in the perspective self, e.g. in tables, or in the papers referred to.