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

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Climate change will force society to abandon the fossil feedstocks, which have been 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.*, political/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.

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1. The paper provides a systemic perspective on the carbon transition, *i.e.*, the defossilisation of fuels and chemicals. It does it by critically discussing feedstock, technology, deployment hurdles and enablers, addressing technological as well as societal aspects of the transition.
2. The switch from fossil to renewable feedstocks 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-persistent chemicals. It addresses the technological as well as societal dimensions of the defossilisation transition.
3. The defossilisation of fuels and chemicals is inevitable. The broad and systemic discussion presented here should help practitioners of green chemistry understand the bigger picture and, thereby, focus their research such that it also addresses the deployment hurdles.

1. Introduction

The exploitation of fossil resources has provided unprecedented wealth in most parts 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 the 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 towards limiting global warming by defossilising their energy systems 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 breadth.

This paper presents a systemic perspective on this carbon transition, addressing not only the energy sector but also the chemical and material sectors, which spun off from the fossil industry. The perspective starts by sketching the present state of the fossil industry, then reviews the potential sources of renewable carbon with their global availability, environmental acceptability and affordability. The 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 resistance, costs and pain of technology maturation. It finally considers sys-

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temic enablers such as local resources, existing industrial infrastructure, broadening of product portfolios, 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 that need 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 now needs 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 approximate numbers and simplified calculations. By prioritizing transparency rather than exhaustive coverage, the perspective will limit the literature references to about 80 illustrative ones, trusting that these will guide and encourage readers to explore abundant and very broad literature. Particularly recommendable are the numerous publications from the NOVA Institute on its Renewable Carbon Initiative.

Interested readers may also appreciate knowing that a multi-author book is being prepared and will be published by the RSC. It will cover the scope of this perspective in far greater depth, through 30 chapters written by specialists, and will hopefully address several gaps that remain beyond the scope of the present article.

2. Demand for renewable carbon

Society is presently consuming about 10 Gt of fossil carbon per annum, mainly as an energy source for industry, transport and building, and, to a smaller extent, as feedstock for chemicals and materials (Fig. 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 lighting and heating of buildings. Heavy-duty applications are much more difficult to electrify, however. 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 uses much of it to deliver high temperatures (>600 °C) that are challenging to reach at scale with electrical heating.[2] Similarly, heavy-duty transport, such as aviation, marine, long-haul trucks and off-road machines, must carry large amounts of energy in a highly compact form. The battery fall short in energy density 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 do not 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 continue to rely on carbon as a versatile foundation for their products.

Different scenarios estimate different rates of defossilisation and electrification and complementary needs for carbon-based fuels. For the sake of illustration rather than prediction, this perspective will focus on one aggressive scenario that aims at limiting global warming to +1.5 °C. This is 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^{-1} for heavy industry, and 2 Gt a^{-1} for heavy transport (Fig. 1, middle;[6]). However, one also needs to add the growing demand for chemicals and materials, which could rise to ~3 Gt a^{-1} (Fig. 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] This evolution of carbon demand eventually results from a balance between decreasing fuel demand due to electrification and the increasing chemical demand. Whether it is 5 or 10 Gt_C a^{-1}, society will need to shift its carbon feedstock from fossil to renewable sources to meet the growing demand for high-duty fuels and chemicals, while keeping global warming within +1.5 °C.

3. Feedstock for renewable carbon

Where will society find 5–10 Gt a^{-1} 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 (Fig. 2, routes 1 and 2). The first one is based on biomass, letting nature capture CO_2 from the atmosphere and convert it to usable forms such as sugars through photosynthesis. The second approach relies on human technologies to capture CO_2 from the atmosphere and convert it, using renewable electricity and water, into fuels or chemical feedstocks. Beyond CO_2, there is another source of 'renewable' carbon, the carbon that is embedded in our products and eventually ends up in our waste (Fig. 2, route 3).

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

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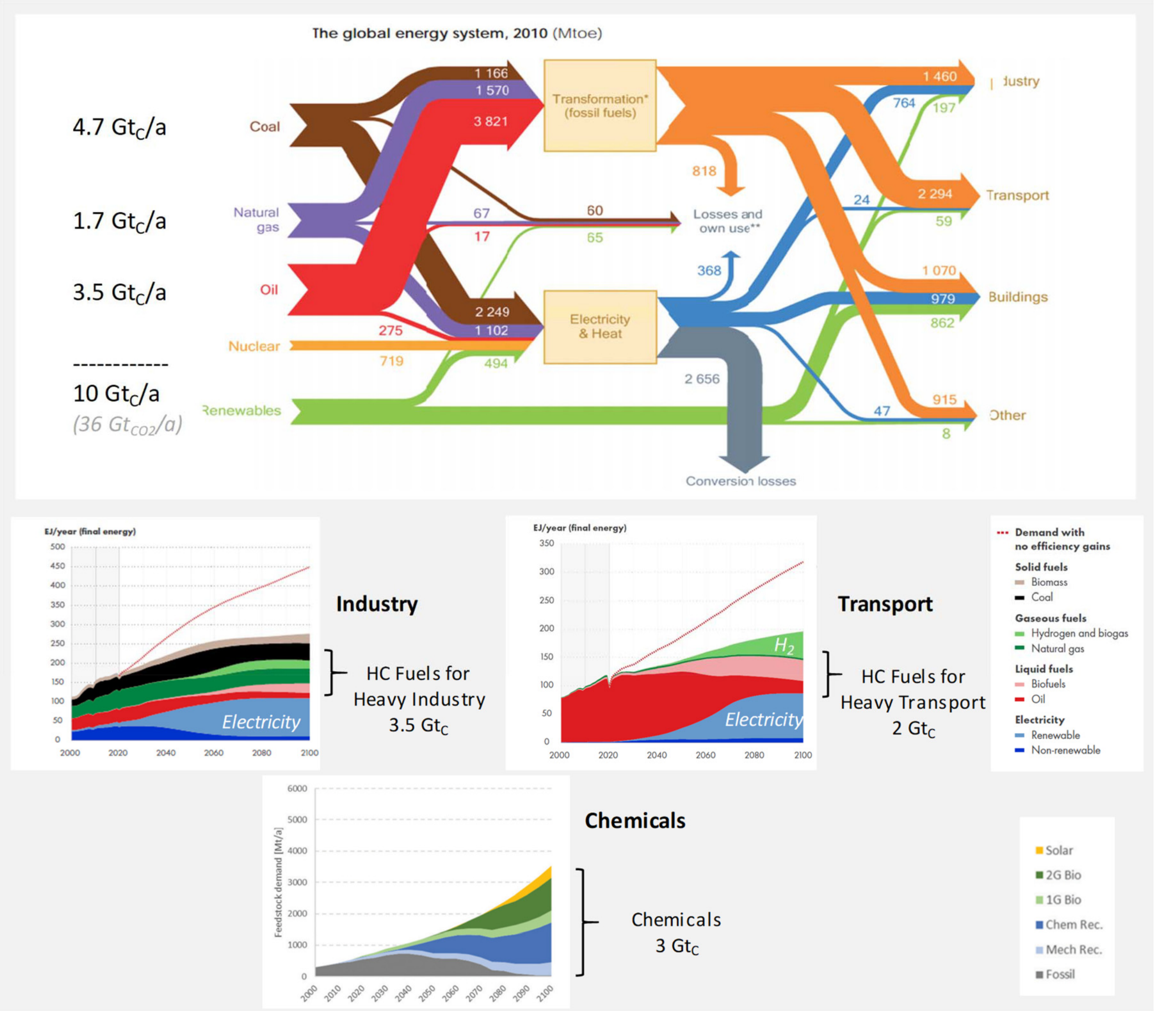

Fig. 1 Present (top[6]) and future (middle[4] and bottom[2]) demand for carbon (top is adapted from IEA, copyright 2012, middle is adapted from Shell, copyright 2021).

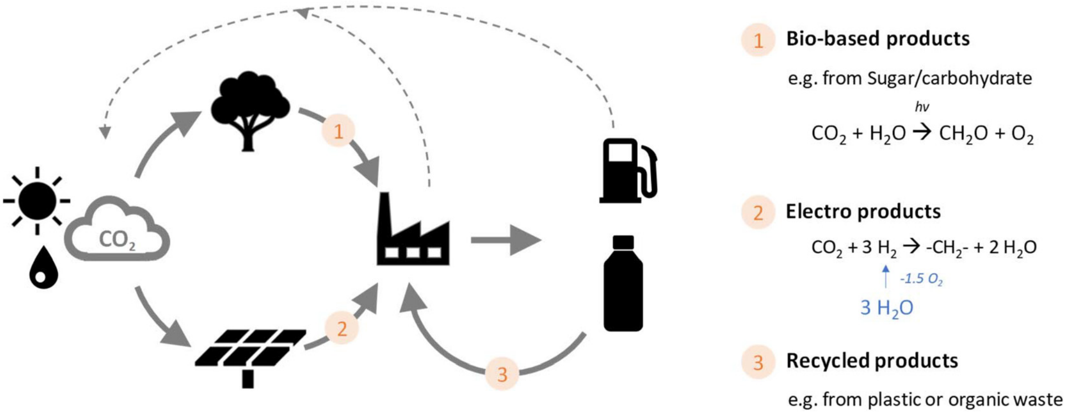

Fig. 2 Potential reserves of renewable carbon.

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Table 1 Approximate availability, acceptability and affordability of renewable carbon feedstocks (see main text for justification and sources)

	Potential volume ($Gt_C\ a^{-1}$)	CO_2 emissions ($t_{CO_2}\ t_C^{-1}$)	Price (\$ per 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 per t from atmosphere and at −\$100 per t (avoided emission) from waste and on renewable H_2 optimistically priced at \$3 per kg.

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 Fig. 4. The readers can choose to jump directly to the combined analysis in section 3.4, and come back to 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.

3.1. Availability

The largest reserve of renewable carbon is indisputably the CO_2 that is present in the atmosphere and the oceans. Atmospheric CO_2 alone has been estimated to be 900 Gt_C,[8] *i.e.*, 100 times the annual demand of renewable carbon estimated above. Humanity could run for a century on it. But capturing atmospheric CO_2 at a rate of 1 $Gt_C\ a^{-1}$, *i.e.*, ~10% of the present emissions of CO_2, would be a gigantic task. It would also require us to produce about 0.5 Gt a^{-1} of renewable H_2 to reduce the captured CO_2 to hydrocarbon, which corresponds to using a third of today's global energy consumption in the form of renewable electricity to split water to H_2, an equally gigantic task.

It is more convenient to let nature capture CO_2 for us. 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 grow at a rate of about 2 $Gt_C\ a^{-1}$,[10] from which we could reasonably divert ~10% for valorisation to fuels and chemicals. But crops are accompanied by a comparable amount (~2 $Gt_C\ a^{-1}$) of lignocellulosic residues,[11] which could be used as feedstock. The same holds for forestry, which produces as much lignocellulosic residue as round wood and other wood products.[12] We could therefore count on having ~5 $Gt_C\ a^{-1}$ of lignocellulosic residue for manufacturing fuels and chemicals. This is consistent with the 100 EJ a^{-1} (5.9 Gt a^{-1}) that is reported as sustainable biomass in the literature. This potential could further increase with improvements in agriculture, reduction in biomass losses and reduction in meat consumption, which would free up crops or land for growing more biomass.

The availability of carbon in waste is much lower at about 0.5 $Gt_C\ a^{-1}$, which is split about equally among plastic waste and organic waste such as paper, cardboard and wood.[13] However, growing global wealth and the correlated growing demand for chemical products will also result in a growing supply of waste to valorise. The 10× increase in chemicals proposed in Fig. 1 (bottom) by 2100 would raise the availability of waste carbon to some 5 $Gt_C\ a^{-1}$.

These resources add up to about 10 $Gt_C\ a^{-1}$ of renewable carbon, which compares favourably with the 5–10 $Gt_C\ a^{-1}$ that we may need by 2100. However, this does not mean they could deliver 10 $Gt_C\ a^{-1}$ 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^{-1} of renewable carbon to produce some 5 $Gt_C\ a^{-1}$ of products with 5 $Gt_C\ a^{-1}$ 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^{-1} of renewable H_2. Notice that this waste CO_2 is more promising than atmospheric CO_2, for it is generally produced at much higher concentrations 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, thereby bypassing 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 planetary boundaries. But it will also recognize the importance of social acceptability.

Climate impact. Many extensive lifecycle analyses (LCA) have been devoted to assessing the overall savings 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 SI. However, many of the conclusions can be drawn more simply by focusing the discussion on the CO_2 footprint of the feedstock, leaving aside the emissions of converting the feedstock to the final product, which—by experience—appear to show much less differentiation. We will use naphtha as the fossil reference, which is produced with the emission of ~1 kg of 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 of CO_2 per kg C from the atmosphere, but reemits a small fraction during harvest and transport. By experience, this results in overall emissions of about $-1.5\ kg_{CO_2}\ kg_C^{-1}$ for crops, $-3\ kg_{CO_2}\ kg_C^{-1}$ for bio-residues and $-2.5\ kg_{CO_2}\ kg_C^{-1}$ for atmospheric CO_2/H_2 (CCU). The moderate final savings of crops and CCU result 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 under-

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ground in the root system and the microbial life that feeds on 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 had not been 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 a saving of $-3.6\ kg_{CO_2}\ kg_C{}^{-1}$ by omitting incineration, to which one needs to add the marginal emissions of sorting and cleaning for recycling. Consequently, waste feedstocks show a CO_2 footprint that varies from about +0.5 to −3 $kg_{CO_2}\ kg_C{}^{-1}$, when diverting waste from landfill or incineration, respectively.

Broader environmental footprint. Beyond CO_2 emissions, one needs to consider other environmental stresses to reduce, *e.g.*, water use/contamination, land use/degradation and pressure on biodiversity. Importantly, however, these are local environmental factors and not global ones, unlike CO_2 emissions. 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 has been estimated to be ~1000 km^2 $(t_{H_2}/a)^{-1}$ 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 tonne of residue per tonne of grain without additional environmental impact.[11] The same applies to forestry residues that also come at a rate of about 1 tonne of residue per tonne of 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 lifecycle analysts argue that the residues need to be a 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, only on eventual credits defined by regulators.

Diverting waste from landfill is bound to be environmentally favourable as it avoids contamination of land, air and water. Diverting waste from incineration reduces local emissions (beyond CO_2), particularly where incineration would be done without exhaust gas 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 income. It can also reduce the risks of food shortage by increasing the production of crops to supply industry, while still prioritizing food use in case of shortages. However, 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 or for collecting and sorting waste, could lead to exploitation, child labour or abuse of migrant labour.

3.3. Affordability

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

However, feedstock affordability should also consider conversion efficiency, which increases the overall costs of the feedstock per tonne of C in the product (Fig. 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 feedstocks that need extensive processing. We will not discuss this matter here, in the section on feedstocks, but will postpone it to section 5.3.

3.4. Triple-A potential

The various A's discussed above can now be combined in Fig. 4 for a comparative analysis. Accordingly, no single source

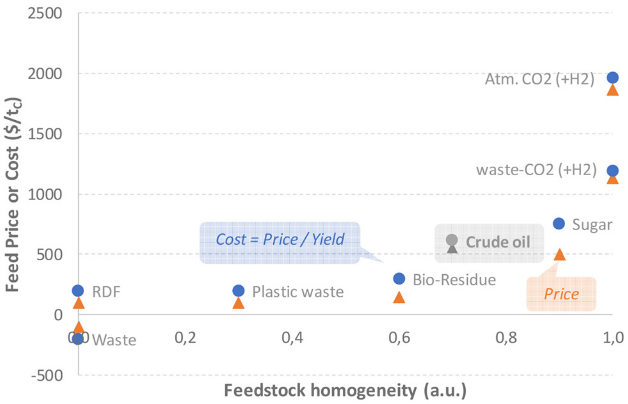

Fig. 3 The approximate prices (triangles) and costs (circles) of renewable feedstocks increase with homogeneity.

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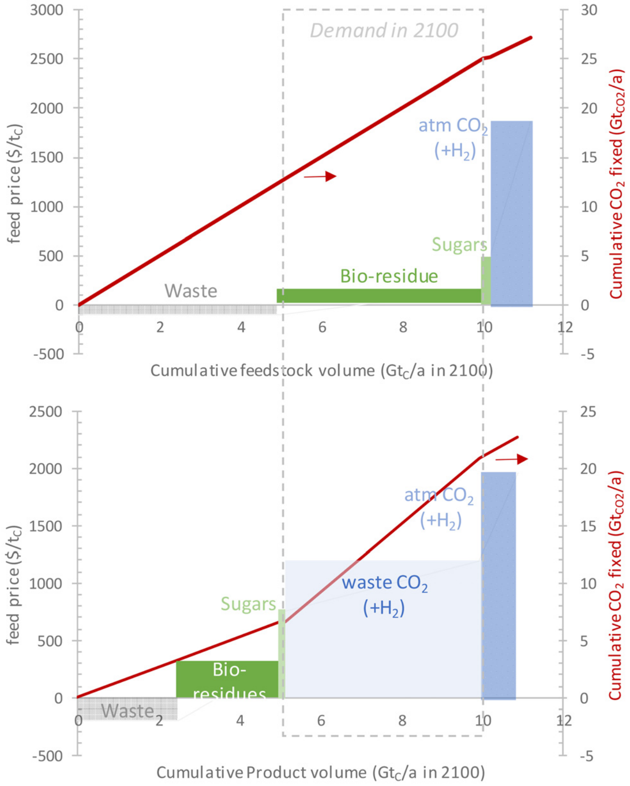

Fig. 4 Potential volume, costs and GHG emissions of renewable carbon feedstocks (top) and their derived products (bottom) after correction for conversion yields. The carbon lost during the conversion of waste, sugar and biomass forms the waste CO_2 feedstock (premises are detailed in the text).

seems capable of delivering the 5–10 Gt_C a^{-1} that we expect to need for our fuels and chemicals by 2100 (Fig. 4, top). Together, however, they may suffice as they add up to 11 Gt_C a^{-1}: 1 Gt_C a^{-1} from atmospheric CO_2, 5 Gt_C a^{-1} from residual biomass and 5 Gt_C a^{-1} from mixed waste. The mixed waste and bio-residues will arguably be the most attractive feedstocks, considering their availability (5 Gt_C a^{-1} each), acceptability (−2.5 t_{CO_2} t_C^{-1} each) and affordability (−$100 and +$150 per 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^{-1}, respectively) but also due to the modest acceptability of crops and the unaffordability of CO_2/H_2.

This analysis changes significantly when including the conversion efficiency to visualize the potential of the products made from these feedstock (Fig. 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 into a smaller product volume. Specifically, about half of the carbon contained in waste and bio-residue (5 Gt_Ca^{-1}) can be directly converted to products, which bear 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 to conversion facilities. It still needs a lot of renewable H_2, about 0.5 t_{H_2} t_C^{-1}, and thereby comes with high feedstock costs (~$1100 per t_C for $CO_2 + H_2$), though still lower than for atmospheric CO_2 (~$1900 per 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).

4. Valorisation technologies

With waste, biomass and CO_2 as potential resources 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, which are consumed at a 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 the assistance of solvents) or be converted back to their building blocks or their feedstock (chemical recycling). These technologies are properly described in the literature[14,21] and will not be discussed in more detail 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 Fig. 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]

However, the waste streams contain carbon sources beyond just 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 pre-

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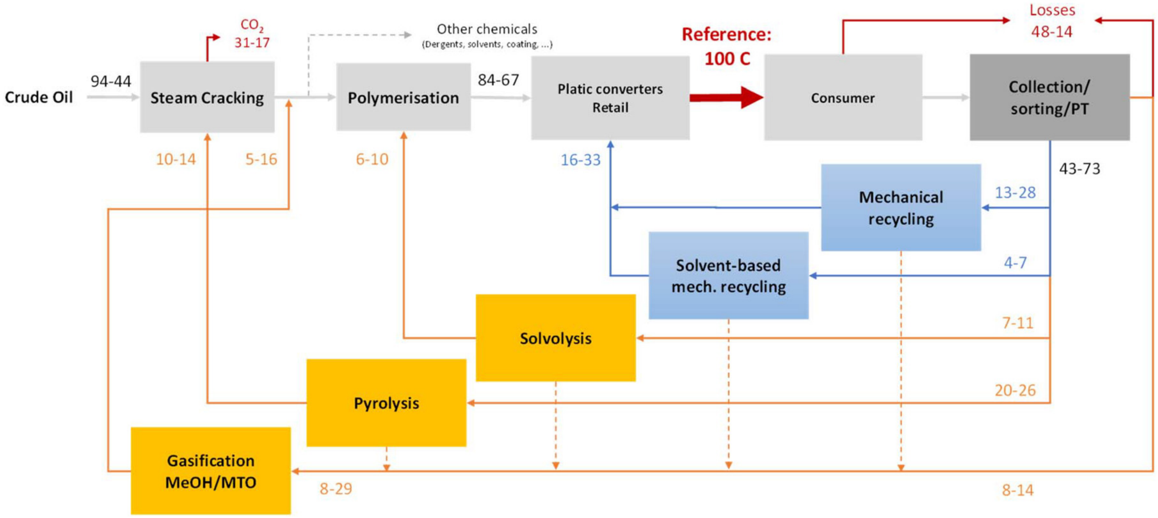

Fig. 5 Plastic recycling technologies are best placed in a cascade to maximize the substitution of fossil carbon with recycled carbon. The numbers represent normalized carbon flows according to realistic and futuristic sorting scenarios.[15]

sently recycled at a 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 up with unsorted plastic in a residual fraction that is called refuse-derived fuel (RDF), which is burned 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 cornerstone 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 this carbohydrate is used as structural elements of the plants, *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 the 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 (Fig. 6).[23,24] These intermediates generally exhibit alcohol and/or acid functionalities. They are thereby well suited for producing polyesters and related condensation polymers. Among these, polylactic acid (PLA) is currently the most common, but others are reaching maturity, *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

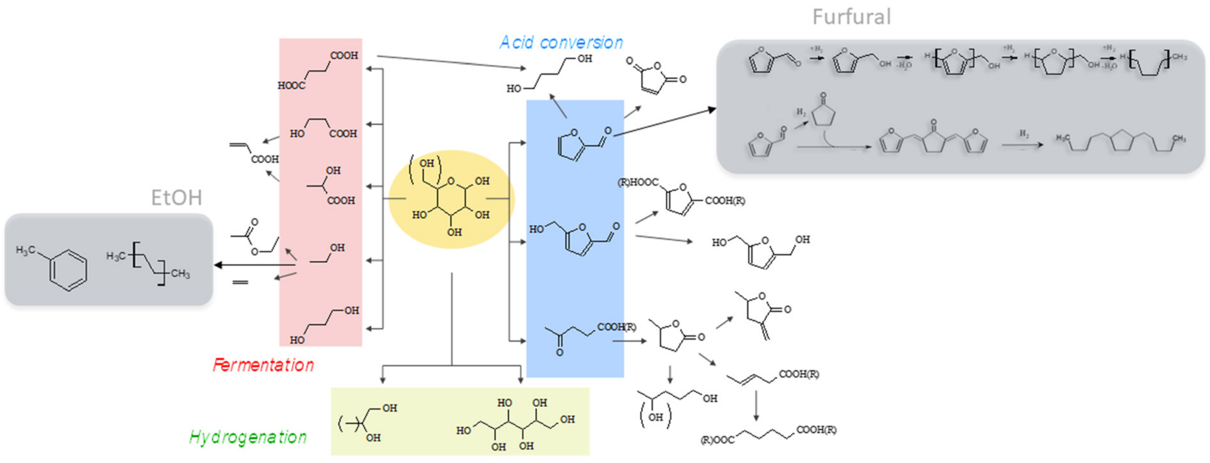

Fig. 6 Sugars can lead to a variety of chemical intermediates and fuel components [adapted from ref. 31 and 34].

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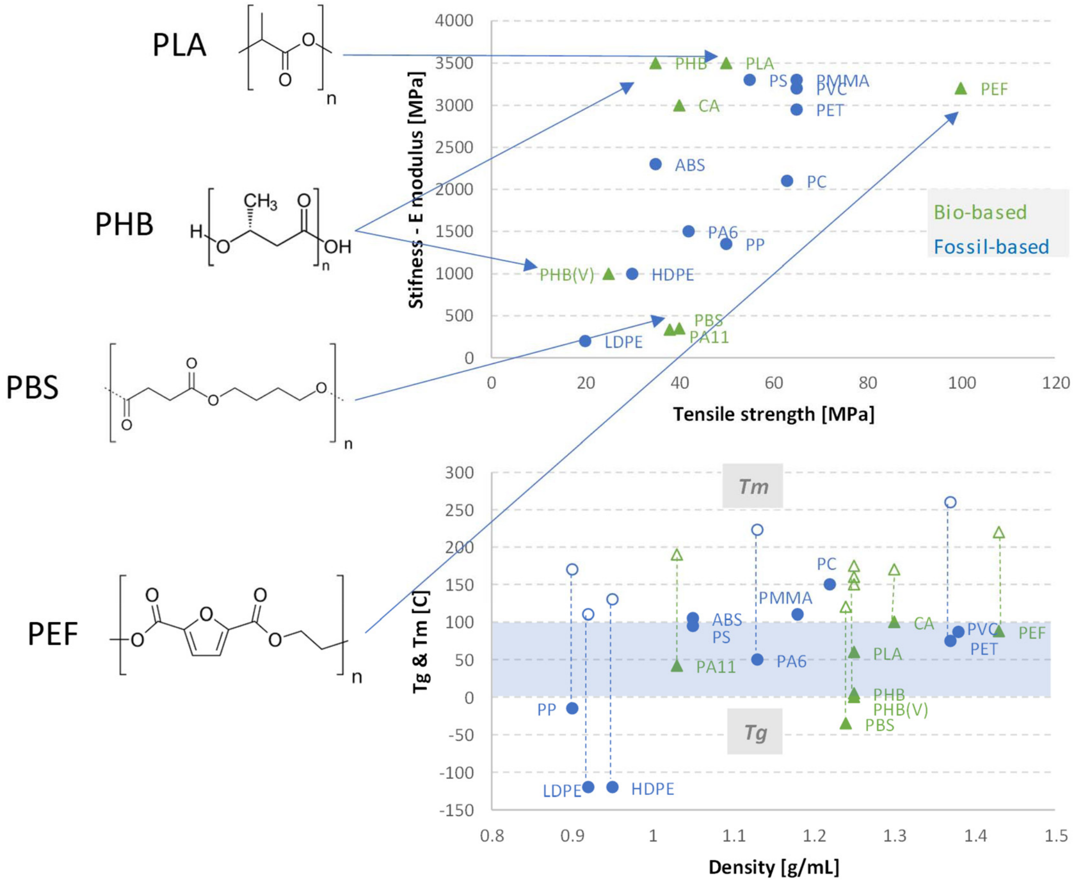

Fig. 7 Sugar-based polymers (green) can provide a variety of properties already offered by today's fossil polymers (blue) (T_g and T_m represent the glass transition and melting temperatures of polymers; adapted from ref. 25).

polyamides (Fig. 7).[25] One differentiating property 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 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^{-1},[30] or by being converted to hydrocarbons for use as diesel or aviation fuel components. Ethanol and furfural are promising fuel precursors (Fig. 6).[31–34]

The technologies developed for the 'digestible' carbohydrates, the starch and free sugars, are 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 (Fig. 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 shows that the hydrocarbon yields remain modest, typically 20–25 wt% of the biomass intake, as the technologies eventually discard all contained oxygen and half the carbon with it (Fig. 9).

A more subtle and efficient, though more complex and costly, approach consists of fractionating the biomass into its main constituents—cellulose, hemicellulose and lignin—and valorising them independently using technologies tailored to each fraction, thereby delivering 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 constituent carbohydrates and processed with technologies that are derived from those for digestible sugars. A special case is the production of furfural from pentoses that are not found in cellulose but only in the hemicellulose of hardwood 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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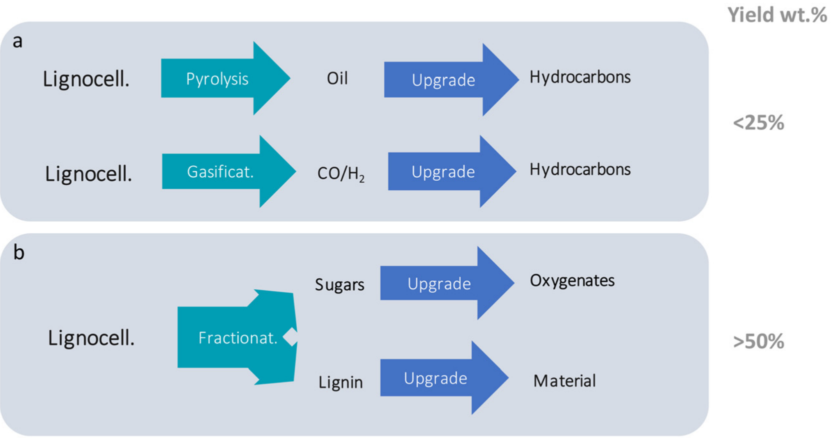

Fig. 8 Valorisation of lignocellulosic biomass *via* pyrolysis or gasification to hydrocarbons (a), or *via* fractionation to sugar-based oxygenates and lignin-based materials or fuels (b).

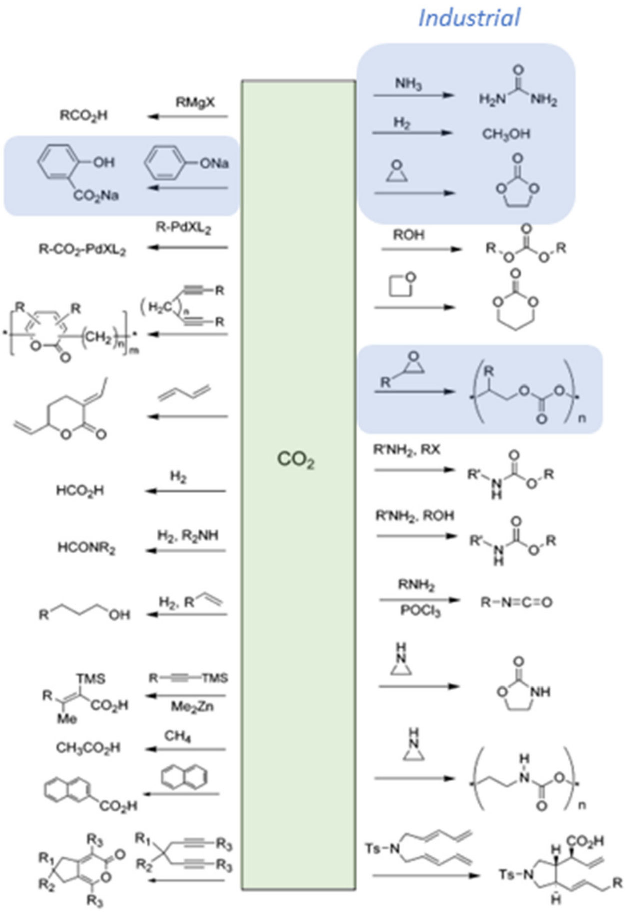

Fig. 9 Approaches to CO_2 valorisation (adapted from ref. 45 with permission from *Chem. Rev.*, copyright 2007).

While it has been the 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 $Mt_C\ a^{-1}$ 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 an electrophile, 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. However, they may not be very impactful, as these products have small markets, possibly a few tens of Mt a^{-1} globally or <1% of the 5–10 $Gt_C\ a^{-1}$ 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 important because it can lead to the fuels and base chemicals used today on a large scale of hundreds to thousands of $Mt_C\ a^{-1}$. However, this route is economically uncompetitive as it requires a lot of expensive renewable hydrogen (0.5 $t_{H_2}\ t_C^{-1}$), as we will discuss in section 5.3.

Much research is focusing on the hydrogenation route in an 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 (Fig. 10). CO_2 has to be captured 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 sources of renewable H_2 are

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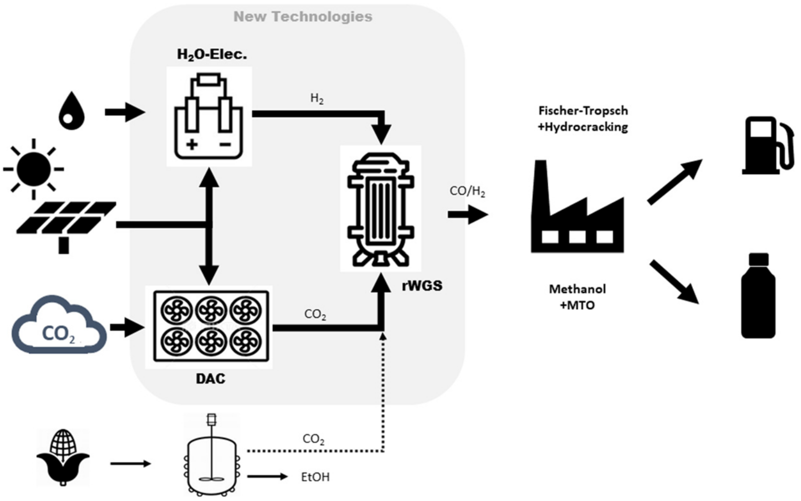

Fig. 10 Portfolio of technologies for CO_2 capture and hydrogenation.

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] 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 leads to loss of degrees of freedom and loss of performance by operating each function away from its optimum conditions. The resulting penalty may offset much, if not all, of the economic benefits targeted.

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. However, 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 remain.[51]

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 started some 25 years ago and has progressed haphazardly since. The progress is even more disappointing when compared to the penetration of mobile/smartphones, which started around the same time and are now ubiquitous in high- and medium-income economies. Why is it so much more complicated? What are the hurdles on the way? We will here discuss 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 design their energy systems to make energy affordable and abundant for all, while securing its supply and, for the last few decades, also minimizing its environmental impact. This balancing act is also known as the energy trilemma. Affordability often claims the highest priority, above security and sustainability, as illustrated in Fig. 11 for the major economic blocks.[54] This balance is not static but keeps 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 of environmental policies approved in 2020 to make the EU climate neutral by 2050, now sees elements being challenged, weakened and/or delayed. Similarly, the US Inflation Reduction Act that was signed in 2022 has seen its Clean Energy elements being challenged by the 2025 legislative order 'Unleashing American Energy'.

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

Ultimately, a government's priorities reflect the balance between the priorities of the people in (or aiming for) power – in politics, finance and industry – and the priorities of the citizens who assign the power in democratic countries. Therefore,

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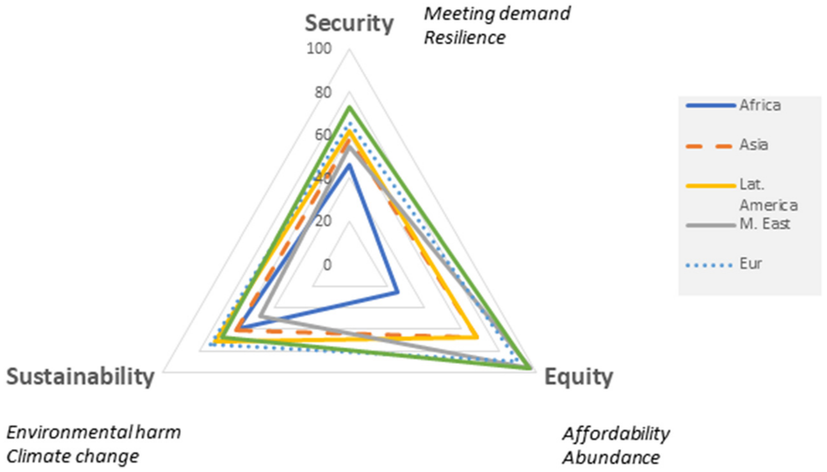

Fig. 11 Energy trilemma of major economic blocks in 2021 (based on data from ref. 52).

let us 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, for example, gain, pleasure, pride/identity, and belonging, which are themselves influenced by personal values and social norms. New products or services become popular when they elicit 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 a 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 distances with an 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, and show no visible results for decades.

This resistance is not limited to citizens but may equally apply to the captains of industry, shareholders and politicians. Decision makers are also driven by emotions such as gain, pleasure, pride, identity, and belonging. 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.

An important point 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 uncertainty. Residual inconveniences may just be limited to sorting waste for recycling or the occasional use of less-performant renewable materials, such as paper packaging instead of plastic. Hence, the carbon transition is mainly suffering from high costs. So, let us talk about costs!

5.3. Costs

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

Among the renewable feedstocks, mixed wastes and residual biomass are economically advantageous over fossil feedstocks (section 3.3 and Fig. 3). But cheap feedstocks generally require extensive processing, and this may eventually make products too 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 eqn (1).[54]

$$\begin{aligned}\text{Min. Product price}[\$\text{ per t}_{\text{prod}}] = {} & (\text{feed price}[\$\text{ per t}_{\text{feed}}] \\ & + \text{processing costs}[\$\text{ per t}_{\text{feed}}])/\text{yield}\,[\text{t}_{\text{prod.}}\ \text{t}_{\text{feed}}{}^{-1}]\end{aligned} \tag{1}$$

Product and feed prices are available in the literature,[55] the processing costs can be crudely related to the number of processing steps and the average step cost (*e.g.*, \$100–300 per t_{feed}

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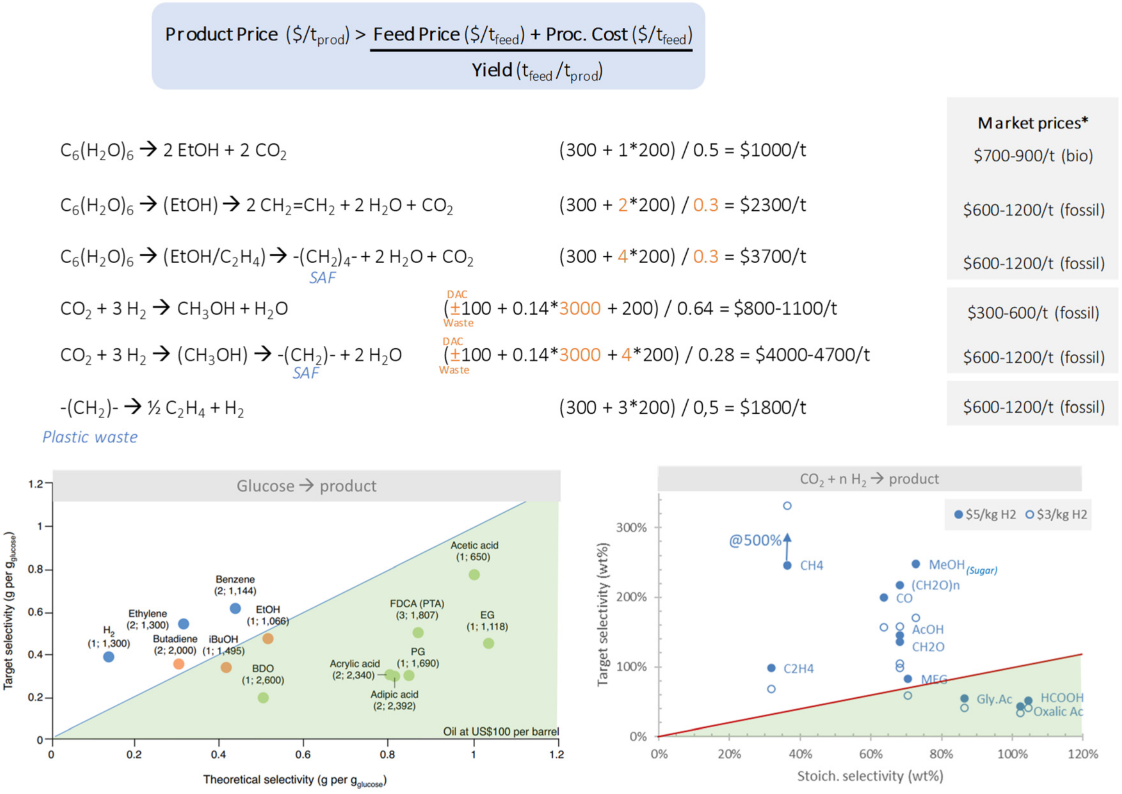

Fig. 12 Screening economics for valorising sugars and CO_2 (premise: glucose at \$300 per t, CO_2 at \$100 per t, H_2 at \$3–5 per kg; \$200 per t per step; multiple steps for glucose but single step for CO_2; bottom left comes from ref. 17).

per step),[54] and the yield can be estimated from laboratory experiments. Fig. 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 Fig. 12 (top).
- It is also imperative to achieve high yield *on a weight basis*, *i.e.*, to sell as many tonnes of product per tonne of feedstock as possible, to have a larger product output bearing 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 in Fig. 12 (bottom), which compares the stoichiometric yield of various products made from glucose (left) and CO_2 (right) with the 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 yields exceeding the stoichiometric yield. Notice that the cost of renewable H_2 makes very few CO_2 derivatives affordable, even when we assume that they are made in a single step and use optimistically cheap renewable H_2 (\$3 per kg), as done in Fig. 12 (bottom, right).

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 feedstocks are generally more difficult to harvest and transport over long distances than crude oil. Hence, their conversion processes will likely operate at a smaller scale (Fig. 13, left). The general scaling laws teach us that a 10-fold decrease in scale leads to only a 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 (Fig. 13, right).[56,57] Water electrolysis is an extreme case of an endothermic reaction with a prohibitive transfer duty (~180 $MJ kg_{H_2}^{-1}$) and, thereby, high investment costs.[58] Thermal cracking of polyolefin waste is also highly endothermic (~3 $MJ kg_{C_2H_4}^{-1}$). Biomass fractionation and sugar valorisation generally proceed at high dilution in

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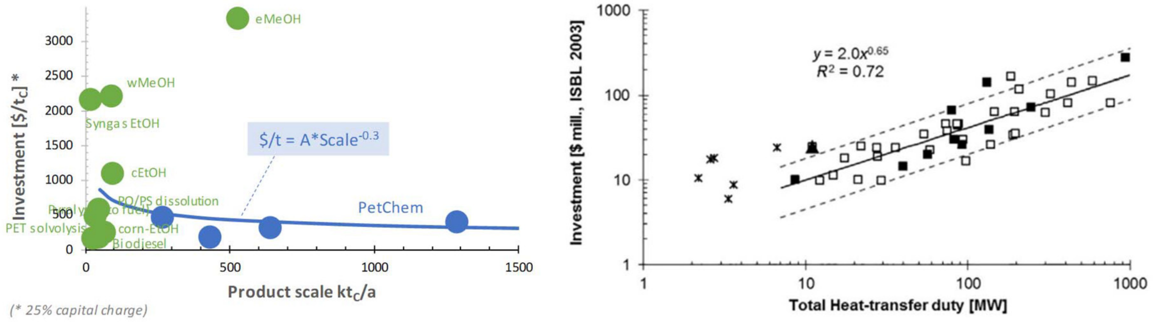

Fig. 13 Process scale (left) and energy transfer duty (right) largely determine the investment and processing costs (left: data from ref. 59, 60; right: ref. 57).

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 them to higher or lower levels within the range of \$100–300 per t_{feed} per step. Such refinement can be incorporated into the economic equation of Fig. 12 (top), and may even become critical when the overall processing costs exceed the feed costs.

Although oversimplified, this discussion on manufacturing economics clearly shows that renewable hydrocarbons will likely remain more expensive than their fossil equivalents, only slightly when derived from plastic waste, more from biomass and prohibitively from CO_2. However, oxygenated intermediates offer better perspectives because they are expensive to make from fossil feedstocks, 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. 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 at a larger scale. All this usually results in an erosion of conversion costs with time, following the well-documented learning curve of eqn (2) (ref. 63) because of the gradual decrease of processing costs and increase in yield (eqn (1)). For typical power, *m*, of −0.3,[63] the cost per unit of product decreases by 20% for every doubling of deployed capacity and by 50% for every 10× increase in deployed capacity (Fig. 14, left – with nuclear as a notorious exception[63,64]).

$$\text{Costs [\$ per t or kW]} = C_0 \times \text{cumulative capacity}^m \qquad (2)$$

Junginger *et al.* report such learning curves for numerous energy technologies, *e.g.*, for wind, PV, concentrated solar power and bioenergy.[61] Therefore, 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 advantageous over their fossil equivalents and possibly making less promising ones competitive. Interestingly, the learning curve is not limited to the conversion costs but may also apply to the production of energy feedstocks, as exemplified for the production of sugar cane and corn,[61] thereby decreasing the feed cost term in eqn (1).

The learning curve also provides information on the overall maturation costs of new technologies, which is illustrated by the red area in Fig. 14 (top). The 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 erode. However, such a 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 (Fig. 14, right).[65]

Accelerating the learning would likely require 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, and public purchase commitments, but this would also shift (part of) the learning costs to society and to the consumers, which is not a popular measure, as discussed above.

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 goods and services. Further progress now needs deeper and more well-coordinated systemic changes. Unlocking the broad infrastructure will require a broad set of strategies at individual, social, institutional, technological and economic levels. For instance, the transition needs new infrastructure to distribute and use the

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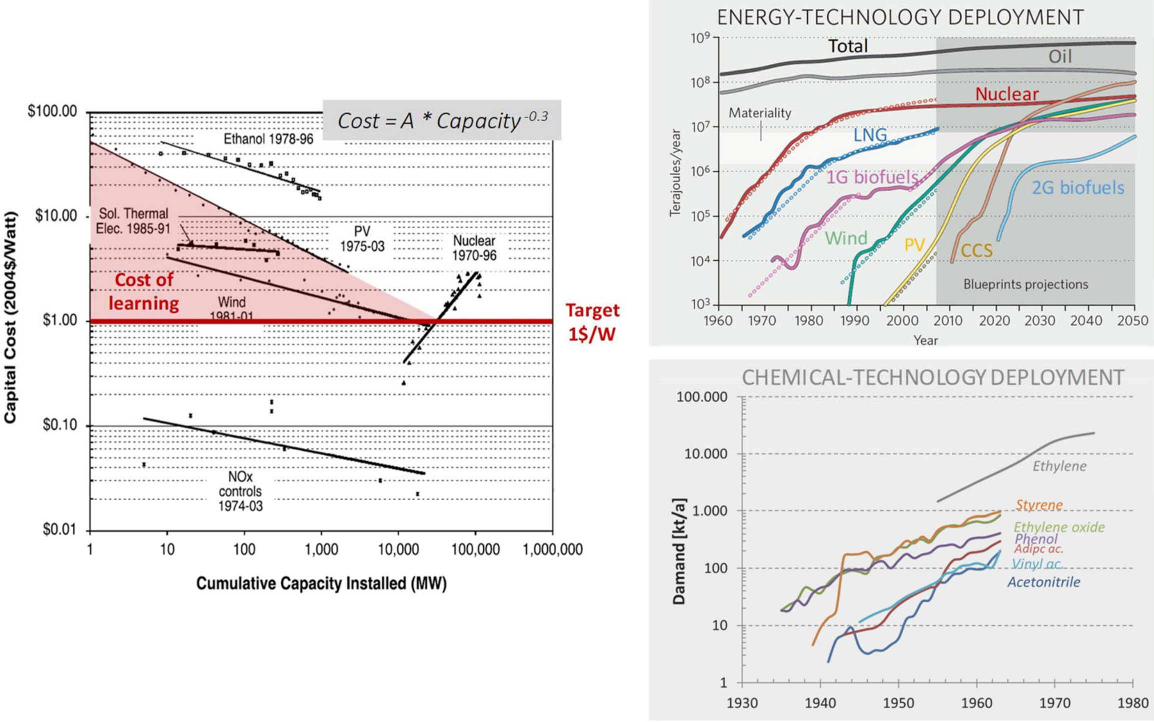

Fig. 14 Technology maturation erodes the manufacturing costs (left) but takes about half a century to complete (top and bottom right) (top left and right adapted from ref. 62 and 65 with permission from Springer, copyright 2007 and 2009; bottom right with data sourced from ref. 63 and 64).

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 costs that will be charged to the consumers, either directly or indirectly.

Interestingly, however, renewable fuels and chemicals do not require 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 surpass these hurdles. Renewable carbon 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 gain support from consumers. But all this is arguably not enough. We may need to reimagine our economic model to stimulate innovation and increase wealth while reducing inequality and protecting the environment. Let us discuss these enablers in more depth.

6.1. Exploiting local feedstocks

The exploitation of local feedstocks is a promising option for overcoming some hurdles, for it also reduces the dependency on foreign feedstocks, corrects trade imbalances, and reduces public resistance by stimulating the local economy and wealth. Renewable carbon sources are indeed more equally distributed over the planet than are oil and gas. All countries have access to their own waste, 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 depend 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 $t_C\ km^{-2}\ a^{-1}$ for Brazil to ~200 $t_C\ km^{-2}\ a^{-1}$ for the USA and 300–400 $t_C\ km^{-2}\ a^{-1}$ 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 5× the UN Reference Food Intake) could cover 10–20% of the carbon demand for the USA, EU and China, 27% for Brazil and 50% for India. The remaining land, however, could potentially provide more carbon than needed, being as biomass

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(*e.g.*, as energy crops or more food and agro-residue) or as products derived from waste CO_2 and renewable H_2.

Box 1 Case study on local feedstocks

We will consider five archetypal '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 products they could produce from their land. The results are summarised in the table below.

The archetypal countries show an energy/carbon demand varying over an order of magnitude, from 0.7 to 5.7 t_C per pers. per a, which follows their GDP. They also show variation in the potential production of renewable carbon. The production of total waste, set at 2× that of plastic waste to include organic waste, varies from <0.01 to 0.11 t_C per pers. per a. We assume that the various countries produce a minimum fraction of their food, which we set arbitrarily at 5× the reference food intake (8400 kJ per pers. per day), corresponding to 0.36 t_C per pers. per a of food and which uses 700 m^2 per Cap of land at an average productivity of 500 t_C km^{-2} a^{-1}. The countries thereby co-produce the same amounts of agro-residue to be used. The remaining land, which varies between 1300 and 39 000 m^2 per 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 land productivity set at 500 t_C per pers. per a for biomass and at 2000 t_C per pers. per 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 per pers. per a of biomass or 3–75 t_C per pers. per 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 a country's 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.

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$ per pers.	75	40	20	13	9
Population density	pers. per km^2	38	117	25	150	492
Energy consumption	t_C per pers. per a	5.7	2.9	1.7	2.6	0.7
	t_C km^{-2} a^{-1}	218	335	42	387	357
Potential ren-C production						
Total waste	t_C per pers. per a	0.21	0.13	0.11	0.08	0.01
	% demand	**4%**	**4%**	**6%**	**3%**	**1%**
Min. ag-residue	t_C per pers. per a	0.4	0.4	0.4	0.4	0.4
	% demand	**6%**	**13%**	**21%**	**14%**	**50%**
Biomass	t_C per pers. per a	13	4	20	3	1
	% demand	**223%**	**137%**	**1156%**	**115%**	**90%**
CO_2 (PV + wind)	t_C per pers. per a	49	15	75	11	3
	% demand	**857%**	**524%**	**4433%**	**442%**	**347%**

Premise: min. agro-residue = min. food = 5× ref. food intake of 70 kg_C per pers. per a; tot. waste = 2× plastic waste to include organic waste; land productivity is 500 and 2000 t_C km^{-2} a^{-1} for dedicated biomass and for PV + wind farms needed for CO_2 hydrogenation.

Hence, there are significant opportunities to produce renewable carbon locally, despite all the oversimplifications 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 (Fig. 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 (Fig. 15, orange infrastructure). Biomass can also feed today's refineries and chemical parks, *e.g.*, with bio-naphtha, bio-pyrolysis oil, bio-ethanol or bio-syngas, leading to renewable hydrocarbon fuels and chemicals (Fig. 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, Fig. 15, blue infrastructure) can also be valorised by co-feeding to the waste gasifier.

6.3. Matching the products to their feedstock

Today's product portfolio mainly consists of hydrocarbons that resemble much of 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 better resemble the new renewable feedstock?

The economic analysis illustrated in Fig. 12 shows that oxygenated intermediates such as ethylene glycol, butane diol, acrylic acid and adipic acids can be affordably made from sugars, while hydrocarbons seem unaffordable. The same applies to the oxygenated intermediates —formic and glycolic acids—prepared from CO_2. Focusing our efforts on converting the oxygen-rich feedstocks to hydrocarbons, as we presently do, promises to displace much larger volumes of fossil resources but with excessive learning costs (section 5.4) that may be rejected by society. It therefore seems preferable to start the transition by targeting higher-value oxygenated chemicals to prove the new technologies, and then gradually transitioning 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, 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 it will take decades to

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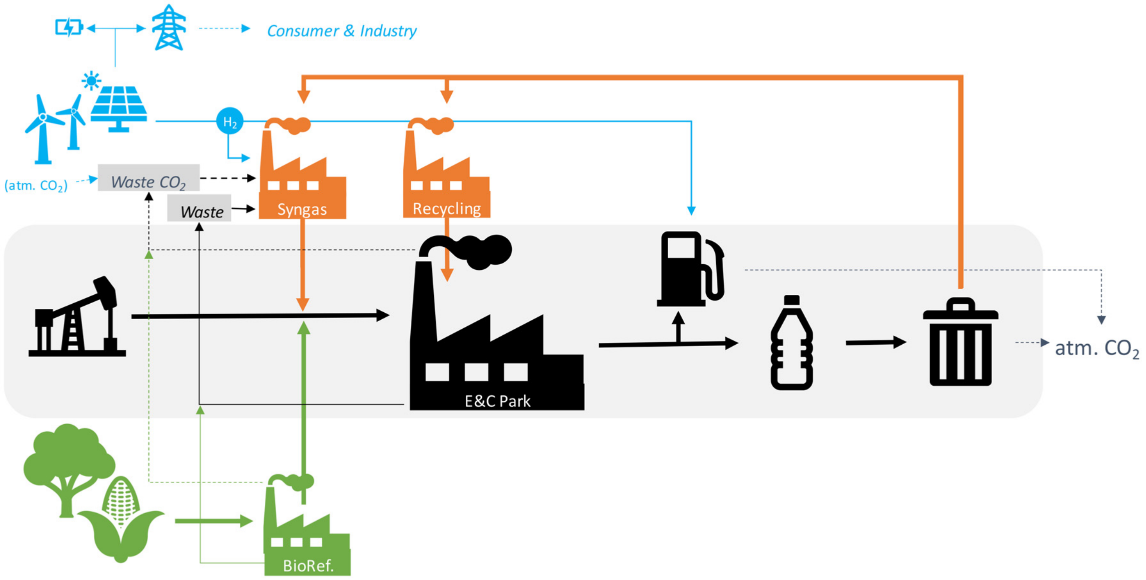

Fig. 15 The renewable carbon economy should be built on the existing industrial infrastructure.

allow the novel products to prove themselves. The bio-based polymer polylactic acid or polylactide, PLA, is a good example of slow market penetration, growing to ~700 kt a^{-1} or ~1% of the well-established fossil polyester PET in 30 years. The *drop-ins* do not need to prove themselves in the market and can 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 to 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 waste containing various plastics and organic wastes, *i.e.*, refuse-derived fuel (RDF), is clearly more challenging, however. The most robust and mature route consists of gasification, which burns part of the carbon to reach the temperature needed for producing synthesis gas.[68,69] 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 than is 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 converting 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 appeal to the wider population. Consumers may claim to support green products and services in opinion polls but often choose otherwise in supermarkets. In fact, the energy transition only attracts a small group of people who are appealed to 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.

'Soft' nudging of consumers and industry may take various forms.[70] Providing feedback on the progress made would encourage more progress, even more if the feedback helps to turn the effort into a game. Creating a community may also help people by sharing experience, encouraging, not feeling alone in the effort, and applying mild peer pressure to contribute. Public choices could be presented with the green option as the 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

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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 regressive subsidies on green options, *i.e.*, taxes/subsidies that increase/decrease with time or with consumption volume. However, care should be taken to ensure that these financial measures are effective, bearable and fair.[53] For instance, subsidies on solar panels have ultimately benefited wealthy homeowners while increasing the electricity bills of less wealthy home renters. Such measures should not be limited to consumers but also be extended to 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 an administrative burden that may be unbearable for small and medium enterprises. For instance, regulations are defined per sector. This often leads to systemic inconsistencies, biases and flaws when comparing different sectors. To effectively unlock a 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 equally considers fuels and chemicals as well as 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 the desired impact (*e.g.*, green H_2 *vs.* green electricity).

Let us dive into one bias that is particularly relevant for the present discussion, namely, the discrimination between fuels and chemicals. So far, regulators, NGOs 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 do not enjoy such support and, consequently, cannot compete fairly with renewable fuels for accessing renewable feedstocks. As a second example, the industry is mandated to use plastic waste for manufacturing circular chemicals but is discouraged from converting it to renewable fuels. Such separation is as artificial as it is 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 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 one to the other in time. Coming back to the example of plastic pyrolysis, it may be cheaper for society to allow the technology to prove itself and develop the industry by using pyrolysis oil for fuels and lubricant blend stock and, only later, tuning the technology to make more demanding feedstocks for the chemical industry. Similarly, sugar and cellulosic bio-refineries produce fuel ethanol today because it is mandated. But it may be (have 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 of finance, which eventually determines where investments are made. They need stronger control and enforcement. Most importantly, they need to become a priority for society. This implies that our whole economic model needs to be revisited – the subject of the next section.

6.5. Reimagining society?

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 previously unimaginable with human and animal power alone. However, this economic model seems to have reached its limits by destroying its foundations, namely the environment, the institutions and equality among people. These are indeed foundational as they provide the resources, the framework, and the stability that capitalism needs to thrive. Today's situation disturbingly resembles that of past human civilizations that eventually collapsed, with the difference of now being at a global scale.[72] Like today, past civilizations ignored the threat (environmental and others) for too long, organized themselves 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 an 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 technological miracles – developing CO_2 removal at an incredible scale and preparing geo-engineering as a 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 in 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 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 the environment, assets and infrastructure), and for much more. R. Ayres[76] argues that the energy transition will reduce economic growth anyway:

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energy-saving and renewable energy are more labour- and capital-intensive than fossil resources; they leave less labour, capital and useful work to feed economic growth.

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

Focusing on industry, R. Henderson[78] warns companies of the major risks they face, including loss of access to supply chains of high-quality resources, reputational damage and consumer boycotts as well as financial risks such as early closure of expensive assets or fines for external damages caused. She pleads 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 is standing on: good natural capital as a resource, good law for smooth operation and well-distributed wealth as a basis for consumers.

A. Buller[79] dives further into the world of finance, particularly green capitalism, which 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 unrealistic assumptions: namely (1) the decoupling of economic growth from the consumption of energy and natural resources – green growth, (2) the apolitical definition of environmental capital and environmental services, (3) the apolitical definition of market values for such 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] including damages that are caused by climate change and that will affect the economy, reserves and assets that may never or insufficiently be exploited, or companies sued for the impact of their activities. In fact, the European Central Bank recently announced that it will 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 hinders 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.*, consumerism and unlimited economic growth.[83]

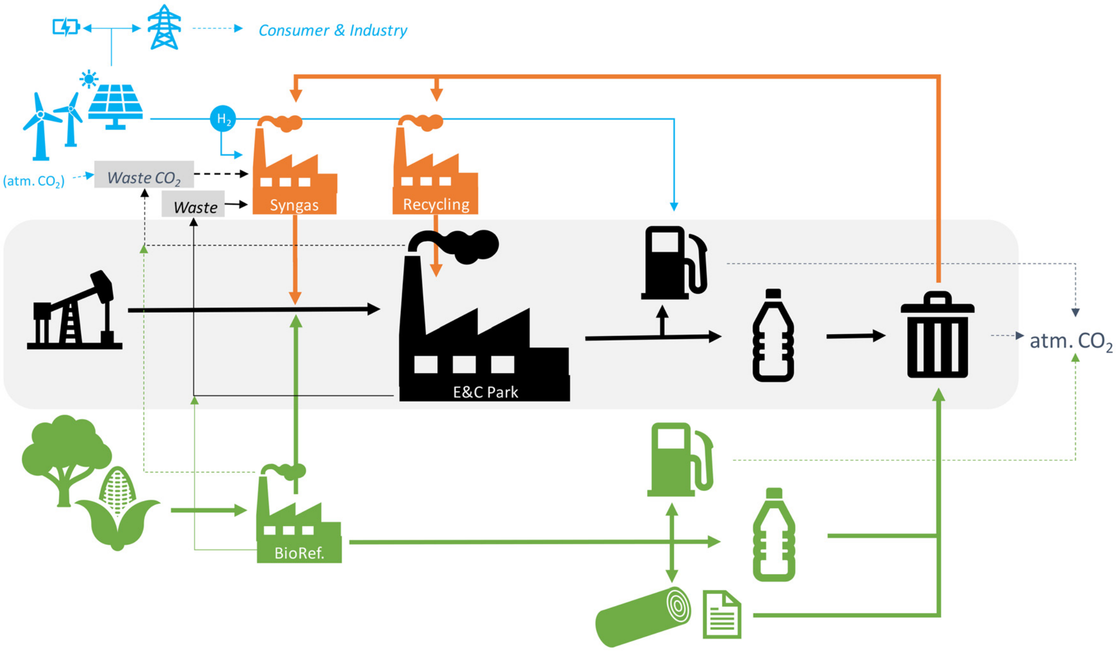

Fig. 16 Integrated network of technologies to transition from fossil products to drop-in and new renewable products.

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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 will likely keep using carbon-based fuels for high-duty applications and keep using carbon-based products for chemicals and materials. Defossilisation will force us 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 an aggressive defossilisation scenario: waste and biomass residues from agriculture and forestry could meet the demand of 5–10 $Gt_C\ a^{-1}$ 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 dedicated crops or marine biomass.

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

We also recommend broadening our product portfolio. Waste and waste CO_2 are well suited for producing 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 accidentally/inevitably released in the environment. We also recommend valuing renewable fuels and chemicals according to their defossilisation merit rather than focusing on CO_2 savings for fuels and on circularity for chemicals.

Simply having the feedstock and conversion technologies does not 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 public resistance: it brings personal and immediate costs, inconvenience and uncertainty in exchange for the vague prospect of a better livelihood for others in the future. This public resistance naturally leads to a political resistance, which prioritizes *Affordability for all* over *Security of Supply* and *Sustainability* for the energy sector (see section 5.1, 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 a 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 feedstocks can support the local economy and secure access to feedstocks. Integrating the renewable economy into the present fossil infrastructure can lower costs, reduce infrastructure lock-in and smooth the deployment of novel technologies (Fig. 16). Initially prioritizing affordable products for the available feedstock, *e.g.*, making fuels from plastic waste and oxygenated chemicals from sugar or biomass, could help reduce the maturation costs of the new feedstock and conversion technologies.

However, the defossilisation of our economy will still bring costs, inconvenience and uncertainty. It will therefore need 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, and fair and affordable regulations, to help society choose defossilisation and accept its inevitable burden. All these pressures are ultimately challenging the foundation of our economic model, which has evolved to serve the economy rather than society, and that has empowered the free market to make arguably the 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.

Conflicts of interest

There is no conflict to declare.

Note added in print

The costs considered in this perspective are limited to direct consumer costs. They do not include the external costs to society that result from side effects, such as pollution, chronic accidents (*e.g.*, spills), congestion, and climate change. These external costs can be very significant, occasionally higher than the direct costs of energy and fuels (Sovacool, 2021[84]). They should be included to determine the true affordability of renewable energy and products to society.

Data availability

The data are reported either in the paper itself, *e.g.* in tables, or in the papers referred to.

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