The Plastics Revolution, Quo Vadis?

Preamble

This book about the Plastics Revolution clearly depicts the large benefits of plastics as well as the challenges lying ahead for this important group of materials. As a result of the significant advantages offered over traditional materials at affordable cost, plastics are expected to grow to ca. 1 billion tonnes/annum in 2050 from 350 million tonnes/annum currently. This will mainly be driven by higher plastics use per capita in lesser developed countries with a strong upcoming middle class in Asia, South America and Africa. It prompts the question if this will (i) result in steady growth of the plastics produced currently (commodity plastics (66% of total), performance plastics and elastomers (11%) and thermoset resins and rubbers (22%)) or (ii) lead to a next and novel, innovative and smart wave in the Plastics Revolution with the introduction of novel building blocks, polymers and materials in the next decades. The answer will be determined by the major challenges for plastics that need to be solved at the same time: lower carbon footprint in the total value chain, sustainable production and solutions & designs that address the plastic soup problem.

What renewable options are most likely to happen?

There are four renewable options available: based on feedstock from the biobased economy (BBE), plastic materials recycling (PR), a hybrid version of the two or CO2 as a building block. Over the past twenty years a lot of lessons have been learned with respect to biobased feedstock and recycling, while the hybrid version and CO2 as feedstock are relatively new developments within the Circular Economy (CE). Until now only a few biobased developments for primary chemicals, intermediates and bioplastics have reached scale or met the set milestones, with the exception of alcohols, glycols, acids and di-acids.*

Note that the listed exceptions are all oxygenated molecules that have good-excellent carbon efficiency, making good use of the biomass feedstock structure. The corresponding bioplastics are existing or new polyesters with their typical strengths (modulus, impact strength, color and transparency) and weaknesses (hydrolytic stability, chemical and stresscrack resistance). Some of these bioplastics (PLA, PBS and starch based plastics) are biodegradable, ranging from easily compostable to compostable under industrial conditions (70 °C). France and Italy are the only countries that appear to benefit from the plastic soup issue by making biodegradable plastic shopping and garbage bags mandatory. This highlights the complexity of the transition where lobbying, national interests, differences of opinion, company preferences, interpretation of data and above all vision and political will play a major role.

The only *biobased non-food* products that have reached *world class* scale so far are biodiesel (B) and bio-ethanol (E), the latter not as a chemical building block, but as biofuel to be mixed with gasoline. This is highly subsidized and incentivized where different regions of the world promote different blending solutions.** In addition, sustainable biofuels for sea and air travel are needed. Since volumes for bioenergy are significant this has led to the food vs. fuel debate, and spurred the development of so-called second generation feedstocks: waste and residual streams from crops are used for the production of biofuels. Moreover there is no level playing field for non-subsidized biobased chemicals & plastics vs. subsidized biofuels & energy, despite growing support for the cascading principle. Today this is an integral part of many biobased national policies (incl. the Netherlands). We need to take this into account by looking into future scenarios, even if the arguments for bioenergy/biofuel do not translate 1-to-1 for biochemicals on scale alone. On a positive note, the scale reached with biofuels can have a beneficial impact on the production of chemicals and intermediates. As an example: SABIC and BASF are evaluating the use of a bionaphtha stream from the production of renewable diesel for use in their naphtha crackers. In this way green olefins are produced with a certificate based on the mass balance of biogenic to fossil feedstock at the cracker.

So what renewables are likely to scale and have commercial impact for commodity plastics?
Ethylene and propylene will continue to benefit from low cost shale gas and shale oil and hence **PE** and **PP** will remain low cost plastic commodities with huge volumes. Some greening might occur via the bionaphtha route described above. The much proclaimed route via sugar fermentation to ethanol and de-hydration to ethylene requires >3 kg sugar for 1 kg of ethylene which results in a poor business case for the foreseeable future. With a targeted policy, certain markets such as shopping and garbage bags might turn to biodegradables. However most effort will be on mechanical and chemical recycling, with emphasis on design for recycling, better collection and separation technology. **PVC** will continue to grow for those applications where it has demonstrated to be irreplaceable in long term applications such as pipe and other Building & Construction products. No renewable offsets are in sight other than recycling, and only moderate growth is foreseen. Polystyrene (**PS)** and PS foam (**EPS**) carry a toxicity concern based on free styrene monomer, which means gradual replacement by PLA is likely for PS and for EPS via Biofoam. Where EPS is used in insulation panels, other indirect biobased replacement products such as flax are possible. What is necessary is lowering the cost of lactic acid and PLA through scale coupled with a phaseout of PS and EPS for certain applications (e.g. food packaging and toys). Certain brand owners require second generation feedstock for the production of lactic acid in order to specify PLA into their consumer products. Recycling options exist for applications such as refrigerator parts, but collection and reliable supply chain appear to be the challenges. **PET** as commodity polyester in the packaging, fiber and film market space provides ample opportunity to be impacted by renewables. Alternative polyesters that enable new performance and functionalities in terms of heat, barrier ($CO2$, $O2$, $H2O$), recyclability vs multi-layer solutions, have high likelihood of reaching scale and commercial impact. Homopolymers based on furanoates as well as PET and PEF copolymers with biobased diols (isosorbide, propanediol) are some of the many possible designs. Not for standard bottles, but for hot fill applications with further glass replacement. In addition, recycling of PET is very well developed and will continue to be an important pillar for re-use and closed loop solutions with good collection and supply chain.

Overall conclusion for the big 5 (PE,PP,PVC,PS,PET): limited opportunities for biobased chemicals and bioplastics in this material space, mainly PLA and other polyesters; ample opportunity for part recycling, mechanical & chemical recycling plus energy recycling (CE). The recycling will have to go above and beyond the existing practices with smart product sensing (e.g. automotive, window, refrigerator parts), monitoring, and new business and finance models.

And what renewables are likely to scale and have commercial impact for performance plastics and elastomers?
There appears to be a good fit for biobased building blocks in this segment, notably in nylons and polyesters, both of these for fibers, films and injection moldings , and also in polycarbonates, acrylics, cellulose esters and various polymer blends and elastomers. For success in this segment it is necessary to have routes available for bioaromatics, such as BTX, phenol, alkylphenols, resorcinol, hydroxy-benzoic aicd, or furanics with aromatic properties. Several groups have projects running that will scale to commercial impact. Feedstock can be (i) various sources of lignocellulosic biomass that are directly converted via pyrolysis (Anellotech, BioBTX), or bioreforming (Virent) or (ii) the biorefined sugar or lignin streams that are converted, like Biorizon does and companies making

furanics from glucose –fructose- HMF- FDCA. No new or existing product can be introduced today in the market without an end-of-life plan. Hence recycling is top of mind, but due to fragmented markets and relatively small volumes (compared to commodity plastics) recycling as a renewable stream is expected to be secondary to biobased options except for market applications that use single materials, such as nylon carpets, polycarbonate automotive headlamps, and thermoplastic elastomer ski boot parts. As in the case of commodity plastics, design for recycling, better collection and separation technology will be needed for all other situations in this segment.

What renewables are likely to scale and have commercial impact for thermoset resins and rubbers?
With PUR representing the largest stream in this segment, we continue to look at biobased opportunities for polyols, ranging from glycerol to sorbitol, to which polyethers or biobased polyester-ethers or renewable carbonate (CO_2 –based) are grafted. But today also novel aromatic polyols based on good quality lignins with phenolic functionalities are being developed. Such lignins become available from the pulp and paper industry and increasingly from lignocellulosics biorefineries employing specific pretreatment and processing technology. Such lignins can also be curing agents for epoxy resins in applications like adhesive systems. Another biobased building block for epoxy resins is glycerol from vegetable oils in biodiesel production from which epichlorohydrin can be made by treatment with HCl. Dow and Solvay have built new plants in Shanghai and Thailand, respectively, using this process: "Growing glycerol-to-ECH plants " (ICIS).

Whereas PUR and Epoxy resin systems have partially renewable content, furan resins derived from furfuryl alcohol are 100% renewable. Furfuryl alcohol is a useful chemical intermediate in for example the manufacture of furan resin prepolymers exploited in thermoset resins and composites, cements, adhesives, casting resins and coatings. The chemistries and products, although naturally occurring, can be quite hazardous. Furfuryl alcohol is produced by hydrogenation of furfural, an important renewable chemical, non –petroleum based, chemical feedstock. It is produced by de-hydration of xylose, a C5 sugar present in hemi-cellulose from lignocellulosic biomass (soft and hard wood, grass, straw). With more biorefineries expected in the coming decades, it is expected that more xylose-furfural- furfuryl alcohol – furan resins will become available. This will enable the production of biocomposites in which the reinforcing fibers (glass, carbon, aramide) will be replaced with natural fibers, such as flax, hemp, or other (ligno)cellulosic fibers. Also carbon fibers derived from lignin are being developed by several groups around the world (Canada, Scandinavia, Finland). This is an excellent example of the potential of smart development of high value biomaterials based on cellulose (micro-cellulose, nano-cellulose), hemi-cellulose (polyglycan), lignin (activated carbon, carbon fiber, feed). The potential for biobased building blocks and materials is evident for thermosets, but less so for rubbers, with the exception of natural rubber. Recycling options for thermoset and rubber are clearly more difficult than for thermoplastics. Thermal options via gasification or pyrolysis are open. In addition there is a lot of attention for recycling PUR mattresses, furniture parts, e.g. towards insulation applications.

In conclusion: Next to steady, incremental growth of plastics towards 2050, there appears a lot of opportunity for smart renewable development. Biobased developments have a fit with performance plastics and thermosets, while recycling mainly with commodity plastics. Development of biomaterials such as cellulose (fiber) and lignin will provide lots of extra opportunities, enabled by more and better operating biorefineries that will be built in the coming decades in the world, including Europe and the Netherlands. C1 chemistry (CO, CO_2, syngas, CH_4) from fossil and biogenic sources will be another exciting field in the next decades with various emerging technologies, such as gas fermentation, electro-chemistry and Carbon Capture Usage towards renewable chemicals and materials.

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Ethylene glycol (India Glycols, Biokim, Braskem, Avantium, S2G Biochemicals), 1,3-propanediol (Dupont, PPT), 1,4 butanediol (Genomatica, Novamont) lactic acid (Nature Works, Corbion/Total, PLA), succinic acid (Bioamber, Succinity, Reverdia, PBS), furanoates (Avantium, Synvina, Corbion, Dupont/ADM, PEF, PPF), levulinic acid (GF Biochemicals) and itaconic acid (Itaconix, Akzo Nobel, Dutch DNA)

***The EU has decided – after initial approval – that blending of biofuel for passenger cars is not the right solution, and that we will go for electric car mobility in the medium term (sustainable when the grid is based on renewable energy); China is also a big driver of E-mobility!*