TOP 10 WMF
TECHNOLOGIES

JUNE 2021

WORLD MATERIALS FORUM

Dear all,

We are excited to bring you the 2nd list of the annual
Top 10 WMF Technologies.

Based on the panel's research and numerous interviews, we confirm that these technologies can reach industrial scale by 2030 and that they can therefore make the WMF objective (decouple economic growth from the current use of our natural resources while creating value for the industry all along the global supply chain) happen sound and fast.

For each of these 10 Technologies you will find:

1. A summary of the technology with expected impact on one or more of WMF decoupling Key performance indicators.
2. The restitution of 4 to 6 interviews with a selection of Top Corporate (CEO or EVP), Top Academia or Experts (or Big Group CTO) as well as representatives from the Start Up community (CEO).

We wish you will enjoy the reading as much as we enjoyed performing the interviews.

PROF. VICTOIRE DE MARGERIE
Founder & Vice Chair WMF

MATT PRICE
President Activate Global

PROF. BRONWYN FOX
Swinburne University

YUTAKA YASUDA
General Manager Metals & Recycling JX Nippon Mining & Metals

PROF STÉPHANE MANGIN
Université de Lorraine

PHILIPPE BIDEAU
Director Emeritus Mc Kinsey

CARLOS DE LOS LLANOS
Environment Consulting

MARK NEWMAN
Chief Commercial Officer Nyobolt

Technology #1

CHEMICAL RECYCLING OF PLASTICS

All key major polymer producers have announced chemical recycling projects in the last 12 months. The technology itself is not new, but substantial improvements in catalysts and energy yields are implemented, making its industrialization possible, with the clear objective to combine the well-recognized usefulness of plastics with a long expected efficient plastic waste management system. Together with mechanical recycling, this set of chemical technologies should make it possible to reach the target of recycling 55% of plastic packaging waste in 2030.

YELENA KANN,

FOUNDER AND CTO, RADICAL PLASTICS (USA)

Radical Plastics works on polyolefins, which are the most widely used plastics. Designed to last, these polymers take a long time to degrade under natural conditions, contributing to plastic pollution. **Our objective is to make polyolefins biodegradable if they end up in the environment, but without limiting their ability to be recycled.**

We have identified a mineral catalyst that provides this dual functionality: providing biodegradability without preventing recycling. Covered by several patents, this catalyst is itself derived from a waste stream and its components are currently used to enhance soil fertility, in line with the principles of a circular economy.

The first application is soil-degradable films used in agriculture. The particle size of the mineral is around 2 microns, allowing the production of thin, possibly multilayered, films. The first step involved extruding rolls of film which were tested under real, outdoor conditions to verify compliance with the EN 17033 standard on biodegradable mulch films (90% biodegradability in less than two years).

We have established close relationships with several industrial players, as our technology could potentially be integrated at different stages of the value chain - polymer production, compounding or film manufacture.

Another opportunity is to use the same catalyst in thermo chemical recycling where it could substantially reduce the energy requirements and produce a better selection of hydrocarbons. While this is still at the laboratory stage, this second approach is promising as this catalyst is more economical than other materials used today, such as zeolites.

JEAN HORNAIN,

CEO CITEO (FRANCE)

In France, the recycling targets of the European Directive for packaging are now transcribed into national Law. **An environmental labelling is planned for consumer products, in which the recyclability of the packaging is becoming a central criterion.**

Some long-awaited measures are becoming operational: **a minimum content of recycled/reusable material is now imposed in the purchasing criteria of public procurement, which represents nearly 10% of GDP.** This will help develop new outlets for recycled plastics. Citeo supports the development of packaging recycling, reuse, and eco-design, by involving all players in the value chain: material producers, packaging manufacturers and users, waste operators and recyclers, major companies or start-ups.

In 2020, Citeo organized the 2nd International Plastics Solutions Forum which was **a great opportunity to connect chemical recycling companies and consumer goods players and to highlight the full set of chemical recycling technologies:** dissolution, depolymerization, pyrolysis and gasification, with innovations coming from many countries that are facing the same plastic recycling challenge in Europe, North America and Asia.

Chemical recycling must help us reach the 2025 and 2030 targets. For this to happen, the outstanding questions on the «mass balance», the costs, the confirmation of environmental benefits, must be answered in order to create the confidence necessary to mobilize the entire chain of actors.

BERNARD PINATEL,

PRESIDENT REFINING AND CHEMICALS, TOTAL (FRANCE)

The market for chemically recycled polymers is of interest to many potential users, particularly because of the high quality of the material produced. The economic model that will make chemical recycling possible **requires both a gate-fee on the waste to be processed and a premium price for the recycled resins delivered.**

Access to waste feedstock in sufficient quantities is another essential condition even if the technology makes it possible to envisage small and medium capacity units, which can be located close to the waste production basins. The regulatory framework is also a determining factor, and Europe with its Green Deal policy offers favorable conditions.

Just after World Material Forum 2020, Total announced their building of France's first pyrolysis plastics recycling plant at its Grandpuits site, together with Plastic Energy. The plant is scheduled to start production in the first half of 2023 and will have an initial capacity of 15,000 metric tons, which can be expanded in the future because the process is modular.

Chemical recycling today offers considerable scope for creativity. Purecycle, for example, with which Total has a partnership, is developing polypropylene recycling using completely new supercritical processes.

LanzaTech, Total and L'Oréal have also premiered the world's first **sustainable packaging made from captured and recycled carbon emissions**. LanzaTech captures industrial carbon emissions and converts them into ethanol, Total converts the ethanol into ethylene and polyethylene, and L'Oréal uses it to produce packaging with the same quality and properties as conventional polyethylene.

Chemical and mechanical recycling together will represent 30% of Total polymer production by 2030.

HARTWIG MICHELS,

PRESIDENT PETROCHEMICALS BASF (GERMANY)

The mass balance approach is the fastest way to reduce consumption of fossil feedstocks in our industry. It allows us to use recycled (or biobased) feedstock together with fossil feedstock in our existing assets. The recycled feedstock is then allocated to certain sales products. If the industry were to separate production of chemicals made from recycled (or biobased) and fossil resources, new plants would need to be built, which is neither economic nor environmentally beneficial.

The target of chemical recycling is waste that cannot be mechanically recycled due to their heterogeneous composition and/or level of contamination. We believe that with chemical recycling included in the regulatory framework, this type of recycling will grow very quickly and make a significant contribution to the EU target of 10 million tons of recycled plastics used by 2025. From today's perspective, **more than 1 million ton of chemically recycled plastic in 2025 in Europe seems realistic.**

BASF has already invested into start-ups specializing in pyrolysis of mixed plastic waste and of end-of-life tyres and we are planning to invest further into capacities and infrastructure needed to feed it into our production setups. **From 2025 onwards, we aim to process 250,000 metric tons of recycled-based raw materials annually, replacing fossil raw materials.**

The ChemCyclingTM project will make a significant contribution to that. In this project, we are cooperating with technology partners for the supply of pyrolysis oil: from mixed plastic waste with Quantafuel, and from end-of-life tires (ELT) with Pyrum Innovations and New Energy.

BASF is working on decreasing the cost gap between products made from recycled products and products made from fossil feedstock with the target to come as close as possible to the fossil costs. However, we do not see direct cost-competitiveness compared to fossil feedstock in the foreseeable future.

One reason for the higher costs is that the recycling of plastic waste into feedstock includes additional processing steps, and that the pyrolysis step is currently carried out in small plants that are not comparable in size and thus cost efficiency with production plants for primary fossil raw materials.

A prerequisite for the profitability of chemical recycling is to use plastic waste that has no or even a negative value ("gate fee"), i.e. waste whose disposal is paid. We also **see greater acceptance in the relevant markets to pay the required premium** for products based on recycled feedstock. This will enable to use chemically recycled feedstock under economic feasible conditions.

BRETT HELMS,

CAREER STAFF SCIENTIST, LAWRENCE BERKELEY NATIONAL LAB, THE MOLECULAR FOUNDRY (USA)

To understand thermochemical recycling, we need to go back to the basic concepts. Polymers obtained by condensation (PET, PA, PU...) present bonds between monomers that are relatively easy to break: these plastics are well suited to chemical depolymerization at low temperature. Polymers obtained by chain growth (polyolefins) have stronger bonds, they require higher depolymerization temperatures and the recycling processes are less precise: the «plastic to plastic» yield is limited due to the production of gas, char, and the heterogeneity of the hydrocarbons obtained. Our team at Berkeley is working on **developing polymers with the same applications as polymers that are challenging to recycle now, but whose molecular bonds will require less energy to make and break.** We call it "Recycle by Design". Poly-diketoenamine (PDKs) are promising because they combine innovative mechanical recycling prospects with chemical recycling possibilities. Their industrial production could be achieved within 5 to 10 years, thanks to artificial intelligence which accelerates the development process. But **the challenge of recycling plastics today is not limited to the choice of one technology: a global approach is needed,** including the origin of the feedstock (renewable or not), the process energy (electrification), the applications of the polymer, the possibility of developing a complete waste recycling loop including collection, sorting and outlets.

For PET, 50 years passed between its invention and its large-scale manufacturing—even longer for recycling. **This is too long, and we need new tools to accelerate the integration of new polymers into the circular economy.** We also need a new economic model that will allow us to absorb the costs of producing and recycling plastic, which will undoubtedly be higher, but amortized over several cycles of use, and not over a single use.

Technology #2

RECYCLING OF EV BATTERIES

The rapid adoption of vehicle electrification is incited by growing consumer demand for greener transportation options and by regulations requiring carbon emission reductions. It is expected that we will have a major outcome of EoL (End-of-Life) EV batteries in early 2030's. Since the battery recycling will require challenges in technology, infrastructure, management, and economics, it is necessary to prepare well in advance. Closed-loop recycling systems for the EoL EV batteries provides a pathway to lower environmental impacts and a source of critical materials that can be used in producing new batteries. The system would incorporate the WMF's concept "Use Less Natural Resources, and Longer". The recycling technologies should make it possible to reach the target of recycling 80% of used batteries by 2030.

ALEXANDER KING,

PH. D AND PROFESSOR, IOWA STATE UNIVERSITY, (USA)

We must learn all the details of battery recycling process now. The only way to learn is by doing it. We really have to do it, now.

This is a crucial time to learn how to recycle cleanly and efficiently. Battery manufacturing waste is a good target to use in the development of recycling efforts, because there is material available, and we can prove the technology of recycling with the same material that will eventually end up as end-of-life waste. We must train on the materials which are available today and learn how to recycle by doing it. 10 years from now, when battery recycling will be proceeding in bulk, then what we have learned will enable recycling to become the primary supply of battery materials. Recycling rates, as traditionally defined, are not particularly relevant in the current rapidly growing market but the fraction of total demand that can be met by recycling is an important challenge. Recycling will have a hard time to keep up with the demand for battery materials because the LIB market is growing very rapidly with the strongly increasing market share of electric cars. When the growth rate becomes smaller, it will be easier to meet the majority of the demand through recycling, but only if our recycling methods are fully developed by then.

Battery technology advances may be the biggest threat to recycling, while it is also the biggest opportunity for battery manufacturers. All around the world, huge research efforts are going into improving and advancing battery technologies and recycling methods will have to change to cope with them. The recycling industry will have to be agile and ready to change during this time of rapid market growth and technological development, so it is ready to become the main provider of battery materials when the electric vehicle market matures.

PRESTON BRYANT,

CEO MOMENTUM TECHNOLOGIES INC. (USA)

Distributed system will become the solution available for recycling EV batteries. The membrane solvent extraction technology may play a key role for the system.

Momentum Technologies Inc. has developed the membrane solvent extraction technology (MSX) for battery recycling in partnership with the US Department of Energy. The technology is modular, economic and environmentally friendly. We can take the technology and put it in places where traditionally a processing plant would not be located. Moving the processing closer to where the heavy batteries are being aggregated and collected allows us to cut energy consumption and CO2 emissions.Since the MSX technology uses organics, it is not necessary to separate out electrolytes and PVDF binders. Less pre-treatment is required, which is a big advantage for the process.

The system is very versatile and flexible. Some of the products include 99.99% pure Co, Cu, and Ni sulfates and Li hydroxides, and we are also working to design custom solutions for cathode active materials. Direct production of cathode materials will save the capital and operational expenditures. We will be moving into the commercial facility soon, which will have 1,000-2,000 tons a year capacity. At this point, we will likely be the only a commercial hydrometallurgical plant in operation in U.S in 2021. In the future, there will be two types of market players available. One will be the big hydrometallurgical plant, and another will be distributed processing plants. Big hydrometallurgical plants, 40,000 to 60,000 tons a year capacity, shall be constructed near the battery production plants to treat their process wastes and scraps.

The MSX technology will target distributed processing plants with 500 to 5,000 tons a year, which allows us to move very quickly at very different areas where EOL EV batteries will be generated. However, in the end, MSX has a lower processing cost compared to any approach in the market and will eventually replace large scale Hydro.

SHIGERU OI,

EXECUTIVE CHAIRMAN, JXNMM (JAPAN)

An appropriate social system shall be established to make the recycling system stable and sustainable.

Battery recycling will have to adopt and utilize more IoT/AI technologies. Currently, OEMs and battery producers install memories and communication devices on their battery packs to identify the charging condition and remaining capacity during operation on the vehicles. It would be better to expand the idea to each module for identifying its life-time historical usage and its current condition, so that the recycling process would become safer and more efficient. Recycling shall be focused on all kinds of metals/materials to be potentially recovered. To evaluate the value and efficiency of recycling, it would be necessary to compare the LCA (Life Cycle Assessment) figures with that of mines, which require large amount of energy and water not only at the operational stage, but also during their development period.

Closed Loop Recycling will be a definitive goal for us. The materials used for batteries shall be directly recycled as the raw materials for batteries. JX NMM has developed a hydrometallurgical recycling technology to recover pure sulfates of Co and Ni, and Li carbonates, which can be directly returned to battery manufacturing process, from EoL (End-of-Life batteries).

Operations at our demonstration test pant will start from June 2021 to process yearly about 1,000 tons of EOL batteries. Since the recycling cost, from collecting EoL batteries, discharging, dismantling and processing to recovery, will become more expensive than the production cost from natural resources, it can be difficult to justify the feasibility of the recycling as a stand-alone business. An appropriate socioeconomic system shall be established to bear such excessive cost in a fair manner. To be sustainable, taking account of common environmental cost and volatile metal prices, the excessive burden shall fairly be borne by all the beneficiaries including automobile and/or battery producers, and finally consumers.

PETER CARLSSON,

CEO NORTHVOLT AB (SWEDEN)

The battery industry is still fragmented in the supply chain. To achieve the closed loop recycling of the EV battery, it is necessary to connect the supply chain.

We are now moving into the decades of EVs and large usage of batteries. Batteries will become very valuable commodities. Big car makers in Europe already recognize the strategic value and significance of battery recycling, and they are all getting into the process development of End-of-Life battery dismantling and use of recycled materials.

A part of current problem is that the battery industry is still fragmented in the supply chain. Raw material suppliers, precursor manufacturers, cathode material manufacturers, battery producers and automobile OEMs are all independent, and there is no one-stop shop to take care of the battery supply chain. Now, Northvolt is going to connect the supply chain and close the loop.

Northvolt has a pilot plant to develop the recycling technology and to prove the recycling rates more than 85% of all the battery materials. Northvolt is now planning to build 4GW recycling plant, which is going to be the largest plant available in the World. A full hydrometallurgical plant will start to be constructed at the next door of Northern Sweden's battery manufacturing plant, later this year. Hydrovolt, a joint venture of Northvolt and Hydro of Norway, is constructing a new dismantling and crashing plant in Norway.

Location of the battery recycling plant is an issue to discuss. According to the "Out-In scheme" in the market, we will ask the regional service and after-market points for the carmakers to locate the regional battery pre-treatment site. The plant will have discharging unit, robotic dismantling process and crashing station.

We will outsource the pre-treatment in the region and take the black mass back to our large-scale hydrometallurgical plant located next to battery manufacturing plant. Manufacturing scrap of battery factory will become another major feedstock for the new recycling plant. Northvolt's ambition is to have 50% recycled materials by 2030.

Technology #3

IMPROVING MOBILITY PERFORMANCE OF EV BATTERIES

Disruptive technologies are expected to revolutionize the LI-Ion batteries by 2025 and, definitely, before 2030. Technology can improve power by a factor 10, energy storage by up to three, lifecycle by up to five and reduce charging time down to minutes. Compatibility with current manufacturing facilities will be of paramount importance as the $200 billion investment in giga-factories in the making will be a barrier to entry for technologies requiring different toolings.

THIERRY LE HENAFF,

CEO ARKEMA (FRANCE)

To meet below 2°C global warming targets vehicles electrification is inevitable and, whatever the scenario, batteries will be at the core of the transformation. Li-ion batteries will enjoy an exponential growth but other technologies will come along, including lithium sulfur, or redox flow.

In order to bring electric vehicles at the performance and cost levels of thermal vehicles, further progress is needed beyond the momentum of the last two years posting charging rates multiplied by two, number of charging stations doubled, and battery recycling now a credible source of key raw materials, while reducing the cost of the battery pack by 25%. **Energy density increase to improve vehicle range, is the name of the game.** It should be multiplied by two or three within the next 10 years, reaching 400 to 500 Wh/kg thanks to silicon or lithium metal anodes and solid-state technology could become a reality. **Safety and sustainability have to improve also.** Solvents used in the manufacturing process should be removed: new solvent-free processes will be introduced with the use of special binder polymers. Solid state batteries will avoid the use of flammable solvents in the battery altogether. New cathode chemistries involving less cobalt, or no cobalt at all, will also improve sustainability.

New materials are not only needed in the battery itself, but also in the "battery pack" that provides casing and protection to the battery: e.g carbon fiber composites for a lighter casing, special adhesives, with an appropriate thermal conductivity to manage the battery temperature, and cooling fluids.

RICHARD WANG,

CEO CUBERG TECHNOLOGY (USA)

Technologies can serve and should first and foremost adapt to market needs that can vary a lot. The divergence in terms of cost and power performance between different cathode types of chemistry is becoming material, and we can expect a great variety of products, depending on the type of usage. In the near term, by 2025, LFP Lithium-Iron -Phosphate will be better suited to equip the mass automotive market, as they will remain much cheaper, while higher cost silicon coated anodes batteries will equip the premium segments like Tesla. **Innovation will be a combination of incremental improvements and breakthroughs.** First, on the cathode side, with a view to using less cobalt and more nickel while improving the energy density by 10%, but also on the anode side, with silicon coating that is expected to increase the energy density by another 10 to 20%.

The disruption will come on the anode by replacing graphite/silicon by lithium metal while pairing with an adequate electrolyte. Beyond 2025 this disruptive technology will deliver superior performance in terms of energy density expected to reach 400 Wh/kg or 1000 Wh/l and by 2030 450 Wh/kg and 1200 Wh/kg respectively. As higher energy density also allows simplifying the packaging, we can expect lower costs by the same token.**Compatibility of manufacturing with existing facilities will remain a prerequisite for all new technologies, given the $200 billion tooling being installed in the world.** Solid-state batteries, that require retooling and a reinvention of process, might, as a result, not win before 2030.

KARIM ZAGHIB

STRATEGIC ADVISOR, INVESTISSEMENT QUÉBEC (CANADA)

Looking forward, until 2030, Li-Ion batteries will be the undisputed winners, as manufacturing compatibility creates a major barrier to entry for competing solid-state batteries, but end-user markets will segment the Li-Ion technologies, based on cost and performance.

With investment costs in excess of $5 md for giga-factories, there is no flexibility to change technologies if, like solid state, they are not compatible with the existing manufacturing capabilities. As for hydrogen-based fuel the time horizon is even longer, probably 2035-2040, for trucks and trains and 2050 for aircrafts. **Lithium Iron Phosphate (LFP) will dominate the mass mobility market and the short-term storage market, while the nickel-based NMC will target premium vehicles.** By 2030, NMC (Lithium Nickel Manganese Cobalt cathodes) will reach an energy density in excess of 400 Wh/kg and a cost around $100/kwh. They will most likely be the preferred choice of OEMs for their premium vehicles. On the other hand, the more cost sensitive mass market will select LFP (lithium Iron Phosphate cathodes) that will be limited to 300 Wh/Kg but with a cost that will be lower than $80/ kwh. On the anode side, the ratio of silicon vs graphite will also differentiate the higher- vs the lower-end of the market. **Controlling the full supply chain, from mining to recycling, will become the name of the game.** Countries like Canada, that benefit from the availability of the key minerals together with green hydraulic energy will be in a position to challenge the current dominance of Asian countries who still control 80% of anodes and cathodes production worldwide.

PETER FRISCHMANN,

CEO SEPION TECHNOLOGIES *(USA)*

By 2025 silicon anodes, and by 2030 lithium metal anodes, will most likely be the true disruptive battery technologies. Increasing the fraction of silicon vs graphite, a possibility up to 30% within the next 5 years, will allow a 20% range extension, reaching an energy density between 350 and 400 Wh/kg, while reducing the cost of the battery. To go beyond, an expensive nanostructured material would be necessary. Lithium metal will be the next S curve, beyond 2025, reaching densities in excess of 400-600 Wh/kg, to be compared with current 200-300 Wh/kg best practice.

Only incremental changes can be expected on the cathode side, essentially to lower the cobalt and nickel content: Cathodes today make up for 40% of cells cost.
. Novel coatings, both electrodes and separators, will enable reductions in the amount of cobalt needed in the cathode. These coatings control the flow of ions and stabilize the electrodes when charging or discharging, and as a result, energy density, power profile or longevity can be substantially enhanced together with safety.

LFP, iron- based cathodes operate at lower voltage. If the resulting range is lower, improvements on the anode side might compensate that loss while allowing a cost reduction in excess of 30%. **Solid-state batteries have limited future, at least in the mid-term, as they are not compatible with current manufacturing facilities** while solutions exist with liquid electrolyte based on bulk solvants to solve the prevailing safety issues.

Reengineering of pack cells also has a potential for substantial performance impact in terms of safety, extended range and lower cost.

MICHAEL LIEDTKE,

HEAD OF BUSINESS DEVELOPMENT ZETA ENERGY (USA)

Materials will be instrumental in the development of future batteries. Up to 2025 all batteries technologies are fixed as OEMs test today what will be used by then. Tesla will remain the key influencer as their investment in giga-factories have paved the way. Their introduction of the dry electrodes process, that is fully compatible with current tools, will contribute to making low cost but high- performance electrodes for Li-Ion batteries. The elimination of the current wet slurry manufacturing method will lower the production cost and make the process more environment friendly while allowing the production of thicker electrodes with high energy density results. Materials are now the main focus of developers to continue lowering the costs as they now make up to 68% of the total costs, with the share only to grow as factories are scaled to ever higher volumes.

Batteries performance will be assessed in terms of energy & power density, safety and recycling capabilities. Li-Sulfur are inherently cheaper batteries using no cobalt or nickel will be able to satisfy the needs of most of the mobility or storage market Using cheap sulfur (12 to 14 cents per kg), cheap carbon material and no cobalt, manganese or nickel is the name of the game. This still allows to reach 350Wh/kg, competing with premium NMC and way more than current batteries. It guarantees easy and local access to the materials and gets along with the localized version of things that now prevail after the risks of long and unsecure supply chains have materialized. The target of well below $80/Wh will be reached, making the technology competitive, beyond mobility, for the storage market as an indispensable complement to windmill and solar.

ULRIK GRAPE,

CEO NAWA TECHNOLOGIES (FRANCE)

Technology can improve power by a factor 10, energy storage by up to three, lifecycle by up to five and reduce charging time down to minutes instead of hours. Combining the best nano and clean technologies to design a revolutionary 3D electrode, NAWA's Ultra-Fast Carbon Electrode unlocks next-level performance for all types of batteries .

- Vertically Aligned Carbon Nanotube (VACNT) structure on Al or Cu substrate is both disruptive and green, as it uses materials that are abundant and easily recyclable
- When used in the electrode for a battery, an Ultra-Fast Carbon Electrode is more efficient as it allows much faster charging, no loss in heat and less metal use
- Revolutionary nano-sized 3D design means batteries are no longer limited by powder-based systems
- **Greater safety and durability are expected from batteries based on nanotube-coated electrodes without adding cost**

Batteries will also be more durable (potential to exceed the lifetime of a car when used as a battery in an EV, for example) and safer as they are more stable and are uniquely efficient in dissipating heat. Despite all these advantages the batteries will not be more costly. **No disruption of the manufacturing process is necessary.** Industrializing is easy as it adds just one simple step to the current manufacturing process. Instead of coating a carbon black, a layer of carbon nanotubes is applied. Hosting of any currently used metals is possible, and the process can be applied to all types of Li Ion batteries, including solid state.

Technology #4

IMPROVING STORAGE PERFORMANCE OF STATIONARY BATTERIES

As the world races toward carbon neutrality, renewables will necessarily become the great majority of power generation globally. However, the sun doesn't always shine, and the wind doesn't always blow. Energy storage technologies are thus critical to enable renewables and a clean, green, carbon neutral future. Lithium-ion batteries play a role but are not suitable for long duration storage, where cost per kWh needs to fall by at least 50%. Flow batteries, lithium-sulphur and hydrogen hold great promise to solve this critical gap.

MAINAK MAJUMDER,

PROFESSOR MONASH UNIVERSITY, (AUSTRALIA)

Energy storage technologies are being developed for stationary storage applications, to enable renewable power in massive scale. For these types of applications, energy density is typically less important, and more importance is on overall cost and longevity. Furthermore, as battery needs ramp up globally for electric vehicles and stationary storage, there is increasing concern on raw materials cost, availability and supply chain ethics and security. The environmental footprint of energy storage systems, maintenance costs and battery recyclability are additional concerns.

Lithium-ion batteries have improved dramatically and are the battery technology of choice for many mobile and stationary applications. However, **lithium-ion batteries have limitations and are not suitable for longer duration applications, which are necessary to enable renewable energy.** Most types of lithium-ion batteries rely on expensive metals such as nickel and cobalt. Some of these raw materials also have geopolitical and ethical supply chain concerns. Chief concern though for longer duration energy storage requirements is cost. The entire system cost for a lithium-ion battery energy storage system is typically over $600/kWh. **There are several interesting alternative battery technologies to lithium-ion that hold great promise for longer duration storage requirements.** Firstly, vanadium redox flow batteries are one alternative, with several companies pursuing this area. Flow batteries work better for longer duration of over 6 hours as the cost of longer duration (bigger tanks full of vanadium) is relatively cheap vs. the cost of power (the stack). The concern for vanadium redox flow batteries is the toxicity of vanadium, and although the cost is competitive with lithium-ion for long duration applications (around $350-500/kWh total system cost), it still isn't cheap enough yet.

Secondly, lithium-sulphur holds great promise due to the very cheap cost and availability of sulphur. Our research suggests this chemistry can reach costs as cheap as $30-40/kWh for cells and $60-100/kWh for the entire energy storage system cost. Lithium-sulphur batteries also can be very light due to the lightweight of sulphur on the cathode side and have often been thought of as an ideal technology for electric aviation. However, the main drawback of lithium-sulphur batteries are the low cycle life (meaning they don't last very long). There is clearly some way before lithium-sulphur becomes a mainstream battery technology, but for sure they hold great promise.

Other battery technologies that hold promise include zinc manganese dioxide and lithium iodine, both of which promise longer term costs below lithium ion, particularly for long duration needs.

BRENDA PARK,

COO STORTERA (U.K.)

Most flow batteries to-date require two separate tanks of liquid electrolyte. The liquids are circulated through reaction cells contained in the power stack where a redox (reduction-oxidation) reaction occurs and ion transfer through special membranes create a current flow.

A flow battery's energy storage capacity is determined by the size of the electrolyte tank(s) which allows almost limitless and easy expansion making flow batteries attractive for large scale applications where long duration power is often required. The power of the battery is determined by the size of the power stack and can be tailored to specific load requirements. The SLIQ single liquid flow battery technology developed by StorTera represents a major step forward in flow battery design and electrochemistry. We only require one tank of catholyte liquid, which has no cooling requirements and no risk of thermal runaway. The fully recyclable liquid is low cost, energy dense and provides millisecond response times. Single liquid design means less system components and lower cost. **We use a single energy dense catholyte liquid based on lithium-sulphur chemistry.** Capital costs are projected to be less than £100/kWh with a product lifespan 30 years without degradation due to a patented flushing and dosing system. Our 8kW/30kWh SLIQ flow battery demonstrator was installed in an off-grid Scottish community in April 2017. The pilot ran successfully during a two year test period with 93% efficiency.

BERNARD SALHA,

CTO EDF (FRANCE)

Our raison d'être is to build a net zero energy future with electricity and innovative solutions and services, to help save the planet and drive wellbeing and economic development As such renewables play a big part. **Energy storage is critical to balance power and energy requirements vs. supply,** particularly where inconsistent renewable energy approaches a high portion of the energy mix.

Broadly speaking, **there are two markets within energy storage: power and energy.** The power market includes ancillary services such as frequency regulation, that requires rapid response in short bursts of power to stabilise the grid. Current lithium-ion batteries perform well in this function, although due to the high cycles sometimes cycle life is an issue for this application. Also, we have some concern on the CO_2 footprint of current lithium-ion batteries. In the energy market, we have peak shifting (duration typically in the hours) and then much longer-term seasonal storage (typically in weeks/months).

Batteries are being used for peak shifting **but battery technologies today are not suitable for the much longer-duration requirements of seasonal storage,** where pumped hydro is the main solution today due to its lower cost per kWh. Pumped hydro, however, has natural geographic limitations as it requires huge bodies of water and natural high elevation (i.e., hills/mountains), thus cannot be the full solution. Hydrogen is another potential solution for long duration energy storage needs as the cost of hydrogen storage reservoirs is relatively low, however green hydrogen round-trip efficiency is currently very low as we lose energy in the electrolyser and again in the fuel cell when hydrogen is converted back to electricity. We at EDF are constantly looking for other storage technologies. Electric vehicles will likely be part of the solution, as these are storage devices on wheels.

TIM VON WERNE,

CEO RFC POWER LTD (U.K.)

As the growth of renewables accelerate, so does the world's need for energy storage. **Global Market Insights predict that the total energy storage systems market size will exceed $500bn by 2025.** This is largely driven by the emerging long-duration market, which will expand significantly in the coming years.

Batteries are the most versatile energy storage option as they can be deployed at different scales in a range of locations for a variety of applications. Batteries based on lithium-ion chemistries will continue to dominate in electronics and electric vehicles but for long duration (>4 hours) energy storage, cost, degradation, safety, temperature control and the availability of raw materials will limit growth. Flow batteries are an emerging technology whose aim is to create cheap, safe, long duration batteries with extremely long cycle lives for large stationary applications. Most importantly, the electrolyte (where the energy is stored) in a flow battery is separated from the electrochemical cell (which produces the power). This means to increase the size of the battery you simply need a larger tank rather having to increase the number of entire cells.

RFC Power's hydrogen-manganese system combines optimised cell architecture with low-cost chemistry. The system has a high single cell voltage, high power density, high round trip efficiency, extremely long cycle-life and crucially, capital costs which are a fraction of competing flow battery systems as the electrolyte is based on inexpensive, non-toxic abundant materials ($10/kWh vs $150/kWh for vanadium). On an overall system cost basis we will be below $100/kWh for an 8hour duration system.

The chemistry can seamlessly link in with the hydrogen economy too, further reducing costs. Hydrogen produced by RFC system is clean and compatible with large-scale storage, with a much higher round-trip efficiency of up to 80% vs. the alternative of fuel cells combined with electrolysers at around 30-40% round trip efficiency.

JIM STOVER,

CMO VRB ENERGY (USA)

Wind and solar projects are booming as costs have collapsed. In the case of solar, costs have plummeted from $8/W to around $0.03/W. **Vanadium redox flow batteries are well suited to the daily storage needs of solar and play an important role in enabling renewable energy globally.** VRB Energy is one of the world's leaders in this technology with huge projects underway in China.

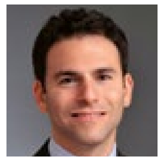
Due to the nature of flow batteries, where the duration can be scaled independent of power through sizing the tanks of liquid catholyte and anolyte, these solutions are most competitive in the longer duration energy storage requirements. Many storage projects have been notionally 4 hours where we believe we can compete with lithium-ion batteries on cost eventually. For longer duration projects of 6 hours and above, VRB's solution becomes even more cost competitive with lithium ion due to the relatively cheap cost of adding larger tanks of vanadium.

Compared to lithium ion, vanadium flow batteries are also much safer. Recently there was a major fire in a 25MWh lithium-ion energy storage system in Beijing, where two firefights lost their lives. This has encouraged even greater interest in vanadium flow as we do not have these safety risks. Vanadium flow can also use its full 100% depth of discharge, unlike lithium-ion which can usually only reliably utilise 80% of its potential capacity. VRB batteries last for up to 100,000 cycles, much longer than lithium-ion, meaning they can last 25 years and don't need to be replaced as often.

Technology #5

LESS ENERGY AND WATER FOR GREEN MINING

Energy transition will mean more metal extraction and recycling. Innovation in technology and processing routes will therefore be key to ensure that green mining supports the development of green energy. All major mining companies have embarked in breakthrough technology projects to reduce their energy and water consumption with objectives varying between -20% and -50% by 2030.



JAMES LITINSKY,

CHAIRMAN & CEO
MP MATERIALS
(USA)

A holistic approach to sustainability must be optimized for the mineral characteristics and operational logistics that define a production system. When evaluated holistically, individual processes that appear cost prohibitive may yield important co-benefits that more than compensate for the drawbacks.

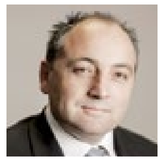
For example, to manage beneficiation waste with minimal risk to human health, safety and the environment, **Mountain Pass employs a dry-stack tailings process which is the 1st one and only if its kind in the rare earths industry.** Just 13 dry stack facilities have been placed globally into operation in the past decade across all resource types. Adoption has indeed stagnated due to significant upfront capital requirements, potentially higher operating and maintenance costs, and lower throughput.

At Mountain Pass, however, when assessed at a systems-level, the dry stack tailing extra costs are more than eclipsed by environmental and operational co-benefits. Water is a major conservation and operations issue for our facility in the Mojave Desert in the state of California, which has suffered from drought for 9 of the past 10 years.

The dry-stack facility **recovers at least 1 billion litres of water from tailings annually** which is recycled into our mining and beneficiation processes to meet 95% of total need — much higher than could be recovered from a wet tailings dam without much higher cost. This closed-loop system increases the resiliency of our operation and reduces the energy and cost associated with meeting our water requirement.

Logistics optimization is also vital. **Unlike most rare earth facilities that have geographically distinct beneficiation and separation operations, and therefore must dispose of waste distant from the primary source, Mountain Pass is co-located.** The ability to co-precipitate waste streams that largely mirror the ore minimizes the production of hazardous waste. It also meaningfully reduces the use of energy associated with moving large quantities of material over land and sea, with significant cost and resiliency benefits.

As we embark on a generational transition to green energy and exponentially scale production of critical materials, **systems level analysis will help industry make informed decision and consistently raise the bar for environmental sustainability.**



LAURENT FRESCALINE,

CEO I PULSE
(FRANCE)

Crushing & milling equipment frequently use diesel as their energy source for operation and emit high amount of carbon footprints. **Around 4% of the electricity in the world is used to crush rocks,** even reaching 14% in Australia. Energy requirement also represents the largest operational expenditures of a mine and this increases over time as the average ore grade is depreciating.

The principle of High Pulsed Power (HPP) disruptive technology is that electrical energy is stored and discharged at high voltage as an electrical arc through minerals and water, thus **creating a strong and short shockwave that enhances and overcomes the limitations of conventional crushing techniques.** This is highly energy efficient due to direct tensile stresses within the rock, the process parameters can be tuned depending on ore types, and the mineral recovery rates can be improved due to increased surface exposure and avoidance of sub-fragmentation for fragile ores.

The physical crushing principle of a HPP facility **decreases the energy consumption of the most consuming crushing operations (mills used for fine grinding) by theoretically more than 10 times.** Conventional mills energy consumption weights for 40% to 50% of a mining facility opex. Another major opex component in traditional mills is maintenance, such as the consumption of steel as milling ball wear, which is in the range of 1.4Kg per extracted ton : the implementation of HPP solutions will remove such a requirement, thus resulting in further opex savings. So investing in HPP will have a very short payback. We plan on developing and delivering first low tonnage industrial prototypes over the next 3 years, **with a higher tonnage market introduction by 2026.** We see the key hurdle of implementing the HPP solution as overcoming the conservative nature of mining sector. However we can leverage our privileged access to the mining community thanks to our senior management and existing partners. The very short payback and the highly material benefits provided by the technology should finalize the demonstration.

AN STEEGEN,

CTO UMICORE
(BELGIUM)

As part of Umicore commitment to sustainability, **we strive to continuously improve the environmental performance of our operations.** On both energy and water, our goals will mainly be achieved through process innovation, a switch to renewable energy sources, strategic collaborations on key technological developments and further improvements in our various processes' efficiencies based on our unique expertise in metallurgy and metal recycling. In addition, advanced digitalization methods and tools are playing an increasing role in monitoring and pro-actively identifying sources of energy and water usage.

Energy consumption is continually monitored and regulated at all sites. Since our activities are very diverse, we run an energy efficiency program which leads to various energy saving projects based upon various technologies. In 2020, 26 sites accounted for 95% of the Group's energy consumption with a total of 38 energy efficiency projects implemented over the course of the year, the bulk of which tackled heating, ventilation, air conditioning, lighting and process efficiencies. Additionally, we look into the potential for clean heat network(s) to save on energy consumption by recuperation of heat from low-temperature streams. **By the end of 2020, Umicore had achieved a 17% reduction in energy consumption compared to the 2015 baseline, correcting for production intensity.**

When it comes to water, our water use management systems and water saving solutions are varied. On some of our plants we recycle water for low grade applications such as road spraying for dust control. We have also recently invested in a more efficient wastewater treatment plant at our Hoboken plant and it has paid off in strongly reducing the water usage (mention a figure here). Finally w**e are convinced that materials for a better life, goes far beyond minimizing the impact of its own operations on the environment. By developing products and services which enable the transition to cleaner mobility and a circular economy, Umicore generates positive and sustainable value to society.**

SAM RIGGALL,

CEO SUNRISE
ENERGY METALS
(AUSTRALIA)

Battery metals are specified as very high-grade inputs to the production process. Their production starts with leaching the metals from the ore, a process which liberates target metals along with many impurities. The separation, concentration and purification of the target metals is an area where significant water and energy are used.

The Sunrise project will be one of the world's largest fully integrated lithium ion battery raw materials plants located on the east coast of Australia and it will incorporate the company's proprietary ion exchange technology, cRIP (continuous Resin In Pulp). cRIP uses polymer resins to selectively extract metal directly from mineral slurries into concentrated solution. Whereas conventional mineral separation processes typically rely on multiple steps to extract, precipitate and concentrate metals, cRIP does not require solids to be separated from liquids, nor a precipitation phase. Instead it uses highly selective chemistry to extract targeted metal ions from solution and reject impurities.

Our IP is focused on the fully engineered system that handles large volume flows with high solids content, and how to make the resins operate optimally in that environment. It uses standard resins and incorporates technologies that have been operating successfully at commercial scale for many decades. Sunrise will be the first project to apply cRIP for the extraction of battery metals.

By redefining and simplifying the flowsheet fewer process steps, we get high metal recovery (98%+), less water usage (-50%) and a reduced operating footprint (-50%). These advantages also convert to an estimated 15% lower capital and operating cost.

Finally, the ability of cRIP to keep metals in solution gives us the option to remove or modify other redundant downstream processing steps. For example, instead of crystallising the metal solution for shipment, we can standardise the metal content of the solution and pipe that solution directly into an adjacent cathode precursor plant. **By removing crystallization and implementing « direct to precursor », we are targeting an additional 10% reduction in energy consumption.**

Once Sunrise is fully funded it will take approximately three years to build and begin production. In the meantime, we are designing and installing other ion exchange units around the world – Australia, China, Africa and the Middle East - to demonstrate the versatility of the technology and its cost effectiveness.

Technology #6

SPINTRONICS FOR LOWER POWER CONSUMPTION OF DATA STORAGE/USAGE

The energy consumption due to data storage and processing increases exponentially because of our increasingly connected society with big data and Artificial Intelligence. Without change of technology, 20 % of world electricity would be used by data storage, processing and communication in 2030! Thanks to spintronics and especially to its non volatile memories with low writing energy and large endurance, this percentage could remain at 12 %. In the past year there has been enormous progress in the field of Spintronics, both in research (3rd generation of MRAM emerge – SOT MRAM) & development (magnetic materials have been shown to be compatible with semiconductor fabrication processes).

ANDREW KENT,

DIRECTOR OF THE CENTER FOR QUANTUM PHENOMENA AT NYU, FOUNDER OF SPIN MEMORY (USA)

Great to see Spintronics highlighted at the World Material Forum again this year. The exciting development is that there is now an emerging ecosystem for spintronics, as **semiconductor companies (Intel, Global Foundries, TSMC, etc.) can now manufacture MRAM because magnetic materials have been shown to be compatible with semiconductor fabrication processes.**

This means that we will all soon use spintronics devices in our daily lives (smartphones, portable devices, computers). It also means that in the future innovative magnetism research can transition more quickly into products. The most important impact will be in energy savings in computation. A key characteristic of MRAM is that it is persistent (or non-volatile); no energy is needed to retain information. Energy is only needed to write and to a lesser extent read data.

This permits "normally off" computing. That is, if a portion of a logic circuit on a chip is not being used, power can be completely shut off to that circuit. Power can then be restored essentially instantly when a computation needs to be started or resumed. As we use our information processing capabilities in bursts, certainly for portable devices (like your mobile phone), but also in high performance computers, there will be an enormous savings in energy.

Initial chips will be IoT and AI enabling smarter devices (mobile devices with increased functionality) and longer battery (i.e. lower energy usage). The longer term impacts I expect to be in high performance computing systems such as semiconductor devices (CMOS), which will be redesigned to closely integrate logic and memory, reducing energy usage in moving information to and from memory.

The challenges today in are in nanotechnology; getting the magnetic and other atoms that make up a spintronic device to go where you want them to with fewer and fewer errors (defects). This learning occurs more rapidly when companies manufacture and test large numbers of chips. These advances also require material characterization methods at the limits of the state-of-the-art, near the scale of atoms. And with spintronics development ramping up in industry, I think it is even more important to continue to educate the engineering and scientific workforce that can advance and sustain this technology.

My company Spin Memory (former named Spin Transfer Technologies), based in California, is developing spin torque magnetic random access memory devices. We have raised over $150 million in funding from Allied Minds, Invesco Asset Management and other sources including the US Federal Government funding. As a next step we see an exciting merging of the fields of magnetism (i.e. spintronics) and superconductivity (superconducting qubits).

DAFINÉ RAVELOSONA,

FOUNDER OF SPIN-ION TECHNOLOGIES, (FRANCE)

Spintronics shows excellent perspectives for development of low-power and more-efficient electronic components, which are key building blocks for future digital applications. Spin based digital devices have the potential to cut down the energy consumption by a factor of 100.

This is specially true since all major foundries (Samsung, Intel, Global foundries, TSMC) have now joined the MRAM race toward volume production ramp-up in particular for IoT and AI applications. Three millions MRAM wafers are anticipated to be fabricated in 2030 and revenue will reach up to 10 billions $.

Spintronics has been a strong part of the European ecosystem since the discovery of " Giant Magnetoresistance" by Albert Fert and Peter Grunberg in 1988. Highly skilled European scientists have contributed to major scientific breakthroughs and filed a legion of key patents from innovative materials to advanced memory design.

IMEC, the European R&D hub for nano- and digital technologies, has launched one of the first MRAM pilot line to serve multiple industrial leaders. Global foundries is ramping up STT-MRAM in its manufacturing plant in Dresden.

Singulus Technology, a German equipment manufacturer, has developed R&D PVD tools to design novel MRAM materials. And a number of Spin-off companies from world leading spintronics labs, including Antaios, Spin-Ion Technologies and Hprobe in France, are developing MRAM innovation across the value chain.

Finally, the SpinTronic Factory (STF) was founded in 2016 to promote European research and innovation in spintronics involving academic and industrial actors from all over Europe.

To remain at the forefront and disrupt the microelectronics industry, public investments together with venture capital and corporate funds need to feed the whole spintronics value chain and in particular support the building of pilot lines.

WEISHENG ZHAO,

DEAN DIRECTOR OF THE SCHOOL OF MICROELECTRONICS AND OF FERT BEIJING RESEARCH INSTITUTE AT BEIHANG UNIVERSITY (CHINA)

Magnetic Random Access Memory (MRAM), as a memory technology based on electron spin for information storage, can achieve superior performance, such as low power (nearly zero standby power and the write energy <~1 pJ) and long retention (endurance> ~10^15). So far, MRAM has experienced several generations of technology evolution:

- the 1st generation called Toggle-MRAM, uses a magnetic field to change the electron spin and becomes one of the major memory technology for aerospace and aeronautics

- the 2nd generation called Spin-Transfer-Torque MRAM (STT-MRAM) employs a spin polarized current to change the electron spin. **Top semiconductor companies like Samsung, TSMC, IBM and GlobalFoundries (in partnership with Everspin), have already industrialized STT MRAM and started shipments of their STT-MRAM chips for smart watches such as the GT2 of Huawei.** A Chinese company Hikstor established in 2016 focuses on developing STT-MRAM technology. Since 2017, Hikstor has constructed a 12-inch wafer MRAM BEOL foundry, and they are developing MRAM mass production technology. Now Hikstor starts to ship samples of its 40nm 4Mb and 64Mb STT-MRAM chips.

- a 3rd generation MRAM technology, called Spin-Orbit-Torque (SOT), is now being developed and it features a series of strengths that can challenge STT-MRAM – especially for industrial electronics and automotive electronics.

Several companies and research institutes including Imec, TSMC and Antaios, have already launched the development of SOT-MRAM fabrication on 12-inch wafer.

A Chinese start-up called Truth Memory Cooperation concentrates on the design and manufacture of SOT-MRAM. At present, the company is developing an innovative technology named Toggle Spin Torque (TST) invented by Beihang University. In 2021, Truth Memory Cooperation raised its first-round financing and the company aims to deliver the samples to clients by 2023.

According to analysts at Coughlin Associates and Yole, MRAM's revenue will see a tremendous boost along with the rapid growth of market. The worldwide market is expected to grow at a CAGR of 136% for embedded MRAM and 45% for stand-alone MRAM by 2025.

HIDEO OHNO,

PRESIDENT OF TOHOKU UNIVERSITY (JAPAN)

I am happy that Spintronics was selected as 1 of the top 10 WMF technologies again in 2021. To decouple economic growth from the use of natural resources, it is key to monitor our world so that we can run things efficiently. **With trillion sensors, our connected society indeed provides means to efficiently use materials (less materials), to use materials smarter, and to monitor materials so we can use them longer.** To fully exploit the potential of this scheme one needs to drastically reduce the power consumption associated with it. Spintronics does this in a dramatic way. For example, if the sensor is battery-powered, it costs you far more materials to replace the batteries than the sensor itself. One possibility is to reduce the power consumption of a sensor (along with its information handling capability and transmission capability) to the level that it can be powered by energy harvesting. This means that we need a microprocessor/ microcontroller operating at less than 100 µW. Recent demonstration at Tohoku University shows that one can operate a controller at 200 MHz with less than 50 µW by the use of spintronics, paving the way to realize IoT driven society of less, smarter and longer materials usage.

Spintronics also makes it possible to replace power-hungry universally used "volatile" DRAM and SRAM that consume power to keep the information by the high-performance nonvolatile working memory option (MRAM) that has not been available in the past. I mentioned in 2020, its potential impact on AI chips developed for autonomous driving. To achieve >1000 TOPS (trillion operations per second) to safely guide the automobile in level 5, current technology consumes 1000 W, far beyond what car batteries can provide. Industry wishes to achieve 10 W by 2030 and 1 W by 2040. **With our AI chip prototype developed with spintronics at Tohoku University one can reduce the AI power consumption by factor of 100 if not 1000, suggesting that the target can be met by further developing the technology.**

Technology #7

NO CO2 PRODUCTION OF BULK MATERIALS

Environmental concerns foster innovation in No CO2 emission disruptive technologies that will be tested at scale by 2030 for the production of aluminum, while pilots will also demonstrate their feasibility for cement and steel.The journey to full carbon neutrality will be long though, as changes in working habits are necessary and major capital expenditures will be required while economics remain the 1st and foremost driver to convince investors without counting on a possible carbon tax.

TADEU CARNEIRO,

CEO BOSTON METAL (USA)

Molten Oxide Electrolysis, is a cost-efficient game changer to produce CO2 emissions-free steel.

The concept of Molten Oxide Electrolysis is to use electrons as reducing agent, concentrates of pure oxides (more stable than iron ore) as feedstock, and molten oxides like CaO or MgO as electrolyte, so that electrolytic cells with inert anodes can transform lower grade iron ore in very pure metal with only Oxygen as by-product.

The one MOE step will replace the traditional multiple steps of Coke/ BF/ BOF, with no need for pelletizing or sintering, **basically transforming dirt into metal in one go.**

At the expected $10/MWh cost of solar electricity in the years to come, and even at the $30/MWh obtainable from various sources in many regions today, **this technology should also bring a sizable reduction in capex and opex.** In countries like Canada, UAE, Scandinavia, Brazil or Australia where cheap electricity is already available, MOE would make economic sense today.

Overall energy consumption is reduced anyway vs traditional processes, from5300 KWH/ton of steel to 4000 KWh/ton. Moreover, Electrolytic cells are also completely modular and scalable. If producers need more capacity they just add more cells. For a 1 million ton steel capacity, 300 cells are necessary. This allows a very efficient capital allocation and a great flexibility of location.

Vale, BHP, BMW and an oil&gas consortium have funded a pilot that will prove the feasibility of MOE, test the life time of the inert anodes and assess the impact of the iron ore quality, by 2023. By then, the commissioning of a full scale facility might be decided in Quebec, with the participation of Primetals, SMS and Danieli.

CODY FINKE,

CEO BRIMSTONE (USA)

Changing the raw material used for producing cement while eliminating non-energy process CO2 emissions as cement production is responsible for about 8% of global CO2 emissions.

The industry is trying to replace a large fraction of cement with SCMs (supplementary cementitious materials) to increase strength but also to decarbonize cement. **A disruptive chemical process can turn any rock into a SCM and avoid burning coal:** by selectively extracting amorphous silica from any rock that contains silica. **This potentially can cut cement process emissions in half while increasing energy efficiency and reducing energy costs.**

The second step will be to make cement out of calcium silicate instead of the exclusive raw material used today -limestone: this will make cement production carbon negative, while remaining compatible with known technologies. As no costly electrochemistry is necessary, this disruptive chemical process can be cost effective and does not necessitate a carbon tax to justify the investment. Portland cement from Ca-rich basalts, also offers side benefits, like the co-generation of SCM and the opportunity to optimize the plants location. All in all, the additional 20% necessary on top of current capex to build a new cement plant is easily paid back. The selection of rock quality is critical though, as up to 80% could be added to usual costs if the quality is too low.

Valuation of tailings with high magnesium hydroxide content ultimately makes it possible to be carbon negative in cement production, even if coal is used in the heating stage. As those rocks that contain calcium silicate also contain aluminum or iron, those materials can be isolated as well. Consequently, it is physically possible to make CO2-free steel, aluminum and cement from one single rock. As the process is carbon negative, CO2 could be sucked out of the air (reacting with calcium) as a business, in addition to making cement.Tailing fields are typically rich in Magnesium hydroxide that will easily react with the C02 in the air.

ENRICO BORGARELLO,

PRODUCT INNOVATION DIRECTOR HEIDELBERG (ITALY)

On the way to carbon-neutral concrete by 2050: A long journey to change working habits, invest in new technologies, while keeping costs under control.

Cement is a rather cheap product. As a result, efficiency is not a key issue at construction sites and significant amounts are wasted during the construction process of housing and infrastructure. **30% and more of materials used could potentially be saved thanks to a significant increase of digitalization within the construction industry** like 3D concrete printing technology or the extended automation of concrete precast elements. **Of course, the result is not in the hands of the cement manufacturer alone, but all stakeholders of the construction value chain need to collaborate.**

On cement manufacturing itself, continuous improvement will come from the use of alternative fuels that currently represent 25% of the fuel mix and will reach at least 42% by 2030. Thereby biomass-based fuels are most prominent but also a switch from coal or petcoke to gas will deliver a not to be underestimated contribution.

The target is to reach less than 500 kg CO2/t of cement by 2030 vs 750 in 1990.

In a next step, the electrification of the kiln and probably also the use of green hydrogen as an energy source will be developed to maturity level. Innovation in alternative clinker production technologies based on altered chemical composition and correspondingly modified production conditions also have the potential to reduce energy consumption and CO2 emission.

Carbon Capture Usage or Storage is also a major area of research but significant results are not expected before 2030 as further research is needed efforts to test their industrial scale applicability as well as their production cost implications (prototype facility in Norway by Heidelberg and other technologies under development by Oxyfuel, Leilac, or Calcium Looping).

GERVAIS JACQUES,

EX MANAGING DIRECTOR RIO TINTO ALUMINIUM (CANADA)

A revolutionary aluminum smelting technology based on inert anodes, will bring a disruptive but economical action on the core process of production, with Oxygen as the only by-product and 20 to 25% gains in Opex.

The retrofit of AP30 potlines with inert anodes, for a $2500-3000/t cost, will potentially reduce the opex by 20-25%. The carbon side of the current production (coke and pitch) that employs 35% of the manpower can indeed be eliminated. Anodes replacement, which also represent a major part of the production cost will also be considerably reduced , from every 30 days to 5 years, and even cathodes , from 3years to 5 or 10. The core process would as a result be totally CO2-free and if the power , like in Canada, is generated by sustainable sources , e.g hydraulic, the aluminum produced would be really green.

Producing aluminum without CO2 emission on an industrial scale will happen before 2027, as a simple retrofit of current smelters, like AP30, is sufficient. The transition is only slowed down by the 1 ½ year opportunity cost generated by the retrofit of the current potlines, ultimately resulting in a 5 year pay back investment.

Inert anodes will not increase the capex of new installations but will reduce opex and will most likely become the new normal. As for the retrofits, the rather long time to make the change in current potlines (1 ½ year) makes the opportunity cost challenging though.

This disruptive technology emerged as a result of the determination of the end-user (Apple) who gave strong incentives to Rio Tinto and Alcoa to join complementary forces and create a JV (Elysis) to come up with a solution to offer CO2-free aluminum.

While continuous improvements, mainly based on increasing amperage in the cells, from 100kA in the Soderberg technology to 400kA in recent plants, have already reduced CO2 emissions by 50%, or more in select plants like in China with 590 kA and even now 640 kA, reaching zero emission needed a true disruption.

Technology #8

HYDROGEN BASED ON RENEWABLES FOR FUEL CELLS AT REASONABLE COST

Green hydrogen, hydrogen created without use of fossil fuels or the emission of carbon dioxide is viewed as an enabling technology for decoupling economic growth and materials consumption while creating value for our industries. 2030 continues to be a timeframe upon which the production cost and use of green hydrogen will be cost competitive for a number of transportation and industrial applications, with a specific goal of green hydrogen getting delivered to customers in the 4.50 EUR / kg range in 2030. Advancements in fuel cell technologies and electrolyzers as well as significant investments in large scale projects are leading the cost reduction efforts.

SHUNICHI MIYANAGA,

CEO MITSUBISHI HEAVY INDUSTRY (JAPAN)

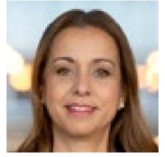
While many of the issues we discussed last year remain, the argument for hydrogen remains valid and will only be realized through continued advances in technology. In power generation, we have seen steady progress in development of hydrogen combustion technology in higher efficiency gas turbines by such companies as MHI, Siemens and GE. **Hydrogen combustion engines are also in actual use and under development for a wider range of applications.** In another field, we have seen increased development activities in hydrogen use for direct iron ore reduction instead of using natural gas and coal. We think that the key technology objective "lower energy consumption" for hydrogen production need not change, because lower cost hydrogen itself is a technological and industrial challenge which requires considerable time for us to realize.

The most important metrics is cost for hydrogen production ($/m3) covering its CAPEX and OPEX, including necessary energy (electricity) cost. When we use renewable energy (RE) for such production, it is necessary for us to carefully study how much RE is constantly available and how stable its cost level is. The associated costs of liquefaction, compression, transportation, storage and regasification for end-use also need to be considered. We have not seen any significant changes in what we identified last year. We, however, think that development of EV's has been accelerated in its speed and application domains. Thus, we need to evaluate further what are the competitive edges of fuel cell based light duty vehicles against battery based ones in terms of energy/cost efficiency with maximum driving range, availability of recharging stations, etc. We also need to find wider areas of application/usage for green hydrogen and fuel cells such as forklifts, marine engines, railway trains, etc. Several companies have started to plan and develop long range commercial vehicles, which seem to have a certain rationale.

We think that the biggest challenge we face is difficulty in reducing the production cost of green hydrogen worldwide to levels competitive with other kinds of hydrogen, such as blue, turquoise and grey, which may be favored depending on the geographical and/or industrial characteristics of a given region.

We had better apply green hydrogen to such regions where it is commercially beneficial or at least affordable, and, in other regions, use other kinds of hydrogen or hydrocarbon fuel with Carbon Capture, Utilization and Storage (CCUS), which is an equivalent solution in terms of net-zero emissions. Companies such as MHI have developed solutions that operate today in these areas.

We look to governments, academia and industry to continue working to improve these technologies while looking for tomorrow's innovative solutions through both internal R&D and, importantly, through partnership with ventures.



ILHAM KHADRI,

CEO SOLVAY (BELGIUM)

We have seen major global market developments in EV batteries and Hydrogen. On green hydrogen, we've seen progress in both the production of electrolyzers and fuel cells. The Proton Exchange Membrane (PEM) seems to be gaining momentum in larger projects and continues to increase competitiveness with the reduction of the membrane thickness leading to improved efficiency and limited consumption of materials. Solid Oxide (SO) starts gaining traction with first significant projects in the pipeline and Anion Exchange Membrane (AEM) sees important start-ups activities which should lead towards first piloting projects. In fuel cells, mobility is the first market segment to convert into green H2, with trucks and lighter vehicles converting before marine and aerospace. This is in the continuation of the electro mobility trend given that we are reaching the limit of Li-powered batteries, regarding energy density an mileage. Finally, PEM continues to increase competitiveness with the reduction of the membrane thickness leading to improved efficiency and limited consumption of materials. Key technology objectives are still valid, but how to reach the durable performance/cost ratio on the global system as fast as possible, whilst tackling the sustainability/recyclability by-design endeavors remains a challenge. For all technologies, the objectives are to reduce Capex and Opex, ensure a longer lifetime, a higher efficiency, the availability of the critical materials. We see the impact of equipment total cost-of-ownership (Capex and Opex per unit of power for electrolyzers or energy for fuel cells) and the material cost-in-use, as the key metric to track. We see a number of initiatives and major projects' announcements, booming since last year, in every region in the world, and mobilization in the value chain to reach this ambitious, yet, achievable target. The key success factor is to intensify collaboration and alignment along the value chain and accelerate the Technology Readiness Level, leading to full commercialization. We are focusing on our solid industrial investment plan to ensure that we can serve the green H2 production and mobility market growth with ionomers and composite materials. We see the availability of appropriate amounts of green energy to feed and to support the development of the green hydrogen ecosystem, syncing production and consumption, as one of the biggest challenges. I*N* addition, the development of the green hydrogen value chain network to align the best materials and achieve the best integrated Electrolyzers and Fuel cells systems to reach global competitiveness for scalable investments is another challenge.

JELENA STOJADINOVIC,

CEO MEMBRASENZ (SWITZERLAND)

The number of companies working on hydrogen solutions is increasing. be it component or electrolysers stack providers, is increasing. Hydrogen early adopters and end users are waiting for efficient and cost-effective products supporting low-cost hydrogen economy. Competitors in the segment of membranes for the use in electrolysers for hydrogen production (alkaline, PEM) are offering their products. Healthy competition among providers of components for electrolysis systems will help reduce the price thereof, which will result in electrolysis CAPEX costs reduction. On the other hand, **excellent ion conductivity of novel membrane materials will enable the reduction of electricity consumption during electrolysis and directly influence the reduction of electrolysis OPEX costs.** 2030 is still a relevant target year for green hydrogen and fuel cells for light duty vehicles. **McKinsey study from January 2021 showed that once relative efficiencies of the power sources and lifetime costs of a truck are factored in, green hydrogen could reach cost parity with diesel by 2030.** Besides numerous demo projects across the world, the first business case related to hydrogen mobility was the result of Hyundai's partnership with Swiss Startup H2 energy, Hydrospider, Linde and Alpiq. At the end of 2020, the firstly delivered dozens of vehicles started their service on the Swiss roads, while the total of 1500 heavy duty vehicles will be delivered to Switzerland and in operation by 2025. **Regarding industry challenges, high green hydrogen price is currently the main obstacle for broader adoption.** According to the H2 mobility Deutchland, the net cost of green hydrogen delivered to a refuelling station is foreseen to decrease by 65% down to 4.50 EUR / kg in 2030.

PATRICK KOLLER,

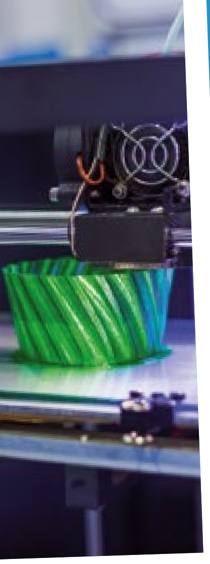
CEO FAURECIA (FRANCE)

We have seen continuous improvements for wind turbines and solar panels reducing renewable energy prices. We also have seen different types of electrolysers which will be adapted to the need including SOFC (Solid Oxide Fuel Cell) having an efficiency of more than 80% and PEM (Proton Exchange Membranes) improving their efficiency. New technologies like AEM (Anion Exchange Membranes) are also good candidates for the future. Another new technology addressing storage and transport of hydrogen is the Liquid Hydrogen, 75% more dense than Compressed hydrogen at 700 bars. There is as well some appetite to use LOHC (Liquid Organic Hydrogen Compound) to transport the hydrogen in a more competitive way. Technologies related to membranes are still to be improved to increase efficiency of the electrolysers and fuel cell stacks, lower the cost and improve the durability. **However, the most important parameter short term is the industrial scale-up which represents more than 50% of the savings we could expect.**

We didn't detect significant changes as the targets to make the full hydrogen supply chain competitive is known. However it could be that in the future we have some breakthroughs which could even further pave the way to increase the deployment of hydrogen, for example conformable tanks for light vehicle implementation. The key metrics to track are H2 energy stored in weight versus the weight of the tank, how much capital is being invested in infrastructure and production capacities and the value and volume of orders and market share.

We confirm that fuel cells for light duty vehicles are interesting especially for intense usage and high payload and a better TCO versus diesel could come from 2025-2026 but for sure before 2030. We also confirm that for medium duty and heavy duty Hydrogen will be competitive by 2030. The pressure from regulation to lower the CO2 emissions on trucks will force the adoption of hydrogen solutions. The biggest challenges we see are 1) implementing hydrogen solutions safely and quickly at the right time to get the right market share, 2) achieving mass availability of H2 at competitive price, and 3) **investing in the massive infrastructure needed to transport and deliver hydrogen.**

Increasing financial support from the countries of Europe and organizing one voice of the industry are critical. We also need to raise the awareness of the hydrogen economy to show that beyond the pure industrial aspects the hydrogen is necessary to get more energy independence, level the renewable energy production and is a raw material to convert CO2 into valuable materials like fuel or polymers.



Technology #9

3D MANUFACTURING

The demand for 3D manufacturing is driven by a rapid increase in the number of mobility, space, and aerospace programs. The key challenge is to increase the scale and speed of manufacturing while realising the advantages of this smart, flexible process. In the past year, much progress has been made to fully capture the benefits of digitalization in accelerating the steps from design to prototype to production by smarter manufacturing. This supports environmentally sustainable manufacturing through the production of high-performance parts with greater material efficiency by reducing scrap in manufacturing processes by 30%.

RAYMOND WEITEKAMP,

CEO AND FOUNDER OF POLYSPECTRA, (USA)

The most common industrial process for polymer part production is injection moulding, which is both capital and energy intensive. A simple structure such as the plastic casing of a phone charger is made in millions of units. **Approximately one third of the embodied energy in these parts is from the injection moulding process, with the remainder from the material production.** PolySpectra have a unique photopolymerization technology that uses solid state light sources and harnesses the energy of the catalyst. This process is 50-100 times more energy efficient than injection moulding and is also capable of manufacturing parts with a higher degree of complexity. High cost precision metal tooling is no longer required, making it easy to rapidly change part design. **The increased durability of this very tough material contributes to a reduction in embodied energy of approximately 20-30%, therefore realizing a total embodied energy saving of between 30-60% by displacing injection moulding.** PolySpectra "COR Alpha" is a cyclic olefin resin with exceptional, isotropic properties. Targeted chemistries are employed to overcome the inherent brittleness and the poor environmental and thermal properties of conventional photo polymers. The early discovery that led to the establishment of polySpectra was that the Nobel prize winning olefin metathesis chemistries could be mediated by light. The markets for these products include space and aerospace components as well as medical and dental devices. The development of this new material has been combined with innovation in digitalization and utilizing the latest tools for generative design and topology optimization. One example is the use of lattice structures where high strength and performance is achieved with the minimum use of materials and minimal waste. As infrastructure costs are reduced and printing machines become more readily available, parts can be made just in time and integrated into production lines. The shipping of goods contributes to about 2-3% of global emissions, scaling up 3D manufacturing will contribute to achieving net zero carbon supply chain solutions. **3D manufacturing is predicted to reduce the embodied energy of polymer parts by up to 60%.**

DR PAUL MACKENZIE,

SENIOR VICE PRESIDENT AND CHIEF TECHNOLOGY OFFICER, HEXCEL (UK)

Additive manufacturing of high temperature thermoplastic materials can replace metal castings to realise significant cost and weight savings. Hexcel is focused on the materials science to enable additive processes including selective laser sintering (SLS). There is a significant increase in market demand for high temperature thermoplastics such as polyetherketoneketone (PEKK). While there are now parts on aircraft with chopped fibre reinforced PEKK, the challenge remains to improve properties through the part thickness and to increase the rate of production. The technology was demonstrated in a project with Boeing to replace a metal casting for the CST-100 Starliner. The Starliner is a next-generation space capsule designed for low-Earth orbit. A complex metal casting was re-manufactured using 3D printed PEKK, demonstrating 20% in recurring cost savings with a weight savings of up to 50%. Other advantages are in a high conversion of the PEKK powder to the part that contributes to sustainable manufacturing solutions. The material waste in this process is reduced through the re-use of residual powder. Current limitations in scale leave room for machine innovation in the future and it is expected that the scales in part geometry and the production volumes will increase in the next 5-10 years. In parallel, there have been significant advances in automated tow/fibre placement technologies in the past 5 years with this technology entering production environments for the first time in the past year. These processes are capable of manufacturing large components where the benefits of continuous fibres are translated to the final part. For the manufacture of twin aisle aircraft the production rates are 10 per month, this increases to 70-80 per month for single aisle aircraft. The challenges are therefore to increase the speed of material deposition, to cure the component outside of an autoclave, to weld components rather than join with rivets and to reduce the amount of post-processing. **Automated tow placement has been predicted to reduce waste of high value carbon fibre from 60% to less than 10% through the digital design of near net shaped pre-forms.**

ROGER ASSAKER,

PRESIDENT, DESIGN AND ENGINEERING SOFTWARE BUSINESS UNIT, HEXAGON, CEO, MSC SOFTWARE (LUXEMBOURG)

Digital twins of 3D manufacturing processes accelerate the path to market and supports part certification. Additive manufacturing requires an end to end approach supported at every stage of the lifecycle and starting at the design. Digitalization enables generative design approaches with topological optimization for a print ready geometry. Recent developments have enabled a deep understanding of how to handle the anisotropic nature of powder selective layer sintering (SLS) printed polymers. Digital twins which incorporate physics based models combined with libraries of materials properties have meant that we now understand how to efficiently nest multiple parts in a powder bed to minimize any part inconsistencies derived from the change of part orientation within the 3D printing machine. We also understand the effect of porosity and can predict the effect of changes in porosity (1-2%) on part performance. **Hexagon has developed rapid, non-destructive, quality evaluation via computer aided tomography, integrating this live data upstream to improve the production process. In order to innovate with product design, development and performance prediction, we need to create trusted ecosystems with the secure sharing of encrypted data.** The digital twin must accurately represent the part, performance, the material as well as the manufacturing process. For example, the digital twin of the material is owned by the supplier (eg Solvay), but made available through our material eXchange platform to the end customer (eg Airbus) and the machine builder (eg Stratasys) in a secure environment. The digital twin combines real time data analytics with artificial intelligence algorithms to simulate production and part performance. Manufacturing execution systems (MES) are used to control workflow and to integrate 3D manufacturing into production and assembly lines. The digital twin can support design for sustainability by accurately measuring carbon emissions and energy consumption throughout the product lifecycle. According to Deloitte, the market for digital twins was US$3.8 billion in 2019 and is projected to more than triple in the next 5 years. **The use of accurate digital tools to support 3D manufacturing can reduce defective parts and waste by up to 40%.**

PROF. DR. PETER MIDDENDORF,

VICE RECTOR FOR KNOWLEDGE AND TECHNOLOGY TRANSFER, INSTITUTE OF AIRCRAFT DESIGN, UNIVERSITY OF STUTTGART (GERMANY)

Multiscale production methods to enable smarter, more flexible manufacturing. 3D manufacturing of carbon fibre composites utilizes either short, chopped strands of fibre or continuous fibre filaments where the mechanical performance of the fibre can be fully translated into the composite material. The aim is to build structures with a load path-oriented design to optimize mechanical properties.The University of Stuttgart has pioneered the freeform winding process using continuous fibre tows impregnated with a polymer matrix. Bio-inspired architectural pavilion structures using this technology have been showcased in exhibitions. **Free form winding uses anchor points to create a structure, increasing process flexibility and avoiding the cost of winding around a mandrel.** Complex geometries and winding over distances of several meters are both possible. The fibre tow is passed from one collaborative robot to another and for very long spans, drones have been used. There are growth markets in architectural prefabrication, however progress has been slowed by a lack of standards and certification. Using this technology, hydrogen storage vessels have been manufactured and tested. This technology can be used for non-cylindrical, conformable tanks within the next 5 years if the hydrogen market demand increases at the predicted rate. **Sterolithography utilizes liquid thermoset, light-cured photopolymers and for the first time these materials are being reinforced with fibres.** The photopolymers are usually based on epoxy or acrylate resin chemistries and the presence of a fibre reduces the optical penetration of the light and therefore cure depth. Recent research has focused on the influence of fibres on the curing behaviour to optimize processing parameters. These materials are used in parts with tight tolerances, for example, powertrains for weight critical electromobility applications. High volume, serial production of fibre reinforced sterolithography 3D manufactured structural parts will be realised in the next 5-10 years. **Recent modelling of an engine mount from an unmanned aerial vehicle predicts that fibre reinforced stereolithography manufacturing results in weight savings of 20% compared to a polymer part.**

EDOUARD MOENS DE HASE,

CO-FOUNDER AND MANAGING DIRECTOR AT AEROSINT (BELGIUM)

Multimaterial precision metal printing enabled by a novel recoating method for powders to support polymer 3D printing processes. Conventional blade recoaters in 3D manufacturing can only apply single material powder layers. **Aerosint has developed a proprietary technology consisting of recoaters with rotating, patterning drums to print different materials in controlled patterns.** This is used to build multimaterial laser sintered metallic structures. The patterning resolution is precise (500 microns) and the build size is in the centimetre range with the opportunity to scale. The immediate applications are in aerospace parts, consumer goods and machine tools with tailored wear resistance. Demonstration parts have integrated inbuilt copper channels for thermal management properties in nozzles for improved efficiencies in polymer injection moulding processes. The tooling market is currently the backbone of the global manufacturing sector and was worth US$200 billion in 2018. Scaling up this process will make it possible to rapidly produce bespoke tooling with inbuilt heating and cooling channels for polymer and composite manufacturing in the next decade. **Current powder printers typically waste up to 85% of the powders integrated in the process and this directed deposition technology can reduce waste by 10% to 30% depending on the process and material.**

Technology #10

AI AND QUANTUM FOR LESS ENERGY AND SMARTER USAGE

AI has gained traction for a variety of tasks ranging from exploratory data analysis to qualitative and quantitative predictive modeling. Of particular interest is its ability to make model-based engineering faster and more robust. Indeed, engineer's models are increasingly fed by observational data from material imaging, manufacturing process monitoring techniques or the exponential growth and storage of numerical simulations results. AI will strongly impact all field requiring big data analysis. In horizon 2030, advances in materials design and discovery will certainly continue. We can also expect large effect on the optimization of the production and the improvement of the quality control process of many production. In 2030 AI will allow smart city with a 50% reduction of their energy consumption as well as level 4 quasi autonomous vehicle.

VINCENT LAFLECHE,

MINES PARIS PSL (FRANCE)

Mines Paris PSL has implemented a specific course to give to all graduate students the fundamentals to deal with IA and deep learning technics; IA will contribute in most engineering sciences. On materials, the expected impact of AI is **first to accelerate by 80% the discovery and new designs** using the capability to construct predictive models that augment the computationally expensive simulation process and realize property prediction by efficiently learning from past experience. Of particular interest is its ability to avoid defects, to reduce energy consumption during production, and more importantly to provide advanced digital platforms and new virtual testing tool for innovative high-tech materials with improvements in (i) mechanical performances, (ii) weight reduction and finally (iii) in increasing lifetime.

Artificial intelligence is going to **fill the gap between real materials and their theoretical representation.** As for patient specific diagnosis in medecine, observation of industrial materials is going to be supplemented by AI for a more accurate estimation of their strength's limits. This can be achieved now for composite materials and aluminum alloys in aeronautical applications and in automotive industry, because available X-ray tomographic observations can feed AI with data for these materials. X-ray tomography observes the 3D shape of defects. In a few years, 2D observational data will be sufficient to feed AI for health diagnosis on materials. We believe that these techniques will yield not only transformative advances in materials design and discovery, but also provide organizing frameworks, infrastructure, and collaborative tools to overcome such challenges. This includes improving the data governance practices, **stimulating interactions between research and engineers,** and finally developing uncertainty quantification research and model checking to increase performances capabilities.

LUC JULIA,

CHIEF SCIENTIFIC OFFICER AT RENAULT GROUP (FRANCE)

Artificial Intelligence, if one considers that it exists, is **neither new nor truly intelligent.** Firstly, the origin of AI can be dated back to 1642 when Pascal invented the first calculator. Secondly, AI is just like a hammer. The former's capacity must not blind us from the fact that it remains a simple tool. Despite its degree of complexity, Artificial intelligence has been created, will be improved and, most importantly, can be controlled by men. To use this technology in order to create "Materials which can be used longer less smarter" or, on the contrarily, to destroy the planet, remains our choice. Nevertheless, this observation does not undermine the possibilities offered by AI. Thanks to algorithms and electronics which are able to generate, compute and store big data, AI can enhance our intelligence. This makes Artificial intelligence a very powerful tool, which can have watershed effects in human activities involving a large amount of data treatment. I believe that in 2030 AI will have a strong beneficial impact in three fields.

Firstly, regarding Healthcare, Artificial Intelligence will be employed to support doctors in multiple ways such as making diagnoses, deciding which treatments are the most adequate, or even predicting risks. In the case of image-based diagnostics, an AI computer vision approach will be faster and more accurate than any human eye. Also, AI algorithm will be able to process large and complex genomic datasets.

Secondly, in the field of transportation AI has the potential to ease traffic congestion, make transportation energy efficient and optimize driver's free time. While I do not believe in completely autonomous driverless vehicles (known as level 5) in a near future, we will soon be able to reach a level 4 of driving automation. The latter refers to vehicles that can perform driving tasks under specific circumstances but still require a limited degree of human control. Joining Renault, I believe that **level 4 vehicles will be produced by 2030.**

Thirdly, AI can expand the concept of Smart homes to entire cities. My home has more than 200 objects connected (heaters, lights, windows, solar panel) and, thanks to the AI algorithm controlling these objects, I generate more energy than I use. This can be generalized to neighborhoods or even cities. **By 2030 the energy consumption of big cities could be reduced by 50%.**

KEVIN CARLIN,

VICE PRESIDENT, ADI_OTOSENSE AT ANALOG DEVICES (USA)

At Analog Devices we have developed an AI-driven sensing interpretation platform (ADI Otosense™) that can acquire, learn, and make sense of any physical phenomena, such as sound, vibration, pressure, current, and temperature. By collecting minimal amounts of data, it is possible to build models which can be used to recognize events and detect anomalies to predict the health of machines either in the field or for 'in process' quality control.

There are many examples where AI is enabling industries, such as, Manufacturing, Transportation, Energy, Water, to extend beyond their traditional approaches **to optimize productivity, minimize unwanted downtime and reduce waste.**

AI can predict the failure of equipment before any human assistance. It detects the early warning signs of deterioration and alert for machine maintenance, reducing downtime while extending the lifetime of the asset. For instance, by predicting the failure of metal stamping presses in automotive, steel losses can be reduced, and machine productivity increased by helping to maintain asset health while reducing the cost of unnecessary scheduled maintenance. We demonstrated this with a **saving of ¼ of a million dollars for one production press.**

Reduction of water consumption can be obtained by identifying failures such as leakage and cavitation in pumps in your waste and water plant. Our AI platform is also helping the optimization of the production of those pumps through the asset test process, enabling the quality control for 100% of the assets, compared to traditional methods of sample testing. It can also identify and diagnose root causes of process issues. In the semiconductor industry, the silicon chip manufacturing process, starting from a silicon wafer, involves many process steps (material deposition, lithography, etching etc..). AI not only ensures optimal air quality and temperature in the cleanrooms, but it can also detect wafer defects across the various process stages. Extracting these wafers upstream prevents further wasteful processing and increases yield, resulting in significant cost savings.

AI Software will continue to learn and improve while complementing and enhancing the human experience across the industry. The ability and modularity of ADI Otosense™ lends itself to an expanding set of applications and use-cases.
The industry is in the early stages of digital transformation where AI processing at the edge is critical. There is much work ahead as these systems are integrated into the higher-level enterprise SW environments.

GREG MULHOLLAND,

CEO OF CITRINE INFORMATICS (USA)

Materials is fundamentally a discipline of tradeoffs: everything our industry does requires balancing a number of materials properties and considerations: strength and weight, durability and biodegradability, optical performance and toughness.
AI and Quantum together create a new opportunity, broken into 2 parts:

Faster responsiveness to industry needs—most OEMs are on a very tight product cycle. Because AI and quantum computing can very effectively simulate new materials and combinations thereof, they enable the creation of the right material for a specific job. This will allow for more integrated design processes (allowing for a smarter and less use of materials) and better tradeoffs.

New materials platforms—at the same time, new materials capabilities are needed every day. While historically, we have worked to create new materials with an iterative experimental approach, materials have become too complex and demands to extreme for that to be an efficient approach any longer. AI and quantum computing allow for the balancing of many properties to find materials platform that will allow us to use much less materials in smarter ways.

Finally, these technologies in the short term allow for substitutes of specific ingredients. This allows for the use of less materials that may be toxic, expensive, or environmentally damaging. Citrine has shown the **ability to eliminate 100% of Materials of Concern from product formulations without sacrificing performance in adhesives and lubricants.**

The materials and chemicals that will be affected first are those where manufacturing capabilities can be adapted quickly and where product lifecycles demand materials updates regularly. The timeline for impact is as follows: Substitutions in formulated products like adhesives, lubricants, masterbatches, and similar are already underway. Similarly, the tailoring of metal alloys, ceramics, and semiconductors is already underway.

In the next 5 years, we will see new plastics, waxes, and coatings with dramatically reduced toxic components.

At the same time new platform technologies are under development. Whether materials with a lighter environmental footprint or more extreme performance features, we would expect to see these introduced at a small scale before 2030, with full-scale production happening in the early 2030s.

Adoption of these technologies requires technical proof that they are valuable.

WORLD MATERIALS FORUM