Progress and Prospects in the Field of Biomass and Waste to Energy and Added-Value Materials

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Progress and Prospects in the Field of Biomass and Waste to Energy and Added-Value Materials

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Abstract This paper reports the conclusions of the three panel discussions held during the WasteEng2016 Conference in Albi, France (http://www.wasteeng2016.org/). It explores the research and development trends aiming at the production of energy and added value materials from waste and/or biomass. Three approaches are investigated: thermochemical conversion (Panel chairs: M. Castaldi, J.M. Lavoie, C. Vandecasteele), biochemical conversion (Panel chairs: J. Legrand, P.T. Vasudevan, W. Verstraete) and, sustainable construction and energy storage (Panel chairs: J. van Deventer, Y. Pontikes, X. Py). The thermochemical conversion session addressed feedstock, technologies for energy recovery and material recycling, gas cleaning and the marketplace. It is shown that combustion (WtE) is the leading technology and that also much research is devoted to gasification and pyrolysis. The biochemical conversion session noted the ability to yield products applied to different sectors such as food and feed, chemical, biofuels, biomaterials and many others. Innovation oriented towards better exploitation of the existing biocatalytic activity of known enzymes and microbes is also discussed. Recycling of solid and liquid waste received substantial focus in construction.

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Materials for thermal energy storage from waste are considered a promising use of recycled materials. The paper also shows how entrepreneurs introducing new technology have to work with both technical and commercial uncertainty, which renders investment into new technology a high risk. Finally, this paper identifies, in the three sections developed below, the trends for ongoing research and highlights the direction where the research is trending from this point forward.

Keywords Biomass and waste · Energy · Added-value materials · Technologies · Market

Thermochemical Routes

The world has an abundance of fossil fuels such as coal, gas and oil that have been efficiently developed during the past century to meet energy demands. Yet there is a disparity among countries and regions throughout the world in the accessibility and affordability of those fuels. Moreover and more importantly, to avoid or reduce further climate change mainly due to CO_2 emission, it was agreed (e.g. in Kyoto protocol, and at the Paris conference) that the use of fossil fuels should significantly be reduced. Concurrently there is an interconnectedness of the 'problem' of solid wastes (municipal solid waste, (MSW), which is common to people of all socioeconomic status and geographical locations. This establishes the possibility to adapt our knowledge of energy production from fossil fuels to alternative sources that transform a solid waste problem to an opportunity. As the CO_2 emitted upon combustion of biomass was first taken up from the atmosphere, its emission is considered not to contribute to climate change. Of the CO_2 emitted upon combustion of MSW, about 50% is biogenic. The energy thus produced is also (partly) renewable. Superimposed on those aspects is the social and political recognition that the main issue for people (and governments) is the fundamental need for affordable and reliable energy.

Specific to the issue of converting solid waste feedstocks to energy or value-added materials or both (i.e. valorization of wastes) is the position of thermochemical conversion in the sustainable waste management hierarchy. Overall the main outputs of thermochemical conversion of solid wastes are energy and materials. In the waste hierarchy, energy production would correspond to "recovery", and extraction of materials, from the residuals, would correspond to "recycling", which is just above "recovery", but below "reuse" [1, 2]. Therefore it is also advisable to separately collect the recyclable fractions of the MSW, and apply thermochemical conversion on the non-recyclable fraction.

Initially, waste combustion (incineration) was merely considered a method for treatment, with the focus on reducing the waste mass and volume leaving a sterile residue suitable for landfill. However, this began to change in the late 1980s and early 1990s, as the interest in producing energy (electricity and heat) or materials was driven by an alignment of rising fuel prices, concerns about CO_2 emissions, energy security considerations and financial incentives for renewable electricity production. Importantly, the interest in the circular economy [1] provides a new stimulus for recycling waste and biomass to added-value materials.

Thermochemical conversion technologies not only include combustion, but also gasification and pyrolysis. The major difference between these relate to the amount of air (oxygen) as a co-reactant and the processing and movement of the waste feedstock through the system. In combustion processes excess air is introduced and as-received waste with little or no processing is accepted. Gasification systems operate with much less air typically below the stoichiometric requirement for full oxidation of the material to CO_2 and H_2O, thus producing a mixed stream of CO_2, H_2O, CO, short chain alkanes (tail gas) and H_2. Pyrolysis units operate with zero air introductions and produce (depending on the process, the temperature, the residence time, etc.) varying amounts of combustible pyrolysis gas, liquid pyrolysis oil, and solid char. Gasification usually requires some feedstock preprocessing and pyrolysis always requires feedstock preparation and processing. Common to all three categories is the discharge of a solid residue in the form of oxidized ash for combustion, low-carbon content char for gasification and high-carbon content char for pyrolysis.

Technologies

Progress cannot be made at all if a technology does not exist to achieve the desired goals. Development of technologies that convert solid wastes has occurred at a steady pace for the last half-century to attempt to capitalize on some of the drivers listed above. Although several variations have been established, the leading thermochemical technology is combustion, currently referred to as waste-to-energy (WTE) or energy-from-waste (EfW). WTE is a proven, highly reliable technology with worldwide recognized equipment manufacturers. It is robust and flexible, as it can operate with waste feedstocks, that vary in composition and size, at a gate fee typically near 100 €/t. State-of-the-art installations allow stable operation with an availability of at least 8000 h/year. Worldwide, about 250 million ton of wastes (mainly MSW) are treated in approximately 2000 plants with an annual capacity of at least 70,000 ton/year. Among the different technologies available, grate (moving or reciprocating) furnace combustion is most popular for MSW and similar waste followed by fluidized bed combustion, which is preferred for some special applications (e.g. sludge and poultry litter)

[3], or for low calorific MSW such as in China and India [4]. WTE has penetrated enough in some countries where the problem of solid waste is adequately managed. For example, Belgium, Denmark, Germany, Sweden, and The Netherlands have achieved about 1% MSW to landfills by processing around 50% of their MSW using conventional WTE.

However, there are continuous efforts to further improve the operations of WTE to make them more efficient and cost competitive. Some of the more recent R&D trends relative to WTE installations (mainly grate furnace) are related to electricity generation and increased energy recovery, flue gas cleaning, recycling and reuse of ash and increasing unit capacity [5].

In the electricity generation efficiency and overall energy recovery area, in a large combustion installation in the Netherlands the electric efficiency (waste-to-energy yield) η_e was improved by applying advanced steam conditions in the superheated steam cycle (130 bar, 440 °C, $\eta_e = 30\%$) [6]. However, such an installation is very expensive, so that in most new installations, standard steam conditions are usually preferred, with smaller design changes applied, such as reduction of the exit temperature of the boiler to 160 °C instead of 230 °C. Moreover, several recent projects boosted overall energy recovery by combining electricity production, from a fraction of the steam generated; with direct application of the remaining steam thus further enhancing energy efficiency. For example, the KeppelSeghers Runcorn Project produces 80 MW of electricity and supplies 52 MW of steam to the INEOS chemical facility [7]. Another is the Indaver, Antwerp, Belgium industrial steam network established between their waste-to-energy plant in Doel and several chemical and logistic companies. Finally, numerous hot water/steam systems have been used for district heating (and cooling) for residential and commercial ventures such as the WTE in Minnesota USA used to heat the grounds of the Minnesota Twins baseball field. The economically optimal application depends on the location (proximity being most important) and on the continuity of the users' energy needs.

Focusing on flue gas cleaning (FGC), there have been continuous efforts since the implementation of air emissions standards. Emissions of pollutants (NO_x, SO_x, HCl, CO, PM, PCDDs) with flue gases posed a major challenge for WTE installations, as with other industrial facilities, due to the potential health hazards. Now properly operated WTE facilities are far below the most stringent EU emissions standards, many near one order of magnitude under. For example, dioxin emissions in the US have been reduced by more than 90% from 1987 levels going from, a collective total for all WTE facilities, of nearly 8.2 kg of dioxin toxic equivalents per year to less than 14.2 grams per year [8]. Unfortunately, there is still sometimes a reluctance of governments to permit construction of new facilities because of their reliance on outdated information. Since state-of-the-art installations all comply with the strict emission standards for WTE (which are the most stringent of all industrial sectors) there is, in principle, not much need to further improve flue gas treatment. Yet, as discussed before, in an effort to boost η_e, the exit temperature of the boiler is in general tending lower. This causes semi-wet flue gas cleaning to become more difficult because all the water from the injected slurry cannot be fully evaporated. Therefore, in new installations, semi-wet FGC is usually replaced by dry FGC. Moreover selective non-catalytic reduction (SNCR) for NO_x reduction is gaining popularity over selective catalytic reduction (SCR) because SCR requires too much energy for gas reheating, and improved SNCR [9] can perform well below the current emission limits [10].

Coming to the recycling of bottom ash it remains an important challenge, to which much research was and is still devoted. This really is the last forefront in WTE operation. If one can identify a process that enables complete usage of the ash (bottom and fly). Then WTE truly will constitute a zero waste strategy. However, fly ash concentrates Pb, Cd, Zn and other heavy metals making it a hazardous waste. Conversely bottom ash (BA) has a much lower concentration of those metals and contains other elements that provide a level of inertization making it currently suitable for beneficial use applications. In the BA, the un-oxidized metals are the most valuable fraction, so there is an immediate economic return on recycling those metals. Water, due the quenching and wet washing operations within WTE systems, causes problems in separation of non-ferrous metals (NFe) by eddy current separation. Recently technologies have been proposed for more or less dry treatment of BA [11–13], which allow over 90% NFe recovery. The mineral fraction of BA represents the largest mass and volume, and, if not recycled, substantial quantities of it (about 25% of the mass of the initial waste) should be landfilled. Verbinnen et al. [14] reviewed engineering applications of WTE BA and the corresponding chemical barriers, as well as treatment technologies. It is clear in this context that combustion not only recovers energy, but also allows recycling of metals and mineral compounds from the BA.

Finally, increasing size of incinerator lines is one of the "developments" of new WTE facilities. To date 70 MWth and 200,000 ton/years are typical, compared to 35 MWth and 100,000 ton/years in 1990. In Asia more and more large capacity, high throughput incinerators for treating MSW from megacities are being constructed. Although the requisite knowledge exists on scale-up, each facility is unique and, as volume to surface increase, heat transfer and combustion air mixing needs continuous attention and engineering.

Gasification is a thermochemical partial oxidation process, using oxygen, air, water, carbon dioxide or mixtures thereof as gasifying agent, that converts a solid or liquid combustible feedstock into syngas, a mixture of mainly CO and H_2. Syngas can be used as a fuel for producing electricity and/or heat, or as building block for the chemical industry. Gasification is not a new idea nor a new technology, since industrial applications for the production of town gas from coke date back to the beginning of the twentieth century, and a number of large scale plants for the production of electricity from coal or heavy oil residues were built in the US and Europe in the last 30 years. Gasification is often put forward to public administrators as a benign, innovative alternative to the conventional combustion WTE plants [15]. However, although much literature is available on gasification of biomass [16, 17] and of MSW [18, 19], the number of operational waste gasification plants (about 26 operating worldwide corresponding to approximately 1.2 million ton of biomass and waste per year) is two orders of magnitude lower compared to combustion [20]. Therefore, operating experience is limited and data on actual performance, cost, etc. is scarce and fragmented.

In most gasification plants, the obtained syngas is subsequently combusted in a steam boiler, to produce electricity in a steam turbine, although this is the least efficient way of producing electricity from hot combustible gas. Such plants are very similar to combustion plants, but full oxidation is carried out in two steps (2 step oxidation): feedstock gasification, followed by syngas combustion [21]. These plants are rather simple to operate, but just like combustion plants only yield electric power and heat (steam, hot water), and may in fact be considered a special sort of combustion plant. Other types of gasification plants (‘full’ gasification) can provide power and heat and a useable syngas that can be converted to make chemicals (e.g. methanol, ammonia, hydrogen, and liquid fuel). To produce the chemical compounds, the obtained syngas must be thoroughly cleaned and treated to comply with the specifications of the downstream processes converting the syngas to the desired product. Extensive gas cleaning to remove tar, acids, particles, etc. from the syngas is also necessary, when it is used for high-efficiency electricity (and heat) production in combined cycle turbines, gas engines, or fuel cells. This would further increase the installations’ cost. Plasma gasification [19] is the newest type of gasification. As the plasma itself is a source of energy, high temperatures can be reached even for low energy fuels such as MSW. Plasma gasification however has higher CAPEX and OPEX constraints.

In gasification the oxidation of carbon with oxygen to CO (or CO_2) is exothermic, but other reactions in gasification are endothermic, certainly if water or carbon dioxide is used as gasifying agents. Gasification may therefore, in addition to the energy from oxidation to CO, continuously require a support fuel such as natural gas, pulverized coal/cokes, electrical heating (‘plasma torch’), as well as oxygen enriched air, which consumes energy to produce. A new initiative has been developed in improving the efficiency of biomass gasification by supplying process heat from concentrated solar systems, which can attain the required temperature of 900 °C [22]. Moreover, in the case of MSW gasification, waste pre-treatment aiming at increasing LHV and homogenization, and at rejecting inert/bulky pieces at the inlet, is usually required. All these increase process complexity and decrease reliability and performance [23]. When calculating the energy output, one should take into account parasitic loads such as oxygen production, additional energy sources in the form of cokes, and energy consumption for pretreatment of waste. When these inputs are subtracted from reported outputs, the efficiency is at most comparable to, but typically well below, that of combustion [23]. Hence, the potential benefits of ‘two-step oxidation’ do not relate to a higher energy efficiency, but may relate to improved material recovery and operation/emission control, including, depending of the process used, recovery of metals in non-oxidized form; collection of ashes in inert, vitrified form and lower generation of some pollutants, particularly NO_x [15]. Another possible advantage of gasification over combustion could be for developing countries and regions where the electrical grid is less established and distributed generators are prevalent.

Expectations on plasma gasification/vitrification for ‘full gasification’ resulting in combined energy and material valorization are quite high and it is claimed that variable waste inputs would not pose problems [19]. Long duration, full scales tests, described in detail in the open literature with all inputs and outputs are needed. This will not only clearly document the technological possibilities of the technique, but will also allow assessment of its sustainability, in view of its environmental impact and resource needs. Moreover, it will provide demonstration data enabling an assessment if plasma gasification/vitrification is economically viable for large scale biomass and MSW treatment. This is important because any decision maker will require data from a demonstration or reference plant to determine the risk associated with installation. In the economic context of Europe and the US (with typically low gate fees and treatment costs), plasma gasification seems normally only justified for wastes that cannot be processed in another way (such as high asbestos containing waste).

Finally, pyrolysis, defined as thermal decomposition in the complete or almost complete absence of oxygen, produces (depending on the process, the temperature, the residence time, etc.) varying amounts of combustible pyrolysis gas, liquid pyrolysis oil, and solid char. Pyrolysis was shown to be a suitable thermochemical process for some waste streams [24], but is less adapted and does not allow complete treatment of heterogeneous feedstocks, such as MSW and biowaste. Moreover, pretreatments (drying, grinding) and after-treatment of the waste and products are required. Since

1990, about 25 installations were commissioned, mainly in South- East Asia and Japan. They are mostly based on a pyrolysis reactor with an added slagging gasifier and produce very little (if any) electricity. In addition, the installations appear difficult to operate, as they are very sensitive to air inlet [18].

Economic Considerations

One of the drawbacks of the thermochemical projects considered is the high cost to procure, install and operate the infrastructure, in contrast to the low cost of the feedstock (i.e. solid waste). Therefore, continual industry-oriented research and development is needed to enable lower costs, while necessarily guaranteeing environmental compliance. Important investments in thermochemical installations will only be made if a suitable feedstock is guaranteed at an acceptable price for at least 20 years. Of course, demand will have a strong impact on the solid waste feedstock price, and political and economic stability is paramount to ensuring stable markets. Extended guarantees over decades for feedstock supply do not pose a problem for combustion installations because of their adaptable operation: a typical grate furnace installation is capable of treating (mixes of) MSW, comparable industrial waste, biomass, etc. with almost no pre-treatment, and all this with exemplary availability. To further improve the economic and environmental situation of WTE, more options for the direct use of heat (steam/hot water) should be incorporated and developed. Contrary to other sources of renewable energy, such as solar and wind energy, electricity generation by WTE (which is about 50% renewable) is continuous. Grid managers should therefore give WTE some priority by admitting it to the grid regardless if much solar or wind energy is generated [25]. Moreover, use of recycled metals and minerals from bottom ash should be facilitated and even encouraged.

Gasification installations, and particularly the ‘full gasification’ ones seem to be much less flexible and resilient because they generally require a homogeneous feedstock (possibly with the exception of plasma gasification although this has other technical challenges). This may be because gasification systems, although not new in general, are relatively new for biomass, so that the oxygen and water content pose new constraints in making gasification technologies economical. In general, there is enough residual feedstock available at specific locations for a gasifier, but a homogeneous supply feed is complicated to secure for more than 20 years. Hence, it may be necessary to use different types of residues (MSW, agricultural waste and so forth), which will require the technology to be versatile in a way that it is not currently.

Economically speaking, an important difference between waste and biomass as feedstock is that waste (e.g. MSW, municipal sludge, and construction and demolition wood) may be available at negative cost (reaching up to −30 USD/ton), whereas biomass prices range between typically 60–80 USD/ton for residual forest biomass or residual agricultural biomass, to 120 USD/ton for wood chips and prime quality straw [26, 27]. Higher qualities of biomass are, in practice, used for applications that align with higher facets of the hierarchy such as reuse and recycle (i.e. mainly food and biochemical as reported by Johnson [28]). The energy sector has a large influence on the price of biomass, as can be illustrated by many examples. The actual low cost of fossil fuels (oil market value at 49.92 USD/barrel and natural gas at 3.300USD/GJ—October 2016) has actually a negative impact on the production of renewable energy. Independently if the target is heat, electricity or liquid fuels, the low cost of natural gas is very detrimental to developing technologies aiming at the utilization of wastes. To be economically viable, refuse of all sorts must be at least as affordable as natural gas per energy unit, which automatically discards biomass because the costs are more than 60 USD/ton (considering an energy value of 19 GJ/ton).

Large investments in natural gas development such as the US exploitation of shale gas decouples the energy aspect with waste processing. When large countries become energy independent via development of nominally low carbon sources such as methane, the impetus for energy production through alternative means diminishes. The recent transition of the US from being energy deficient to having a surplus of energy supply changes the attitude toward thermochemical conversion of wastes, so that there remains little interest in waste conversion for energy generation. The same attitude change may occur related to CO_2 emissions: since the transition to shale gas for power production and many other industrial heat applications, CO_2 emissions in the US are equal to 1995 levels.

Conversely, the development of natural gas technology may not be completely detrimental for implementation of thermochemical processes applied to wastes and dedicated liquid fuel production. Since conversion of natural gas sometimes requires reforming of syngas to produce homogeneous intermediate building blocks, it is a common pathway for the production of downstream products as alkanes, alkenes, methanol, ammonia, etc. Combined with the fact that landfilling is becoming an increasingly banned practice around the world, wastes are often found at cheaper prices than natural gas. Companies around the world are starting to seriously consider the utilization of wastes as a cheap source of carbon. A good example are the efforts of Enerkem, that is operating their first industrial scale facility in Edmonton, Alberta, where the source of carbon is municipal waste (after separation for composting and recycling) and the end product is methanol (soon to be followed by ethanol) sold on the market. Natural gas exploitation also opens a new perspective for the valorization of the ultimate carbon residue, carbon dioxide. The latter most oxidized form of carbon is considered as a significant contributor to climate change. Hence, new technologies such as dry reforming, that have been considered for many years may soon become very interesting options to use natural gas as an energy vector to reduce carbon dioxide and insert it back into the carbon valorization loop [29]. Linde in association with BASF are working on a demonstration unit in Germany [30].

Waste (MSW and bio) is common to all countries, none is without it, whether industrialized or emerging. Recovering energy and materials from waste should be viewed as an opportunity. Major distinctions exist between developed (mature, industrialized) and developing (emerging, industrializing) countries on the subjects considered. In general, the main issue for people (and governments) is the fundamental need for reliable energy. Developed countries already have reliable energy systems and waste management systems in place, and can afford to make decisions based on sustainability goals. The developing countries' prime requirement is to secure energy, so that they use, in general, the most accessible and cheapest feedstock, which usually coincide. Overall, developed countries and regions also started developing more adequate waste management: first landfill, and subsequently recycling (including composting) and thermal conversion, but did so out of direct economic or environmental necessity, rather than for long term sustainability considerations. Notably, the world should not be viewed as only consisting of developed and developing countries, but rather as a development spectrum. Markets are therefore similarly structured as a spectrum where some technologies can be incorporated in a given country and not in another, for financial, economic, political, and logistic reasons, but the availability of feedstock and its price remains a major consideration. Biomass, preferably biowaste, as an energy source for thermochemical processes is obviously more attractive in forest-rich countries as Canada, US, Finland, than in other developed countries, where the availability of biowaste or biomass is low and must be imported from long distances, causing again fuel consumption and CO_2 emission. There is a gap between activities associated with research and development in academia and what industry and politicians push forward as solutions. It is important for academia to work on relevant initiatives and communicate to groups such as the government, public, stakeholders and decision-makers their findings and projections. Researching, defining the drawbacks and advantages of the available technologies depending on all the factors presented here, and disseminating this information is both the challenge and role for academia.

Biochemical Routes

In light of declining oil prices, biofuel cannot be the only product obtained from biomass or wastes. For example, many companies have abandoned their quest to produce biofuels from algal oil. Solazyme (now Terra Via) is no longer focusing on its fuel business, and instead is selling its algal oil to the food and personal care industries. More efforts have to be made for the complete valorization of biomass/wastes. The question is how to optimize from economic, energetic, environmental points of view the refinery process to produce both energy and added-value molecules. Biorefineries are integrated bio-based industries, using a variety of different technologies to make products such as chemicals, biofuels, food and feed ingredients, biomaterials and heat and power, aiming at maximizing the added value with respect to sustainability [31].

The key feature is not what it may seem at the first instance, i.e., to develop new processes and products. Although the latter is essential for progress, there is first and foremost a need for a strong 'attractor' from the market side. Indeed, scientific and technological developments generate lots of new items, but few of these find a place in the market economy. At present, a very positive feature is that the message of scanning the 'needs for new and better products' gradually becomes understood at the 'push' side. There is at present a genuine need for new processes to produce nutritious protein. The possibility exists to use recovered CO_2, NH_3 and phosphate and produce, by means of green energy, H_2 and O_2 by electrolysis of water, microbial based proteinaceous feed and food. Clearly, such technological routes need strong backing up from the regulator and the consumer must be consulted very strongly in all steps of the chain development.

We are not suggesting that we abandon our goal to become less reliant on fossil fuels and the issues of recovering energy from biomass. Declining oil prices should not divert our attention from managing the climate problem. The environmental consequences of relying solely on fossil fuels have been devastating. At the same time, governments have to reexamine their renewable fuel standards, especially the ones that mandate blending corn-based biofuels. The question of high water consumption in the production of some biofuels has to be addressed as well.

The biotechnology route is a promising way for biomass/wastes valorization. Industrial or white biotechnology uses microorganisms and isolated enzymes [32] to generate production in different sectors including food and feed, chemistry, biofuels, chemical specialties, biomaterials [33] and many others. Among other things, research in this area considers the optimization of the natural capacities of micro-organisms (bacteria, fungi, yeast, microalgae) and/or enzymes in biotransformation processes, the improved performance via process innovation and the genetic selection. There is a strong expectation for innovation oriented towards better exploitation of existing biocatalytic activity of known enzymes and microbes. In terms of processing, the main issue is the identification and the development of the appropriate extraction techniques (multiple techniques, energy cost and water recycling), with a strong impact on the downstream industrial processing.

What we actually call ‘wastes’ are the inputs of the circular economy. One goal is the optimization of biotechnology processes with bacteria, fungi, yeast and microalgae fed with gaseous or liquid effluents [34]. Synergies between industrial activities need to be valorized in order to reduce natural inputs, minimize energy consumption and reduce waste by utilizing by-products in the ecological engineering concept [35]. New types of production processes need to be developed that integrate sustainable agricultural production, energy- and resource efficient industrial biorefinery processes providing competitive products, and close the cycle, for nutrients and water as examples [36]. For food application, the resources recovered from sewage could carry a stigma. Clearly there is a need to optimize the process to get ‘clean and clear’ compounds from wastes to guarantee the quality of the food product. There should be no doubt: we must have the ambition that food and feed production from wastes are achievable and we should communicate very openly about this with the consumer. The corner stone of the circular economy is the concept that a product is not judged by its origin, but by its quality.

Algae biomass fits well with the scope of biorefineries [37]. The advantages of microalgae production are clear with the co-production of lipids and proteins with commercial value at high productivities per land area, with the opportunity to use nutrients coming from waste streams (N, P and CO_2). Algae production, harvesting, separation of the different compounds from the biomass, and conversion technologies are the different steps of the global process. The main research topics are the exploration of the biodiversity of macro- and microalgae, the development of an integrated system for biotechnological processing/treatment of industrial wastes such as wastewater and flue gases for production of microalgae biomass [38], the determination of the optimal growth conditions for enhanced growth and metabolic productions, including novel technologies and strains, the development of cost-effective large-scale microalgae and macroalgae cultivation systems, and the development of post-processing of algae.

Concerning biorefineries, expertise using a systematic approach is necessary for the development of an integrated process with optimization tools at different scales [39]. Life cycle assessment can help to guide and to refine sustainable development of biotechnology applied to bioeconomy. But most of all, we must strongly endeavor to generate interest at the side of the consumer. The best way to do so is to provide facts and figures that demonstrate to the citizen that it is in the best of his/her interest that indeed the cyclic economy becomes part of the daily life of each and every one of us.

Sustainable Construction and Energy Storage

The recent Paris Climate Agreement [40] should provide impetus to research and development in sustainable construction in view of the significant embedded energy and ongoing energy demands of the built environment. Likewise, with the growing trend towards renewable energy and the growing concern in waste heat valorization there is a need for thermal energy storage (TES) technology.

The global investment in infrastructure development is expected to exceed USD 27 trillion by 2025, with Asia-Pacific accounting for a 37% share and with expected investments of $10.5 trillion from 2010 to 2025 [41]. Therefore, the construction industry can be expected to be more than USD 10 trillion by 2020, which is about 10% of global gross domestic product and hence one of the largest industry sectors. Significant growth in construction is expected in the developing countries rather than the industrialized world. Simultaneously in developing countries, there is a global shift towards buildings that are considered to be “green” and hence have a reduced carbon footprint; in fact, entire eco-cities and eco-resorts are being planned. In China, the world’s largest construction market, there is a strategic shift towards prefabrication/modularization to save construction cost, minimize waste, improve quality and reduce carbon emissions; this is called “industrialization” of construction in China.

Buildings are the largest energy consuming sector in the world, and account for over one-third of total energy consumption, and are an equally important source of CO_2 [42]. Although heat insulation, off-grid energy generation, recycling of solid and liquid waste, and improved heating and cooling systems have received substantial focus in construction, there has been little focus on the use of binders with ultra-low carbon emissions such as chemically-activated materials (instead of Portland cement). Such binders could be made from industrial waste such as fly ash and slag, hence creating a new value chain. An additional source material that is expected to become more topical is the slag from a new generation of pyrolysis/gasification and other high temperature processes converting fresh or landfilled municipal solid waste into electricity and/or fuels. An alternative approach is to use CO_2 bonded materials or cements that will sequester CO_2 over time, like certain calcia-rich or magnesia-rich binders. Policy reforms and a shift from prescriptive to performance-based standards are required for the wide-spread adoption of alternative binders [43]. The research community must play a proactive role if these complex changes are to gain traction. Although the cement industry has considered carbon capturing and sequestration methods in conventional Portland cement plants, it is not a viable option at present. The outsourcing of building management and services offers an opportunity for the introduction of new technologies and a concomitant reduction in carbon emissions. In that trajectory, the link between end-of-life and residue quality, and how to integrate these materials back into the system has to be addressed. For instance, construction and demolition waste has been identified as a priority waste stream in the EU, as it is one of the most voluminous waste streams generated, accounting for approximately 25–30% of all waste generated [44]. Ideally, the new construction materials and technologies are designed in a way that supports sustainability and the path to circular economy.

The current options for TES systems are sensible heat, latent heat or thermo-chemical reactions. Sensible heat is the most mature technology, but at present is not sustainable, because the molten salts used are in limited supply and already used as fertilizers [45]. Therefore, there is an urgent need to search for sustainable TES materials synthesized from waste in a cost-effective way. A first generation of recycled ceramics, such as conventional mullite, from inorganic industrial wastes has already demonstrated the viability of the concept and the high performances of the obtained materials [46]. The emerging second step based on silicon carbide containing ceramic materials manufactured from mixed industrial wastes offers the opportunity to produce advanced low-cost ceramics, but much more needs to be done. A suitable TES material must have a high availability and low cost, be resistant to fatigue and aging, not have scale-up issues, have high thermal conductivity and a high specific heat capacity [47].

Consequently, there is a need for more involvement of material scientists with thermal engineers in the development of TES materials; it appears that the broader materials science community is unaware of this opportunity. TES is a highly multi-disciplinary field that requires more attention to become sustainable. It is indeed a critical issue for our transition to more sustainable energy generation. The international market opportunity is huge and will grow over the next decades; hence, there is a high potential for innovation.

In the Paris Climate Agreement [40] under “Technology Development and Transfer” Decision 67 states: “Decides to strengthen the technology Mechanism and requests the Technology Executive Committee and Climate Technology Centre and Network, in supporting the implementation of the Agreement, to undertake further work relating to, inter alia: (a) Technology research, development and demonstration; (b) The development and enhancement of endogenous capacities and technologies.” Unfortunately, this decision reflects a narrow focus on technology development and does not provide guidance about how obstacles to commercialization could be overcome. Sustainable construction and TES technologies face many hurdles along the pathway of wider adoption, but this is often not appreciated by governments, the industry or researchers. The fact that a technology is excellent is no guarantee that it will be adopted, and the reasons are non-technical. For example, in 1956, SOFINA, the main shareholder of ‘Le Purdociment’ received an offer of 10,000,000 BEF (corresponding to ~Euro 250,000 euro) from CIMBEL (an association which defended the interests of the Belgian cement manufacturers) to stop their activities. On 2 May 1957, ‘Le Purdociment’ accepted that offer and later went into liquidation [48].

The vested interest of incumbents serves to protect their value proposition in the market, which often acts against the interests of superior and sustainable technology [49]. For example, despite the public demand for more renewable energy, a new renewable energy generator often faces resistance from incumbents to gain access to the distribution network. In the construction materials industry incumbents control the materials supply chain and logistical infrastructure, which makes it difficult for new entrants to compete as they have to set up a parallel supply chain.

Standards are based on existing technologies, reinforcing the status quo, especially in the case of construction materials, where standards committees are dominated by incumbent industry players. If a new cement with low carbon emissions is not based on Portland cement, while the standard prescribes a minimum content of Portland cement, the new cement cannot be used in construction [44]. In many ways, legislation has been introduced to protect existing industries, hence offers barriers to new technologies. Entrepreneurs introducing new technology have to manage both technical and commercial uncertainty, which renders investment into new technology a high risk.

It is possible to overcome these obstacles by vertically integrating and controlling the value chain from processing waste to the final customer [50, 51]. Usually, an entirely new business must be set up to achieve this and to avoid existing companies offering even subtle resistance to new technology. It is essential to identify the key to market entrance, and what will make or break the business. The standard model of the researcher as a technology provider to an existing industry does not work if the technology is disruptive. It took a computer company like Apple originally outside the mobile phone market to revolutionize the smart phone market and then again, an outsider to tell to Apple that there is room for improvement [52]. It took a company like Tesla outside the car industry to introduce the electric car and disrupt an existing industry. Likewise, it will take a company outside the Portland cement industry to introduce a disruptive binder with low carbon emissions.

It is essential to control the deal-making and facilitate capital raising, hence to link the market and finance to materials supply and technology [53]. A new technology without the right commercial setting should not be pushed for its own sake [49]. Rather identify a market need and investment opportunity first, and perhaps use an old technology but in a new commercial setting. The conventional view that a patent is the store of value is not valid; rather where the value lies is in the understanding of how to penetrate the market. It is essential for technology entrepreneurs to build networks of trust with investors and other entrepreneurs, and to leverage credibility. Unfortunately, the skills set required for such entrepreneurial activities lies outside what is taught in a university environment, with a few exceptions. Universities will do well for their students and staff by bringing such entrepreneurial culture onto campus. There is considerable opportunity for innovation and the creation of new businesses in the field of sustainable construction materials and the synthesis of TES materials from waste.

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