Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in Biotechnology

Scaling up of renewable chemicals

Karl Sanford[1], Gopal Chotani[1], Nathan Danielson[1] and James A Zahn[2]

The transition of promising technologies for production of renewable chemicals from a laboratory scale to commercial scale is often difficult and expensive. As a result the timeframe estimated for commercialization is typically underestimated resulting in much slower penetration of these promising new methods and products into the chemical industries. The theme of 'sugar is the next oil' connects biological, chemical, and thermochemical conversions of renewable feedstocks to products that are drop-in replacements for petroleum derived chemicals or are new to market chemicals/materials. The latter typically offer a functionality advantage and can command higher prices that result in less severe scale-up challenges. However, for drop-in replacements, price is of paramount importance and competitive capital and operating expenditures are a prerequisite for success. Hence, scale-up of relevant technologies must be interfaced with effective and efficient management of both cell and steel factories. Details involved in all aspects of manufacturing, such as utilities, sterility, product recovery and purification, regulatory requirements, and emissions must be managed successfully.

Addresses
[1] DuPont Industrial Biosciences, 925 Page Mill Road, Palo Alto, CA 94304, USA
[2] DuPont Industrial Biosciences, 198 Blair Bend Drive, Loudon, TN 37774, USA

Corresponding author: Sanford, Karl (karl.sanford@dupont.com)

Current Opinion in Biotechnology 2016, **38**:112–122

This review comes from a themed issue on **Energy biotechnology**

Edited by **Andrew S Ball** and **Jamie HD Cate**

http://dx.doi.org/10.1016/j.copbio.2016.01.008

Introduction

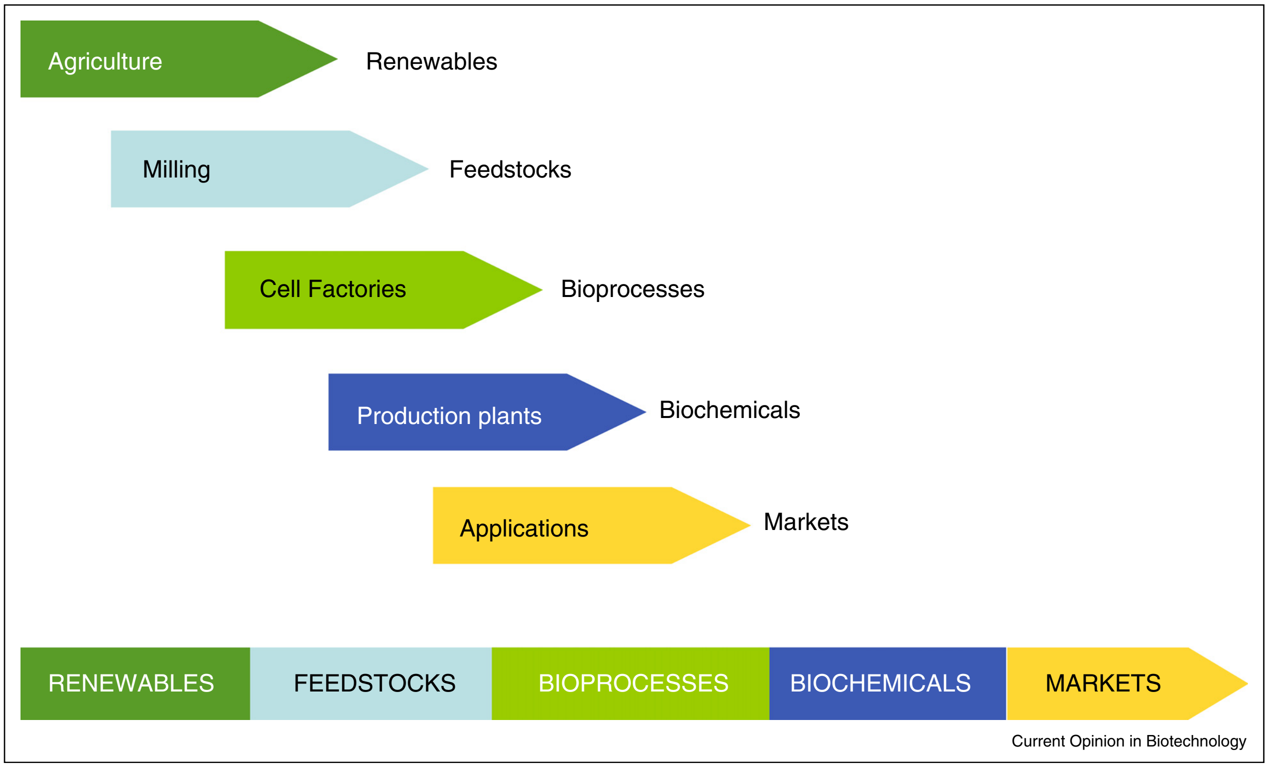
Low petroleum prices have made the successful introduction of new bio-based processes more difficult and risky. But global climate change scenarios demand more sustainable manufacturing processes for the chemical and materials industries. Although the arbiter of what is sustainably advantaged is a life cycle assessment, as a general rule, bio-renewable processes use less toxic chemicals and operate at ambient temperature/pressure, thus are considered advantageous [1,2••]. Hence, there is a pressing need to successfully scale these processes at the first attempt. Creating the necessary process flow sheets, assessing cost sensitivities, and identifying bottlenecks upfront by the use of modeling, simulation, and techno-economic analysis, will aid in a successful scale-up [3–6]. In this article, we review various categories germane to a fermentation based process scale up (Figure 1), for the production of bio-industrial products.

The volumes of bio-based products (derived from renewables, not necessarily fermentation based, and excluding biofuels) globally are estimated to be 50 billion kilos per year and these volumes are anticipated to grow significantly in the near future [7••]. The growth of biobased products is occurring at a rate 3–4% per year globally. In 2013, the United States alone generated $126 billion direct sales of biobased products. The steady progress made in the manufacturing of these products over the recent years with a line-up of products and stages of scale-up is shown in Table 1. The difficulties associated with scale-up are reflected in the delays and/or severely reduced volumes commercialized compared to the announced capacities. Getting from the laboratory scale to market is an enormous challenge, particularly for start-up type companies that may excel in certain aspects but lack all that is needed to scale up. A thorough analysis of the current world-wide production capacity and projected capacities to year 2020 of the most important bio-based building blocks that are precursors of polymers has been performed by Dammer *et al.* [8]. A comprehensive assessment of the commercialization status of both biofuels and biochemicals is reported by Barovsky *et al.* [9•]. Comprehensive reviews by Choi *et al.* [10••] and Chen *et al.* [11••] on the production of top building block chemicals provide the commercial status of over 30 initiatives, many of which are in the 'preparing' for commercialization stage.

Commercial scale — successes and failures

Industrial enzymes, ethanol based biofuels, lactic acid, and 1,3-propanediol exemplify some of the early successes of commercial scale-up. The process for commercial production of 1,3-propanediol for Sorona® polymer is based on a unique collaboration between technology leaders DuPont and Tate & Lyle [12•]. The process has become a hallmark of an emerging commercially viable biomaterial era, competing with and complementing petrochemically derived materials [13]. The production of lactic acid based biomaterial (polylactide polymers) from corn sugar led by NatureWorks® LLC is another

Figure 1



High yielding agricultural crops combined with efficient steel and cell factories will enable product & process innovations for sustained success. Better products, competitive economics, and positive environmental impact are absolutely essential for successful launch of new chemicals from renewable feedstocks.

example of successful commercialization. The current market size for its production is approaching 200 000 tons/year [10••]. The production route employs a fermentation process to produce two chiral isomers of lactic acid from glucose, which are then combined to form lactide isomers and polymerized to polylactic acid (PLA). Scale up for PLA is complex since it involves combining biological processes with polymerization chemistry and materials science. Additional successes include companies such as Myriant Corporation, BioAmber Inc. and Succinity GmbH that recently have entered commercial phase for bio-based production of succinic acid with announced capacities of 10–30 ktons/year culminating significant R&D and scale-up efforts [14].

In contrast, KiOR Inc.'s technology [15] focused on the thermal conversion of biomass to drop-in transportation fuels had significant scale-up issues. SEC filings state that KiOR's commercial facility ran significantly below nameplate capacity of 500 ton-per-day. The facility was unable to reach steady state due to structural design bottlenecks and reliability that limited the amount of wood that it could input to its Biomass Fluid Catalytic Cracking system. This setback occurred despite running a pilot plant at 10 ton-per-year and a demonstration plant at 10 ton-per-day capacities. KiOR's impediment demonstrated that combination of two known but disparate technologies can pose significant challenges (KiOR Q2 2014 10Q report, http://www.sec.gov/Archives/edgar/data/1418862/000143774914014972/kior20140630_10q.htm). As a result, KiOR has faced liquidity issues. Another recent failure to scale up is the production of polyhydroxyalkanoate-based plastics by Telles, LLC, the joint venture between ADM and Metabolix. The uncertainty around projected capital and production costs, combined with the rate of market adoption, led to projected financial results that were too uncertain (ADM Press Release, January 12, 2012, http://www.sec.gov/Archives/edgar/data/7084/000119312512011819/d282748dex992.htm). As a result, ADM took a $339 million dollar charge on their Clinton, Iowa production facility (ADM Q2 2012 Financial Report, http://www.adm.com/en-US/investors/Documents/ADM%20FYQ212%20Earnings%20Presentation.pdf). The resulting termination of alliance validates that long-term commitment to process improvement and market development is essential even in very late stages of scale up. Microbial fermentation processes utilizing living cell factories add an additional level of complexity related to life functions [16] unlike the scale-up