# Deliverable report

## D2.1 Report Technology Assessment lignin conversion technologies on the state-of-the-art of conversion technologies: A lignin specific technology readiness level scale

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# D2.1 Report *Technology Assessment lignin conversion technologies on the state-of-the-art of conversion technologies: A lignin specific technology readiness level scale*

## Working Group 2

## 1 Introduction– Technology readiness levels

The past 10-15 years has seen a renaissance in activities on lignin valorization with many activities emergence of many lignin production processes as well on the further valorization of isolated, technical lignins; in addition, combined fractionation and conversion in one single process, the so-called lignin-first routes, has also been established as a promising technology for lignin utilization. These advances include studies that are aimed at gaining fundamental insights into the chemistry of fractionation or conversion processes, others present first examples of innovative, novel technologies, while others aim at advancing reported technologies to higher operating levels, i.e. focus on aspects related to scale-up challenges. Thus, the field comprises activities at various levels of process maturity, from proof-of-concept to demonstration of a technology at (close to) commercial operation. To appreciate the stage of development of a given process is getting of increasing importance for stakeholders in academia, for industry and for policy makers. The time it takes to go from an initial first proof-of-concept based on some smaller scale laboratory experimentation to a pilot or demo facility that operates at more commercially relevant scales (or provides data from which commercial activities can be extrapolated), is sector or industry dependent and takes relatively long in the chemical industry [1]. To gauge the maturity of a technology therefore takes a sector-specific assessment method. A popular method to assess the maturity of a technology is to rate its readiness for a certain purpose defined in levels, the so-called 'technology readiness level' assessment. This methodology was originally developed by NASA, but has seen been much more widely adopted. The EU also widely adopted this methodology and uses it to benchmark activities in funding calls such as in Horizon Europe. Recently, a chemistry-specific technology readiness level scheme has been proposed [1], in which the nine conventional technology readiness levels are defined for the chemical industry, with detailed indicators (Figure 1). These nine levels follow the typical pathway of chemical innovation, from ideation to applied research to development and deployment.

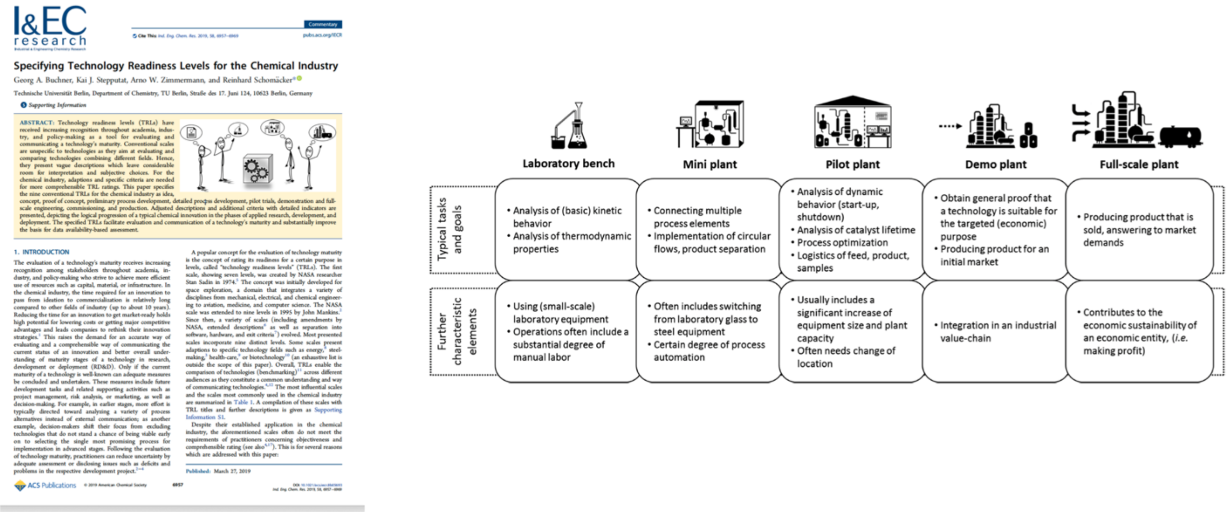


**Figure 1.** A recent paper proposes a technology readiness level scheme tailored for the chemical industry, with specific indicators for assessment. This framework has been adopted and modified to lignin specific processes. The figure on the right is reproduced from ref. [1].

Within LignoCOST, the various working groups have been concerned with building a landscape of the production and conversion routes for lignin, with an assessment of various applications of lignin and with the techno-economic assessment of some of these routes. As lignin valorization efforts and biorefinery operations in general are different from the current large-scale chemical industry operations, a further specification of the proposed chemistry industry technology readiness levels for lignin processes would be desirable. This way, the many efforts can be compared and scaled, as some will operate at the lower levels and others are already reaching maturity and are getting ready for commercialization. Indeed, for lignin valorization processes, performance *assessment of e.g.* biotechnological/chemical lignin production and conversion processes in the form of relevant technology readiness levels (TRLs) would be very relevant, e.g. for the participating industry stakeholders, but also for policy makers, e.g. aiding the latter in funding call definitions.

# 2 Approach

Working group 2 was tasked with generating an overview of existing and novel lignin production and conversion technologies, i.e. technologies concerned with the 'upstream' part of biorefining (separating biomass into its constituent components and generating the lignin) and the 'downstream' part of biorefining (further conversion and valorization of isolated technical lignins). The exercise was technology agnostic and thus would cover all up- and downstream examples. In addition, a major recent development in lignin valorization, i.e. the so-called lignin strategies, combines up- and downstream conversion in a one-step process, liberating the lignin and rapidly converting it away to a more stable end product. As the field has (re)exploded in the past 10-15 years or so, the numbers of pretreatment (upstream) technologies, the number of downstream conversion technologies and the number of examples of lignin-first strategies has also exploded; this is not only the case in terms of the technology/conversion method used, but also in terms of the feedstock and process operations involved in the lignin valorization efforts. The second part of the assignment was to assess the technology readiness levels of the various technologies. As detailed also in deliverable 2.2 and 2.3, it should be noted that the activities are too numerous to efficiently and comprehensively review; furthermore, as of March 2023 >4500 original review papers are available in the public domain that cover the field of lignin valorization (scopus search), showing that a large body of literature is already available (and to a large extent also actively collected by WG1's lignin kiosk) and that this should not be duplicated. These review efforts, however, lack a systematic technology maturity assessment, as a lignin-specific technology readiness level scheme is not yet available. Given this observation and given that task 2.2. required WG2 to organize emerging and more established technologies based on intrinsic technology, feed, and technology readiness level, we opted to provide a first proposal for a lignin specific technology readiness level scheme. To this extent, information collection sessions were held with WG members at several different LignoCOST meetings and an interactive, open white board was set up to discuss/iterate on a first proposal for a lignin-specific technology readiness level scheme (**figure 2**). This first proposal, courtesy of one of the industrial partners of LignoCOST (M. Lersch, Borregaard), was opened up for discussion with WG2 members in varying composition.

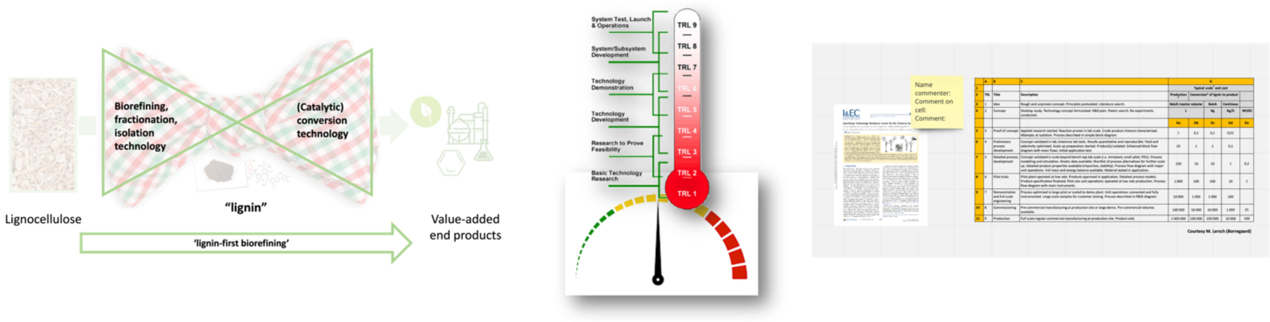


**Figure 2.** Efforts of WG2 to define a lignin-specific technology readiness scheme to assess both upstream and downstream lignin production and conversion processes.

# 3 Results

Four sessions of WG2 at LignoCOST meetings were (partly) devoted to discussions/request for input on the proposed technology readiness level scheme and the indicators defined. In the Reims meeting in early 2023, the it was decided to close the white board for further comment and to fix the table in its current state. Please note that the technology readiness level scheme should be seen as a first attempt at defining this for lignin specific processes and that further work is needed to firmly establish this into a standard that could be more widely adopted by the field; nevertheless the table does provide means to assess technology maturity and this information could be added to e.g. the processes that will be included in the wiki lignin book. The table as agreed on in the Reims meeting is depicted below.

| | A | B | C | D | | | | |
|---|---|---|---|---|---|---|---|---|
| 1 | | | | Typical scale[1] and cost | | | | |
| 2 | TRL | Title | Description | Production[2] | Conversion[3] of lignin to product | | | |
| 3 | 1 | Idea | Rough and unproven concept. Principles postulated. Literature search. | Batch reactor volume | | Batch | Continous | |
| 4 | 2 | Concept | Desktop study. Technology concept formulated. R&D plan. Patent search. No experiments conducted. | L | | Kg | Kg/h | MUSD |
| | | | | Da | Db | Dc | Dd | De |
| 5 | 3 | Proof of concept | Applied research started. Reaction proven in lab scale. Crude product mixture characterized. Attempts at isolation. Process described in simple block diagram. | 1 | 0,1 | 0,1 | 0,01 | |
| 6 | 4 | Preliminary process development | Concept validated in lab. Extensive lab tests. Results quantitative and reproducible. Yield and selectivity optimized. Scale up preparation started. Product(s) isolated. Enhanced block flow diagram with mass flows. Initial application test. | 10 | 1 | 1 | 0,1 | |
| 7 | 5 | Detailed process development | Concept validated in scale beyond bench top lab scale (i.e. miniplant, small pilot, PDU). Process modelling and simulation. Kinetic data available. Shortlist of process alternatives for further scale up. Detailed product properties available (impurities, stability). Process flow diagram with major unit operations. Full mass and energy balance available. Material tested in application. | 100 | 10 | 10 | 1 | 0,2 |
| 8 | 6 | Pilot trials | Pilot plant operated at low rate. Products approved in application. Detailed process models. Product specification finalized. Pilot size unit operations operated at low rate production. Process flow diagram with main instruments. | 1 000 | 100 | 100 | 10 | 1 |
| 9 | 7 | Demonstration and full scale engineering | Process optimized in large pilot or scaled to demo plant. Unit operations connected and fully instrumented. Large scale samples for customer testing. Process described in P&ID diagram. | 10 000 | 1 000 | 1 000 | 100 | |
| 10 | 8 | Commissioning | Pre-commercial manufacturing at production site or large demo. Pre-commercial volumes available. | 100 000 | 10 000 | 10 000 | 1 000 | 25 |
| 11 | 9 | Production | Full scale regular commercial manufacturing at production site. Product sold. | 1 000 000 | 100 000 | 100 000 | 10 000 | 100 |

# 4 Conclusions and outlook

That the establishment of a biobased economy, with a slate of commercial biorefinery, is still a transition in process, makes the establishment of a firm technology readiness level assessment with appropriate indicators in additions to proper definitions of the levels itself still difficult. In addition, the wide variety of technology developments and innovations, covering many different fields with different methods of operation and scale up hamper a uniform assessment method. Nevertheless, this first proposal can serve to foster discussion and elaboration on this scheme, to ultimately come to tailored lignin-specific assessment methods.

# 5 References

[1] Specifying Technology Readiness Levels for the Chemical Industry; Georg A. Buchner, Kai J. Stepputat, Arno W. Zimmermann, and Reinhard Schomäcker, Ind. Eng. Chem. Res. 2019, 58, 6957−6969