NETWORK OF RESEARCH PILOT LINES
FOR LITHIUM BATTERY CELLS

D1.1 Pilot line definitions and terms of reference

Deliverable Information

Related work package(s)	**WP 1**
Contractual date of delivery	**M3**
Actual date of delivery	M4
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Contributing participants	TUBS, CEA, AIT, ABEE
Estimated person months used	
Dissemination level	**Public**
Nature	Report

Project Information

Project title	Li-ion cell pilot lines network
Project acronym	LiPLANET
Project call	H2020-LC-BAT-2019-2020 (CSA)
Grant number	**875479**
Project duration	01.01.2020 – 31.12.2021

This Project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement N. 875479

Executive Summary

The overall objective of the LiPLANET project is to create a European innovation and production ecosystem by forming a network of Li-ion cell pilot lines that integrates industrial stakeholders and establishes unique selling propositions towards EU industry in support of its market access within the cell manufacturing ecosystem. Moreover, reinforcing the position of the European Union (EU) in the Li-ion cell manufacturing market will be further achieved by exploiting synergies between pilot line operators, identifying knowledge and equipment gaps, creating common training and standardization initiatives, and ultimately jointly developing strategies for scaling up the impact of the network.

Although LiPLANET is established based on the LIB technology, it will be a constant updated about the progress on those post-lithium-ion technologies, especially activities related to R+D pilot line configuration. In the latter, the matter of choice would depend on the adaptability of the conventional Li-ion cell production line and the final battery target.

The LiPLANET Terms of Reference (ToR) are developed in M3 of the project to set boundaries on the project; know what is and is not within their jurisdiction; understand the context in which the ToRs have been framed; have a clear idea of where they should begin; and, about what is the outcome/product. The ultimate purpose of this exercise is to keep the target, involve only organizations really fulfilling the criteria that will be set up, and basically avoiding unjustified oversubscription.

Three levels of Definitions are proposed as a basis for the development the LiPLANET Terms of Reference:

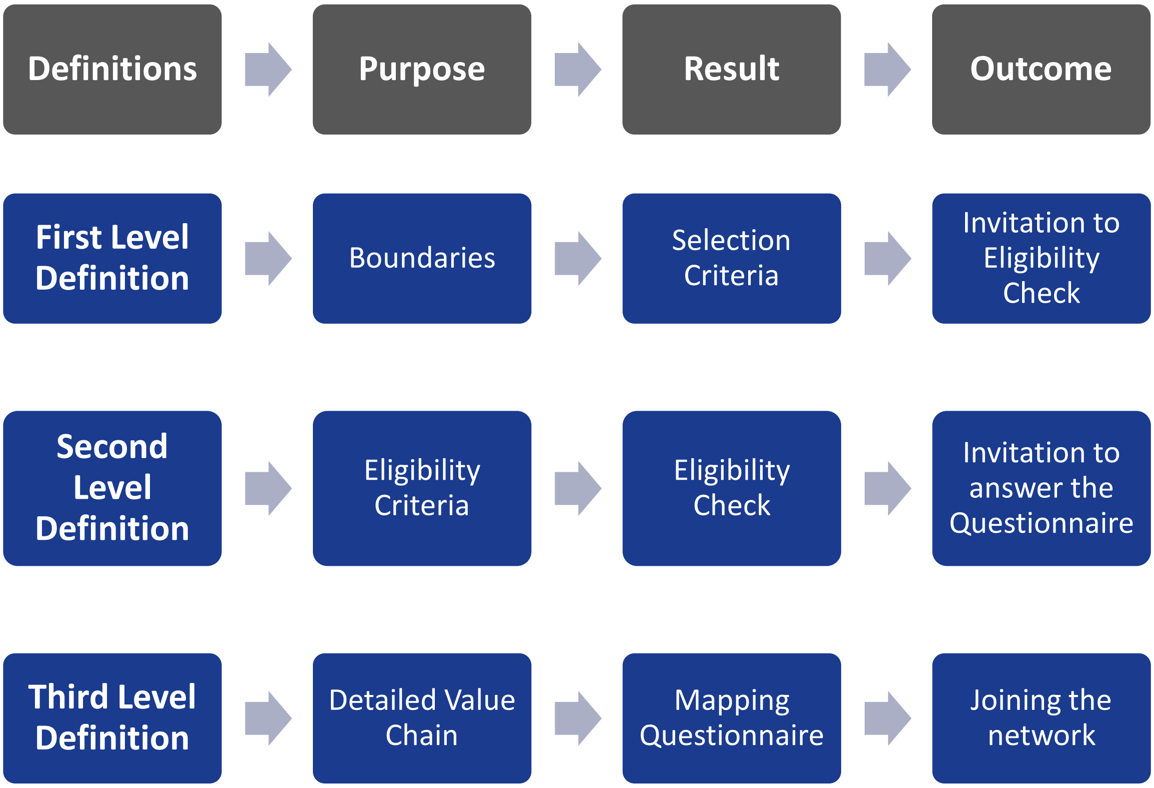
1. First Level Definition. The purpose of this definition is to set the boundaries of a typical Lithium cell pilot line offering a first ***Selection Criteria*** for facilities out of focus –e.g. a facility only for battery testing or only for materials scale up -. Organizations passing this criterion are invited to go through the Eligibility Check step (see next).

2. Second Level Definition The purpose of this definition is to identify the main steps that a Lithium cell pilot line should include. This definition will become the ground for a set of more detailed eligibility criteria for candidate facilities to pass an ***Eligibility Check***. Organizations passing this step are invited to answer the Mapping Questionnaire (see next).

3. Third Level Definition. This definition goes directly into a ***Detailed Value Chain*** for the pilot lines including all possible processing options with identification of KPIs, and will constitute the basic ground for the Mapping Questionnaire to be developed in D1.2.

Answering the Mapping Questionnaire in due time is set as the necessary requisite to join the network, specifically the effective starting point for further activities.

These three-level definitions are summarized in the diagram below:



These Definitions and their contribution to Terms of Reference are summarized as follows:

1. First Level Definition

A Lithium battery cell pilot line can be defined as "*A linear, complex system to process battery materials into electrodes, then into cells, according to industry relevant manufacturing techniques, giving rise to state-of-the-art-like products in terms of electrodes and cells*".

Linear means that there should be continuity along the process. There is not a priority need to have all manufacturing equipment in physical connection, but it should be a clear process composed of defined steps that compose the overall pilot line. Complexity is not a requirement per se, but a consequence of the overall process itself involving several sequential manufacturing steps.

2. Second Level Definition

The manufacturing of a lithium battery cell consists basically of three main process steps, broadly speaking: (i) Electrode manufacturing, (ii) Cell Assembly and (iii) Cell Finishing. These three broad steps are composed of several different individual operations. From the other hand, to keep focused on scalability of R+D results into pre-commercial-like products and processes, it is mandatory to establish a set of minimum requirements that LiPLANET candidate organizations need to fulfill. This is a must to avoid oversubscription and to ensure that all members comply with a minimum common ground.

Therefore it defines a LiPLANET **Lithium cell R+D pilot line** as a facility fulfilling the following criteria (**Second Level Definition**):

Definition items	LiPLANET appraisal	Eligibility Criteria / KPIs
Cell format	✓ Pouch ✓ Prismatic and/or ✓ Cylindrical	✓ ≥ 1Ah cell size
Electrodes manufacturing	✓ Continuous production ✓ Both side of current collector coated (LIB) –sequentially or simultaneously–	✓ ≥ 2 m/day ✓ ≥ 2 m/batch (roll)
Essential machine-led manufacturing steps	✓ Electrode production ✓ Electrode calendering ✓ Electrode cutting ✓ Electrode stacking or winding ✓ Tab welding ✓ Electrolyte addition (LIB) / production (ASSB) ✓ Cell formation	✓ These essential process steps must be at least semi-automatic (machine controlled) ✓ ≥ 20 cells (< 10 Ah) /day or ≥ 10 cells (> 10 Ah) /day

3. Third Level Definition

For facilities complying with the above requirements, the last step is to develop an exhaustive value chain for a complete Lithium cell R+D pilot line, including the most common processes and machinery –understanding that a particular pilot line facility does not need to cover ALL of them-. Also, the main KPIs that characterize the main steps of such a value chain are identified.

This detailed Third Level Definition would not be complete without a suitable framework characterization of the candidate facility, with special focus into the type of pilot line in terms of purpose. In summary, the Third Level Definition is composed of:

3.1) Framework pilot line characterization:

i. Type of pilot line in terms of purpose:
   a. Battery technology development and materials validation
   b. Process engineering and optimization

c. Manufacturing techniques research
d. Product development (electrode / cell)
e. Manufacturing plant simulation (industrial R+D pilot line)

ii. Battery chemistries manufactured under pilot line operations
iii. Host organization type (RTO, University, Industrial R+D lab)
iv. Year of fully operational facilities fulfilling the eligibility check

3.2) Detailed value chain

i. Identification of processes included along the complete value chain
ii. Main KPIs

In conclusion, three levels of definitions have been established in order to, sequentially, (i) set the boundaries of what a pilot line is, (ii) set the minimum features that a pilot line should include, and (iii) facilitate a detailed characterization of the pilot line.

These definitions lead to the Terms of Reference that a candidate facility must comply in order to join the LiPLANET network, avoiding oversubscription and ensuring a base line of technical capabilities, as a first step to further harmonization of operations.

Nevertheless, LiPLANET network will be paying close attention to those facility candidates that currently do not match the eligibility criteria. Upgrading of those facilities would raise their probability to be considered as a new member as long as they meet the LiPLANET established criteria. The same will be applied for those organizations considering in the near future the investment of setting a new lithium pilot line. LiPLANET are open to assist those organizations to implement a reliable pilot line.

A questionnaire that all organizations willing to join LiPLANET will need to fulfill before becoming members, will be developed in Task 1.2 (output in D1.2) by following the present exercise.

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1 Introduction

1.1 LiPLANET in brief

The overall objective of the LiPLANET project is to create a European innovation and production ecosystem and reinforce the position of the European Union (EU) in the Lithium battery cell manufacturing market. LiPLANET plans to build a more competitive lithium battery cell manufacturing ecosystem and increase the production of lithium-based cells towards industrial scale, by bringing together the most relevant European Li-ion cell pilot lines and the main stakeholders of the battery sector. The project LiPLANET lays the foundation for a network of battery cell pilot lines in Europe. This network allows exploiting synergies between pilot line operators, identifying knowledge and equipment gaps, organize joint trainings as well as, favor collaboration with industry and academia, and facilitate the access to market.

For this purpose, different activities are followed throughout the project:

- ✓ mapping of the European lithium cell pilot lines and implementation of a network,
- ✓ creation of a standardized legal framework and a data exchange platform for the cooperation between industry, academia and pilot lines,
- ✓ round-robin test to compare qualification methods,
- ✓ development of a roadmap for joint strategies of the network towards industrial scale battery cell production in Europe.

1.2 Scope and objective of this deliverable

The objective of this deliverables is to agree on a basic set of Definitions and Terms of Reference (ToR)[1] that will mainly serve three purposes:

1. To set a selection criteria for candidate facilities aiming to be recognized as a "LiPLANET Lithium cell R+D pilot line"
2. To serve as basis of the Mapping Questionnaire to be developed in frame of task T1.2.
3. To provide a coherent and homogeneous ground in order to communicate with an agreed and common language with regard to the ultimate customers of the Network: the EU battery industry community, as well as the rest of the battery RTD community.

Point 1 is the main target of Task 1.1 and hence, of Deliverable 1.1, while point 2 is a necessary primary step for Deliverable D1.2 with impact also on WP3. Finally, point 3 will be addressed in depth in WP6.

Having as scope the setting of the selection criteria, this deliverable will establish a series of Definitions in order to, sequentially, (i) set the boundaries of what a pilot line is (first level as **Selection Criteria**), (ii) set the minimum essential features that a pilot line should include (second

[1] http://faculty.bcitbusiness.ca/kevinw/4800/documents/HOWTOwriteTORs.pdf

level as **Eligibility Check**), and (iii) facilitate a detailed characterization of the pilot line (third level as **Mapping Questionnaire**). This exercise set the **Terms of Reference** that a candidate facility must comply in order to join the LiPLANET network.

Such ToRs will help to avoid oversubscription and ensuring a baseline of technical capabilities to further harmonization of operations. Consequently, a **Detailed Value Chain** for the pilot lines including all possible processing options with identification of KPIs will constitute the basis for the Mapping Questionnaire to be developed in D1.2.

Before elaborating the above-mentioned definitions and ToR, a brief overview of the context of pilot line activities will be given. It will help to contrast the LiPLANET perspective about those.

2 Context for Pilot Line Activities and the LiPLANET perspective

2.1 General Statements

In this section a previously released relevant document will be taken as a starting point. The title of this document is: **"Pilot Production in Key Enabling Technologies: Crossing the Valley of Death and boosting the industrial deployment of Key Enabling Technologies in Europe".** This publication was prepared on behalf of the European Commission, DG GROW—Directorate General for Internal Market, Industry, Entrepreneurship and SMEs, under the service contract "Multi-KETs Pilot Lines" (www.mkpl.eu, a project started in 2012 and completed in 2015)[2].

Crossing the so-called Valley of Death corresponds to the research, development and innovation (R&D&I) activities required to transform a laboratory prototype into a product ready for full-scale production and commercialization. The Valley of Death is characterized by both high costs and high risks. The approach differentiates three fundamental stages: **(1) Technological research; (2) Product demonstration and (3) Competitive manufacturing**; from basic research to competitive manufacturing.

LiPLANET initiative does not pursue getting products ready for full-scale production nor market introduction per se, but to support the European industry to do so. In spite of this, several statements contained in this report will be also applied and deserve a critical analysis that will assist us in giving shape to the LiPLANET initiative.

Technology Readiness Level (TRL) *can be used to assess the position of a product to the technological valley of death*; however, this approach cannot be used as a criterion to assess the product's state to cross the commercial valley of death. The **Manufacturing Readiness Level** (MRL) *can be also used as an additional selection criterion*. This scale is used to assess the level of readiness of the manufacturing to enable crossing the commercial valley of death. Nevertheless,

[2] http://www.mkpl.eu/fileadmin/site/final/mKETs_brochure_web.pdf

while ***TRL characterizes the stage of development of the core product to be produced, the MRL characterizes the stage of development of the manufacturing process***. A detailed definition of TRLs and MRLs is provided in appendix 4.1.

As shown in **FIGURE 1**, pilot activities can be considered the linking set of activities between technology development and the first commercial market introduction of a product, where the ***pilot lines are** considered as the physical infrastructure and equipment needed to produce small series of pre-commercial-like products* in addition to the activities related to market analysis and engineering to optimize the production process. In that way, one of the key advantages of the **pilot line** activities is the ability to *carefully evaluate each step in the production process* to *deliver enough output to validate pre-commercial-like prototype products, materials, or manufacturing equipment*. *This* ***needs small, but fully operational manufacturing technology***.

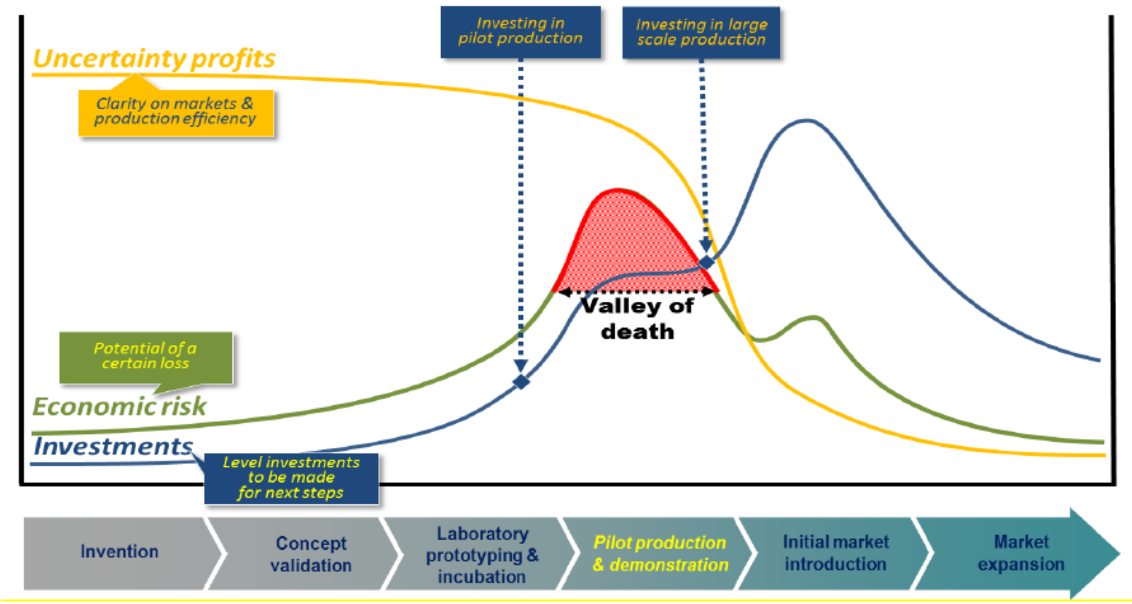

Figure 1. *Risk and cost associated with innovation.*[3]

Consequently, the environment of a pilot line incorporates all of the key production elements (equipment, personnel skill levels, facilities, materials, components, work instructions, processes, tooling, temperature, cleanliness, lighting etc.) required to manufacture production configuration items, subsystems or systems that meet design requirements in low rate production.

As mentioned, this referent publication (*viz. Pilot Production in Key Enabling Technologies: Crossing the Valley of Death and boosting the industrial deployment of Key Enabling Technologies in Europe*) contains valuable statements regarding the definition and purpose of what is considered as pilot

[3] http://www.mkpl.eu/results/

line. Such statements will be taken as a basis for the understanding of the role that **lithium cell R+D pilot line** would fulfill at the present time. However, the focus of the statements contained in such document does not always match the contextual specifications of the LiPLANET lithium cell R+D pilot line under scrutiny in this coordination action. In Section 2.2, these mismatches will be analyzed, highlighted and adapted accordingly in order to fit the needs of the LiPLANET action.

2.2 Perspective of LiPLANET regarding to Pilot Line Activities

Several statements of the *Pilot Production in Key Enabling Technologies* (…) report are analyzed on the basis of the LiPLANET perspective. A summary of such analysis and the general comments are provided in the **Table 2** below.

Table 2. *Analysis of Pilot Production in KETs report on the basis of LiPLANET perspective*

Statements from "Pilot Production in Key Enabling Technologies" report	Comments from the perspective of LiPLANET
(Foreword) *Close-to-market innovation and pilot production in particular, is essential. As the "scale-up" stage needed to cross the "Valley of Death", it allows enterprises to test and demonstrate innovative solutions and gather information about the performance and behavior of a future product and production line.*	✓ Statement fully endorsed by LiPLANET
This turns laboratory prototypes into products ready for commercial production. Pilot production is a vital link, which needs to be supported otherwise promising innovations may fail to get off the ground.	✓ Statement fully endorsed by LiPLANET. LiPLANET does not necessarily intend to: generate products ready for commercial production, but to help with the transition of "laboratory prototypes" (battery materials, etc.) into "commercial production"
(Introduction) *Close-to-market R&D such as pilot production and demonstration is found at the heart of the Valley of Death, where both costs and risks are very high.* *…* *The so-called Valley of Death needs to be crossed, which corresponds to the research, development and innovation (R&D&I) activities required to transform a laboratory prototype into a product ready for full-scale production and commercialization. The Valley of Death is characterized by both high costs and high risks.*	✓ Statement fully endorsed by LiPLANET.

Statements from "Pilot Production in Key Enabling Technologies" report	Comments from the perspective of LiPLANET
(What is a pilot line? What is pilot production?) *Pilot production is about scaling up an invention from the laboratory into pre-commercial production.* *Although the development of a manufacturing-oriented pilot line remains at the core of pilot production, crossing the Valley of Death through pilot production requires much more.* *It is also about engaging with customers to get their feedback on the future product, identifying how the organization must be adjusted for this new business, understanding better what the characteristics of the market are, and coordinating with suppliers and other partners in the value chain. It is about tweaking the product to a format that can be manufactured and sold.*	✓ Statement endorsed by LiPLANET but with following comments: Pilot Lines within LiPLANET activities are NOT intended to: Delivery of pre-production battery cells per se, but to deliver product-like battery electrodes and cells for testing and evaluation of such products in final-product-like formats. Cover the business development perspective of the Valley of Death, but only what is concerned with scaling-up and pilot production of battery electrodes and cells.
(A holistic approach) *Pilot lines are the technological equipment needed to produce commercial products, like chips and electronic components. In industrial biotech and advanced materials, they are often called "pilot plants". Because of these differences in terminology and given that the Valley of Death is not only about physical equipment, the term "pilot production" is seen as more adequate. It is more neutral and holistic and includes all the problems encountered during the scale-up of prototypes to low-rate pre-commercial manufacturing.*	The principles of LiPLANET although does not cover strictly the Valley of Death in its full understanding as described in the report, considers as well the term "Pilot Production" adequate for the philosophy of LiPLANET LiPLANET main focus are based on ✓ technological equipment needed to produce commercial-like products ✓ raising the TRL of R+D results ✓ promoting the synergies, training and skilled professional development. ✓ reaffirming its own definition as a *network of Pilot Lines*.

Statements from "Pilot Production in Key Enabling Technologies" report	Comments from the perspective of LiPLANET
(...To define and demarcate pilot production... the most practical way is to use a set of activities, including…) 1. R&D to validate both technology/component/ subsystem development in a laboratory environment and "transferability" to the level of pilot manufacturing 2. A pre-commercial pilot manufacturing system operated by one or more industries including external bodies like SMEs and research organizations 3. The first small series of pre-commercial products and prototypes for testing and validation of the manufacturing process (including cost efficiency) and by customers 4. Adjustment of product design based on pre-commercial manufacturing 5. Creation of market relationships giving lead customers access to new technologies, preparing for full commercialization 6. Business development with investors 7. Preparation of internal and external organizations for full manufacturing, including development of a value chain	✓ LiPLANET endorses fully the statements 1, 3, 4, and 7. ✓ Statement 2 with comments: LiPLANET focus is at R+D oriented Pilot Lines –*regardless if they are operated by RTO, academia or industry*– Nevertheless, potential industrial candidates should will to openly cooperate and share knowledge rather than act as an end-user of the LiPLANET network. It is understandable that such cooperation/sharing will be done under IPR protection issues.
(Barrier 2: To market or not to market: that is the question) *There is broad consensus that robust anticipation of market needs and demand is crucial to crossing the Valley of Death. However, there is a deadlock at the pilot production stage. Customers wait for a product they can test (not a lab prototype but a pre-commercial product very similar to the final one) before committing to any future orders (...) coordination of the market is crucial (…)*	✓ Statement fully endorsed by LiPLANET. This sentence in particular reflects the target and philosophy of LiPLANET: "*Customers wait for a product they can test (not a lab prototype but a pre-commercial-like product very similar to the final one*)"
(Barrier 3: Pilot production needs fertile soil) *Pilot production needs a high-quality innovation network. This offers the "fertile soil" in which inventions can grow into successful businesses. Finding partners, establishing trust and creating a long-term, agile innovation ecosystem is difficult and requires public funding. Not only customers, but also other partners in the value chain, such as equipment suppliers, need to get involved in pilot production activities. Only then can R&D results be optimally maximized.*	✓ Statement fully endorsed by LiPLANET.
(Barrier 4: No pilot production without human resources) *Human resources are needed both for research and for operating the pilot lines/plants, and it is important to remember the multi-disciplinary character of the skills and expertise needed. (…)* *Cooperation between educational institutions and industry within multi-KETs pilot production projects should especially be supported.*	✓ Statement fully endorsed by LiPLANET. This is in fact one of the aims of LiPLANET: To promote curricular development of future manufacturing professionals

Statements from "Pilot Production in Key Enabling Technologies" report	Comments from the perspective of LiPLANET
(Shared facilities for pilot production) *The cost of pilot production can be reduced by using shared facilities, which provide technology, infrastructures and equipment, and highly skilled personnel. Often crucial to SMEs, shared facilities also benefit larger companies. They can be run by public entities (such as research and technology organizations and universities) as well as private entities. Shared facilities are about sharing expertise and equipment to reduce costs and have access to specific know-how. In all cases, their long-term sustainability is a challenge and will require long-term public support.*	✓ Statement fully endorsed by LiPLANET.
(Three out five policy strategies for crossing the Valley of Death) *(3) Enhance the innovation ecosystems in which pilot production is carried out. Support to an isolated pilot production project would not have optimal benefits. It should be part of longer-term ecosystem development, with a long-term innovation strategy. (…)* *(4) Support shared facilities for pilot production (open or semi-open technology infrastructures where companies can access the necessary services and equipment). These are crucial to SMEs and start-ups and this is, more generally, an important policy mechanism for reducing the barriers during pilot production. Shared facilities reduce costs by sharing equipment and can offer important expertise and specific services often not available in a single company. They can also play an important role in improving the ecosystem.* *(5) Enhance the availability of human capital to support pilot production and overall valorization of research. The development of the specific multi-disciplinary skills and expertise needed to operate pilot production will support new business developments.*	✓ Statements fully endorsed by LiPLANET.

3 LiPLANET lithium cell R+D pilot line – Terms of Reference

In this section a general value chain for battery manufacturing will be defined. From this stand point, and from the perspective of Lithium battery R+D pilot manufacturing, three levels of definitions will be proposed, each one leading to a set of Terms of Reference for the LiPLANET initiative. These Terms of Reference will be the basis for the identification and selection of suitable partners of the initiative.

3.1 The Lithium Battery Manufacturing Chain

The Industry value chain includes various activities that, when combined, represent the process from raw materials production to the delivery of the final product.

The ***lithium battery industry value chain*** (**Figure 2.**) can be broke into upstream, middle stream, and downstream components.

1. **Upstream** players: provide lithium compounds used for cathode and electrolyte manufacturing.
2. **Middle-stream** players: produce components of lithium batteries, including cathode, electrolyte, anode and separator as well as the resulting cell.
3. **Downstream** battery producers: focus on assembly and packing.

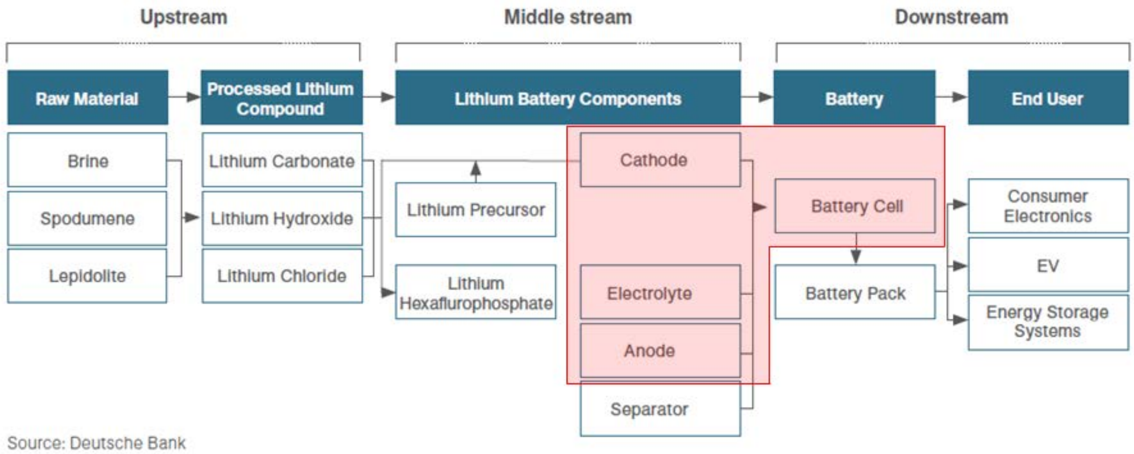

Figure 2. *Lithium-ion Battery Manufacturing Chain*[4]. *The reddish shading represents LiPLANET pilot line activities.*

As illustrated in the **Figure 2**, the lithium-ion battery industry chain is a complex system to process battery materials into electrodes and subsequently into cells and, finally, into battery packs for a given application.

In frame of the LiPLANET network, the battery value chain will be considered that one constituted by the battery cell manufacturing (*viz*. electrode production, cell assembly and finishing) and thus, limiting the LiPLANET pilot line activities to partially the middle and downstream components of the battery industry chain (reddish shading in Fig. 2). This criteria will allow LiPLANET to include as well the advances of the under-developing post-lithium-ion technologies like those based on lithium cell generation 4 and 5 (see Table A4 in appendix 4.2). In this regards, for example, for All-Solid-State Batteries (ASSB), the first step of the Li-PLANET battery value chain will be then electrode and electrolyte production instead of only electrode production like that for Li-ion technologies.

[4] http://www.metalstech.net/wp-content/uploads/2016/07/17052016-Lithium-research-Deutsche-Bank.compressed.pdf

On the other hand, LiPLANET aims at defining the boundaries between which the R+D pilot lines belonging to the LIPLANET network should operate. In order to achieve that, a series of definitions and terms of reference will be set in order to understand what is actually consider a LiPLANET lithium cell R+D pilot line.

3.2 First Level of Definitions and Terms of Reference – Selection Criteria

A Lithium battery cell pilot line can be defined as "*A linear, complex system to process battery materials into electrodes, then into cells, according to industry relevant manufacturing techniques, giving rise to state-of-the-art-like products in terms of electrodes and cells*".

Analyzing this definition will support the setting of a **Selection Criteria** to be implemented in order to narrow the number of potential candidate facilities aiming to become part of the PL network.

In that sense, how this general definition can be then adapted to the LiPLANET vision of a pilot line in order to establish such Selection Criteria? In the following table an analysis sentence by sentence of this concept is done as a function of LiPLANET perspective.

Table 3. First set of Terms of Reference: *Criteria for being considered as a pilot line candidate of LiPLANET network*

Definition items	LiPLANET appraisal	Selection Criteria
"…linear, complex system…"	✓ Complete cell manufacturing process (including electrode production). ✓ No need of having all manufacturing equipment in a physical connection ✓ Clear sequential steps that compose the overall pilot line. ✓ Complexity is not a requirement per se, but a consequence of the overall process itself involving several sequential manufacturing steps.	Facilities operating only one of the following processes are not considered candidates to join LiPLANET –non exhaustive list- ✓ Material up-scaling ✓ Cell testing
"…to process battery materials"	✓ Manufacturing and/or scaling up of battery materials/components belong to the middle stream of the battery manufacturing value chain. ✓ Those are not per se a Lithium Cell Manufacturing Pilot Line.	Facilities operating only one of the following processes are not considered candidates to join LiPLANET –non exhaustive list- ✓ Material synthesis ✓ Materials scaling up ✓ Manufacturing of battery components

Definition items	LiPLANET appraisal	Selection Criteria
"…into electrodes, then into cells"	✓ A fully Lithium Cell R+D Pilot Line must be capable of include both electrode (incl. solid electrolyte in ASSB) manufacturing and cell assembly.	Not included in LiPLANET (out of scope): ✓ Module / pack assembly
"…according to industry relevant manufacturing techniques" *"…state-of-the-art-like products in terms of electrodes and cells"*	✓ Sequential cell manufacturing process steps should be analogue to state-of-the-art industrial techniques. ✓ The cell manufacturing processes should be essentially automatic in their key process steps in order to provide a cell prototype tuned to the industry needs/standards. ✓ Cell prototypes should be analogue to SoA in terms of quality, form factor, internal structure. This does not prevent or exclude advanced (*viz*. cell generations 4 or 5) or innovative concepts or components. ✓ Hand-driven steps are acceptable provided that they involve only side operations (e.g. transport of mother rolls, etc.)	Facilities doing key operations by hand are not considered suitable partners for LiPLANET, like: ✓ Electrode (electrolyte) manufacturing ✓ Electrode calendering ✓ Electrode cutting ✓ Electrode stacking or winding

3.3 Second Level of Definitions and Terms of Reference – Eligibility Check

The purpose of this definition is to identify the main steps that a lithium cell pilot line should include. This definition will become the ground for a set of more detailed eligibility criteria for candidate facilities to pass an **Eligibility Check**.

As pointed above, a lithium cell R+D pilot line is that one capable of developing, testing and optimizing materials and manufacturing process to properly adapt those to requested electrodes profiles and cell formats fulfilling industrial usual procedures.

The R+D pilot line could be though as a flexible semi-automatic sequential process where the **manufacturing of the lithium battery cell** consists basically of ***three key manufacturing process steps***, namely[5]:

1. Electrode (and solid electrolyte, when applicable) manufacturing
2. Cell Assembly
3. Cell Finishing

[5] https://www.researchgate.net/publication/330902286_LITHIUM-ION_BATTERY_CELL_PRODUCTION_PROCESS

Consequently, from LiPLANET perspective, the lithium battery manufacturing value chain can be simplified to the **three main process steps** above-mentioned as shown in **Figure 3**. These boundaries process steps define somehow the **Eligibility Criteria** to define what LiPLANET considers a **Lithium Cell R+D Pilot Line**.

The *complete production chain for conventional Li-ion batteries (LIB)*, encompassing slurry preparation and characterization, electrode coating and calendering, cutting of the coated electrode tapes, assembly of the battery, electrolyte filling, and cell formation (**Figure 3.**), *is mapped and optimized in a collaborative process* with the end-user needs *defining what can be considered as a* Lithium R+D Pilot Line.

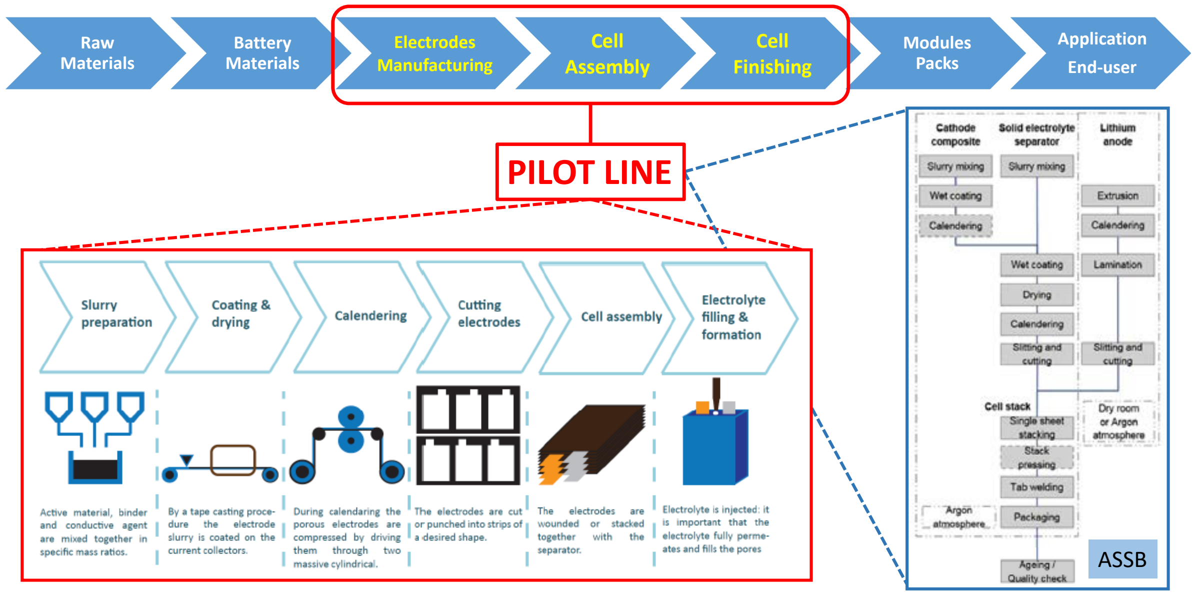

Figure 3: *Defining a Lithium Cell Manufacturing Pilot Line within the battery value chain. Red marked: Li-ion[6] and Blue marked: alternative All-Solid-State-Battery (ASSB)[7].*

On the other hand, considering that **ASSB technology** is not yet at a stage of maturity for large-scale production, the assessment of its industrial manufacturability is still limited due to the variety of remaining challenges on both the product and the process[8]. In consequence, a general valid process chain for ASSB does not exist; instead, a large number of alternative process chains may be applied. These differ in part from the manufacturing process of a lithium-ion battery. Nevertheless, it allows further research, development and optimization even at scale of prototype pilot line (**Figure 3**). However, this technology must be always able to compete with state of the art lithium ion technology which will continue to improve in the upcoming years.

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[6] J. Smekens et al., Energies 9(2) (2016) 104; https://doi.org/10.3390/en9020104

[7] J. Schnell et al., J. Power Sources 382 (2018) 160; https://doi.org/10.1016/j.jpowsour.2018.02.062

[8] http://elektromobilitaet.vdma.org/documents/7411591/15357859/Production+ASSB_eng/b1abd698-9cad-5213-48f1-21c85a13265f

Among the challenges of ASSB, it should be mentioned those possible ones for automated manufacturing and quality control which need to be addressed already during the design stage as well as the production environment (controlled atmosphere) which has a high impact on the final manufacturing cost. If large-scale production is targeted, the physical and chemical properties in addition to the requirement for processing the materials need to be also tackled. This goes from the conditions required for materials handling and processing until care of the final cell components properties (*e.g*. the coating densities, thickness variations, adhesiveness, bending stiffness and, elastic and plastic).

3.3.1 Key Process steps in the Lithium R+D Pilot Line

Each of the *key manufacturing processes is constituted by several sequential steps which should be essentially (semi-)automatic and scalable to industrially relevant size*. It does not mean that all three key processes should be integrated as a whole in a fully automatic continuous manufacturing line, but **relevant key steps** such as coating, calendaring, cutting, stacking or winding among others **should be at least machine-led steps**.

To keep focused on scalability of R+D results into pre-commercial-like products and processes, it is mandatory to establish a set of minimum requirements as **Eligibility Criteria** that each LiPLANET candidate organizations need to fulfill. This is a must to avoid oversubscription and to ensure that all members comply with a minimum common ground.

Based on the cell format/design (*namely*, pouch, cylindrical or prismatic cell), *it is required to have all the following **key machine-led** (at least semi-automatic) **production steps***:

1. **Electrode manufacturing**: semi-automatic steps conformed by
   - ✓ **Coating**: top and bottom side of the current collector coated (*i*) continuously and (*ii*) sequentially.
   - ✓ **Calendering**: continuous roll-to-roll process with thickness control
   - ✓ **Cutting**: slitting process with reduced burrs on the edges
2. **Cell Assembly**: semi-automatic steps consisting of the following sequential process
   - ✓ **Separation**: flexible cutting process for pouch cells
   - ✓ **Stacking/winding/Sealing**: for pouch and for cylindrical/prismatic cells, respectively
   - ✓ **Welding:** cell tabs welded ultrasonically or by laser welding process
   - ✓ **Electrolyte filling**: high-precision dosing
3. **Cell finishing**: semi-automatic processes including
   - ✓ **Pouch cell**: roll pressing and degassing

Although LiPLANET is currently grounded on the LIB technology, it will be constantly updated about the progress on those post-lithium-ion technologies, especially activities related to R+D pilot line configuration. In the latter, the matter of choice would depend on the adaptability of the conventional Li-ion cell production line and the final battery target.

As known, the major different between ASSB and LIB production lies in the need of a controlled atmosphere all along the manufacturing process for the ASSB (**Figure 3**)[9], adapting a LIB cathode fabrication process to an ASSB one includes major differences like solid electrolyte particles, adhesion, apolar solvents, low target porosity, brittleness, and low bending stiffness, filtering techniques or heating steps. Such differences come as a function of the processing step chosen (*viz.* slurry mixing, continuous extrusion process, wet coating, calendaring or slitting and cutting). Nevertheless, beyond these differences no major changes of the current LIB cathode fabrication process have to be implemented (**Figure 3**). In contrast, at *the level of solid electrolyte and anode fabrication, the production processes are basically new concepts for ASSB in comparison to that for conventional LIB*.

Nevertheless, the second level definition allows establishing the **Eligibility Check** that each candidate facility must fulfil. On the other hand, LiPLANET requires a minimum demonstrable Key Performance Indicators (KPIs) for those processes as indicated in the **Table 4** below:

Table 4. Second set of Terms of Reference: *Eligibility criteria to assess the pilot line candidate to join LiPLANET network.*

Definition items	LiPLANET appraisal	Eligibility Criteria / KPIs
Cell format	✓ Pouch ✓ Prismatic and/or ✓ Cylindrical	✓ ≥ 1Ah cell size
Electrodes manufacturing	✓ Continuous production ✓ Both side of current collector coated (LIB) –sequentially or simultaneously–	✓ ≥ 2 m/day ✓ ≥ 2 m/batch (roll)
Essential machine-led manufacturing steps	✓ Electrode production ✓ Electrode calendering ✓ Electrode cutting ✓ Electrode stacking or winding ✓ Tab welding ✓ Electrolyte addition (LIB) / production (ASSB) ✓ Cell formation	✓ These essential process steps must be at least semi-automatic (machine controlled) ✓ ≥ 20 cells (< 10 Ah) /day or ≥ 10 cells (> 10 Ah) /day

3.4 Third Level of Definition and Terms of Reference – Mapping Questionnaire

For facilities complying with the above requirements, the last step is to develop an exhaustive and **Detailed Value Chain** for the pilot lines including all possible processing options with identification of KPIs, and will constitute the basic ground for the **Mapping Questionnaire** to be developed in

[9] J. Schnell et al., J. Power Sources 382 (2018) 160; https://doi.org/10.1016/j.jpowsour.2018.02.062

D1.2. All organizations willing to join LiPLANET network will need to fulfill this questionnaire as a requisite to become a formal member of the network.

The detailed mapping of the candidate facility should start with a general view of the framework in which such facility operates. This operational framework will facilitate the classification of the pilot lines in function of their general objective as well as serves as orientation to identify potential gaps and synergies among the pilot lines belonging to the LiPLANET network.

The third level of definition will be then constituted by two main sections

1. Operational framework of the pilot line facility
2. Detailed information of the manufacturing process steps and production environment along the Value Chain – Detailed Value Chain

~~In the following it~~The following will provide brief information about the content of each section as preamble of the mapping questionnaire. It does not pretend to be the final structure of the questionnaire, but it at least ~~to~~ provides a general idea of the content. Furthermore, any criterion regarding post-lithium-ion technologies is included at the present, although consideration may be taken during the preparation of the mapping.

Table 5. Third set of Terms of Reference: *Preliminary structure of the mapping questionnaire (to be developed in D1.2)*

Definition items	LiPLANET appraisal	Questionnaire items
Operational framework of the pilot line facility	Type of host organization	✓ University ✓ Research Institute ✓ RTO ✓ SMS ✓ Industrial R+D lab
	Fully operational facilities (eligibility check)	✓ Year of establishment
Operational framework of the pilot line facility	Pilot line R+D main focus	✓ Material validation ✓ Battery technologies development ✓ Process engineering/design and/or Optimization ✓ Product Characterization/development ✓ Manufacturing plant simulation (industrial R+D PL)
	Pilot Line production scope	✓ Testing facilities ✓ Product development ✓ Generation of new technologies ✓ Low volume production ✓ Scaling-up (market validation) ✓ Innovation process ✓ Build up complementary competences (value chain) ✓ Service provider ✓ Quality assurance ✓ Development of skilled human resources

<table>
<tr><th>Definition items</th><th>LiPLANET appraisal</th><th>Questionnaire items</th></tr>
<tr><td rowspan="2"></td><td>Pilot Line joint activities</td><td>✓ If yes, indicate reason
• PL production activities (value chain)
• Opportunities of cooperation
• Shared facilities
• R&D Platform
✓ Model of joint activity
• Local
• Regional
• National
• European
• Third country</td></tr>
<tr><td>Cell chemistries manufactured under Pilot Line operations</td><td>✓ LIB up to generation 3b
✓ Alternative lithium systems (gen. 4 and/or 5)</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Detailed Value Chain
1. Production Environment</td><td>Clean room</td><td rowspan="2">✓ Area (m^2)
✓ Dew point (°C)
✓ Temperature (°C)</td></tr>
<tr><td>Dry room</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td rowspan="6">Detailed Value Chain
2. Electrode Manufacturing</td><td>Mixing</td><td>✓ Type of mixing
✓ Dry
✓ Wet
✓ Temperature (°C)</td></tr>
<tr><td>Coating</td><td>✓ Coating width (mm)
✓ Coating accuracy (± mm)
✓ Production (m/ day)</td></tr>
<tr><td>Drying</td><td>✓ Drying speed (m/min)
✓ Length (m)
✓ Temperature profile (°C)</td></tr>
<tr><td>Calendaring</td><td>✓ Calendaring speed (m/min)</td></tr>
<tr><td>Slitting</td><td>✓ Cutting speed (m/min)</td></tr>
<tr><td>Post-Drying</td><td>✓ Batch (e.g. vacuum oven)/Continuous (e.g. IR)
✓ Pressure (mbar)
✓ Drying time (h/batch)
✓ Drying temperature (°C)</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td rowspan="8">Detailed Value Chain
3. Cell Assembly</td><td>Cell format</td><td>✓ Pouch
✓ Cylindrical
✓ Prismatic</td></tr>
<tr><td>Cell size</td><td>✓ Ah</td></tr>
<tr><td>Cell production</td><td>✓ Cell / day</td></tr>
<tr><td>Overall production</td><td>✓ Ah / day</td></tr>
<tr><td>Separation</td><td>✓ Pouching tool
✓ Cutting/pouching speed (sheet / min)</td></tr>
<tr><td>Stacking (pouch)</td><td>✓ Z-folding and single-sheet stacking (cycles)</td></tr>
<tr><td>Winding (pris./cyl.)</td><td>✓ Machine throughput (cells / min.)</td></tr>
<tr><td>Electrolyte filling</td><td>✓ Dosing method
✓ Working pressure (mbar)
✓ Consistent, continuous or cyclic filling</td></tr>
</table>

Definition items	LiPLANET appraisal	Questionnaire items
		✓ Control of the electrolyte quantity
Detailed Value Chain 4. Cell Finishing	Roll pressing (pouch)	✓ Pressure (mbar) ✓ Process time (s / cell)
	Formation	✓ Process duration (h)
	Aging	✓ SOC at the beginning (%) ✓ Aging time (days) ✓ Temperature range (°C) ✓ Internal resistance (Ohm)

4 Appendices

4.1 Definition of Technological and Manufacturing Readiness Levels

Table A1. Scales of Technology (TRL) and Manufacturing (MRL) Readiness.

#	Technology Readiness	#	Manufacturing Readiness
1	Basic principles observed and reported	**1**	Basic Manufacturing Implications Identified
2	Technology concept and/or application formulated	**2**	Manufacturing Concepts Identified
3	Analytical and experimental critical function and/or characteristic proof of concept	**3**	Manufacturing Proof of Concept Developed
4	Technology validated in lab environment	**4**	Capability to produce the technology in a laboratory environment
5	Technology validated in relevant environment (industrially relevant environment in the case of KETs)	**5**	Capability to produce prototype components in a production relevant environment
6	Technology demonstrated in relevant environment (industrially relevant environment in the case of KETs)	**6**	Capability to produce a prototype system or subsystem in a production relevant environment
7	Technology prototype demonstration in an operational environment	**7**	Capability to produce systems, subsystems, or components in a production representative environment
8	Actual technology system completed and qualified through test and demonstration	**8**	Pilot line capability demonstrated; Ready to begin Low Rate Initial Production
9	Actual technology system qualified through successful operations	**9**	Low rate production demonstrated; Capability in place to begin Full Rate Production
		10	Full Rate Production demonstrated and lean production practices in place

**Highlighted* rows refer to Pilot Activities.*

Table A2. Technological readiness Level (TRL)[10]

TRL	Description	Example
1	Basic principles observed	Scientific observations made and reported. Examples could include paper-based studies of a technology's basic properties.
2	Technology concept formulated	Envisioned applications are speculative at this stage. Examples are often limited to analytical studies.
3	Experimental proof of concept	Effective research and development initiated. Examples include studies and laboratory measurements to validate analytical predictions.
4	Technology validated in lab	Technology validated through designed investigation. Examples might include analysis of the technology parameter operating range. The results provide evidence that envisioned application performance requirements might be attainable.
5	Technology validated in relevant environment	Reliability of technology significantly increases. Examples could involve validation of a semi-integrated system/model of technological and supporting elements in a simulated environment.
6	Technology demonstrated in relevant environment	Prototype system verified. Examples might include a prototype system/model being produced and demonstrated in a simulated environment.
7	System prototype demonstration in operational environment	A major step increase in technological maturity. Examples could include a prototype model/system being verified in an operational environment.
8	System complete and qualified	System/model produced and qualified. An example might include the knowledge generated from TRL 7 being used to manufacture an actual system/model, which is subsequently qualified in an operational environment. In most cases, this TRL represents the end of development.
9	Actual system proven in operational environment	System/model proven and ready for full commercial deployment. An example includes the actual system/model being successfully deployed for multiple missions by end users.

Table A3. Manufacturing Readiness Level[11]

MRL	Description	Definition
1	Basic Manufacturing Implications Identified	Basic research expands scientific principles that may have manufacturing implications. The focus is on a high-level assessment of manufacturing opportunities. The research is unfettered.
2	Manufacturing Concepts Identified	Invention begins. Manufacturing science and/or concept described in application context. Identification of material and process approaches are limited to paper studies and analysis. Initial manufacturing feasibility and issues are emerging
3	Manufacturing Proof of Concept Developed	Conduct analytical or laboratory experiments to validate paper studies. Experimental hardware or processes have been created, but are not yet integrated or representative. Materials and/or processes have been characterized for manufacturability and availability but further evaluation and demonstration is required.
4	Capability to produce the technology in a laboratory environment	Required investments, such as manufacturing technology development identified. Processes to ensure manufacturability, producibility and quality are in place and are sufficient to produce technology demonstrators. Manufacturing risks identified for prototype build. Manufacturing cost drivers identified. Producibility assessments of design concepts have been completed. Key design performance parameters identified. Special needs identified for tooling, facilities, material handling and skills. **Technologies should have matured to at least TRL 4**.

[10] https://www.twi-global.com/technical-knowledge/faqs/technology-readiness-levels

[11] (a) https://www.dodmrl.com/MRL_Deskbook_V2.pdf (b) https://www.twi-global.com/technical-knowledge/faqs/manufacturing-readiness-levels

5	Capability to produce prototype components in a production relevant environment	Manufacturing strategy refined and integrated with Risk Management Plan. Identification of enabling/critical technologies and components is complete. Prototype materials, tooling and test equipment, as well as personnel skills, have been demonstrated on components in a production relevant environment, but many manufacturing processes and procedures are still in development. Manufacturing technology development efforts initiated or ongoing. Producibility assessments of key technologies and components ongoing. Cost model based upon detailed end-to-end value stream map. **Technologies should have matured to at least TRL 5.**
6	Capability to produce a prototype system or subsystem in a production relevant environment	Initial manufacturing approach developed. Majority of manufacturing processes have been defined and characterized, but there are still significant engineering/design changes. Preliminary design of critical components completed. Producibility assessments of key technologies complete. Prototype materials, tooling and test equipment, as well as personnel skills have been demonstrated on subsystems/ systems in a production relevant environment. Detailed cost analysis include design trades. Cost targets allocated. Producibility considerations shape system development plans. Long lead and key supply chain elements identified. Industrial Capabilities Assessment for Milestone B completed. **Technologies should have matured to at least TRL 6.**
7	Capability to produce systems, subsystems, or components in a production representative environment	Detailed design is underway. Material specifications are approved. Materials available to meet planned pilot line build schedule. Manufacturing processes and procedures demonstrated in a production representative environment. Detailed producibility trade studies and risk assessments underway. Cost models updated with detailed designs, rolled up to system level and tracked against targets. Unit cost reduction efforts underway. Supply chain and supplier Quality Assurance assessed. Long lead procurement plans in place. Production tooling and test equipment design and development initiated. **Technologies should have matured to at least TRL 7.**
8	Pilot line capability demonstrated; Ready to begin Low Rate Initial Production	Detailed system design essentially complete and sufficiently stable to enter low rate production. All materials are available to meet planned low rate production schedule. Manufacturing and quality processes and procedures proven in a pilot line environment, under control and ready for low rate production. Known producibility risks pose no significant risk for low rate production. Engineering cost model driven by detailed design and validated. Supply chain established and stable. Industrial Capabilities Assessment for Milestone C. **Technologies should have matured to at least TRL 7.**
9	Low rate production demonstrated; Capability in place to begin Full Rate Production	Major system design features are stable and proven in test and evaluation. Materials are available to meet planned rate production schedules. Manufacturing processes and procedures are established and controlled to three-sigma or some other appropriate quality level to meet design key characteristic tolerances in a low rate production environment. Production risk monitoring ongoing. Low Rate Initial Production (LRIP) cost goals met, learning curve validated. Actual cost model developed for Full Rate Production environment, with impact of Continuous improvement. **Technologies should have matured to at least TRL 9.**
10	Full Rate Production demonstrated and lean production practices in place	This is the highest level of production readiness. Engineering/design changes are few and generally limited to quality and cost improvements. System, components or items are in rate production and meet all engineering, performance, quality and reliability requirements. All materials, manufacturing processes and procedures, inspection and test equipment are in production and controlled to six-sigma or some other appropriate quality level. Full rate production unit cost meets goal, and funding is sufficient for production at required rates. Lean practices well-established and continuous process improvements ongoing. **Technologies should have matured to at least TRL 9.**

As mentioned, while ***TRL characterizes the stage of development of the core product to be produced, the MRL characterizes the stage of development of the manufacturing process***. This translates in the fundamental difference in objective and actors participating:

Manufacturing: Development of the manufacturing process that produces a first batch (low volume) production output in order to evaluate and fine-tune economic and technological feasibility of the manufacturing process and offers a first output to be evaluated by users.

Product: Co-innovation of the manufacturing process and the product by evaluation of small scale produced products in an operational environment. Objective is to further fine-tune the product based on technological, economic and user-demand feasibility.

Next to these pilot activities, there the ***technological infrastructure*** is often mentioned as being crucial for pilot activities. Thus, it must distinguish[12]:

Prototyping facilities are a more general development facility, offering equipment which can be used to develop prototype products and test especially the technological viability (part of the technological valley of death). These facilities are often crucial for SMEs to develop their prototypes

Materials testing facilities are used as a more general production facility that can be used to test the economic and technological viability of new prototype products. These facilities are often crucial for SMEs to upscale their product prototypes. A subcategory are **test-beds** or **test labs**.

Demonstrator facilities are dedicated facilities to show potential clients both the production process and the commercial produced products. The installation is not primarily used for the testing of the process, but more used as demonstration.

Shared access facilities pointing to the organizational structure (e.g. prototyping or testing facilities) i.e. rather public/University/RTO driven.

Shared financed facilities pointing to the financial risk, i.e. rather industry driven. These facilities can address both up scaling of TRL3-6, as well as MRL4-8.

4.2 Lithium Cell Generations

The lithium system can be then classified by generations as function of the ***cell chemistry***. Currently, it has been recognized five generations as shown in the table below

Table A4. Lithium cell generations

Cell Generation	Cell Chemistry
5	Li/O2 (lithium-air)
4	All-Solid-state with Li metal anode; Conversion materials (Li/S)
3b	Cathode: HE-NCM, HVS (High voltage spinel) Anode: Silicon/carbon
3a	Cathode: NMC622 to NMC811 Anode: Carbon + Si (5-10%)
2b	Cathode: NCM523 to NCM622 Anode: 100% Carbon
2a	Cathode: NCM111 Anode: 100% Carbon
1	Cathode: LFP; NCA Anode: 100% Carbon

[12] http://www.mkpl.eu/results/

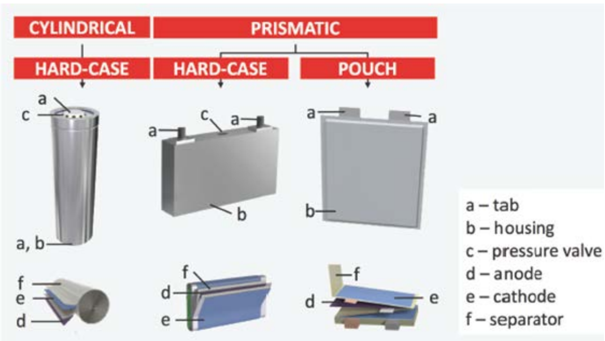
4.3 Lithium Cell Formats

There are three Li-ion cell formats which can be identified as product of a Li-ion PL: cylindrical, prismatic and pouch cells[13].

1. **Cylindrical**: The cylindrical lithium batteries have high specific energy and good mechanical stability. The design allows added safety features, offers a long calendar life and, is low cost, but it has less than ideal packaging density. It is commonly used for portable applications.
2. **Prismatic**: Prismatic batteries are encased in aluminium or steel for stability. Jelly-rolled or stacked, it is space-efficient but is more expensive to manufacture than the cylindrical battery. They are generally used in the electric powertrain and energy storage systems.
3. **Pouch**: Pouch shaped lithium battery uses laminated architecture in a bag. It is light and cost-effective but exposure to humidity and high temperature (susceptible to mechanical damage compared to other formats) can shorten its life. Adding a light stack pressure prolongs longevity by preventing delamination.

Figure A1 summarizes the component for each design and the general characteristics for each of the Li-ion cell format.

(a)



(b)

Format	Small cylindrical	Large cylindrical	Small prismatic	Large prismatic	Pouch
Size	Small	Medium-large	Small~ medium	Large	Small~ medium
Capacity	1~3.0[1] Ah	8~40 Ah	1~20 Ah	20~1000 Ah	0.1~100 Ah
Case	Metal	Hard plastic	Light metal	Plastic	Soft Mylar
Cross section	Round[2]	Round	Rectangular	Rectangular	Flat
Terminals	None	Threaded studs	Tabs or studs	Threaded holes	Tabs
Expansion retention	Inherent	Inherent	Good	Some: requires external retention	None: requires external retention
Typical application	Laptop computers Personal EVs Consumer products	(Not many)	(Not many)	Hobby EVs Large stationary Marine house	Cell phones Race EVs Production EVs Model airplanes
Assembly	Hard	Easy	Hard	Very easy	Very hard

Figure A1. *Lithium Cell Formats according to (a)[13] and (b)[14].*

[13] R. Schröder et.al., Procedia Manufacturing 8 (2017) 104; https://doi.org/10.1016/j.promfg.2017.02.013

[14] https://www.slideshare.net/DavideAndrea/liion-batteries-and-applications-chapter-3-liion-cell

4.4 Definition of the Key Process steps in the Lithium Manufacturing Pilot Line

The general information is extracted from two technical reports entitled "**Lithium-Ion Battery Cell Production Process**"[15] and "**Production of All Solid State Battery Cells**"[16] both prepared by PEM of RWTH Aachen University and The German Mechanical Engineering Industry Association (VDMA).

4.4.1 Electrode manufacturing

For LIB, the general electrode manufacturing process is constituted by six steps

1) **Mixing**: In the first step with the help of a rotating tool at least two separated raw materials are combined to form ***slurry*** where active Material (AM), binder (acting as glue), conductive additives and, solvents are mixed together in specific mass ratios to make the composite electrode (CE). A distinction is made between ***mixing*** (dry mixing) and ***dispersing*** (wet mixing). In addition, the process can be performed under vacuum to avoid gas inclusions.

2) **Coating:** By a tape casting procedure, the electrode composite slurry is coated on the current collectors: for the NE, this is copper and for the PE, this is aluminum. Generally, the top and bottom sides of the foil are ***coated sequentially***. Alternative, ***simultaneous coating*** could be implemented: The top and bottom sides of the foil are coated simultaneously by two opposite application tools.

3) **Drying**: after coating, the applied active material is dried in a continuous process. After passing through the dryer, the foil is cooled down to room temperature and, depending on the type of system, rewound (***conventional***) or directly coated on the second side (***tandem coating***). Alternatively, the conventional convection dryers can be supplemented by (i) infrared heating and thus made more efficient (***infrared drying***) or by using a (ii) laser where the dryer length can be shortened and energy costs can be saved (***laser drying***).

4) **Calendering:** During calendering, the electrodes are compressed by driving them through two rotating cylindrical rolls and hence, the electrode thickness and porosity is reduced to a controlled value. Line pressure defines the porosity of the coated material which influences the subsequent wetting properties of the electrodes and the energy density of the cell. As a result, the adhesion of electrode materials is improved and the density is increased. Alternatively, **hot rollers** can be implemented depending on the system concept. The top and bottom rollers can be heated. In this way, the ductility of the active material can be brought to a defined value.

5) **Slitting**: the electrodes are cut or punched into strips of a desired shape. A clean cut is necessary to avoid burrs on the edges which can cause short-circuit in the cells. Therefore,

[15] https://www.researchgate.net/publication/330902286_LITHIUM-ION_BATTERY_CELL_PRODUCTION_PROCESS
[16] http://elektromobilitaet.vdma.org/documents/7411591/15357859/Production+ASSB_eng/b1abd698-9cad-5213-48f1-21c85a13265f

the cut quality of the electrode edges and the cleanliness of the coils are considered as the main quality criteria. Generally, rolling knives are used for this purpose, although Laser Slitting can also be used for the cutting process. The *cutting width* can vary depending on the cell design and lies *between 60 mm and 300 mm* in many applications.

6) **Vacuum Drying**: After slitting, the coils are then stored in a vacuum oven to dry about 12 h to 30 h. During the drying process, residual moisture and solvents are removed. It is advised to operate the vacuum ovens under inert gas atmosphere in order to prevent corrosion. After vacuum drying has been completed, the coils are transferred directly to the dry room or dry packed under vacuum.

All Solid State Batteries

In this technology, the first key process consists of Electrode and Electrolyte production. Although, the pouch cell format appears to be the most suitable for all-solid-state batteries, a generally valid process chain does not exist; instead, a large number of alternative process chains may be applied. These differ in part from the manufacturing process of a lithium-ion battery, but can also be similar. In the following alternative process chains compared to the standard process chain for electrode production described for LIB are given:

Cathode/electrolyte manufacturing process:

1) **Compounding**: The cathode and electrolyte melts are produced in two separate compounding processes where the material components are fed to the heated barrel of a twin screw extruder. Rotational movements of the extruder bring in energy into the material components resulting in a homogeneous melt. In addition to cathode active material, eventually electrolyte particles, which reduce the resistance between cathode and electrolyte, as well as binders and additives, are mixed for the cathode.

2) **Co-Extrusion**: The cathode and electrolyte melts are co-extruded in a suitable die. This creates a composite of cathode and electrolyte layer. Cathode and electrolyte melts pass through separate channels to the outlet of the extrusion die. Here the melts are extruded via a slot die onto a current conductor. Subsequently, the bond is calendered to improve adhesion between the individual layers and achieved the desired layer thicknesses.

Anode manufacturing:

3) **Extrusion and Calendering**: A metallic lithium foil can be used as the anode. The lithium film can be produced by extrusion with subsequent calendaring in order to assure homogeneity and desired film thickness. For this purpose, the film is rolled under pressure by two rollers with the addition of a lubricant. The rollers must be compatible with the adhesive properties of lithium.

Layer compound production:

4) **Laminating**: After the lithium foil has been manufactured, it is laminated onto the cathode

electrolyte composite. For this purpose, the two layers are pressed together by two rollers, being then heated in order to achieve higher adhesion forces. During heating and pressing, polymers penetrate from one layer to the other, forming the bond between the anode and electrolyte.

Alternative electrode/electrolyte production step consists of a **physical vapor deposition** (PVD) process with which the individual layers are applied one after the other. This process chain is particularly suitable for oxide-based ASSB. The process includes (i) Grinding and Mixing; (ii) High Frequency Sputtering; (iii) Sintering; and (iv) Thermal Evaporation. They will not be elaborated in this deliverable.

4.4.2 Cell Assembly

Depending of the cell format, the sequence of the cell assembly process step varies. For *pouch* format, the cell assembly process step follows the following order

1. Separation
2. Stacking
3. Packaging
4. Electrolyte Filling (not for ASSB)

while for *cylindrical* and *prismatic* cells, the cell assembly process step consists of

1. Separation
2. (Flat) Winding
3. Packaging
4. Electrolyte Filling (not for ASSB)

For all formats:

1) **Separation**: This step describes the separation of anode, cathode and separator sheets from the roll materials. The dried rolls are unwound and fed to the separation tool. The cutting process is usually carried out with a shear cut (punching tool) in a continuous process. Depending on the system concept, the individual sheets (coated on both sides) are stored in a magazine or transferred directly to the next process step.

Pouch Format:

2) **Stacking**: During the stacking process the separated electrode sheets are stacked in a repeating cycle of anode, separator, cathode and separator. There are a wide variety of stacking technologies exist, being a common variant of stacking the so-called Z-folding. There is *alternative process* as the Lamination process where the individual electrode and separator sheets are laminated onto each other in a continuous process and then usually pressed together by a heat press. The *exact positioning of the individual sheets is considered as the central quality criterion*.

3) **Packaging**: To package the pouch cell, the current collector foils (anode - copper and cathode - aluminium) are first contacted with the cell tabs using an ultrasonic or laser

welding process. The cell stack is then positioned in the pouch foil. For this purpose, the pouch foil is deep-drawn in an earlier process step. The deep drawing of the pouch foil is carried out either directly in the production line or in a separate process.

4) **Electrolyte Filling**: Finally, in case of LIB electrolytes are filled in. During electrolyte filling, a distinction must be made between the sub-processes *filling* and *wetting*. To achieve a maximal wettability, it is important that the electrolyte completely permeates and fills the pores in the separator and electrode. The calendering step will inevitably influence the wettability because it alters the porosity and particle distribution. The wetting formation-step takes up lot of time (1.5 to three weeks) and capital. Finally, the pouch foil is sealed under vacuum.

Cylindrical and prismatic cell assembly process steps

2) **Winding**: The electrode foils and two separator foils are wound around a winding mandrel (prismatic cell) or a centre pin (cylindrical cell). The foil sequence is similar to the stacking process. The wound product is called jelly roll. The *exact positioning and alignment of the electrode foils and separator foils is regarded as the central quality criterion*.

3) **Packaging**: The jelly roll is inserted into a robust metal housing. In the ***prismatic cell***, the edges of the jelly roll are compressed, fixed and ultrasonically welded to the contact terminals attached to the lid of the battery. An insulation foil protects the jelly roll during insertion into the prismatic housing. The first step in the ***cylindrical cel***l process is to insert a bottom insulator and the jelly roll into the cylindrical housing. The current collector of the anode is usually welded to the bottom of the housing and the current collector of the cathode is welded to the lid. Finally, an insulation ring is inserted between the jelly roll and the lid.

4) **Electrolyte Filling**: The electrolyte filling takes place after the jelly roll has been inserted into the housing. The electrolyte is filled into the cell under vacuum (filling) with the help of a high-precision dosing needle. To achieve a maximal wettability, it is important that the electrolyte completely permeates and fills the pores in the separator and electrode. A vibrating table could be used for prismatic and cylindrical cells to ensure optimum electrolyte wetting.

All Solid State Batteries

During cell assembly, the ASS battery cell is made up of existing elementary cells. Compared to conventional LIB production, the cost and time intensive formation and aging can be simplified for the ASSB. In addition, electrolyte filling and degassing is no longer necessary.

Cell Assembly for ASSB consists then of (i) Cutting; (ii) Stacking and (iii) Contacting and Packaging

4.4.3 Cell Finishing

The cell finishing process consists of the following steps:

1. Roll Pressing (pouch format)
2. Formation
3. Degassing (pouch format)
4. Aging
5. EOL Testing

1) **Roll Pressing (pouch)**: After electrolyte filling, an optional roll pressing process can take place for the pouch cell. Roll pressing ensures optimum distribution and absorption of the electrolyte under defined pressure. This step serves as preparation for the subsequent formation because electrochemically inactive areas are avoided by the pressurization. Roll pressing ensures that the maximum capacity of the cells is achieved and the rejection rate is reduced.

2) **Formation**: The formation describes the first charging and discharging processes of the battery cell according to a precisely defined current and voltage curves. There are different procedures for the formation depending on the cell manufacturer and cell chemistry having a high impact on cell performance.

3) **Degassing (pouch)**: During degassing, the gas bag is pierced in a vacuum chamber and the escaping gases are sucked off. The cell is then finally sealed under vacuum. Final folding and, if necessary, gluing of the seal edges to reduce the external dimensions of the pouch cell can be carried out as an option.

4) **Aging**: *Aging represents the final step in cell production and is used for quality assurance*. During aging, cell characteristics and cell performance are monitored by regularly measuring the open circuit voltage (OCV) of the cell over a period of up to three weeks. The duration of the aging process depends strongly on the respective cell manufacturer and the cell chemistry used.

5) **EOL Testing**: In the testing station, the cells are discharged to the shipping state of charge (capacity measurement). Depending on the manufacturer, pulse tests, internal resistance measurements (DC), optical inspections, OCV tests and leakage tests are carried out. After testing, many cell manufacturers sort the cells according to their performance data (grading).

All Solid State Batteries

This finishing process for ASSB consists of (*i*) Formation; (*ii*) Aging and; (*iii*) Testing and Grading. Formation and Aging are largely based on extensive experimental knowledge, which does not yet exist for all solid state batteries due to lack of series production maturity. Regarding grading, there is no standard yet.

4.4.4 Lithium Ion Battery Production Environment[17]

	Clean room class	Dry room (dew point)	Temperature	Annotations
Mixing	ISO 8	/	22 ± 2 °C	The electrode manufacturing takes place under clean room conditions, since foreign particles in the coating cannot be removed in the later process by cleaning methods (e.g. suction).
Coating	ISO 7	semi-dry (5°C to -5°C)		
Drying				
Calendering	ISO 7 - ISO 8			
Slitting				
Vacuum drying		Dry (0°C to -30°C)		
Separation	min. ISO 7	Dry (-25°C to -35°C)	22 ± 2 °C	The cell assembly must be carried out under dry conditions, as water inside the cell leads to strong quality losses (service life) and to a safety risk (formation of hydrofluoric acid).
Stacking / Winding		Dry (-40°C to -50°C)		
Packaging				
EL filling		Extra dry (-50°C to -70°C)		
Formation	/	/	22 ± 3 °C	Cell finishing takes place in a normal environment. Since the cell is already sealed and degassing takes place in a vacuum chamber, there are fewer requirements for the particle environment and humidity.
Degassing				
HT aging			30 °C to 50 °C	
NT aging			22 ± 3 °C	
EOL testing				

All Solid State Batteries

As represented in **Figure 3** (Section 3.3), the major different between ASSB and LIB production lies in the need of a controlled atmosphere all along the manufacturing process for the ASSB. That means the use of a dry room and/or inert gas atmosphere.[18]

[17] https://www.pem.rwth-aachen.de/global/show_document.asp?id=aaaaaaaaabdqbtk

[18] J. Schnell et al., J. Power Sources 382 (2018) 160; https://doi.org/10.1016/j.jpowsour.2018.02.062 and http://elektromobilitaet.vdma.org/documents/7411591/15357859/Production+ASSB_eng/b1abd698-9cad-5213-48f1-21c85a13265f