White Paper
Why the Battery Pusher Kiln?

1. Investment Benefits - Price and Production Capacity

Perhaps the most important driving force for the global use of electromobility is its price. In order to achieve a widespread use of electric vehicles, manufacturers are being forced to further reduce prices of EVs (Electric Vehicles). The producers of automotive batteries are also experiencing this pressure. The battery price must be reduced from currently approx. 110-135 $/kWh to 85-112 $/kWh in 2025[1]. And the battery price itself is mainly influenced by the cathode material and its preparation or production[1].
The second major driving force in this market is the production capacity. E-mobility has already found an important role in future planning and strategies of many industrialised and emerging countries. In recent years, more and more ambitious goals have been defined in terms of technological demands and market shares. A large number of automobile manufacturers are currently investing massively in electric mobility or have already done so in high double-digit billion US dollar ranges.[2] The manufacturing capacities have to be multiplied rapidly worldwide [2] (figure 1). Such an increase in capacity typically results in a price reduction. This is referred to as "economies of scale". In case of e-mobility, the situation is slightly different because the increase in production capacity is also required independently of the price reduction. Therefore all (cathode) material suppliers worldwide are massively increasing their delivery capacities.

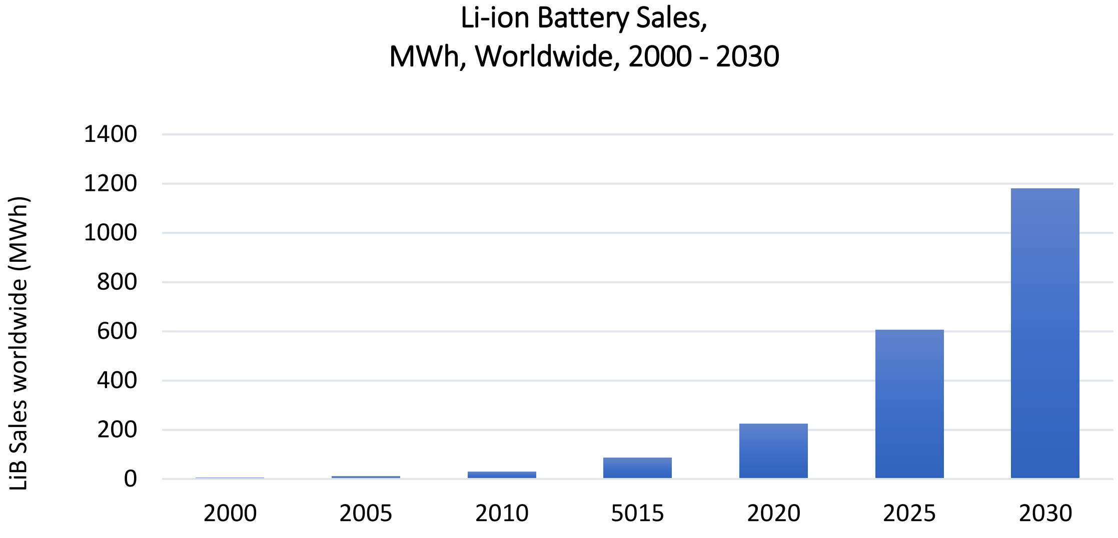

figure 1 - Rapid growth of the LiB turnover in different applications in the upcoming years

The electrode powder used for electric vehicles is typically filled into ceramic capsules (saggars) and conveyed through the kiln. Therefore, the production capacity of a kiln is directly related to the number and filling quantity of the saggars that can be passed through this kiln within a specified time. The production capacity of a roller kiln, which meets today's industrial standards and is used for cathode production, is limited to approx. 1.500 tons per year. An increase in production capacity of the roller kiln is not

[1] Menahem Anderman, Total Battery consulting Inc. Oral Presentation at AABC Strasbourg 2019
[2] Christophe Pillot, Aviecene Energy, Oral Presentation at AABC Strasbourg 2019

easily possible and is construction wise limited to approx. 2.300 tons/year. It is therefore already predictable that the currently established technology of roller kilns will not be able to meet the current demands on future quantities and processes.
The production capacity of a kiln depends directly on the number of saggars per row. This applies when all other process parameters like process time, saggar filling amount and product's weight loss during heating are the same. Modern roller kilns are loaded with 4 saggars per row. In some cases, also with 6 saggars side by side. In order to further increase production capacity, some manufacturers load their kilns with an additional layer of 4 saggars. The result is a row with a maximum of 8 saggars (4 in width; 2 in height). Some kiln manufacturers have extended the usable length of their kilns. The roller kilns used for calcination of cathode powder have been extended in length from approx. 38 m to up to 55 m in recent years. The longer the roller kiln is, the more difficult it is to keep the saggars in line. It is almost inevitable that the saggar rows drift apart and twist due to roll bending. In the worst case, the saggars may block each other or collide with the kiln wall or the kiln door. Such accidents can often lead to a complete shutdown of production. Furthermore, a longer kiln requires a larger floor area or hall space, is ecologically and energetically less favourable and therefore brings few economic advantages for the corresponding surcharge.
An extension in width or height is directly related to the roller dimensions. The roller length is limited due to production-related reasons. In addition, the deflection of the longer rollers under heavy load is higher, which increases the above-mentioned problems of the saggar flow. Due to the general sensitivity of ceramics to bending stresses, such rollers are then more susceptible to breaking and therefore even more unreliable. An increase in height requires larger roller diameters and a smaller roller distance to each other. The typical roller diameter for roller kilns has already been increased from 34 mm to 45 mm in recent years. This is where the roller kiln reaches its natural system limit. The diameter cannot be increased any further without extending the roller distances again. Too large roller distances can lead to destabilization of the saggar superstructure and finally to its collapse; a dangerous intervention in the production stability. There is almost no potential for further improvement and increase in capacity of roller hearth kilns.
The production capacity of a Battery Pusher Kiln, however, can reach up to 8.500 tons per year (at a process time of 18 h). With a Battery Pusher Kiln, the saggars are not conveyed on ceramic rollers, but on a solid floor of the so-called pusher track. This means that there is considerably less restriction on the load weight. The heating elements in a Battery Pusher Kiln are arranged vertically. Each saggar, regardless of its position in the kiln and vertical in the stack, therefore has the same process conditions. It is consequently easy to stack up to 7 saggars on top of each other. The saggar superstructures are conveyed either individually or in pairs through a corridor of heating elements. Ideally, a saggar superstructure (tower) is located between two heating elements and next to a process gas supply lance. This offers the best process conditions. If it is possible to make compromises here, two towers can also be positioned between

two heating elements and a lateral gas injection (figure 2). This simplified design is more economical under similarly good process conditions.

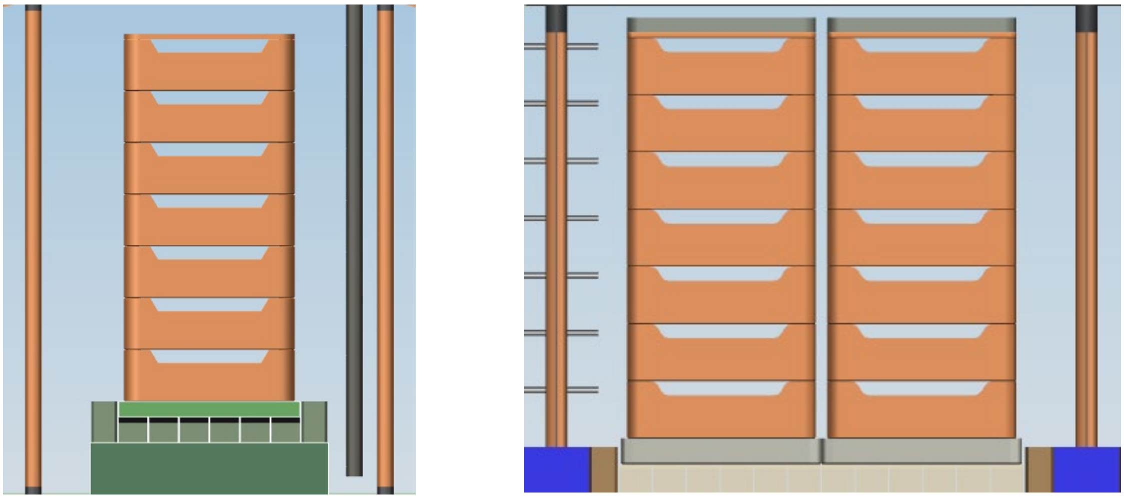

figure 2- Typical arrangement of the saggar superstructure, heating elements and gas supply lances a) single conveyor b) pair conveyor

The longest known roller kilns for the electrode production have a length of 43.7m, 50m and 55m. In an example case the capacities of these kilns were compared with two Battery Pusher Kilns; the BPK 4x7 where each row consists of 4 saggars side by side and 7 saggars one above the other, and the BPK 6x7 where each row consists of 6 saggars side by side and 7 saggars one above the other. As shown in figure 3, the production capacity of the Battery Pusher Kilns is significantly higher than of the largest roller kilns.

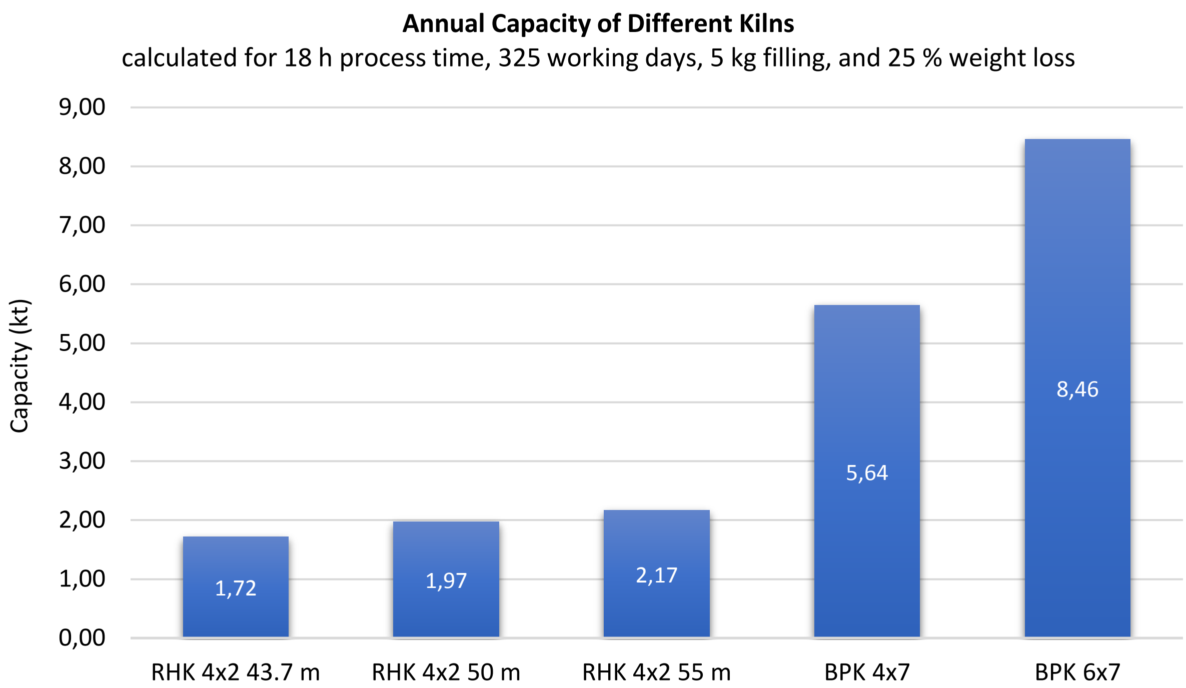

figure 3- Comparison of the production capacities of different roller kilns (RHK 4x2) and two Battery Pusher Kiln (BPK) variations

2. Improvement of the Production Quality

Besides price and capacity, the material quality is the decisive factor. Above all, the range of electric vehicles still must catch up significantly compared to vehicles with combustion engines. The overall performance of electric vehicles depends directly on the electrochemical properties of the battery, which in turn depend directly on the powder quality of the electrode material.

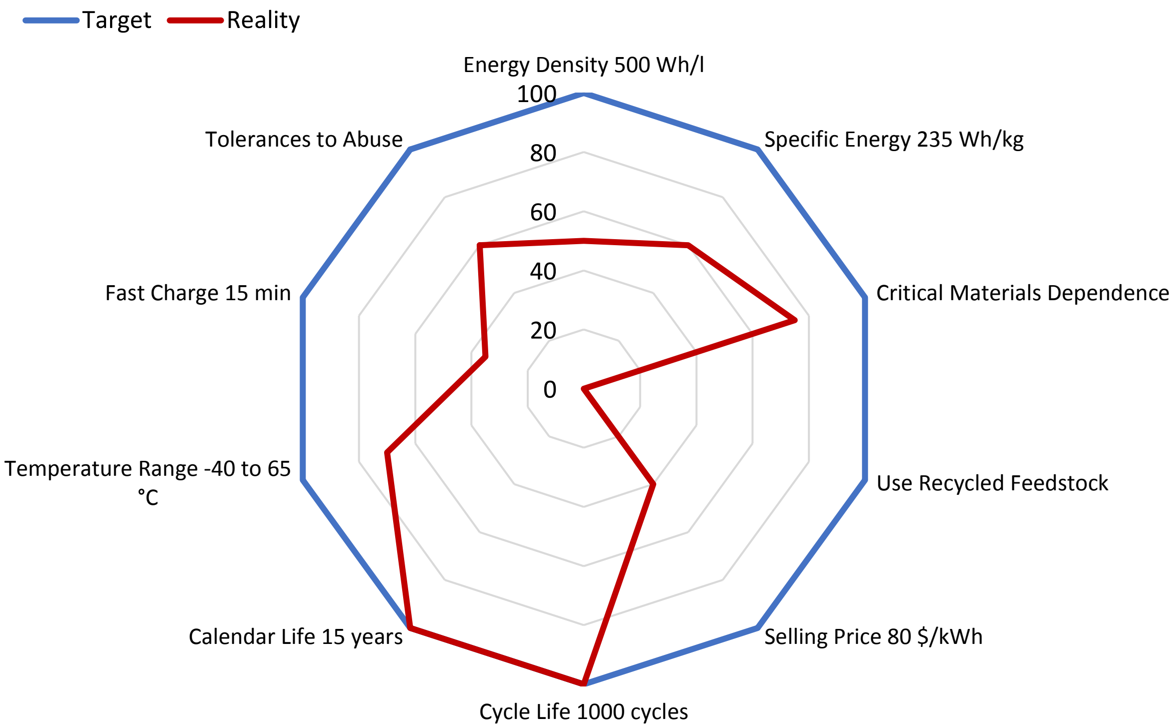

figure 4- Comparison between the desired (blue) and current (red) parameters for car batteries

Figure 4 shows a comparison between the required performance and the present material features[3]. However, while intensive research is currently being carried out on alternative material systems with improved properties, the theoretically available potential of existing material systems cannot be realized in practice. From a theoretical point of view, an energy density of approx. 450 Wh/kg can be achieved with existing automotive batteries. However, the energy density values that can be found in today's production world are limited to approx. 230 Wh/kg (figure 5). This is basically due to two main reasons: 1) contaminations and imperfections, which are unavoidable when it comes to upscaling and which affect the performance of the system; and 2) insufficient performance of the plants, in which these material systems are prepared and manufactured (figure 6). While the first cause is natural and

[3] George Crabtree, Joint center for Energy Storage Research, Aregonne National Laboratory & University of Illions at Chicago, Oral Presentation at AABC Strasbourg 2019

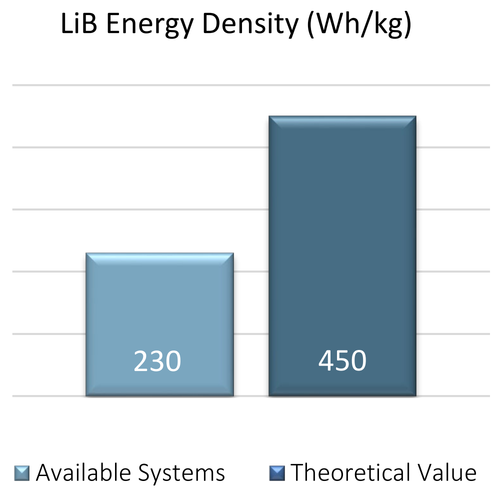

figure 5- The existing systems can only retrieve a part of the potentially available energy density.

almost unavoidable, the second cause is due to technological and partly even economic facts. A short research in technical literature makes clear that in recent years many very interesting and up to date material systems have been developed which have excellent features in the laboratory and a significant potential for the use in e-mobility. The main reason why these systems cannot be produced on an industrial scale with correspondingly improved properties is that the industrial plants for thermal processing of these materials cannot provide the required performance. In other words, the currently commercially available kilns cannot cope with the high process and capacity requirements for the heat treatment of the electrodes (cathode or anode) or solid electrolytes.

The Battery Pusher Kiln can in comparison to today's roller kilns reach up to three- and four-times bigger production capacities without quality losses at the same foot print. In many cases the quality of the powder can be increased by the optimisation of the thermodynamic parameters.

When designing a kiln, there are three particularly important aspects that must be considered in order to meet the high process-related requirements.

1) The calcination reactions are strongly endothermic, i.e. they need a permanent and sufficiently large heat supply to be able to continue.
2) During calcination, gases are always released. These gases must be removed from the reaction front, otherwise a so-called oversaturation will occur due to the too high partial pressure of the formed gases. Consequently, the reaction slows down and may come to a reaction stop.
3) During the subsequent sintering process, temperature homogeneity is of great importance. The sintering temperatures influence the morphology of the electrode particles and their size, surface quality and crystal structure. These in turn have a direct influence on the electrochemical characteristics of the

electrode material. It is therefore of great importance that the whole powder is sintered at the same temperature conditions.

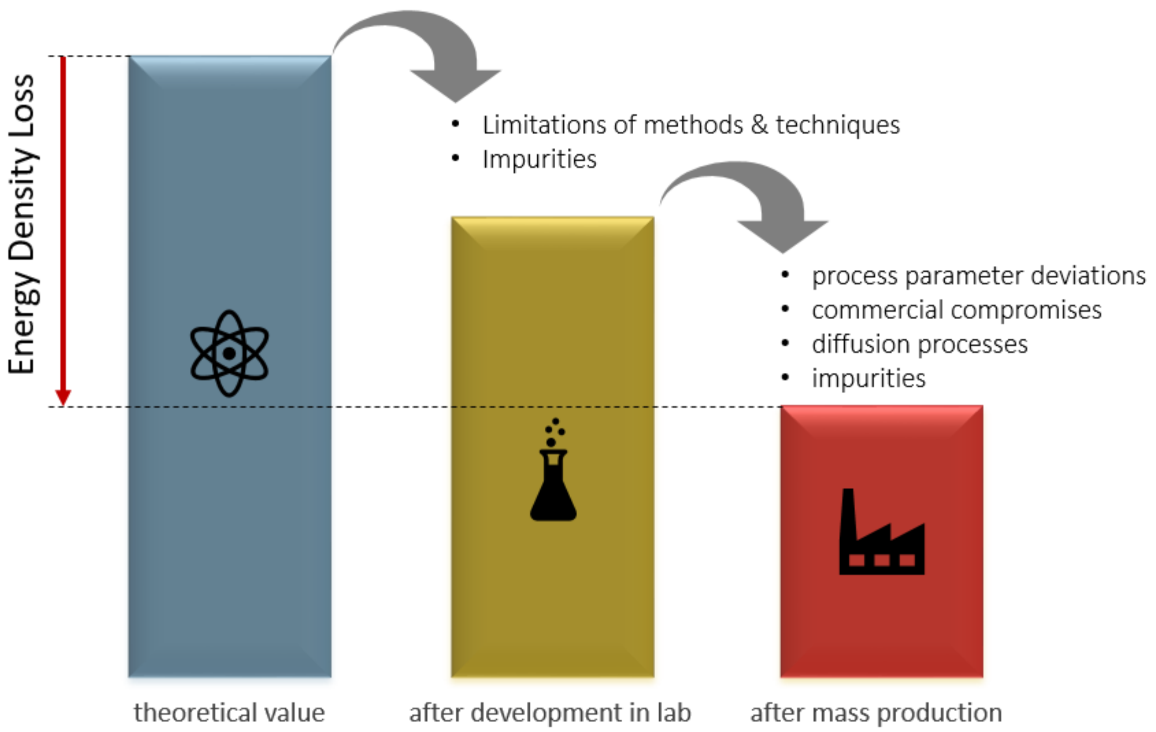

figure 6- Reasons for the energy density drop from the theoretical to the current industrially achievable value

For all the above-mentioned requirements the Battery Pusher Kiln offers significant advantages compared to the conventional roller kilns. While in a roller kiln the heat supply is only possible from above and below, in a BPK additional vertical heaters are installed. In a roller kiln, the product carriers (saggars) are heated differently depending on their position in the setting (top or bottom; central or lateral). While some saggars are directly irradiated, the others are in the shadow of the other saggars (figure 7). This leads to large temperature differences between the saggars, especially in the temperature range up to 800 °C (figure 8). Thus, the calcination reactions in some saggars begin later and at higher temperatures than in others. This in turn means that several hours extra time must be provided for thermal homogenization of the product at the end of the intended calcination time.

The temperature homogeneity is significantly better in the BPK. In both the heat-up and the soaking area, the BPK can reach significantly more homogeneous temperature distributions (figure 9). While in a roller kiln and during the heat-up period temperature differences of up to 400 °C can occur between the individual saggars, these temperature differences during heating up in a BPK are only ± 20 °C. This leads to enormous time and cost savings. Even in the soaking area of a roller kiln and after holding at a constant temperature for several hours, there is still a minimum difference of approx. 20 °C between the temperature of the saggars. The same value for a BPK can be reduced to ± 2 °C, which leads to an improvement in product quality.

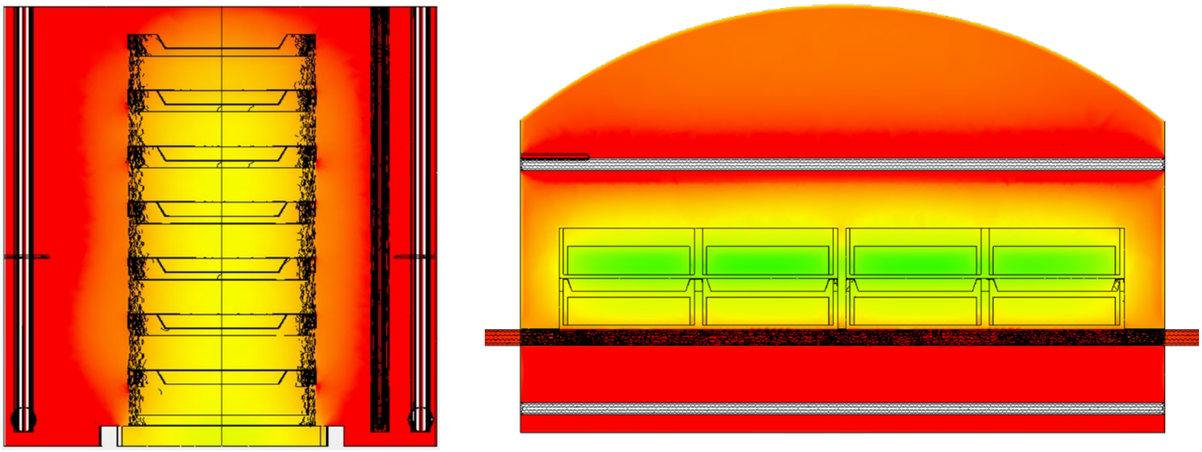

figure 7- Influence of the relevant position of heating elements to the saggars on the temperature homogeneity in a roller kiln (right) and a BPK (left).

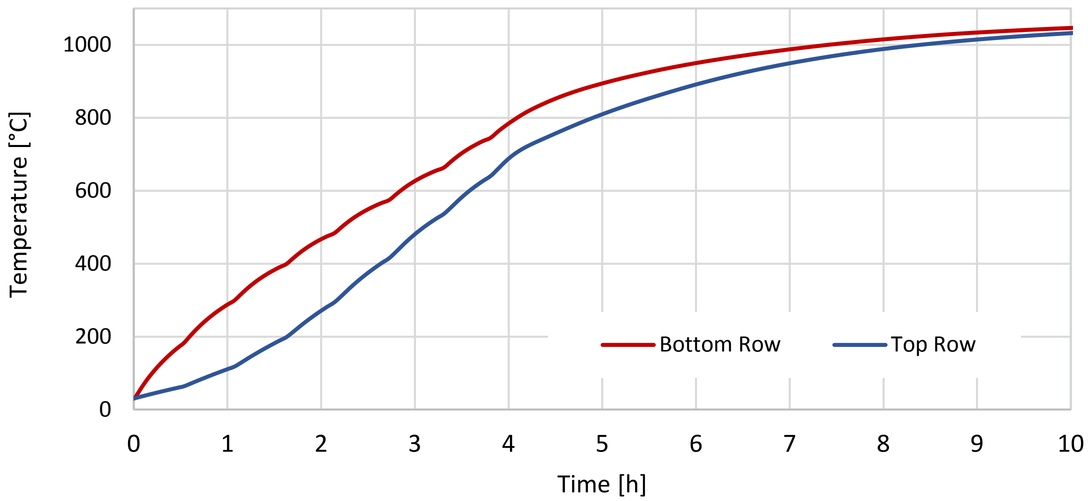

figure 8- Temperature differences between the saggar rows in a typical roller kiln (4x2)

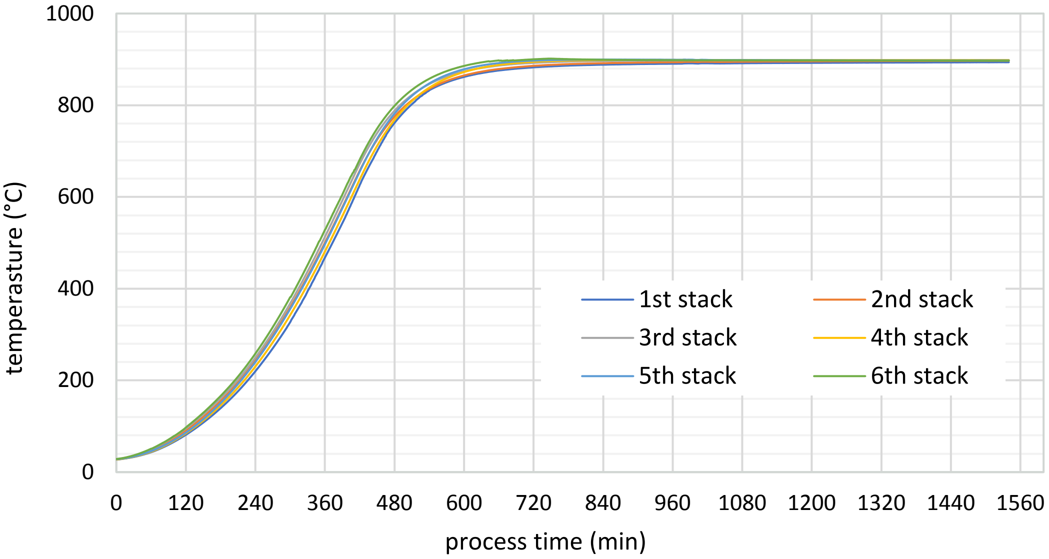

figure 9- Temperature differences between the saggar-rows in a BPK (4x6)

The BPK continues to impress with clear advantages in efficient process gas feeding and exhaust gas removing. While the exhaust gases in a BPK are removed away homogeneously by a directed flow of fresh process gas immediately after their formation, local exhaust gas oversaturation often occurs in a roller kiln because the saggars have different access to the process gas and therefore cannot be sufficiently flushed. As a result, the calcination reactions in the middle saggars often remain incomplete or are completed too late.

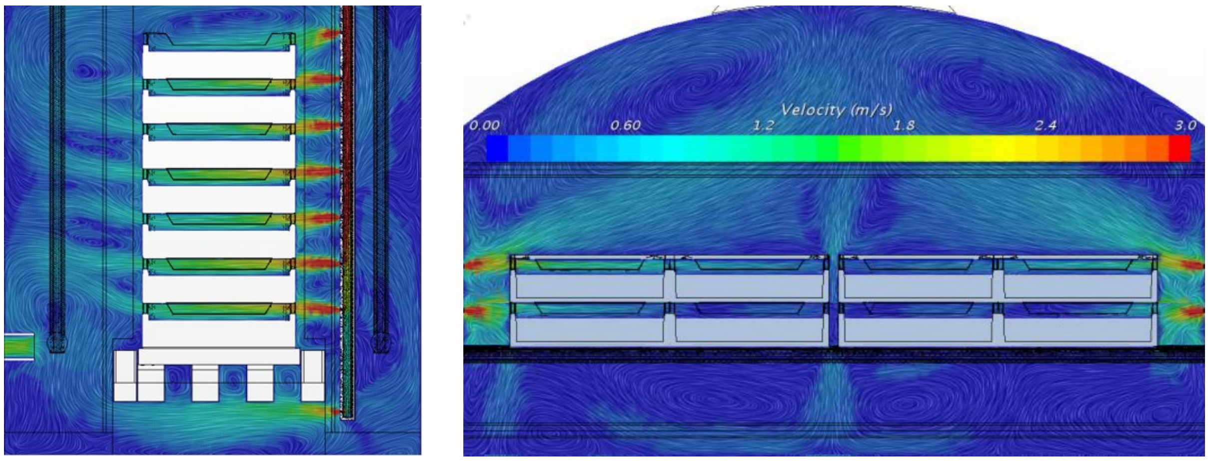

figure 10- Influences of the kind of saggar-construction on the gas flow in the gaps between the saggars inside a roller kiln 4x2 (right) and a BPK (left).

3. Savings at the Operating Costs

In addition to the effective fresh gas supply and exhaust gas transport, the homogeneously directed gas flow between the saggars has another major advantage.

In a BPK, the total volume flow of the process gas can be drastically reduced while maintaining the directed homogeneous flow. Figure 11 shows how the fresh gas is flushed into the saggar interspaces in a controlled process. In the left picture, the flow velocities of the gas in the saggar interspaces are shown as a function of the total volume flow of the gas.

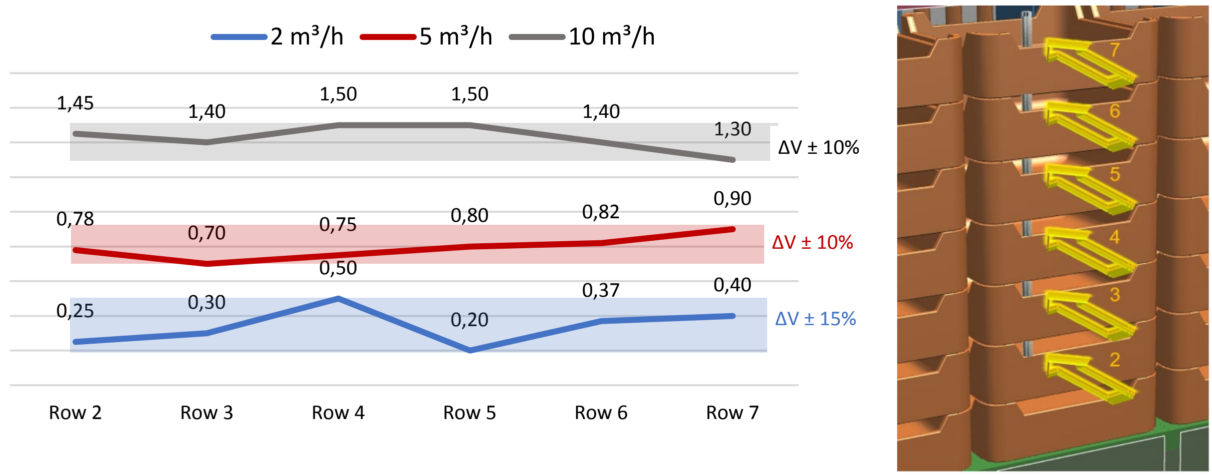

figure 11-Controlled homogeneous gas streams in the saggar interspaces

Deviation of the measured velocities at the different heights is very low (ΔV ± 10 %). Even if the total gas flow rate is significantly reduced (from 10 to 2 N^3m/h), the flow velocities remain homogeneous. Even with small gas volumes, it can be ensured that all saggar gaps are sufficiently purged. This gives the manufacturer the great economic advantage of reducing the process gas quantity to the essential minimum. In conventional heat treatment plants for the cathode, large quantities of special gases such as oxygen are consumed (300-1000 m^3/h), although only a small part of this is necessary for the process from a chemical point of view. Thanks to the innovations presented for more effective use of the gas, gas savings of up to 27% are possible in a BPK. Especially with expensive gases such as oxygen or silane, large cost savings are possible. Figure 12 indicates that in the example case more than 400,000 € can be saved in one year if a 4x2 roller kiln is replaced by a 6x7 BPK.

The Battery Pusher Kiln also offers significant energy savings. The savings in gas consumption itself leads to large annual energy savings, because the gas which is purged into the kiln also needs to be heated. On average, each kilogram of gas requires about 0.2 kWh of heat energy. Further significant potential savings with the pusher kiln can be achieved through the better sealing of the kiln chamber to the outside and the much smaller dead spaces (spaces not used for the process, which are nevertheless heated) in the kiln.

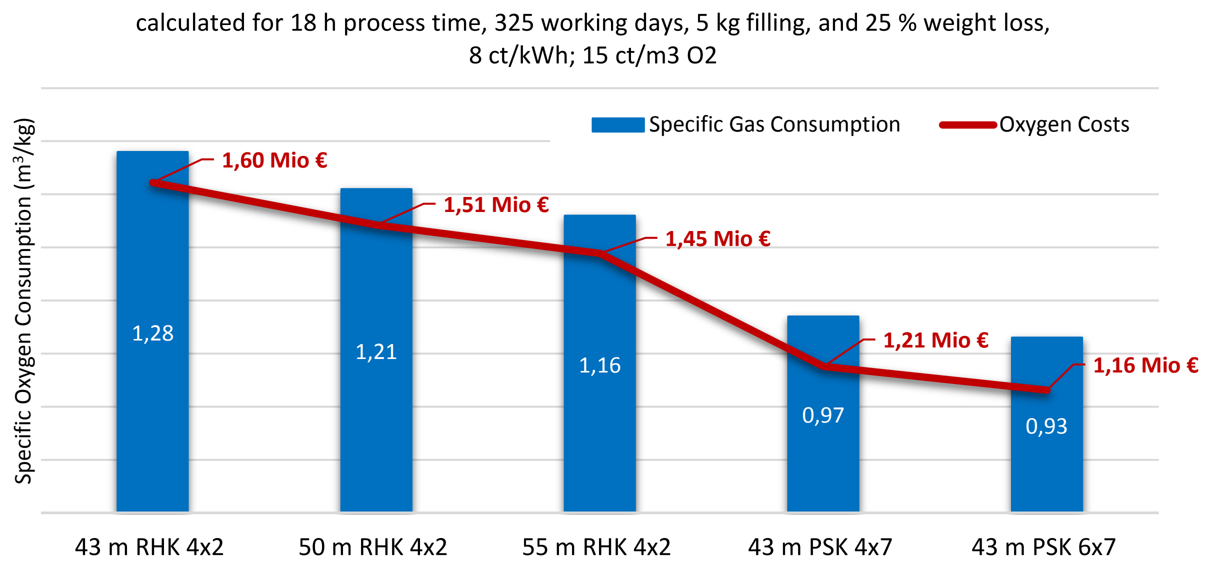

figure 12- Specific O_2 consumption of different furnace types with the corresponding annual gas costs

The BPK loses significantly less energy (e.g. through the rollers and roller openings). This is not only very important from an economic point of view, but also from the point of view of public awareness. This is because energy from batteries can only be presented credibly as an alternative to fossil fuels if the battery manufacturing process is also energy-optimised. By reducing energy consumption in the heat treatment processes, significant savings in the CO_2 footprint of the entire battery manufacturing process can be achieved. This in turn increases the acceptance of LiB as a green energy source.

As shown in figure 13, replacing a conventional 4x2 roller furnace with a 6x7 BPK results in a 25% energy saving in the entire heat treatment process. This is the result of a sample calculation of the total heat demand of a process with the following conditions: 18 h process time, 325 working days, 5 kg charge into the saggars, 25% mass loss, and 8 ct/kWh energy costs. The process gas quantities were estimated as in the last example (figure 12).

Another important point is the saving in the Footprint (floor space used). Due to the vertical design, which allows for significantly higher saggar towers, a lot of floor space can be saved.

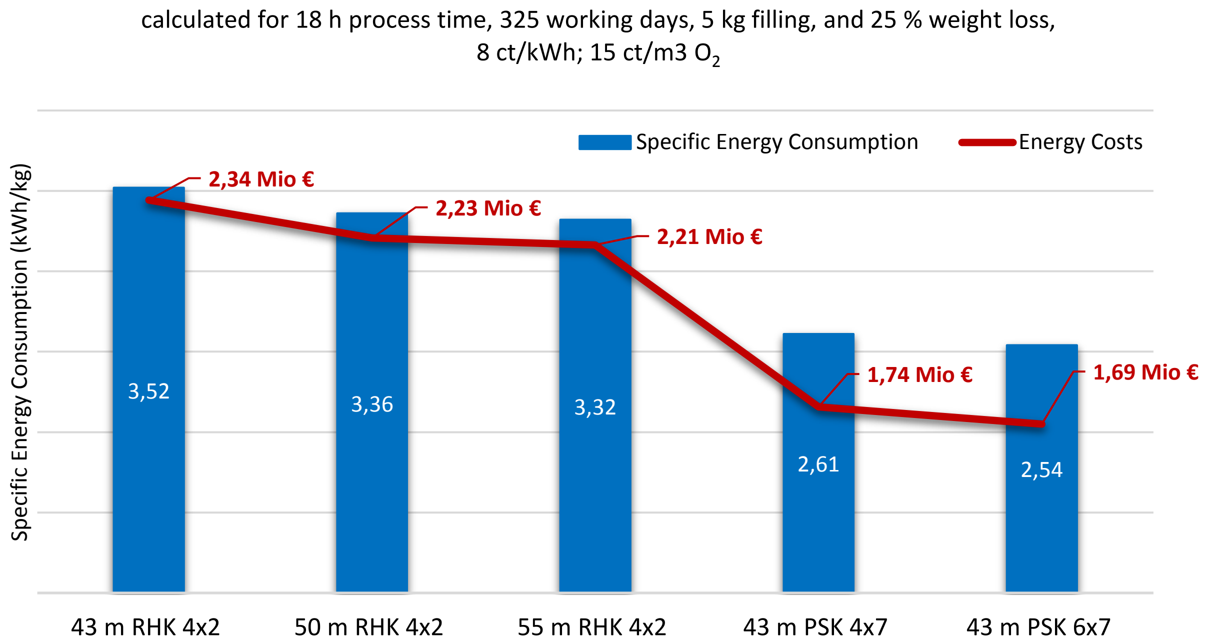

figure 13- Specific energy consumption of different furnace types with the corresponding annual energy costs

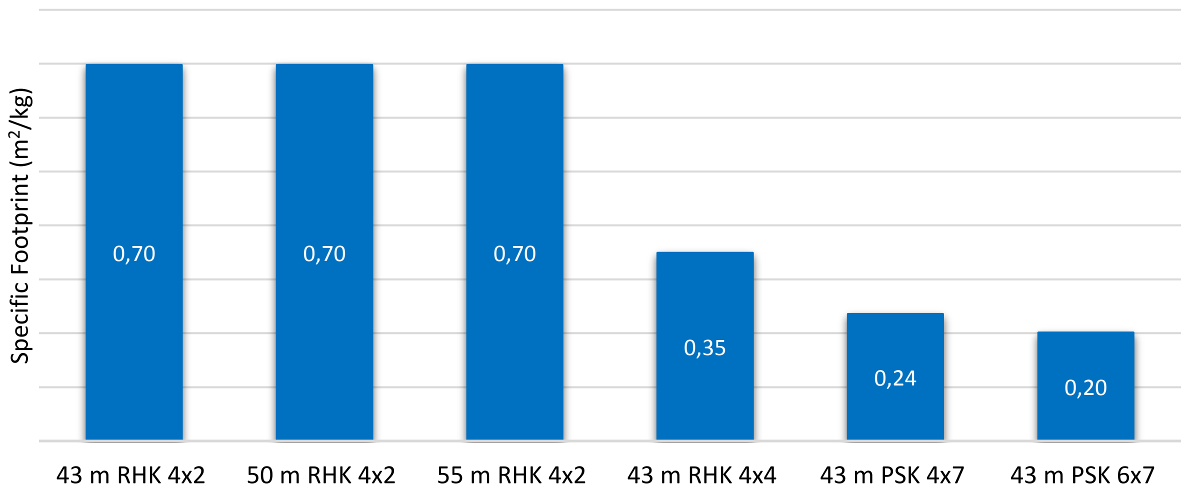

figure 14- Specific floor space of different furnace types

A large production BPK can save up to 70% of the footprint compared to a conventional roller kiln (figure 14). Less space usage, smaller halls and therefore a significant cost saving are the direct consequences.

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4. Summary

The high technical and commercial advantages of the Battery Pusher Kiln have been proven in theory and practice. Many of the advantages have been tested and confirmed in practical conditions by experimental studies and simulations. A near-industrial prototype furnace with a nominal annual capacity of 460 tons is available for validation tests in our company's pilot plant.

The "Battery Pusher Kiln" is consequently the best kiln available in the world for the heat treatment of battery electrodes and similar processes; it is this not only because of its great advantage for increasing the production capacity and thereby significantly reducing the investment costs, but also because it enables the characteristics of the material produced to be maintained or improved at the same time. Using the "Battery Pusher Kiln", processes can be implemented on an industrial scale which, without this kiln, might not be interesting for series production for economic reasons. This kiln is clearly leading the way in terms of both initial investment and operating costs (TCO).

If you need more information about the Battery Pusher Kiln, feel free to contact us.