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Technical Performance and Energy Intensity of the Electrode-Separator Composite Manufacturing Process

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Abstract

Energy storage is one of the key technological factors that determine the success of a sustainable future. Especially green mobility concepts for electric or hybrid electric vehicles highly depend upon storage technologies with high energy density and light-weight materials. At the same time, innovative production processes should be conceived that ensure energy and resource efficient manufacturing of these energy storage devices. This paper focuses on the technical as well as dynamic energetic performance analysis and evaluation of an innovative electrode-separator composite manufacturing process of lithium-ion batteries for automotive applications. The technical performance indicators such as battery capacity and the energy intensity of the manufacturing process are highly dependent upon process parameters, machine and product design. Hence, in-depth process knowledge must be acquired to understand interdependencies between all system components. Thus, the manufacturing process is analysed in terms of its dynamics, and correlations between process parameters, process energy demand and final product properties are assessed. The resulting knowledge is important for the subsequent design of large-scale products and processes involved design, as well as for characterisation of the manufacturing process for life cycle inventory databases or life cycle costing calculations.

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Keywords: battery production; energy monitoring; energy intensity

1. Introduction

As energy costs are steadily increasing, and the awareness for the environmental impact of the manufacturing industry of high tech products is rising, knowledge about the dynamic energy performance of innovative processes becomes crucial. Data about the dynamic energy performance allows the total costs of ownership of production machinery and equipment to be estimated. It also helps in assessing the environmental impact of the manufactured product in its production phase [1]. Furthermore, only a parameter-dependent energy assessment of manufacturing processes can be used for valid scale-up scenarios and energetic improvements of the production equipment.

The production of automotive lithium-ion batteries (LIBs) is a highly innovative process technology in Germany and Europe, interconnecting the disciplines of electro-chemistry, and mechanical, electrical and process engineering. Due to the fact that the LIB production has its technological roots located in Asian countries (especially Korea and Japan, as they have a long history in developing and producing electrochemical energy storage devices), the technological background in Germany and Europe is rather young. Nevertheless, large scale battery cells with high quality and reliability in terms of functional safety are needed for the automotive industry to

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meet the demand for the upcoming electric vehicles (EV) and hybrid electric vehicles (HEV). Especially large scale battery cells have a very high energy capacity and therefore pose strict requirements in terms of product reliability and quality. This leads directly to the production processes of a battery cell and to the technical, energetic and environmental evaluation of the entire value chain. The objective is to gain transparency and knowledge about the process and the product's burden within the production phase of its life cycle.

In light of this situation, the availability of information regarding the production processes and their energy intensity is crucial, when carrying out an entire life cycle assessment. This contribution highlights one specific process step - the electrode-separator composite manufacturing, where the individual anode and cathode sheets are assembled into an electrode package. The electric insulating separator is continuously folded between the electrodes. This kind of production procedure is called z-folding and is established at the *Battery LabFactory Braunschweig*, an interdisciplinary research platform for production processes, diagnostics and modelling of LIBs.

This article investigates the entire process chain for LIB manufacturing and presents an in-depth analysis of the z-folding step. This is the last time that the electrodes and the separator are treated directly, e.g. by handling systems and vacuum grippers. The machine functionality is therefore of particular interest for this study. Here, a focus is put on the electric and pneumatic energy consumption of the machine in correlation with the individual production sub-steps. In addition, a relationship between the energy consumed during the process and the energy of the manufactured good is established in order to derive a performance index based on the process and the product. This key indicator is utilized to scale up the process from laboratory to large scale format batteries, which are relevant for EV and HEV batteries.

2. Functionality and Design of a Lithium-Ion Battery

A lithium-ion cell works according to the principle of intercalation batteries, where Li-ions are embedded in the lattice host structure of the electrodes. During the reaction, the solvated Li-ions move from the anode to the cathode, and vice versa, through a liquid electrolyte. The electron flux is provided by an external current circuit.

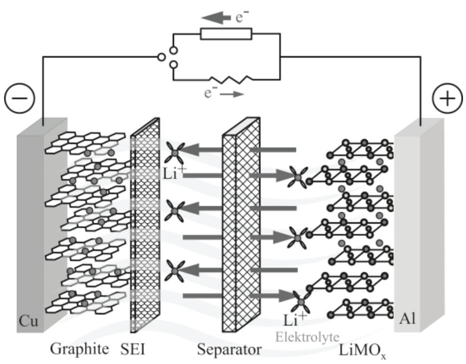

Figure 1: Working principle and set-up of a Lithium-Ion battery

A LIB is usually designed as a stack or a jelly roll made from continuous or discrete anode-, separator- and cathode-foils. The active material of an electrode is coated with other additives, e.g. carbon black and binder on a copper (anode) and aluminium (cathode) foil. The separator generally consists of a polyolefin-based nanoporous membrane, which electrically insulates the anode and cathode from one another but allows the ionic flux through its structure. Both, electrodes and separator, are wetted with electrolyte. Fig. 1 shows the working principle of a LIB and the labelled components.

The process chain for the manufacturing of large scale batteries, e.g. for automotive applications, is very complex and involves about 20 process steps, beginning with material preparation. The raw material (powder) is dry and wet mixed with a solvent before it is coated on the substrate material in a comma bar or slot die process. After the film is dried at 80-120°C, the electrodes are calendared. This is done to improve the mechanical contact of the coating on the substrate, the inter-particular adherence, and the volumetric energy density, and also to adjust the pore radii distribution. The following confectioning process via laser or blanking technology cuts the electrodes in sheets or to length according to the following packaging principle: stacking (sheets) or winding (coils). In this step, the electrode-separator-package is built in order to define the required capacity of the cell by the assembled layers or the amount of wounded material of the jelly roll. This electrode stack or jelly roll is packed into a pouch housing or a hard case can afterwards. The housing is finally vacuum sealed after the electrolyte has been filled in. Lastly, the closed cell is formed under a low C-rate to build up the solid electrolyte interphase (SEI). The SEI is a protective layer that is conductive for Li-ions and insulates against other electrolyte components. The shortened process chain described above is shown in Fig. 2

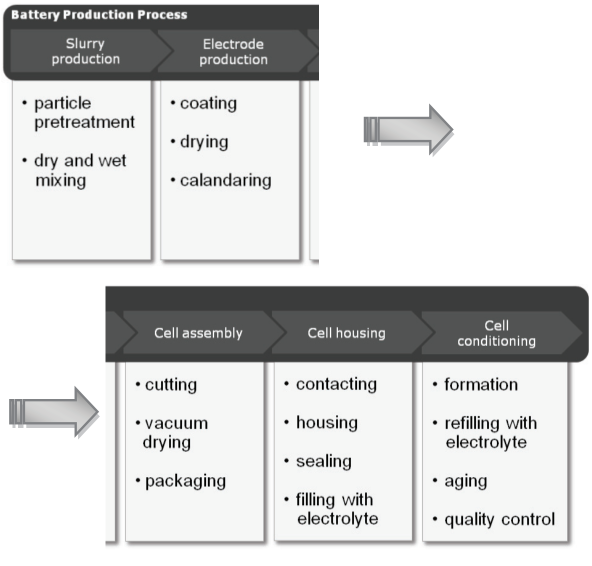

Figure 2: Battery Production Process Chain

The entire cell manufacturing process is conducted in a dry atmosphere because of the hygroscopic behaviour, especially of the anodes, and the high reactivity of the lithium-salt with water. Common dry rooms have a humidity of -45°C dew point.

The briefly presented value chain is established at the Battery LabFactory Braunschweig (BLB).

3. Electrode-Separator Composite Manufacturing

The objective of this contribution is to study the energy intensity of a representative step in cell manufacturing, where the electrode-separator package is produced. This process step is not the most energy intensive step but it is rather analysed due to the following aspects: First, it allows a good scalability and reference to the product (e.g. high energy and high-power cells for automotive applications). Second, the different sub-process steps can also be identified by the energy profile. Third, different energy types are utilized in the process.

The production processes for manufacturing the electrode-separator composite of a LIB are very different. Winding, stacking or folding technologies are commonly industrialized [2]. Generally, these production methods can be differentiated by the continuous and/or discrete material provision. This contribution focuses on the z-folding process that is established at the Battery LabFactory Braunschweig [3]. Here, the electrodes are supplied in discrete components, as laser cutted sheets, and the separator is fed from a coil. Fig. 3 shows the machine configuration with the essential mechanical modules.

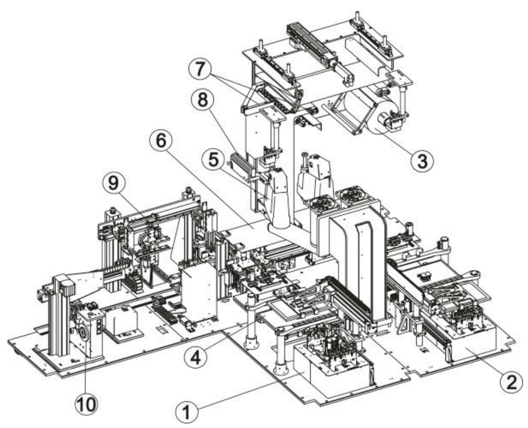

Figure 3: z-folding machine

The z-folding machine comprises an anode sheet ① and a cathode sheet ② supply magazine, from which the electrodes are separated and transported to a camera-based rear inspection unit via a handling unit ④. Thereafter, the electrodes are transferred to a 180°-rotatable, handling system, where the front side inspection and the position detection and -correction take place. If a damaged area of d ⩾ 1 mm is detected on the electrode, the defective electrode can be sorted out. Flawless electrodes are positioned on the stacking table ⑥ by a SCARA robot ⑤. Until this process step, the anode and cathode space are physically separated from each other in order to minimize potential particulate cross-contamination. Parallel to this, the electrodes are suction-cleaned from the front and the back. In addition, the process space is kept clean by a laminar flow box installed above the magazine area. The separator ③ is continuously supplied on the stacking table by a double dancer system ⑦. The separator tension is controlled by a servo and a pneumatic dancer. In order to control the mechanical tension on the sensible separator, a force sensor is used, which is integrated in the unwinding roll. Furthermore, a web-edge guide control ⑧ provides the accurate path of the separator. The stacking table alternates between the transfer points of the robots. The electrodes and the separator are both fixed by separate blank holders. In the back-end of the process, the manufactured n-layer package is wrapped with separator ⑨, fixed by a tape ⑩ and can be taken out by the operator.

This specific realization of the z-folding process is characterized by a flexible parameterization of the essential process, material and geometry parameters from a 70 mm x 50 mm, over a 150 mm x 110 mm to a 310 mm x 210 mm large format cells.

The BLB machinery provides an energy monitoring system for the real time assessment of the electric and pneumatic energy demand of each process step.

The following paragraph introduces the framework that helps to monitor the energy intensity of the entire value chain for the battery production. A system for deriving performance indicators to evaluate the state-based energy intensity of the production machine is also presented.

4. Dynamic Energy Performance Monitoring

4.1. General Machine and Process Data Monitoring Method

To evaluate the energetic performance of a process chain, a metering strategy has to be applied to ensure a cost-benefit compatible degree of energy transparency [4] [5]. The energetic impact is ranked according to the energy portfolio principle to evaluate the relevance of the specific entity within the regarded process chain [6].

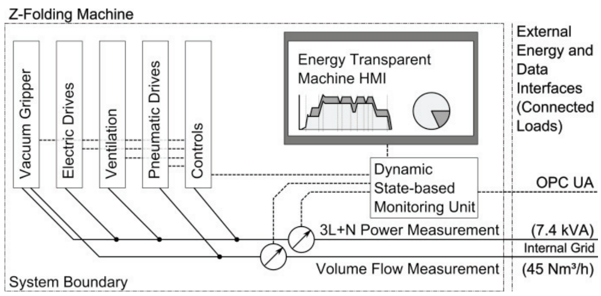

Figure 4: Simplified energy and information flow scheme of the dynamic performance monitoring

Along with the direct energy impact, the indirect energy impact, resulting from the peripheral entities that provide technical building services, must be considered. A methodology to allocate indirect energy demands has been adopted from [7]. The machine of interest is a handling and assembly type entity, which, with a connected electric power of 7.4 kVA and pneumatic power of 45 Nm^3/h (normal cubic meter per hour), lies in the top-medium range in comparison to the complete set of production entities of the BLB. The z-folding process demands an oil and water free ambient environment, which is provided by the central dry room conditioning system. As expected, this causes a high indirect power demand for operation on top of the direct demand. These issues provided a motive for deploying a physical metering point at the entity's main power inlets as depicted schematically in Fig. 4. The selected system has local monitoring capabilities as it incorporates an embedded control system (PLC). The monitoring unit is based on a Beckhoff CX50XX platform with analogue interfaces for electric power measurements for all three conducting phases, and with a true RMS calculation at a sampling rate of 64 kHz for voltage and current measurements. The cosine phi (phase shift indicator) is internally calculated from the true RMS values for each phase. The compressed air energy flow is captured by an air flow meter with a calibrated measured section based on the thermal mass flow principle. Thermal mass flow sensors can capture the normal cubic meter flow (1 m^3 at a pressure of 1.01325 bar, a humidity of 0% and a temperature of 273.15 K). The normal cubic meter allows the compressed air flow to be monitored independently of the pressure level at each component. Hence, the normal cubic meter can be multiplied directly with the internal energy intensity of the compressed air generation system in the BLB. The internal energy intensity is measured in kWh/Nm^3 and is specific to the energy conversion system. The electric energy equivalent depends on the average electrical power demand of each compressor system, each conditioning (e.g. air drying) system, the individual operating hours, and the total air supplied to the internal grid. This indicator cannot be derived from local measurement and monitoring systems, the value can only be roughly estimated based on the system pressure level, connected load, nominal output rate and age of the compressed air generators, and the adiabatic and isentropic compression of an ideal gas [8]. The internal electric energy equivalent allows the compressed air flow to be treated with the same dimension (kW) as the electrical power. Consequently, a direct comparison becomes possible with the monitoring system.

The PLC-based monitoring system allows to capture energy flows as stated above and machine states via digital inputs or via field bus on the same granularity in time as the energy data. In the case that no digital output for machine states is present, a simple logic is implemented that interprets the absolute and relative changes within the captured energy flow data stream. In the presented case, a threshold-logic was applied to differentiate between *online*, *ready for operation* and *operation* state. This *virtual metering point* for machine states is used to generate entity-specific energy statistics to be displayed pn the *Energy Transparent Machine HMI*.

For upper level communication with the supervisory control and data acquisition (SCADA) and enterprise resource planning (ERP) system, an *OPC UA* server is implemented on the PLC to provide the current energy statistics and the process variables in the automation network. Visualisation of the performance indicators is done directly at the human machine interface (HMI) of the monitoring unit. The PLC generates a graphical user interface, where the actual power curve with stacked energy types is visualised in a trend view over a selectable period of time. The current entity state along with energy statistics is provided within the reach of the working room of the assembly cell for direct interpretation by the process owner. The monitored data can be accessed from the external database to be blended with process parameters and product quality characteristics to gain suitable performance indicators and energy models. This information can be used for the energy assessment of the z-folding process.

4.2. Energy Intensity and Performance Indicators for Battery Manufacturing Processes

The metering point described above provides continuous process variables (electric active power in watt, pneumatic power in watt), state quantities (electric energy counter, pneumatic energy counter, entity state), and entity state dependent energy statistics. In the following, these process and state quantities serve as a basis for the formulation of suitable energy intensity and performance indicators. These indicators are to be entity and product specific, as such detailed process knowledge has not been published yet in the domain of automotive battery manufacturing.

From a production planning perspective, it is of high interest to derive and monitor state-dependent power demands for non-value adding states, which are only machine-specific, and value-adding states, which are multi-parameter dependent. The average load per non-value adding entity state

$$P_{NonValueAddingState} = \frac{E_{NonValueAdding}}{\Delta t_{EntityStateDurationTime}}, \quad (1)$$

is derived from the state energy counter divided by the duration time of the individual sate. The power demand for each non-productive state gives insight into the energy efficient design of machines and equipment. Low energy and hibernation mode that reduce the system capacities to a necessary minimum can be tested for innovative machines in the area of conflict, with quick ramp up to ready for operation and constant working conditions.

For value adding states, the performance indicators are more complex and should depend on the dominating product or process characteristics, e.g. the number of electrode pair layers or the cycle time (feed rate of the electrode and separator material). A linear dependency can be found for example in the performance indicator: value adding energy per product as a function of the number of electrode stacks.

$$E_{ValueAdding} = \int_{t_0}^{t_1} P_{OperationFreeRun}(t) + P_{Operation\,Processing}(t) \cdot k_{NumberStacks} dt \quad (2)$$

The process owner is generally interested in the correlation of the energy demand with or more process parameter changes.

Extending the perspective from technical and time interdependencies to quality interdependencies, an integrated assessment can be performed, as all dimensions can be directly evaluated in cost dimensions.

Especially, a battery cell as an electrochemical energy storage allows assessment of the energy intensity *E* of a special production process *i* with respect to the product and process energy content as

$$E_{rel,process\ i} = E_{process} / E_{product}\ , \quad (3)$$

where the energy of the process *i* is comprised by the pneumatic and electric consumption as

$$E_{process} = E_{pneu} + E_{elect}\ . \quad (2)$$

The energy of the product is influenced by the process and the product design. It can be calculated for a stacked battery cell as a function of the number of assembled layers *s* and the anode and cathode materials used, respectively their potential *U* according to the electrochemical series against Li/Li^+ as

$$E_{product} = (s-1) \cdot A \cdot C_{spec} \cdot ML \cdot U\ , \quad (3)$$

where *A* is the active area of one electrode sheet (cathode capacity is generally the limiting factor), *ML* is the mass loading, which is defined during the coating process and C_{spec} as the specific materials' capacity. A performance indicator is calculated based on these data that describes the energy demand of the production process in with respect to the "produced" capacity of a cell.

The energy demand (electric, pneumatic and cumulative) of the presented electrode-separator composite manufacturing step for a representative 30-layer cell is monitored over the process time as shown in Fig. 5.

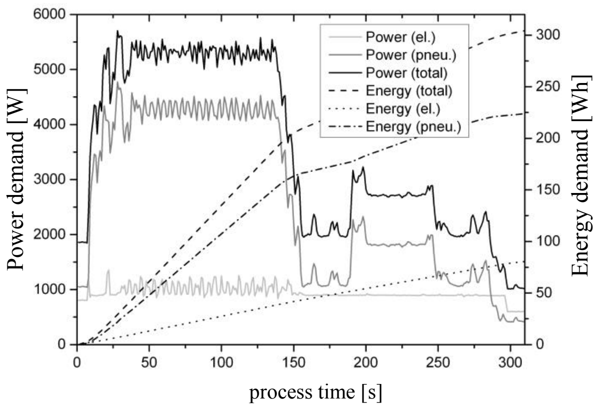

Figure 5: Power and energy demand curve of a representative z-folding process

The pneumatic energy demand of the process is about 2.6 times higher than the electric power consumption. The cumulative energy intensity is about 304 Wh. The produced NMC/graphite battery with 30 layers has a capacity of about 5.8 Ah, which yields to an energy content of 20.35 Wh. Utilizing the performance index E_i for this battery, the process energy needed is 15 times the energy content of the product.

In order to develop a general approach for assessing the energy intensity of the z-folding process, the energy profile shown in Fig. 2 is analysed regarding the sub-processes to assemble the electrode package. Five steps within the process can be defined as sub-processes (see Fig. 3). First, the electrodes are initially transferred to the inspection platform① by a pneumatic handling system. There, the front side of each electrode and the back side are optically inspected②. Afterwards a SCARA robot picks up the anode, another one the cathode in order to start the layer built-up process ③. If the electrode package is assembled with the desired number of layers *s*, it is wrapped with additional separator material in order to increase the package's stiffness ④. Finally, the package is transferred to the back-end of the process, where the electrode package is fixed by an adhesive tape ⑤.

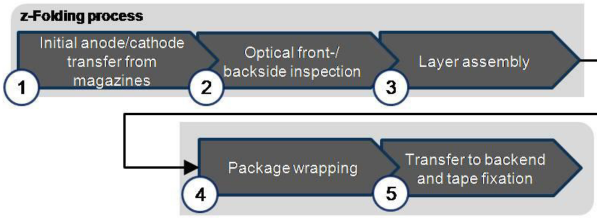

Figure 6: Sub-processes of the electrode-separator assembly via z-folding technique

This categorization of the production process is also represented in the energy consumption profile seen in Fig. 5. Tab. 1 shows the phases in correlation with the totally consumed energy within each sub-process. Furthermore, the scalability is distinguished in "constant" and "scalable" due to the sub-process characteristics.

Table 1: Energy consumption of each sub-process step and its ratio to the entire process energy consumption

Sub-process	E_{total}	Process ratio	Scalability
①	19,22 Wh	6,3 %	constant
②	22,61 Wh	7,4 %	constant
③	146,1 Wh	48,0 %	scalable (# layers)
④	46,97 Wh	15,4 %	constant
⑤	69,2 Wh	22,8 %	constant

The layer assembly is the essential value adding step. The transfer operations and the optical inspection of the front- and rear side are handling steps and quality assurance processes and thus not value adding. The wrapping and taping steps ensure a fixed electrode-package, but do not contribute to the battery capacity or its function. Thus, only one sub-process is scalable and all others are constant.

"Scalable" in this context means that, with a rising number of electrode layers in a battery, the energy demand of the process increases on the one hand, and the energy content of the product performance increases on the other hand. Because of this, a general energetic process characterization can be derived as a function of electrode layers, as all other sub-processes are (nearly) constant regarding the energy consumption. Therefore, the energy demand to feed and assemble one electrode is calculated and scaled up until 150 layers. This yields a capacity of about 40 Ah with a NMC/graphite material system and a HEV electrode design with a mass loading of about 5 mg/cm² and a specific capacity of 176 mAh/g.

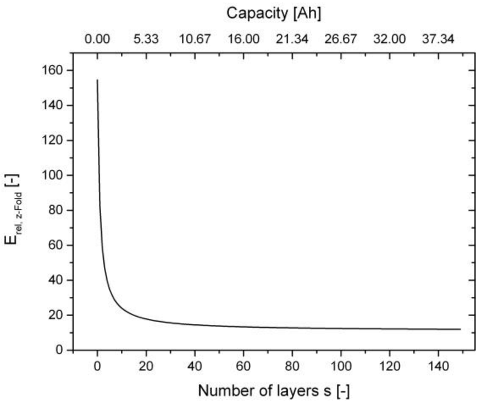

Figure 7: Relative energy consumption with respect to the number of layers within a battery cell

Based on this analysis, a reasonable level of product and process related energy consumption $E_{rel,\ z\text{-}Fold}$ can be reached by production cells for s>30. For packages with layers greater than this number the energy impact on the relative energy is negligible. As already stated, the example shown is based on an electrode design for HEVs. EVs or stationary batteries have generally thicker electrodes to enhance the storable energy. Contrarily, the power delivery is constrained due to the larger Li^+ diffusion ways through the thicker coatings. This instance has also consequences on the energy impact of the production process, as the capacity content of each layer is much higher.

5. Conclusion

The contribution has shown a first step towards an integrated approach to assess the energy intensity of a representative process for building the electrode-separator package (z-Folding) of a lithium-ion battery. Furthermore it demonstrates how this energy demand can be associated with the specific product (design). Furthermore, the z-folding process has been divided into sub-processes in order to identify the amount of energy for the essential value adding process sub-step. In this context, it is shown that only the layer assembly is scalable and that all other sub-process steps are constant. As the relative product and process energy content indicator $E_{rel,process,i,}$ is scalable to the number of electrode layers, the relationship to the this is shown with respect to a specified electrode design.

Future research activities will focus on a fully integrated material and energy model of the battery production process chain as provided by the BLB. Additionally, further research will also address the coupling between influencing factors on the product in the production processes, taking into account the energy consumption to manufacture a cell in an alternative processes.

Acknowledgements

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