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Model-based energy analysis of a dry room HVAC system in battery cell production

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Abstract

The operation of drying rooms is an essential part of battery cell production, in order to provide a save and well conditioned environment during the cell assembly. A specially dimensioned Heating, Ventilation and Air Conditioning (HVAC) system is required to operate a dry room, which depends on a large number of parameters and accounts for a substantial part of the total energy demand in battery cell production. Therefore, a dry room significantly contributes to the energy embodied in battery cells and affects their cost and environmental footprint. In this context, model-based, quantitative analysis are of interest in order to dynamically evaluate the effects of changed of ambient conditions at different locations. In this paper, we investigate the operation of an existing drying room through a case study at the Battery LabFactory Braunschweig with a physical simulation model. We validate the model against recorded measurement data in high temporal resolution. The model is able to represent the measured data of the total energy demand over one month at an hourly time step with only 3.27 % deviation. Using the validated simulation model of the HVAC system, we examine the operation of the system at different locations regarding their economic and ecological footprint. To achieve this, we virtually relocate the system to five different locations around the world and operate it over a typical year at each location. We carry out an economic and environmental assessment for each site under consideration and for each location we report relevant KPIs that are independent from production throughput and potentially transferable to other use cases. Such investigations allow interesting findings to be derived for practical applications in brown-field applications, but also for the planning of new systems at different locations.

Keywords:
economic and ecological evaluation of dry rooms for battery cell production; dynamic, physical modelling of HVAC system;; environmental impact evaluation of dry rooms

1. Introduction

Electric vehicles (EV) allow to decouple individual mobility from greenhouse gas emissions (GHG) during the use phase, if renewable energy is used for electricity generation [1]. Energy storage systems are a key element of EVs. This is one of the reasons why there is an increasing demand for lithium-ion batteries (LIB) [2] and therefore also an increased production demand of LIBs. Dry room technologies are required for LIB production and due to the increased demand, numerous suppliers offer these types of technologies [3, 4]. As dry rooms are energy intensive, questions about their exact energy demand and their environmental impact (in form of GHG) arise. It is important to examine the influencing factors on the energy demand and the environmental impact, which in turn can benefit the planning and operation phase of dry rooms.

The LIB production consists of three main manufacturing processes: electrode manufacturing, cell assembly and cell finishing [5]. The cell assembly is a process that is very sensitive to humidity in the air due to the reactivity of lithium with water [4, 5, 6] and consequently requires constantly high rates of conditioned, dry air. Variations in the room moisture content can potentially affect the capacity and/or the lifetime of the produced cells [5, 7]. The moisture concentration in the room is influenced by three main influencing factors, namely the out-

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side air conditions, the Heating, Ventilation and Air Conditioning (HVAC) setting parameters and the internal loads from personnel and processes. As the operation of the dry room related HVAC system is production throughput-independent, the energy intensity of the cell assembly depends mainly on the production throughput [1]. Currently only theoretical studies of dry rooms exist ([4, 8]), employing static modelling approaches, that are not suitable to capture the dynamics of real application cases. In this paper, we focus on the development and validation of a dynamic, physical model of an existing dry room for LIB production, that enables the study of the influences of external conditions (such as temperature and humidity) on the energy demand and derive production throughput-independent Key Performance Indicators (KPIs), that are potentially transferable to other applications.

For this purpose we conduct a case study on the Battery LabFactory Braunschweig (BLB), where research is done on the production of battery cells on a laboratory to pilot plant scale. In the BLB the semi-automated cell assembly takes place in a 169 m^2 drying room, which is supplied by a specially designated HVAC system, that requires significant amounts of energy to operate and that has an extensive data acquisition system. To demonstrate the influence of the outside air conditions, we virtually relocate the LIB production to five different locations around the world and operate it over a typical year. Finally we assess the results from an economic and environmental point of view and derive relevant KPIs that are independent from production throughput and can be potentially transferred to similar applications, not only restricted to the battery cell production. This is a unique aspect and contributes towards a more energy transparent assessment of battery cell production. Using the proposed KPIs, practitioners can now easily assess and compare the energetic performance of dry rooms for battery cell production.

2. State of research in battery cell factories

Yuan et al. [9] reports the results of an energy analysis of lithium-ion batteries for electric vehicles with data collected and modelled from real industrial processes. They find that most of primary energy ($58.7GJ$ or 66 % of overall energy) is required for battery cell manufacturing and that for the manufacturing 43 % of the energy is used for dry room conditioning. The authors report a specific energy use per pack of $21.78kWh/kg$ for the dry room unit. Thomitzek et al. [10] performs a hierarchical multi-paradigm simulation to further assess the energy intensity of the involved process steps in battery cell manufacturing. The authors find, that the technical building services, including the dry room, contributes to 60 % of the total energy demand of $24.8kWh/cell$. Philippot et al. [11] studies the influence of the location and commodity prices on the greenhouse gas emissions and costs. With a life cycle assessment they find that the electricity mix is a key parameter for the environmental impact of the battery manufacturing. However, through an improved energy efficiency and a high energy density the global warming potential per pack during manufacturing can be decreased from more than $150kgCO_2eq/kWh$ to $39.5kgCO_2eq/kWh$. Davidsson Kurland [12] analyses the energy use of the GWh-scale lithium-ion battery production, estimated for two large-scale factories based on publicly available data. The author reports that these facilities use around 50 - 65 kWh (180-230 MJ) of electricity per kWh of battery capacity (not including mining, processing and other steps of the supply chain).

Despite the energetic relevance of the operation of a dry room in battery production, relatively few studies are available that deal in detail with the operation of the associated technical building services, in particular the HVAC system. In [4] a dry room in battery manufacturing is investigated, however, the used process model is based on a static calculation and only a virtual dry room model is used. In addition the costs per pack are examined, nevertheless the total costs are difficult to determine and are based on a complex cost model according to Peters and Timmerhaus [13], which complicates the transferability of the results.

In the current state of research respectively the sources cited, the dependence on external conditions (such as temperature and air humidity) is not sufficiently addressed. To the best knowledge of the authors, only theoretical studies of dry rooms exist employing static modelling approaches ([4, 8]), which are not suitable to capture the dynamics of the real system. Therefore, real world investigations that report transferable, production throughput-independent KPIs for evaluation are interesting for the current state of research.

3. Approach for the model-based energy analysis of industrial dry rooms

The applied model-based energy analysis follows five phases depicted in Figure 1.

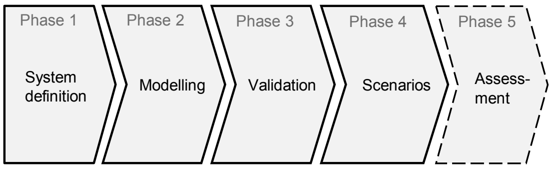

Fig. 1: General procedure applied for the model-based energy analysis

In phase 1, the system definition, we analyze relevant energy and material flows and set the system boundary. Supplying the drying room with conditioned air requires a complex HVAC system, which is dependent on a large number of parameters and influencing variables. The system consists of several components, that require different energy types. The main components of the system are fans, a drying unit, heat exchangers and the drying room itself, whereas the heart of the system is the drying unit. The drying unit dehumidifies the mixed air and divides it into process air and a purge air stream. The purge air stream is heated and recovered in the regeneration air system and finally released into the environment through exhaust air. The purge air flow is, in addition to the volume flow and the set dew point temperature, an important HVAC system setting parameter. A higher purge air flow also increases the energy demand of the overall system, however, the purge rate should also not be too low to avoid the concentration of emissions in the room [4].

In phase 2, the system shown in Figure 2 is modelled in detail as a physical system model. All relevant influencing factors are taken into account and each depicted system component is modelled as a physical submodel. The object-oriented modelling language Modelica is used for modelling the HVAC system. Modelica enables the equation-based modelling and solution of complex, physical systems.

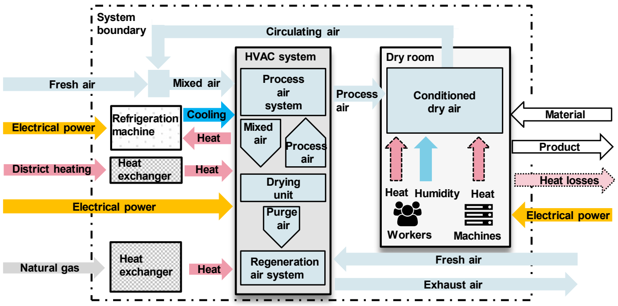

Fig. 2: Phase 1 - Energy and material flows of the HVAC system of a dry room

In phase 3, the overall physical model can then be validated on the basis of extensive existing measurement data. One challenge in validating the model is to set the correct system parameters so that the model can represent the system behaviour as accurately as possible. Further details regarding the modelling and validation can be found in Section 4.3.

In phase 4 we calculate different scenarios for the validated system model, by virtually relocating it to four different locations in different countries. With the results we intend to evaluate the energy requirements and environmental impact at different locations and thereby want to contribute to the determination of suitable locations for battery cell production.

Finally in phase 5, we evaluate and discuss the results of these scenarios at different locations from an economical and ecological point of view. The detailed discussion of phases 4 and 5 can be found in Section 4.4.

4. Case Study at the Battery LabFactory Braunschweig (BLB)

The case study performed at the BLB, a battery research facility of the Technische Universität Braunschweig with a strong focus on production processes of battery cells and future energy storage. The BLB contains an industry scale pilot line, from material development to electrode and cell manufacturing as well as recycling, for LIB cells of different pouch cell formats. The LIB cell assembly and cell cutting takes place in a conditioned, dry environment, which is realized by using specially designed drying rooms. The large dry room, which is the focus of this study, is constructed as a so-called room-in-room concept and can be seen schematically in Figure 3 and has a surface area of 169 m^2 and a volume of 507 m^3.

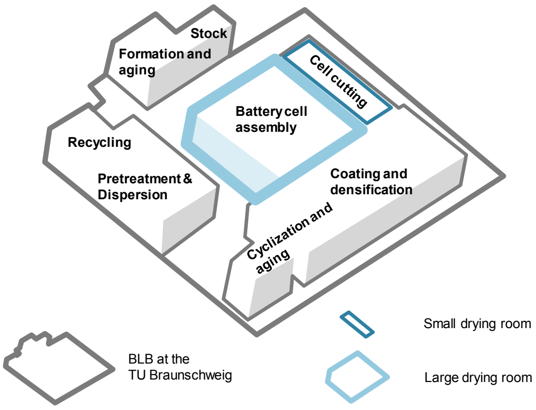

Fig. 3: Schematic drawing of the Battery LabFactory at TU Braunschweig

Two identical in construction, but differently dimensioned HVAC systems are built on a pedestal above the large and small drying rooms. The larger dimensioned HVAC systems supplies the large drying room with conditioned air and the smaller HVAC system supplies the small drying room and the coating and densification process machine with conditioned air. Since the smaller HVAC system is approx. 30 % below the dimensions of the large system and there is a mixed use of the conditioned air (with the room and machines), only the larger HVAC system is considered in this study. The contribution of both HVAC systems to the final energy share is almost 80 % of the total final energy of the BLB. The detailed technical data and further explanations of the HVAC system of the large dry room are listed in Section 4.2.

4.1. Data acquisition at the BLB

The BLB has an extensive data acquisition system that laid foundation for the acquired data of this case study [14]. Machine data, sensors (also for ambient conditions) and programmable logic controllers (PLCs) are connected in a network. Sensors and ambient conditions are read out by a master PLC using either analogue and digital signals or Modbus protocols. Machine data, provided by other automation components rather than PLCs, and the PLC data, including master PLC, is acquired via either S7-protocols (Siemens proprietary protocol of Siemens S7 PLCs) or OPC UA (**o**pen **p**latform **c**ommunication **u**nified **a**utomation) using the JavaScript runtime node.js. Data used for the physical model of the dry room, was acquired directly from the PLC of the HVAC system by using node.js. All the data of over 90 data points, including the dry room data, is directly stored in high temporal resolution into a **s**tructured **q**uery **l**anguage (SQL) database.

4.2. HVAC system of the BLB

The operation of a drying room at the BLB poses high demands on the HVAC system. On weekdays from Monday at

00:00 to Friday at 24:00 relative humidity conditions of 0.1 % are achieved at a room temperature of about 18 °C, which corresponds to a dew point temperature of -60 °C. At the weekend, relative humidity is about 0.5 % and at 18 °C room temperature, which corresponds to a dew point temperature of -45 °C. The HVAC system consists of several components, including two pre-coolers (54.8 kW & 43.8 kW), the process fan (15 kW, 11.000 m^3/h), a reheater (33.2 kW), a regeneration heater (125 kW) with a 15 kW heat recovery and the heart of the system, the sorption wheel, that is responsible for dehumidifying the large process air flow and has a water dehumidification rate of 25.8 kg/h. Within the sorption wheel, the supply air flow is divided into process air (9850 m^3/h) and a purge air stream (1150 m^3/h). During the dehumidification process, the purge air is heated up to 95 °C in the sorption wheel and then fed to the regeneration air. The regeneration air stream is heated to temperatures between 60 °C and 135 °C before entering the sorption wheel [15].

4.3. Modeling and validation of the BLB HVAC system

An overview of the whole model developed in Modelica in the simulation environment Dymola is depicted in Figure 4.

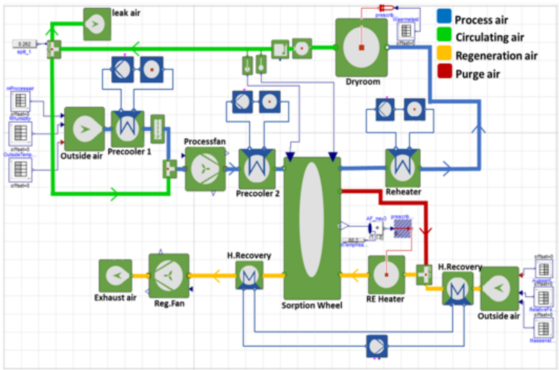

Fig. 4: Overview of the developed HVAC model of the BLB

Some of the numerous system setting parameters are not available from the documentation or cannot be determined without extensive experiments (such as heat transfert coefficients or control setting parameters). Therefore, they must be fitted to measurement data. The assumption in this context is that if the model can reproduce the measurement data with sufficient accuracy, it will reflect the actual system. To fit these parameters to measured data the Python tool ModestPy, a Modelica compatible open source tool for parameter estimation, is used [16]. With the suitable system setting parameters found using ModestPy, the overall model of the HVAC system of the BLB can be validated. In Table 1 it is demonstrated how well the model represents the energy requirements of each component compared to measured data. The deviation of the total simulated versus the measured energy consumption is statically only about 3.27% and dynamically of 14.12 % measured with the normalized root-mean-square deviation (NRMSD) over a whole month at an hourly time step.

Table 1: Comparison of overall simulated and measured energy requirements over one month per component of the HVAC system

Energy in kWh	Simulated	Measured	Δ(%)	NRMSD (%)
Process fan	5692	5702	0.18	0.9
Regeneration fan	1807	1777	1.67	5.5
Regeneration Heater	24437	25880	5.74	14.72
Pre-cooler	17769	17787	0.10	3.9
Supply air heater	8871	9351	5.27	18.74
Total	58576	60497	3.27	14.12

4.4. Economic and environmental assessment at different locations over a typical year

By virtually relocating the system from its initial location to four different locations around the world, we want to investigate the influence of completely different environmental conditions on the energy requirements and environmental impact of the current system located in Braunschweig. In this assessment we consider the following locations:

- **Braunschweig (BS)**, Germany: initial location. Average Temperatur $\overline{T}$: 9.73 °C, Average relative Humidity $\overline{\varphi}$: 76.43 %, Average dew point Temperature $\overline{T_{dp}}$: 5.46 °C
- **Jaipur (JP)**, India. $\overline{T}$: 26.32 °C, $\overline{\varphi}$: 51.08 %, $\overline{T_{dp}}$: 13.49 °C
- **Oslo (OS)**, Norway. $\overline{T}$: 8.76 °C, $\overline{\varphi}$: 80.07 %, $\overline{T_{dp}}$: 5.41 °C
- **Seoul (SE)**, South Korea. $\overline{T}$: 13.12 °C, $\overline{\varphi}$: 57.69 %, $\overline{T_{dp}}$: 4.45 °C
- **Beijing (BJ)**, China. $\overline{T}$: 13.19 °C, $\overline{\varphi}$: 51.55 %, $\overline{T_{dp}}$: 1.99 °C

To assess these different locations, local wheater data, CO_2 emission factors and energy prices are taken into account. As local wheater data we use typical weather data obtained from [17] in hourly resolution. The authors of [17] generate the local typical meterological year (TMY) data on the basis of hourly weather data from the US NOAA's Integrated Surface Database over a period from 2004-2018 using the methodologies explained in ISO 15927-4:2005 [18]. These TMY data represent typical rather than extreme conditions and are therefore representative data for the energetic assessment of an HVAC system at different locations. The CO_2 emission factors were estimated following the methodology described in [19] and energy costs are listed in Table 2 and the respective sources are mentioned there. The variations are then performed starting from the validated model of the BLB in Braunschweig presented in section 4.3. Here and also for all other variants, the whole-year TMY data with an hourly time step is used for the locations, in order to be able to correctly account for the influence of the typical seasonality in the environmental data and to increase the accuracy of the results generated by the virtual relocation. Therefore, 8760 samples of data are considered for each location to calculate the energetic demands in Table 2. The occupation of the room with persons and machines from the observation period of one month is assumed here as a constantly repeating profile over the whole year and is left the same in all variants, so that the difference is only the changed environmental conditions. Based on the changed energy requirements of the variants, the environmental impact is calculated in tCO_2-eq and the operating costs of the whole system are also calculated. The complete results of this analysis are represented in Table 2.

Table 2: Environmental and economic impact assessment over whole year using the validated HVAC model at different locations. CO_2 emission factors for the different locations and energy forms from [19]. Electricity prices from [20], natural gas prices from [21] and district heating prices from [22]. For district heating in case of the locations JP, BJ and SE the all countries average from [22] was taken, due to lack of reliable information.

	BS	JP	OS	SE	BJ
Electricity (kgCO_2-eq/kWh)	0.63	1.23	0.02	0.65	1.04
Natural gas (kgCO_2-eq/m^3)	0.48	0.28	0.14	0.28	0.28
District heat (kgCO_2-eq/MJ)	0.07	0.12	0.07	0.12	0.12
Electricity (€/kWh)	0.20	0.10	0.07	0.09	0.08
Natural gas (10^{-3}€/kWh)	23	29	23	30	24
District heat (10^{-3}€/MJ)	21	18	20	18	18
Electricity demand (MWh)	557	788	526	624	557
Natural gas demand ($10^3 m^3$)	63.7	57.0	64.0	62.4	63.7
District heat demand (MWh)	162	127	160	174	163
Environmental impact (tCO_2-eq)	422	1040	60	498	667
Total energy costs (k€)	137	102	62	84	69

BS=Braunschweig; JP=Jaipur; Oslo=OS; Seoul=SE; Beijing=BJ

Based on Table 2 it is possible to visualize the results and further assess the economic and environmental impact of operating the dry room and its HVAC system at the different locations. Figure 5 shows the economic and environmental assessment over a whole typical year. The results show very clearly that operating the plant in Oslo is the most suitable solution from both an economic and environmental point of view. From an environmental point of view, the current location in Braunschweig is in second place. From a cost point of view, however, it is far behind and by far the most expensive. Economically, the other sites in Seoul, Beijing and Jaipur are comparable, but from an environmental point of view, the operation of the plant at these sites is increasingly unfavorable.

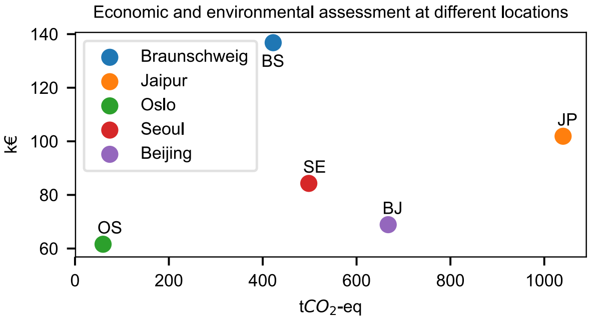

Fig. 5: Visual representation of the economic and environmental assessment at different locations around the world over a whole typical year

Based on the results from Table 2 and the surface area of the considered dry room, which is 169 m^2, further interesting results can be derived, which are potentially transferable to other sites. Figure 6 shows the emissions and the average energy consumption in respect to area and operating hours (in reference to an operating time of 8760 h). The calculation of these KPIs is interesting because they are potentially transferable to other locations and room sizes. Furthermore they are mostly independent of the production throughput and in addition by using them it is relatively easy to determine the amount of energy consumed and emissions generated per cell for the specific use case. In Figure 6 it is again confirmed, that Oslo is by far the most suitable location for battery production from an energetic and environmental point of view. Braunschweig is in the second place and the remaining sites are ranked in the same order as in Figure 5 (from an environmental point of view).

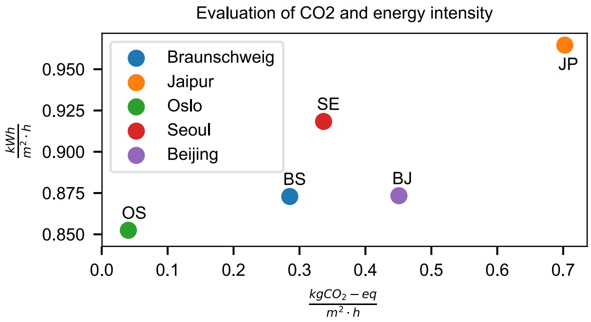

Fig. 6: Evaluation of energy and CO_2-eq intensities relative to the surface area and operation time

As already mentioned, Figure 6 can now be used to determine the amount of energy and emissions produced by the processes. The production steps that take place in the dry room are separation, packaging, contacting, final drying, housing, electrolyte filling & closing and tempering [23]. For each production step it can now be determined how long it takes and how much space it takes up in the dry room. In this manner, the amount of energy used per cell can be calculated for the entire process chain. In this case study, all processes together require an area multiplied by time of 9.44 $m^2 \cdot h$, which corresponds to a value of 8.24 kWh/cell for Braunschweig. With respect to the manufactured cell, having a capacity of 33.3 Wh and a weight of 0.2736 kg [23], this represents a value of 30.14 kWh/kg of final energy used. This is in good agreement with literature values from an industrial application case [9].

5. Conclusion and outlook

We developed and validated a physical model of an existing dry room located at the Battery LabFactory in Braunschweig and investigate the performance of the system from economic and environmental point of view at five different locations (Braunschweig, Jaipur, Oslo, Seoul, Beijing) for a typical year at an hourly time step. From an economic and environmental point of view Oslo is the most suitable location for operating a dry room for battery cell assembly due to its affordable green electricity mix. From an environmental point of view, the location Braunschweig is in second place. However, it is less suitable from an economic point of view because of the relatively high energy prices. The locations Seoul, Beijing and Jaipur are increasingly unsuitable from an environmental point of view, but from an economic point of view they are within a similar range. Additionally, in this paper we report relevant KPIs regarding the energy and environmental intensity, that are independent from production throughput. These KPIs are useful to assess the energy and environmental intensity of the battery production in dry rooms and can be evaluated at different locations. The established KPIs are potentially transferable to other applications, because the KPIs are independent of the room size and the processing time and thus of the specific production process (cf. Section 4.4).

In future work, the model will be used to investigate further locations, thus creating additional KPIs for a wide range of locations. Furthermore, the physical model can also be used to investigate different plant and room sizes (scale-up) and examine the development of the KPIs in these cases. In addition different control strategies and operating modes can be tested with the validated model that can be applied in reality, in order to enable a more energy efficient operation of the existing systems. In this context, the work presented in this paper sets important steps towards model-based planning but also model-based control of dry rooms, which in turn can benefit future work in the context of LIB production and EVs.

6. Acknowledgements

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