Proceedings of the 2018 Winter Simulation Conference
M. Rabe, A.A. Juan, N. Mustafee, A. Skoogh, S. Jain, and B. Johansson, eds.

APPLICATIONS FOR MODELS OF RENEWABLE ENERGY SOURCES AND ENERGY STORAGES IN MATERIAL FLOW SIMULATION

Johannes Stoldt
Bastian Prell
Andreas Schlegel

Department Resource Efficient Factory
Fraunhofer Institute for Machine Tools and
Forming Technology IWU
Reichenhainer Strasse 88
Chemnitz, 09126, GERMANY

Matthias Putz

Scientific Field Machine Tools, Production
Systems and Machining
Fraunhofer Institute for Machine Tools and
Forming Technology IWU
Reichenhainer Strasse 88
Chemnitz, 09126, GERMANY

ABSTRACT

The increasing reliance on volatile renewable energy sources in the European Union raises questions regarding the future mechanisms of the energy markets. Energy-intensive production industries are particularly expected to take a more active role by shaping their energy demand according to the availability of wind and sun. Hence, they will need to align their production processes with external energy market signals. This paper presents an application example for a Siemens Plant Simulation extension that makes holistic material flow and energy flow studies of factories possible. The so-called eniBRIC class library provides functionalities for investigating the flow of energy between infrastructure and production equipment. Since its latest update, it can also be used to model renewable energy sources as well as energy storages. A case study of the E³-Research Factory showcases the features of eniBRIC and provides an outlook on future research in the field of energy-flexible production.

1 INTRODUCTION

Between 2005 and 2015, the share of renewable energy sources (RES) on the net electricity generation in the European Union (EU) grew from 13.3 % to 25.3 % (eurostat 2017). While hydropower has the largest share (11.9 %) among all renewable sources in 2015, wind and solar generation account for 9.7 % and 3.5 %, respectively (eurostat 2017). These shares vary between the member states, but also indicate a significant and growing volatility (i.e., dependence on day-to-day weather) in electricity generation. Focusing on wind and solar energy (like in Germany) will lead to increasingly long periods of time of negative energy prices (Klobasa et al. 2016). Coping with such effects on the supply side only (e.g., by operating idle power stations) is increasingly costly. Demand side management (e.g., through load shedding) may improve this situation. Thus, the industrial sector, which accounts for 36 % of Europe's electricity demand (eurostat 2016), will need to take a major role in stabilizing the electricity grids.

This paper reports on an extension for Siemens Plant Simulation called "eniBRIC" that allows for the simultaneous investigation of material and energy flows. It is intended as a tool to simulate, study, and validate novel approaches to production organization but also to technical equipment control, which aims to align a factory's energy demand with local as well as external supply profiles under simultaneous consideration of logistic key figures. eniBRIC's latest update adds functionalities to model and simulate volatile RES as well as energy storages, which are required in such studies. Section 2 summarizes the state of the art on energy-flexible manufacturing and modeling of the aforementioned elements. Thereafter, the latest eniBRIC class library version and its application in a simulation of the E³-Research Factory are presented. Section 5 gives an outlook on future research planned with the developed models.

978-1-5386-6572-5/18/$31.00 ©2018 IEEE

2 STATE OF THE ART

The requirements for the recent developments in eniBRIC but also ideas that went into the implementation were drawn from previous publications in this field of research. The following sections briefly discuss the state of the art with a special focus on energy-flexible manufacturing as well as modeling approaches for renewable energy sources and energy storages, respectively.

2.1 Research on Energy-flexible Manufacturing

As the share of volatile renewable energy sources increased over the years, the focus of many research groups was extended or shifted from energy-efficient manufacturing towards energy-flexible manufacturing. Research in this field aims to find solutions for aligning a factory's energy demand with a company-internal decentral supply, an external supply (with volatile pricing), or a combination of both.

The dissertation by Graßl (2015) is one of the earliest works in this field and investigated the assessment of energy flexibility in production systems. Therein, seven flexibility measures are defined: shifting the start time of a process, shifting shift times, halting a process, changing the job-machine-assignment, changing the order of jobs, changing process parameters, and changing break times. Additionally, Lielbl et al. (2015) introduce the measure "storing energy" and Roesch et al. (2017) suggest "switching the source of energy". All these measures require a certain span of time before they can be activated for a characteristic duration and vary in the extent of their influence on the flow of production (Roesch et al. 2017). Simulation provides means to quantify their effectiveness in aligning a factory's energy demand with a volatile energy supply. Furthermore, it allows for investigating the consequences that specific measures have on logistic target figures.

On the supply side, previous research investigated questions concerning the control of decentral energy sources (e.g., Ghadimi et al. 2015) or energy storage sizing and operation strategies (e.g., Lehmann et al. 2016). Other works focused on the demand side, considering the machine operation level (e.g., Popp et al. 2017), the production control level (e.g., Schultz et al. 2017), as well as the production planning level (e.g., Keller et al. 2016). Beier (2017), in particular, developed a methodology for the use of simulation for investigating opportunities for energy flexibility measures of various kind using simulation. Chu et al. (2016), on the other hand, devised a production planning framework that applies simulation-based optimization for maximizing the use of self-produced renewable energy to save costs.

The aforementioned works underline the importance of research on energy-flexible manufacturing. Most of these make use of simulation at least to some extent. Yet, most of these approaches either simplify or neglect the modeling of energy supplying or transforming production infrastructure, or are only available for a specific tool. Siemens Plant Simulation is a well-established tool for material flow simulation in various industries. However, to the best of the authors' knowledge, there are no extensions for Siemens Plant Simulation that allow for modeling energy storages as well as volatile renewable energy sources. Motivated by this apparent lack, the extension of the eniBRIC class library was initiated.

2.2 Modeling Volatile Renewable Energy Sources (VRES)

Hydropower has the largest share of all RES in the EU's energy mix (see Section 1) and it can be predicted quite well. However, the availability of hydropower is closely related to a country's geography. Hence, wind and solar power are a lot more important in some countries (e. g., Germany). Unlike hydropower, these RES have a volatile output that depends on the weather. Even though forecasting and prediction of future energy generation from such sources is advancing, a quick response to balance energy supply to demand will always be necessary, as forecasts usually include a margin of error (Grimm 2007).

The challenge for VRES lies in modeling this characteristic fluctuating behavior. According to Beier (2017), two basic classes of modeling approaches can be distinguished. Time series are constituting one of them (e.g., Haessig et al. 2013 or Zheng et al. 2018). Other approaches calculate the output by dependencies between meteorological or other input data and the expected energy output (e.g., Ramos et al. 2012 or Shi et al. 2012). A more in-depth review on these is found in Allegrini et al. (2015).

Stoldt et al. (2015) propose an approach for the abstract modeling of energy consumers and suppliers derived from an extensive literature study. The basic component model makes use of operating states that determine the intensity of inbound or outbound energy flows of conventional suppliers and consumers. VRES, as discussed above, are modeled with a combination of time series and an analytic function for calculating the actual supply capacity (output). Additionally, an input-dependent energy source is described to determine the supply capacity from the current input using a function, similar to the VRES but without a predetermined time series.

2.3 Modeling Energy Storages

While models of VRES depend on difficult-to-accurately-obtain weather data, energy storages can be modeled a lot more precisely. According to the extensive review of Beier (2017), five fundamental storage technologies are particularly important for the integration of decentral VRES (Table 1).

Table 1: Overview of storage technologies for the integration of decentral VRES (based on Beier 2017).

Technology	General principle	Current application for VRES integration
Electrochemical storage (battery)	Chemical reactions to store and release energy	Short-term demand/supply machining (minutes to hours) and for ancillary services
Thermal energy storage	Temperature or latent (phase changing) heat storage	Direct heating/cooling (solar energy) or from electricity if economic (e.g., fuel switching)
Flywheels	Rotating mass energy storage	(Very) short-term demand/supply matching, special applications
Supercapacitors	Electric field energy storage	Very short-term storage and smoothing of, e.g., power output and frequency control
Superconducting magnetic energy storage	Electromagnetic field energy storage	Frequency regulation, power quality applications (e.g., uninterrupted supply)

Other more long-term energy storages are also being used on the grid level (see Huggins 2010). Yet, these are not within the scope of this paper as they are typically of no interest to production companies. Considering the technologies in Table 1, those with a very short-term focus will need to be modeled very precisely. This is usually done using analytic functions that describe the physical principles of the storage along with equipment-specific parameters obtained from experiments (e.g., Papic 2006; or Sebastián and Peña Alzola 2012). Models for mid- to long-term storage applications often do not require such level of detail (see Beier 2017; Grimm 2007; and Lehmann et al. 2016). They typically describe a storage's behavior using characteristics like: maximum charging and discharging rate, storage capacity, upper and lower boundaries for allowed charge levels, degradation coefficients for power and capacity (per charge cycle or over time), self-discharge factor, and efficiency for charging and discharging. These are also used in the storage model proposed by Stoldt et al. (2015). While such functional modeling approaches partly disregard the actual physics, they suffice for economic analysis as well as for testing operation strategies.

3 MODELING ENERGY FLOWS IN PLANT SIMULATION WITH ENIBRIC

When the class library eniBRIC was initially developed for Siemens Plant Simulation, this software had no out-of-the-box functionality to support the simulation of energy flows. More recent versions support the simulation of a single energy carrier, but eniBRIC still holds more functionality (e.g., to model multiple energy carriers simultaneously). Following Section 2.1, however, no solution existed that supported modeling and simulating VRES as well as energy storages. The following section provides a brief introduction to eniBRIC based on Stoldt et al. (2016b). Afterwards, its extension to close the aforementioned gap is summarized based on Stoldt et al. (2017).

3.1 eniBRIC

The original implementation of eniBRIC in Siemens Plant Simulation (a multi-purpose material flow simulation software) relies on the component model for conventional suppliers and consumers (Figure 1a). Put simply, elements modeled as such can operate in a finite number of operating states that are associated with certain, averaged inbound and outbound energy as well as material flow intensities. Thus, an element's current operating state determines which energy carriers or process media are flowing in or out of the element at which intensity. In Siemens Plant Simulation, operating states are used to track time statistics of system elements (e.g., machines) and to control their ability to process objects (e.g., parts).

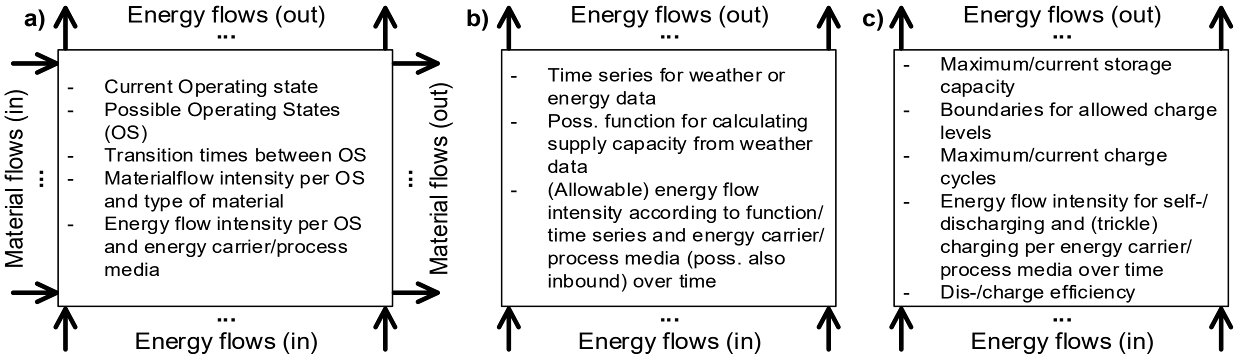

Figure 1: Component models for energy flow elements for: a) conv. suppliers/consumers; b) VRES; c) energy storages (simplified from Stoldt et al. 2015).

This intentional overlap meant that the horizontally depicted material flow can be modeled using standard classes and an extension was only necessary for the vertically depicted energy flows. In contrast to the standard software, the number of operating states as well as the number of energy carriers or process media that can be modeled concurrently were designed to be chosen freely. Hence, eniBRIC's core module was conceived as a self-contained class that provides all necessary functions to model energy flows and could be used to extend a standard material flow element class or to work by itself (e.g., as a conventional energy source). Additionally, a configuration as well as a data collection and evaluation module were developed. These provide parameters to the individual instances of eniBRIC's core module and collect data on their consumption during simulation runtime, respectively.

To allow for the greatest possible flexibility when using eniBRIC, its core module's internal logic is limited to switching between operating states (minding possible transition times) and tracking and validating the supply and consumption of energy. Changes of the current operating state are expected to be announced to individual instances in a model through three specific interfaces:

- Material in/out: called by the material flow element to trigger changes between idle and working operating states and vice versa according to previously configured parameters.
- Error: called by the material flow element to trigger a change into an error state or back to the previous state.
- Switch of operating state: called by a special logic that controls the dominant operating state of all instances in a model, e.g., an active energy management system (see Franz et al. 2017).

Upon changing the operating state, an instance of eniBRIC's core module will inform the supplying instances for each energy carrier of the new demand. In the case of the last interface, it will further validate the availability of the new demand according to the suppliers capacity. The appropriate relations between each consumer and its respective suppliers per energy carrier are parameterized in a matrix, e.i., the configuration module, effectively enforcing a 1:n supplier-consumer-relation per energy carrier.

3.2 eniBRIC Extensions for Energy Flexibility Research

To ensure downwards compatibility for existing models, the eniBRIC class library was extended mostly reusing the pre-existing interfaces. Instances consuming energy needed to remain naïve regarding the nature of the supplying sources (conventional or renewable). Due to the fact that VRES do not always supply sufficient power, a mechanism needed to be introduced that diverts demand from one source to another whenever necessary (e.g., to the grid if the decentral supply is insufficient). This means that the restriction for 1:n supplier-consumer-relations (Figure 2a) had to be relaxed to m:n supplier-consumer-relations (Figure 2b). For this purpose, the energy supply manager (ESM) module was conceived and implemented. It imitates a single source for any number of consumers, aggregates the energy flow intensity supplied to them and distributes the same demand to any number of sources (following a priority rule). Accordingly, the ESM can be regarded as a factory's distribution network. One of the principal assumptions that went into its development defines that the energy supplier with the lowest priority will be able to cover any remaining demand the other suppliers could not. This logic follows a typical strategy for the decentral integration of VRES in production companies, according to which a grid connection is always retained as a constant backup or supplementary source.

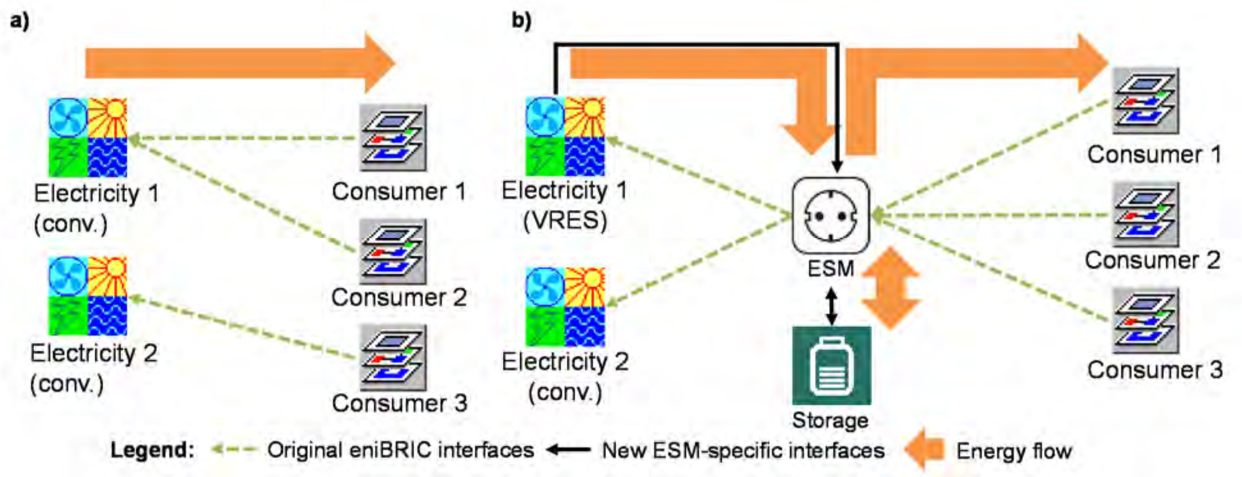

Figure 2: Implementation of eniBRIC considering interfaces and energy flow with a) 1:n supplier-consumer-relations and b) with m:n supplier-consumer-relations.

By means of the ESM it becomes possible to also simulate VRES and energy storages. The following sections discuss the implementation of standard classes for modeling these.

3.2.1 A Model Class for Volatile Renewable Energy Sources (VRES)

The model class for VRES was implemented according to the concept proposed in Stoldt et al. (2015) (see Figure 1b) by extending eniBRIC's core module. In particular, functionality for automatically changing the energy supply capacity had to be added. This could theoretically be achieved by configuring all possible capacity levels and changing the operating state according to a time series. However, to avoid high numbers of operating states, only two alternating default operating states are used and their output is determined dynamically. The class needs to be parameterized with a time series of weather data or energy data (supply capacity). To comply with the aforementioned concept's specification, means for flexible data handling were implemented. Hence, the supply capacity is determined by a mathematical function that can be specified by the user. It may reference any number of time-dependent or static parameters that are configured in the time series or an additional data object, respectively. This allows for using analytic (physical) models without relying on any software interface. For most cases, though, the use of pre-existing supply capacity (output) profiles will suffice, which is possible using trivial linear functions.

During runtime, the class' logic adds simulation events according to the parameterized time series. These trigger a method which overwrites the supply capacity of the currently inactive operating state and induces a switch command to this operating state via the original interface. To calculate the correct supply capacity, the user-specified function is parsed into executable script code upon model initialization. These supply-altering events also trigger the ESM's routine for distributing its consumer's accumulated demand to all connected sources. This ensures that the overall consumption always equals the overall supply after the supply capacity of any VRES has changed.

3.2.2 A Model Class for Mid- to Long-term Energy Storages

The model class for energy storages follows a simplified linear modeling approach (Section 2.3) that was proposed by Stoldt et al. (2015) and is depicted in Figure 1c. It is most closely related to battery storages, but may also be applied for other types of mid- to long-term storages. Short-term storages, nevertheless, are not within the scope of the implementation, because the entire eniBRIC class library is not intended for simulating physically accurate energy flows.

eniBRIC follows a strong event-driven approach to its logic. However, estimating the time until a storage is empty or full depends on the current capacity as well as the charge and discharge rates and determining the correct timing of the full or empty event is not trivial considering volatile loads. Polling, on the other hand, was not desirable because it would upset the event-driven approach. Hence, the energy storage class was implemented relying on Siemens Plant Simulation's fluid library. The storage capacity is represented by a tank element that can be connected to a fluid source or a fluid drain. In the runtime, internal logic controls whether in- or outbound connections to the tank are made and enforce the appropriate flow (charge or discharge) rates. Additional interfaces to be used by the ESM exist to set the desired values for the latter. When the tank reaches a parameterized boundary, the flow will stop and the ESM is informed. The ESM, again, has interface methods that can be used to control the charge and discharge behavior of all storages. These are intended to be used by another model logic that implements use-case-specific storage control strategies.

4 APPLICATION IN THE E³-RESEARCH FACTORY

Fraunhofer IWU's E³-Research Factory was designed to be a test bed for research on energy-efficient solutions for the production of the future. It is equipped with a multitude of sensors for various kinds of energy- and machine-related data. A photovoltaics (PV) system on its roof and a combined cold, heat, and power unit in the basement, it is capable of operating autarkic, just relying on decentral energy sources. The following sections present an application of eniBRIC's most recent version in a simulation model of the E³-Research Factory to validate its capabilities. Firstly, an overview of the case study is provided. Section 4.2 elaborates the integration of VRES and energy storage elements in the simulation model and Section 4.3 discusses some exemplary simulation results of scenarios that put the former to use.

4.1 Case Study Overview

The E³-Research Factory includes a wide range of production equipment and covers three main fields of activity: ultra-short process chains for automotive power train components, robotics solutions for flexible car body manufacturing, and holistic energy and resource management systems. While the physical equipment allows for machining parts like an industrial manufacturer could, constant production does not take place. Nevertheless, the installed machines can be used for measuring times, energy data, etc. in order to build a basis for simulating an upscaled realistic operation. This was done in order to develop, test, and assess organizational approaches to energy flexibility. The resulting simulation model is depicted in Figure 3. The model implementation is elaborated by Stoldt et al. (2016a).

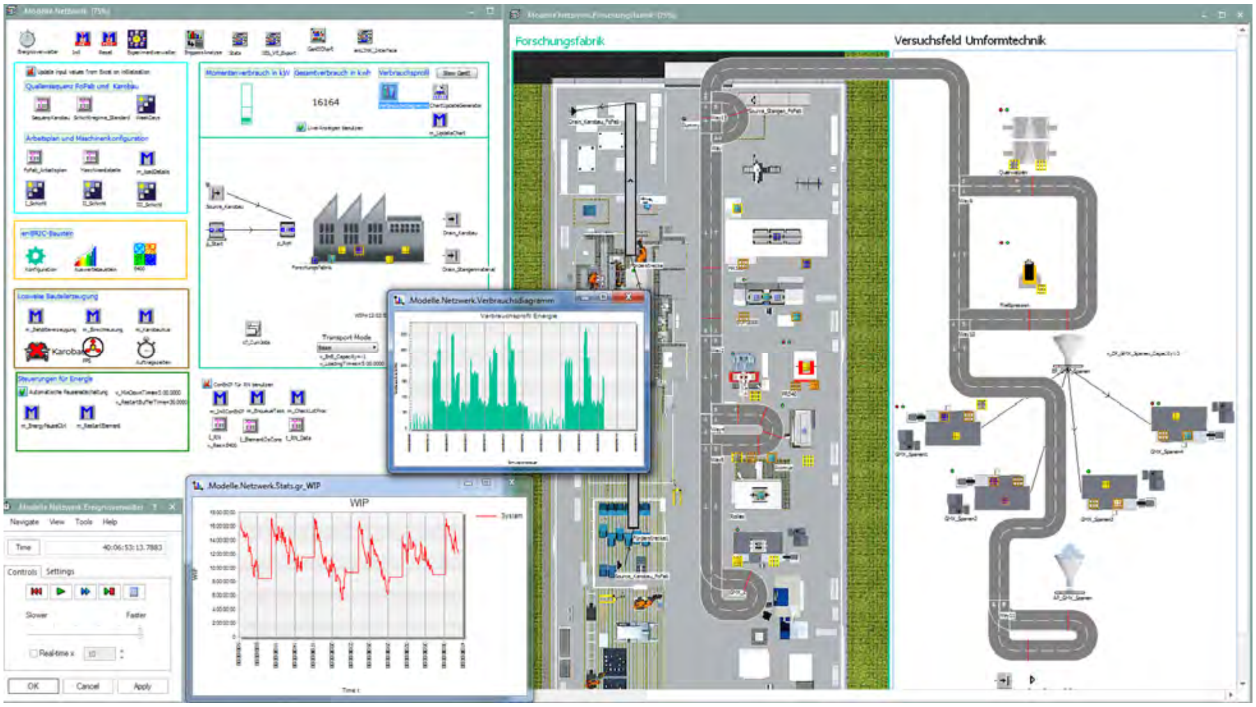

Figure 3: Screenshot of the upscaled simulation model of the E³-Research Factory.

The simulated production program comprises nine rotationally symmetric parts that can be manufactured using the existing equipment of the power train area in the E³-Research Factory as well as machines from other laboratories at Fraunhofer IWU. The yearly production volumes are designed to result in a utilization rate of between 30 % and 95 % on all machines, which either follow a schedule with three shifts on five days a week or one shift on five days. Individual orders have a size that requires them to take less than one shift to be processed on any machine. They are randomly generated during runtime using stochastic distribution functions to determine the time between two orders of the same type entering the system. Each order has to be processed on between one and seven machines before it is completed. Newly generated orders are released for manufacturing according to a user-defined logic, e.g., once a day following a first-in-first-out (FIFO) rule. Similarly, the sequence of orders waiting for processing at a machine can be predetermined or determined using a priority rule (e.g., FIFO).

In total, the simulation model comprises nine types of machines and a total of 13 individual machines (i.e., one machine was virtually upscaled to five machines). All machines are modeled using eniBRIC's core module to simulate the flow of electricity in the system. The relevant parameters have been determined from previous measurements.

4.2 Integration of VRES and Storages in the Original Simulation Model

The simulation model of the E³-Research Factory was extended by instantiating a VRES class element for the PV system to accompany the originally implemented supplier for electricity, which is a grid connection of virtually unlimited capacity. Additionally, an ESM class element was instantiated to link the two. The parameterization for the supplier-consumer-relations was adjusted accordingly. The roof-mounted PV system is rated with a peak power of 58.5 kW. A time series with 15-minute-intervals was loaded into the provided time series table of the VRES model for input data. The data covered half a year from mid-2017 until the beginning of 2018 and was derived from high resolution measurement data from the actual PV system. To cover longer simulation runs, the time series is looped until the simulation terminates. As energy data were used directly, the VRES instance was parameterized with a trivial linear function that adjusts the input data to the correct order of magnitude for the simulation (i.e., conversion from W to kW). During the 15-minutes-intervals, the PV system's power output is assumed to be sufficiently constant to use this resolution. Output changes are applied through the VRES class' logic.

An energy storage model was instantiated as well. Its parameters were chosen freely for the purpose of illustrating the storage class' mechanisms (Section 4.3), rather than meeting current state of the art storage specifications. Specifically, the storage capacity was set to 350 kWh. The efficiency coefficient was set to 1 and the maximum rates for charging and discharging to 90 kW and 80 kW, respectively. Rudimentary storage operation logic was implemented to control the times of charging and discharging. This sufficed to evaluate the storage model integration in general, although a sophisticated storage management strategy was not implemented, yet.

4.3 Exemplary Simulation Results

The presented models for VRES and energy storage in combination with the ESM were already validated by Stoldt et al. (2017) as a minimalistic example. To exemplify the potential of these elements, two scenarios were simulated in the above model. In the first scenario, the PV power is used alongside grid power. The second scenario is based on the former, but adds the utilization of the energy storage.

The simulation of the first scenario verified the correctness of the VRES and ESM classes. Figure 4a illustrates the electric power graph for an exemplary day. The PV's power output is depicted as yellow bars, the grids' load as red bars. The combined output of these equals the accumulated electricity demand of all consuming elements (machines). This was also checked by comparing the stacked bars' value with the sum of demands of all machines. The constant and low energy demand at the beginning of the chart is the baseline usage that is maintained at all times (e.g., during off-shifts). Further dips are caused by breaks. The lower energy demand later in the day is the result of different shift schedules for some of the machines (i.e., one shift only instead of three shifts a day). If the PV output exceeds the current demand in the model, its output to the system will be reduced accordingly. This emulates the typical course of action to feed excess power into the grid. The corresponding intensity could be logged for later evaluation.

This scenario shows how the new elements can be used to evaluate the share of renewable energy generated from on-site sources. In one year, a total of approximately 440 MWh electricity were used by production equipment while the PV system generated around 74.2 MWh and supplied roughly 62.5 MWh of these to the production system. The remainder would have been fed to the grid (generating a turnover from selling the energy), but could also have been stored locally. All considered, ca. 14 % of the system's energy demand could be satisfied using the PV system. Assuming a CO_2 emission equivalent of 527 g/kWh for grid electricity, this would amount to a reduction of 32.9 t of CO_2 in this scenario.

The simulation of the second scenario was intended to verify the storage class implementation and to exemplify how energy flexibility measures could be tested using the latest version of eniBRIC. A rather simplistic operating strategy for energy storages could initiate charging when a certain lower price threshold is reached and start discharging when a higher price threshold is reached. For this scenario, spot market prices for six periods throughout an exemplary day were retrieved from the EPEX. Based on these, a time series was created according to which charging starts as the day begins and discharging begins as the highest price is reached. The time series is enacted through the rudimentary logic mentioned in Section 4.2. Charging and Discharging will cease when the storage is empty, respectively full. Figure 4b shows the load profiles for the same day as in scenario 1, but using the storage. The storage's power output (positive) and input (negative) is depicted as well as energy price. It is apparent that the machine load is identical to the previous scenario. Thus, any changes of the load stem from the storage's activity. It is noteworthy that in times with little load, the storage discharge intensity will (1) prevent the utilization of PV power, and (2) be reduced according to the actual demand. This is neither environmentally nor economically efficient and shows the importance of more-advanced storage control logic.

Considering the prices used in this example, € 87.95 or 9.5 % of the daily costs could be saved. Due to the aforementioned effect, CO_2 emissions would be higher than in the previous scenario. Even so, this scenario showed the usefulness of eniBRIC's latest version for energy flexibility research.

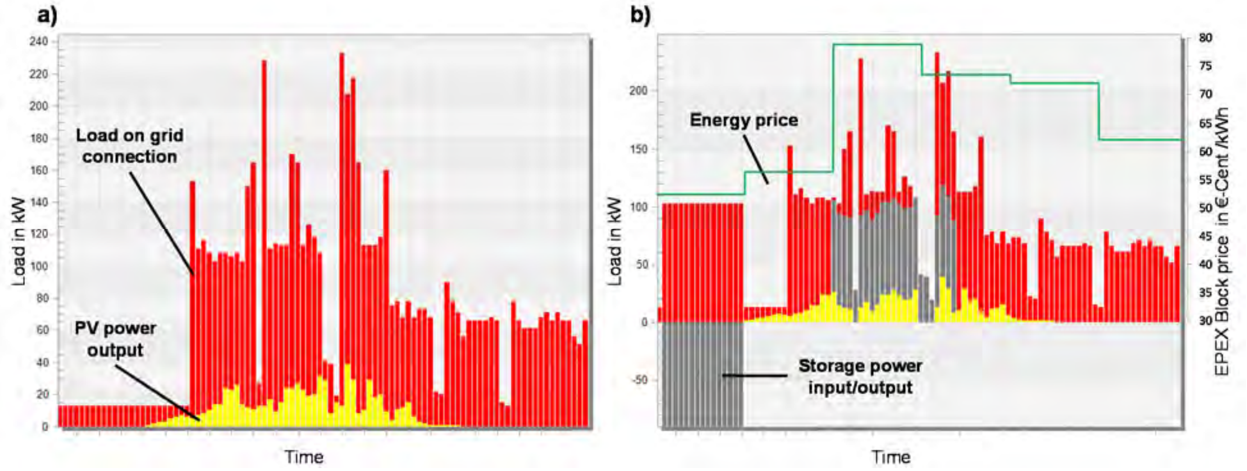

Figure 4: Load profiles for the energy supplied to the system by each source and the energy storage as stacked bar charts a) without an energy storage b) with energy storage.

5 ENERGY-SENSITIVE FACTORY OPERATION

Using the simulation model of the E³-Research Factory, it is possible to investigate holistic approaches to energy-sensitive factory operation in a push production system. This includes novel strategies for production planning and control (PPC) and for equipment control. A primitive approach to the latter is a simple shut-down strategy that switches production machines to an energy-saving operating state during breaks or unplanned shifts. Preliminary results showed that this measure alone could save more than a third of the energy demand. This saving potential's size can be explained by the fact that six of the machines only work a third of the time that the others do and all machines remain inactive during the weekend. Keeping them idle throughout this unproductive time is a tremendous waste of energy.

In order to cope with decentral VRES, more advanced PPC tactics are required. Another preliminary study investigated the application of a production control strategy that aims to enforce a restriction on the system's demand. It is called Constant Energy in Process (Putz et al. 2014) and has been implemented in the model to limit the overall energy demand to 250 kW at all times by shutting down machines that are inactive or cannot be allowed to operate within the limit. Halting production on some machines is intended to distribute the load over time. Figure 5 shows load profiles with and without its application. Simulation may serve to find parameterizations that maintain productivity.

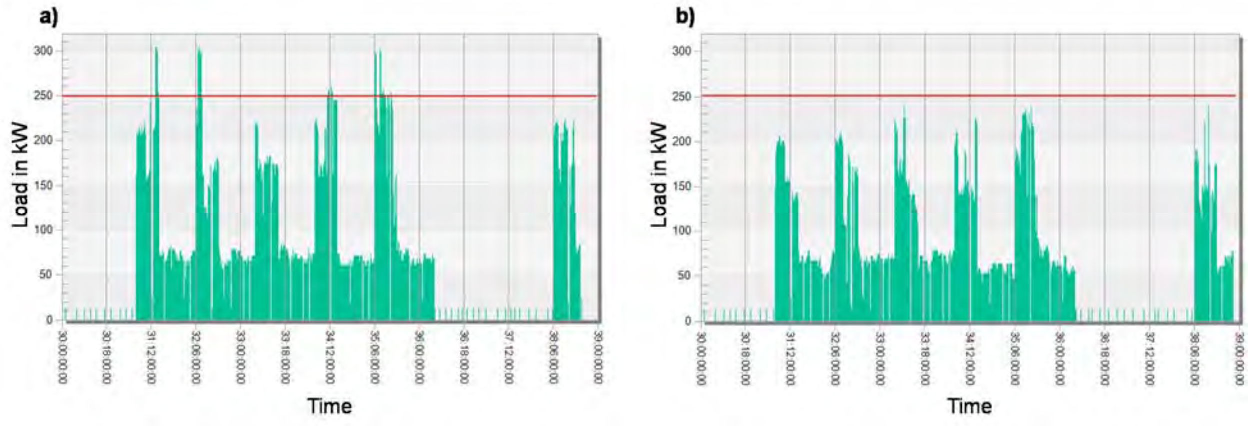

Figure 5: Load profile of the production demand a) with and b) without demand restriction to 250 kW.

A more holistic approach, which is currently under development (Raue et al. 2018), will be implemented and tested. It is intended to incorporate production planning algorithms that optimize order sequences and timing according to the expected availability of energy. Since these plans will be disturbed in their execution through probabilistic events (e.g., machine failures), additional energy-sensitive production control strategies will try to ensure that the actual demand profile does not deviate too much from the planned profile through energy-flexibility measures. Further equipment control algorithms, particularly for charging and discharging behavior of energy storages, are going to be devised to complement the PPC. The simulation model will serve to generate test data for the scheduling algorithms as well as to evaluate the performance of the various interlinked operational approaches for energy flexibility.

6 CONCLUSION AND OUTLOOK

The growing reliance on volatile renewable energy sources gives rise to issues of net stability and increasingly variable energy prices. Industrial companies will need to (partially) match their demand profiles to the availability of energy. The investigation of suitable energy flexibility measures requires simulation tools which were hitherto not or not sufficiently available.

In this light, an update to the Plant Simulation class library eniBRIC that can be used to simulate the energy flows of a factory alongside its material flows is presented. It adds the means to model VRES as well as energy storages. This paper particularly introduces a case study that employs this updated library and describes (hitherto unpublished) research in progress on factory operation strategies, based on this case study and previous work. Using an exemplary production system derived from Fraunhofer IWU's E³-Research Factory, two scenarios that use these new simulation elements were investigated, showcasing their potential use. Furthermore, an overview on current and future research using the simulation model of the E³-Research Factory is provided. Summarizing, the new capabilities of eniBRIC allow for investigating new factory design concepts (e.g., what effect would doubling a PV system's size have on the CO_2 footprint), energy-sensitive production planning and control strategies (e.g., how can the demand be matched to the supply), or novel equipment control strategies (e.g., which thresholds should be used to determine whether to charge, respectively discharge, a storage). Future research will focus on integrating these three to make energy flexibility viable from an economic point of view for production companies. The validity of the discretization approach to modeling energy flows also requires further investigations.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support of the Federal Ministry of Education and Research (BMBF) and the project supervision of the Project Management Jülich (PtJ) for the project „SynErgie“ (funding mark 03SFK3G1). The authors are responsible for the contents of this publication.

REFERENCES

Allegrini J., K. Orehounig, G. Mavromatidis, F. Ruesch, V. Dorer, and R. Evins. 2015. “A Review of Modelling Approaches and Tools for the Simulation of District-Scale Energy Systems”. *Renewable and Sustainable Energy Reviews* 52:1391–1404.

Beier J. 2017. *Simulation Approach Towards Energy Flexible Manufacturing Systems.* Cham: Springer International Publishing.

Chu K. C., K. Kaifuku, and K. Saitou. 2016. “Optimal Integration of Alternative Energy Sources in Production Systems With Customer Demand Forecast”. *IEEE Transactions on Automation Science and Engineering* 13(1):206–214.

eurostat. 2016. Electricity consumption by Industry, Transport Activities and Households/Services. http://ec.europa.eu/eurostat/tgm/table.do?language=en&pcode=ten00094, accessed 13.3.2018.

eurostat. 2017. Electricity Production, Consumption and Market Overview. http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_production,_consumption_and_market_overview, accessed 13.3.2018.

Franz E., F. Erler, T. Langer, A. Schlegel, J. Stoldt, M. Richter, and M. Putz. 2017. “Requirements and Tasks for Active Energy Management Systems in Automotive Industry”. *Procedia Manufacturing* 8:175–182.

Ghadimi P., S. Kara, and B. Kornfeld. 2015. “Renewable Energy Integration into Factories: Real-time Control of on-site Energy Systems”. *CIRP Annals / Manufacturing Technology* 64(1):443–446.

Graßl M. 2015. *Bewertung der Energieflexibilität in der Produktion*. München: Utz.

Grimm V. 2007. Einbindung von Speichern für erneuerbare Energien in die Kraftwerkseinsatzplanung: Einfluss auf die Strompreise der Spitzenlast. Bochum: LEE.

Haessig P., B. Multon, H. Ben Ahmed, S. Lascaud, and P. Bondon 2013. “Energy Storage Sizing for Wind Power: Impact of the Autocorrelation of Day-ahead Forecast Errors”. *Wind Energy* 18(1):43–57.

Huggins R. A.. 2010. *Energy Storage*. Boston, MA: Springer US.

Keller F., C. Schultz, S. Braunreuther, and G. Reinhart. 2016. “Enabling Energy-Flexibility of Manufacturing Systems through New Approaches within Production Planning and Control”. *Procedia CIRP* 57:752–757.

Klobasa M., A. Eßer, B. Pfluger, F. Sensfuß, M. von Bonin, N. Gerhardt, V. Lerm, D. Nill, S. Schäfer-Stradowsky, and U. Holzhammer. 2016. “Monitoring der Direktvermarktung: Quartalsbericht (12/2016)”. Karlsruhe/Kassel/Berlin. https://www.erneuerbare-energien.de/EE/Redaktion/DE/Downloads/Berichte/monitoring-direktvermarktung-strom-ee-quartalsbericht-12-2016.pdf?__blob=publicationFile&v=2, accessed 13.3.2018.

Lehmann C., M. Weeber, J. Böhner, and R. Steinhilper. 2016. “Techno-economical Analysis of Photovoltaic-battery Storage Systems for Peak-shaving Applications and Self-consumption Optimization in Existing Production Plants”. *Procedia CIRP* 48:313–318.

Liebl C., R. Popp, and M. F. Zäh. 2015. “Energieflexibiltät von Produktionsanlagen–Energieflexibilitäts-Kennfelder zur Abschätzung der Energieflexibilitäts-Potentiale unterschiedlicher Anlagen”. *wt Werkstattstechnik online* 105(3):136–140.

Papic I. 2006. “Simulation Model for Discharging a Lead-Acid Battery Energy Storage System for Load Leveling”. *IEEE Transactions on Energy Conversion* 21(2):608–615.

Popp R. S. H., Liebl C., and Zaeh M. F. 2017. “Evaluation of the Energy Flexible Operation of Machine Tool Components”. *Procedia CIRP* 63:76–81.

Putz M., A. Schlegel, J. Stoldt, E. Franz, and T. Langer. 2014. “Energy-sensitive Control Strategies for Decoupled Production Systems”. *International Journal of Sustainable Manufacturing* 3(3):250–268.

Ramos S., J. Soares, M. Silva, and Z. Vale. 2012. *Short-term Wind Forecasting for Energy Resources Scheduling*. European Wind Energy Association (EWEA).

Raue C., H. M. Strehle, J. Stoldt, A. Schlegel, M. Richter, and T. Langer. 2018. “Mehrstufiges multikriterielles Job Shop Scheduling”. *wt Werkstattstechnik online* 108(4):210–216.

Roesch M., M. Brugger, S. Braunreuther, and G. Reinhart. 2017. “Klassifizierung von Energieflexibilitätsmaßnahmen”. *ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb* 112(9):567–571.

Schultz C., S. Braun, S. Braunreuther, and G .Reinhart. 2017. “Integration of Load Management into an Energy-oriented Production Control”. *Procedia Manufacturing* 8:144–151.

Sebastián R., and R. Peña Alzola 2012. “Flywheel Energy Storage Systems: Review and Simulation for an Isolated Wind Power System”. *Renewable and Sustainable Energy Reviews* 16(9):6803–6813.

Shi J., W. J. Lee, Y. Liu, Y. Yang, and P. Wang. 2012. “Forecasting Power Output of Photovoltaic Systems Based on Weather Classification and Support Vector Machines”. *IEEE Transactions on Industry Applications* 48(3):1064–1069.

Stoldt J., M. Cherkaskyy, E. Franz, M. Putz, N. Oertwig, and E. Uhlmann. 2015. “Modellierung von Energietechnologien zum nachhaltigen Reengineering von Produktionsunternehmen”. In *Planung und*

Betrieb von Produktionssystemen im digitalen Zeitalter: VPP2015 / Vernetzt planen und produzieren, October 23rd, Chemnitz, 81–90.

Stoldt J., M. Münnich, E. Franz, A. Schlegel, and M. Putz. 2016a. "Simulative Untersuchung energie- und ressourceneffizienter Betriebsstrategien in der E3-Forschungsfabrik". In *Tagungsband ASIM 2016 / 23. Symposium Simulationstechnik (Dresden),* edited by T. Wiedemann, 45–52. Wien: ARGESIM / ASIM.

Stoldt J., A. Schlegel, and M. Putz. 2016b. "Enhanced Integration of Energy-related Considerations in Discrete Event Simulation for Manufacturing Applications". *Journal of Simulation* 10(2):113–122.

Stoldt J., B. Prell, A. Schlegel, and M. Putz. 2017. "Modellierung von volatilen erneuerbaren Energieerzeugern und Energiespeichern in Siemens Plant Simulation". In *Simulation in Produktion und Logistik 2017*, edited by S. Wenzel and T. Peter, 49–58. Kassel: kassel university press.

Zheng Y., B. M. Jenkins, K. Kornbluth, and C. Træholt. 2018. "Optimization under Uncertainty of a Biomass-integrated Renewable Energy Microgrid with Energy Storage". *Renewable Energy* 123:204–217.

AUTHOR BIOGRAPHIES

JOHANNES STOLDT is a research associate and group leader for Factory Design and Simulation in the department Resource Efficient Factory at the Fraunhofer Institute for Machine Tools and Forming Technology. Until 2012 he studied Mechanical Engineering/Production Technology at the Technische Universität Chemnitz and is currently a Ph.D. student at the faculty for Mechanical Engineering. He is a member of the ASIM group Simulation in Production and Logistics (SPL) and is one of the founding members of the ASIM SPL work group on the Investigation of Energy-related Influences in SPL (BeESPL). His research interests include discrete event simulation, energy efficiency and digitalisation in factories. His email address is johannes.stoldt@iwu.fraunhofer.de.

BASTIAN PRELL is a research associate in the department Ressource Efficient Factory at the Fraunhofer Institute for Machine Tools and Forming Technology IWU in Chemnitz. He holds a B.Sc. in Industrial Engineering from the Karlsruhe Intstitute of Technology as well as a M.Sc. in Industrial Engineering and a B.Sc. in Mechanical Engineering from the Technische Universität Dresden. He is a member of the ASIM group Simulation in Production and Logistics (SPL). His research interests include DES and energy flexibility. His e-mail address is bastian.prell@iwu.fraunhofer.de.

ANDREAS SCHLEGEL is head of the department Resource Efficient Factory at the Fraunhofer Institute for Machine Tools and Forming Technology IWU, which he joined in 2001. He studied Production Technology and Operations with a specialisation on computer-aided production planning at the Hochschule Zwickau and holds a Ph.D. from the Technische Universität Chemnitz. He is a member of the ASIM group Simulation in Production and Logistics (SPL) and deputy spokesperson for the ASIM SPL work group BeESPL since its formation. His research interests include resource efficient production, ICT in manufacturing, and Digital Factory. His email address is andreas.schlegel@iwu.fraunhofer.de.

MATHIAS PUTZ is Director of the Fraunhofer Institute for Machine Tools and Forming Technology IWU and holds the Professorship for Machine Tools and Forming Technology at the Technische Universität Chemnitz. He gained his Ph.D. in 1986 in the Field of Machine Tool Construction at the Technische Universität Chemnitz. In 2007 he obtained an Honorary Professorship at the Dresden University of Applied Sciences (HTW Dresden). He is an Associate Member of the International Academy for Production Engineering (CIRP), member of the DFG review board for engineering, co-spokesman of the DFG special research field SFB TR 96, expert at various Scientific Committees, Co-ordinator of the Fraunhofer-Lighthouse Project »E^3-Production«, as well as Member of the Board at the ACOD Automotive Cluster Ostdeutschland e.V. His e-mail address is mathias.putz@iwu.fraunhofer.de.