Implementation of a Smart Grid in an Operation-independent Simulation Model

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SNE 35(3), 2025, 143-147, DOI: 10.11128/sne.35.sn.10744
Selected ASIM SST 2024 Postconf. Publication: 2024-12-10
Rec. Impr. English version: 2025-08-01; Accepted: 2025-08-15
SNE - Simulation Notes Europe, ARGESIM Publisher Vienna
ISSN Print 2305-9974, Online 2306-0271, www.sne-journal.org

Abstract. This study describes the development of an operation-independent simulation model for electrified die-casting foundries which use a smart grid system to cover their energy requirements. The model uses real weather and electricity price exchange data for the simulation period. It can be used to determine and compare electricity costs for production at specific times of day and year, as well as the economic efficiency of different photovoltaic (PV) system and electricity storage variants. It also enables the proportion of different energy sources for each configuration to be analysed. This can be carried out using the model for locations throughout Germany. Additionally, this paper presents exemplary simulation studies that demonstrate the model's wide range of applications. The results provide an initial overview of the potential savings and optimisation. In the future, the model will provide a basis for determining optimum plant layouts and production times using simulation-based optimisation.

Introduction

Against the backdrop of climate targets and the European Supply Chain Directive, reducing emissions during production is becoming increasingly important, particularly for energy-intensive companies. At the same time, companies are focusing on sourcing energy in the most cost-effective way possible. However, these aspects do not necessarily compete with each other. The volatility of renewable energies means that emission-free electricity can sometimes be sourced very cheaply, making CO_2-emissions and low-cost electricity procurement compatible.

Additionally, manufacturing companies with suitable sites can generate their own renewable electricity, although this initially incurs high investment costs and requires a certain degree of logistical flexibility, which is not always easy to implement. To be able to test and analyse the economic effects of corresponding adaptations in companies without having to intervene in real operations, which is always associated with economic risks, this study will develop a simulation model for this purpose. As part of this work, this functionality is implemented in an existing operating model of casting plants. To enable statements to be made about different company sizes and to allow for possible transferability to other sectors, the model is company-independent and geared towards flexibility.

1 Field of Application

With an average annual demand of 12.6 TWh between 2010 and 2021, the German foundry industry is one of the most energy-intensive sectors of the economy. In 2021, more than half of this demand was still covered by fossil fuels [1]. In order to reduce the resulting emissions, it is unavoidable that these fossil fuels must be substituted. The most important approach is to electrify the melting process. However, the effectiveness of this measure depends heavily on the composition of the electricity mix used. Additionally, this conversion alters the operating process [2]. This study analyses a simulation model of a converted plant. The model aims to determine the energy costs of production for any configuration of such an operation using a smart grid system that considers weather data, electricity storage, and electricity exchange prices. In this application, the smart grid system is limited to the site in question. Its task is to monitor electricity demand during production and cover it as cost-effectively as possible using the currently available electricity supply, which is also recorded.

2 Previous Work

The simulation model developed in this study is based on previous work, in which two models were developed: an operation-independent model for a conventional die casting operation [3], and a specific model for an electrified operation [2]. This study focuses on implementing a smart grid approach using real-time data and variable electricity costs resulting from production. The use of flexible energy prices and smart grids to optimise costs in the manufacturing industry is a widely discussed topic in the literature. Literature analyses such as [4] can be consulted for an overview.

Table 1 provides an overview of the focal points of studies in this area, compared to this study. This study is the first to analyse operational smart grids in a foundry context alongside real weather and electricity price data.

Contents	[5]	[6]	[7]	[8]	This study
Simulation study	*	*	*	*	*
Felxible energy prices	*		*	*	*
On-site power generation				*	*
Electricity storage				*	*
Real weather data					*

Table 1: Comparison of the focus of different studies.

3 Simulation Model

The simulation model is based on the conservation laws of energy and mass, and has been developed using the MATLAB/Simulink programming environment. It has an object-oriented structure and can be individually parameterised via a configuration file before a simulation is started. The simulation uses real start and end times to retrieve weather and electricity price data. The model comprises three sub-models. Figure 1 shows the interaction of the sub-models within a simulation step. One simulation step corresponds to one second of simulated operating time.

Combining a detailed simulation model of a die-casting foundry with real weather data and electricity prices allows for insights into energy costs and the energy mix in various simulation scenarios.

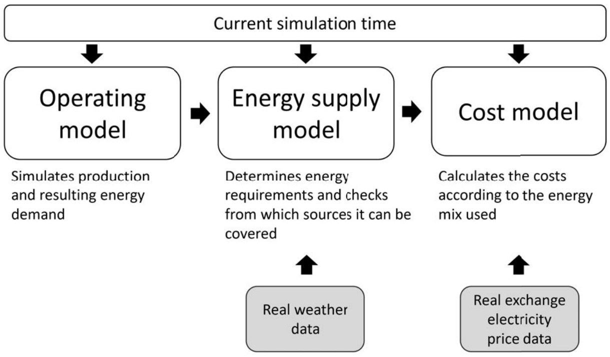

Figure 1: Procedure of the simulation model in each simulation step.

Thus, the model can support and evaluate strategic decisions. More detailed explanations of the individual sub-models can be found below.

3.1 Operating model

The model is based on the principles of energy and mass conservation and maps the entire production process from melting to casting in an object-oriented manner. It considers energy and material flows together, while a control module regulates the overall process. Energy flows are simulated continuously and material flows are simulated discretely. Calculations in the energy model are based on the internal energy of the processed metal. This is shown schematically in Figure 2. Using these calculations, the model determines the current temperature and solves the differential equations for the mass of the liquid and solid metal. In the discrete part of the model, each simulation step checks for the occurrence of certain events. If necessary, processes are triggered accordingly.

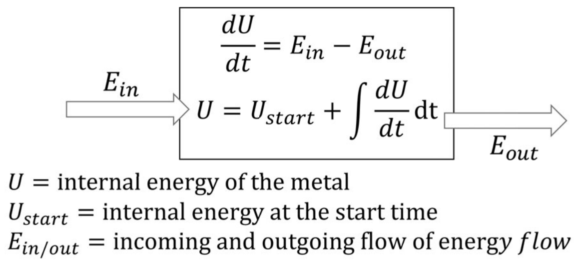

Figure 2: Internal energy of the processed metal.

The model consists of various simulation objects whose properties change during the simulation according to the parameters of the simulated operation.

3.2 Energy supply model

In the simulation, only the electricity required to operate the melting furnaces is taken into account. This electrictiy is determined by adding the energy required by each furnace and the heat losses that occur in each simulation step. The electrical energy required for operation can be provided in the simulation model in three ways (more detail on the various sources is provided below):

1. Electrical energy from the PV system
2. Electrical energy from the battery storage system
3. Electrical energy from the power exchange

Figure 3 shows the sequence of utilisation of these energy sources schematically:

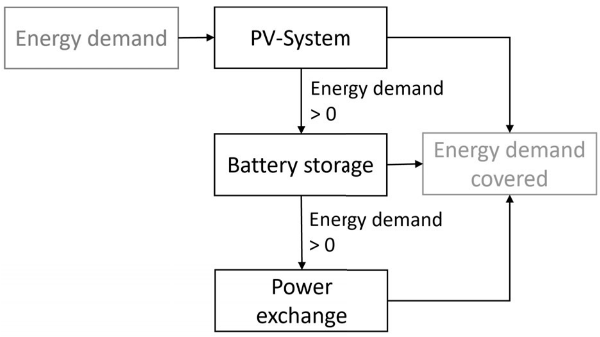

Figure 3: Order of electricity usage.

Electrical energy from the PV system. The yield of the PV system is calculated using the weather data from the Duett project [9], which has been providing hourly data with a local resolution of 2x2 km for the whole of Germany since the beginning of 2024, depending on the specific system data and the stored operating location.

Electrical energy from the battery storage system. The battery storage system is charged when more PV electricity is produced than the site currently requires and discharged when more electricity is required than is currently being produced. A certain degree of efficiency is associated with electricity storage.

Electrical energy from the power exchange. If the energy demand cannot be met by the electricity currently being generated and stored, the difference is purchased on the European Power Exchange (EPEX SPOT) spot market.

3.3 Cost model

The costs of the PV system and battery storage are calculated using straight-line depreciation for both acquisition and operating costs. Electricity purchased from the spot market is included in the total costs at the current price and required quantity for each time step. Accordingly, the energy costs C in each simulation step consist of fixed and variable costs according to equation 1:

$$C = \frac{C_{\text{inv}} + C_{\text{op}}}{T} + C_{\text{spot}} \tag{1}$$

C_{inv} = Investment cost
C_{op} = Expected operating costs
C_{spot} = Electricity costs of exchange electricity
T = Expected life cycle

4 Simulation Study

To analyse the model's potential, the electricity mix and resulting costs of an operation with four casting units and an identical production plan are investigated by varying the battery storage sytem, the PV system and the geographical location. Each simulation considers an identical 24-hour operating day. The reference configuration for all studies is an operation with a 1 MWp PV system and 320 kWh storage capacity in Nuremberg. These simulation studies aim to demonstrate the possible applications of the developed model.

4.1 Variation of the storage capacity

The first sub-study analyses the influence of the battery storage system. To this end, the capacity is varied from 0 to 640 kWh, together with the corresponding power. Figure 4 shows the resulting energy mix and associated costs.

The study found that total costs decrease with increasing storage capacity, as a larger storage volume is associated with lower additional costs than purchasing electricity on the spot market. The extent of this effect depends on the storage system's investment costs, the PV system used and spot market prices during the relevant period.

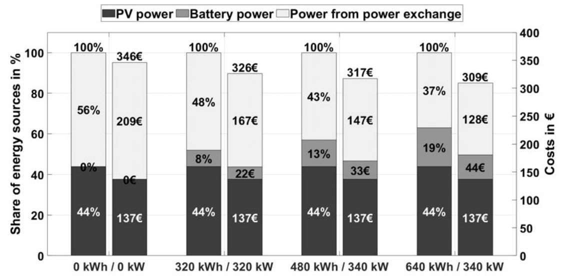

Figure 4: Electricity mix and costs for various batery storage systems.

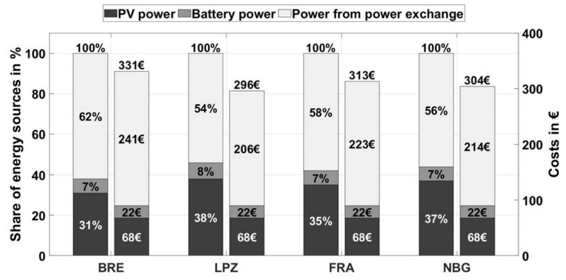

Figure 6: Electricity mix and costs for various production sites.

Accordingly, studies of this type can aid decision-making regarding the optimal size of a new or replacement battery storage system for an operation with existing PV system.

4.2 Variation of the PV system

This simulation study analyses the impact of the size of a PV system. It is varied in four stages, ranging from 100 kWp to 2 MWp. Figure 5 shows the resulting energy mix and associated costs.

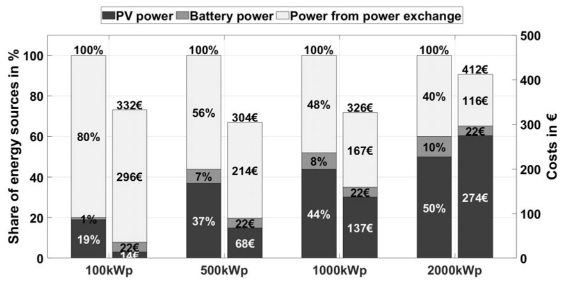

Figure 5: Electricity mix and costs for various PV system sizes.

Although the configuration with the largest PV system produces the most PV electricity, a smaller system (500 kWp) is more cost-effective. This is due to limited storage capacity and production at night.

4.3 Variation of the location

Finally, the factory's location varies between Bremen (BRE), Leipzig (LPZ), Frankfurt am Main (FRA) and Nuremberg (NBG). The simulation is based on the optimal configuration from simulation study 4.2: a 500 kWp PV system with 320 kWh of storage capacity. Figure 6 shows the resulting energy mix and associated costs.

The study shows that, for otherwise identical operations at different locations, the energy mix and energy costs can differ significantly in some cases. This is due to different levels of solar irradiation and the resulting variation in PV yields. Therefore, optimal system configurations depend on the location of the site, and this must be taken into account in the simulation model. Supporting site selection is another potential application of such models. However, a longer time period must be simulated to make an informed statement on site selection.

5 Discussion

The main advantages of the model described here are its flexible structure and the incorporation of real data. This makes the model suitable for a wide range of applications. As the model uses real data on weather and electricity prices, it can also take into account time- and location-specific influencing factors in the simulation. The test studies presented demonstrate the model's suitability for a wide range of applications. For instance, it can be used to determine the optimal size of a storage system for an existing PV system, and vice versa. It is also possible to optimise the design of both components.

Additionally, the model considers specific weather data, enabling its flexible use for different locations. The model can be used to aid strategic investment planning and the assessment of the profitability of changes to the production plan or location choice. As specific acquisition costs can be varied within the model, it can be used to determine the marginal costs above which an investment becomes worthwhile.

However, since a simulation model is always a simplified representation of reality, it is important to validate it using real data in order to confirm its validity.

Due to the lack of electrified foundries, this cannot currently be done for this model. Therefore, the current validation is based on energy balances and a comparison with a validated model of a conventional die casting foundry [3].

6 Outlook

In future, optimisation algorithms will be used to determine the best possible system configurations and production times for specific operations with the help of the model described here. Due to its flexible structure, the model can be extended in many directions. While it is primarily intended for operational production planning, further work will investigate its potential for strategic plant design in particular. Furthermore, the smart grid model can be easily transferred to other industrial application areas. All that is required is a load profile for the new application.

Publication Remark

This contribution is the revised English version of the (German) conference version published in
Tagungsband Langbeiträge ASIM SST 2024,
ARGESIM Report AR 47,
ISBN ebook: 978-3-903347-65-6,
volume DOI 10.11128/arep.47,
article DOI 10.11128/arep.47.a4734, p 61-65.

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