Evaluation of the effects of a load shedding at a lignite power plant

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Abstract
The load-shedding scenario describes an unscheduled load reduction in a power plant so that it produces only the electricity that is needed by the plant itself. The reason for such a scenario is a collapse of power supply in the transmission network. In the subsequent restoration of the electrical supply, different options are distinguished. An essential part of each option is island operating or black start capable thermal power plants. The load-shedding scenario is complex and multilayered. If process steam is also decoupled during the load shedding, high exhaust steam temperatures in the turbine stages can lead to plant shutdown. In addition, component damage can be expected in thick-walled components due to high temperature and pressure amplitudes. Thus, it can be shown in this paper that the lifetime losses are highest at the high-pressure preheater 6 and at the deheater and that the process heat coupling cannot be operated with constant mass flow under all circumstances. In order to investigate these issues, a detailed model of a lignite power plant has been created, which was developed in Modelica for simulating and comparing scenarios for a variety of applications. The model comprises the entire water-steam cycle including turbines, preheaters and pumps, as well as a very detailed boiler model including the air supply, coal mills, heating surfaces, and piping. Furthermore, the power plants' control system has been implemented in a very precise way. In addition, the study involves a calculation of lifetime consumption for specific components to evaluate the effects. In summary, it can be stated that this study examines the thermodynamic aspects during a load-shedding scenario for the first time. It focuses on processes within the power plant and thus differs significantly from other studies on this topic, which approach the issue from the electrical grid side.

Keywords
dynamic modeling, lifetime consumption, load shedding, power plant
1 | INTRODUCTION

Due to the increasing integration of renewables energy in electrical energy production and their priority treatment, fossil-fired power plants are increasingly being pushed out of the market. However, the grid stability of Europe’s interconnected grid is becoming more important in this perspective. The main indicator in this context is the grid frequency. In order to maintain the target frequency of 50 Hz, thermal power plants cannot yet be replaced. They have a positive impact at different levels and time scales. On the one hand, large power plants provide control power. In the case of primary control power, this system service takes effect after 30 seconds at the latest. On the other hand, it is the system-immanent buffer function of the synchronous generators that has a considerable positive influence on the grid stability. The positive influence is caused by the inertia of the rotating generator masses.

Due to various possibilities, such as an undersupply of thermal power plants, large surpluses of wind and solar energy, or the temporary loss of power capacities, the measures outlined above may not be successful and the grid frequency may continue to rise or fall. In this case, it may be necessary to disconnect the power plant from the power grid in order to prevent extensive damages. Depending on the severity and magnitude of the breakdown, this disconnection from the grid can result in considerable power outages. This scenario is also problematic for industrial plants that are supplied with process steam from the power plant concerned. Depending on the size of the decoupling, this process steam mass flow cannot always be completely guaranteed, which can result in production failure or even damage to the industrial plant.

In order to reconnect thermal power plants to the grid as quickly as possible and thus keep the power outage time low, large power plants are expected to be capable of island operation. The power plant, including its ancillary plants, supplies itself with electricity for at least two hours so that it is able to rebuild the power grid after the problem has been solved (top-down principle). Although the capability for island operation must be proven in test runs, these tests are not without risk to operational safety. In addition, increased lifetime consumption to thick-walled components cannot be avoided. On this basis, the duration and number of test runs must be severely limited and may only be carried out if substantially new characteristics are to be expected in the operational behavior.

Therefore, a fully physical process model was developed for the investigation of this scenario, taking into account the complete control system of the power plant. For the analysis and impact assessment of a load-shedding scenario, this method of physical, dynamic modeling is completely new.

2 | LOAD SHEDDING

Interferences in large power plants or subnetwork shutdowns can cause conditions in the electrical network that disturb the balance between generation and consumption. In order to avoid supraregional grid breakouts, generators are able to deliver active power over a relatively wide frequency range (47.5-51.5 Hz). Depending on the level of the frequency deviation, a package of measures is run through after a major disturbance. As a rule, these measures are limited to the provision of control power products. For frequency deviations of more than $\Delta f = 200$ mHz, the procedure shown in Table 1 comes into operation. In order to avoid damage caused by resonance phenomena at the power plant, power plants must be disconnected from the grid at a frequency of 47.5 Hz (cf. [1]). The regulations for such cases can be found in Ref. [2] (Table 1).

For start-up processes, thermal power plants usually need a power grid, for example, to start coal transport systems or electric pumps. Only a few thermal power plants have their own diesel generators and are therefore capable of black starts. However, in order to ensure that the grid is set up as quickly as possible, thermal power plants should support their own infrastructure, including any existing opencast mines and carry out a load-shedding operation. Technically, such a scenario goes hand in hand with the spontaneous closing of the turbine valves. At the same time, the corresponding bypass valves open to prevent an uncontrolled increase in pressure in the boiler. This poses a number of challenges in power plant operation, including increased exhaust steam temperatures on the one hand and higher turbine speeds for short periods of time on the other. The higher exhaust steam temperatures result from reduced heat transport caused by small steam mass flows. The increased turbine speed is caused by the nonimmediate closing of the turbine valves so that in the first moments, excess steam flows into the turbines, which

| Frequency (Hz) | Measure |
|----------------|---------|
| 1 49.8         | Use of the not yet mobilized generation capacity on instruction of the transmission system operator, shedding of pumps |
| 2 49.0         | Immediate load shedding from 10% to 15% of the power load |
| 3 48.7         | Instantaneous load shedding of a further 10%-15% of the power consumption |
| 4 48.4         | Instantaneous load shedding of a further 10%-20% of the power consumption |
| 5 47.5         | Disconnection of all generating plants from the electrical grid |
leads to an increase in the turbine speed. This can result in a frequency of 54 Hz in the power plant grid (cf. [1]).

Starting with, load shedding has often been calculated with scientific models and its effects and consequences have been predicted. For example, island operation has been investigated in Refs [4–7]. While these sources deal with this scenario from an electrotechnical point of view, this paper focuses on thermodynamics and power plant technology.

In contrast to, a fully physical power plant model is used here together with a realistic control system model, whereby time effects such as delays in the provision of process steam and under or overshoots in the process variables can be observed. The use of these detailed models results in significant improvements in the impact assessment of such a scenario. In this context, physical models are referred to when they use the physically relevant equations to calculate the heat flow in a heat exchanger or the energy content of a vessel. Mathematical models, on contrast, are based on delay elements, mathematical functions, or correlations of two or more parameters to represent the empirically determined operating behavior. The model discussed and used here is a physical model, and the fundamentals of this model are presented in more detail in the following chapter.

### 3 | POWER PLANT SYSTEM MODEL

#### 3.1 | Reference power plant

The system under investigation is a lignite-fired power plant. It consists of two almost identical units. The air and flue gas path consists of two strands. Each has a steam air preheater, which is used according to the generator load and the inlet temperature of the fresh air. In addition, one fresh air fan and one regenerative air preheater are installed per line. After the boiler, in which the flue gas flows from bottom to top, is an electrostatic precipitator, the induced draft fan and the desulfurization plant. The water-steam cycle consists of two condensers, the condensate pumps, the low-pressure preheater—consisting of four preheaters—the feedwater tank, an electric or turbine-driven feedwater pump, two high-pressure preheaters, the heating surfaces in the steam generator, and the condensation turbines. The turbine part consists of high-pressure, medium-pressure, and low-pressure turbines with single reheating and partial condensation. A special feature is the use of process heat, which is mainly obtained from tapping four. A simplified block diagram is shown in Figure 1.

The power plant obtains its fuel from a nearby open-cast lignite mine. The average calorific value is 8.7 MJ/kg. The water content in the coal is 54.3% of the weight and the carbon content 26.3%. The coal is fed into the respective mills via feeder belts.

The investigated plant currently operates in base load, producing a significant amount of electrical energy. In addition, it offers considerable amounts of control power.

#### 3.2 | Dynamic modeling

By considering storage masses and system dynamics during the dynamic simulation, statements can be made not only about the beginning and end point of a change of state but also about their intermediate quantities at any time. From these values, relevant quantities can be derived, for

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**FIGURE 1** Implemented components of reference power plant.
example, the gradients of the steam temperatures, which are of decisive importance for thermal stresses and thus for the low-cycle fatigue of components. Moreover, statements can be made about the control quality as well as about overshoots or undershoots, which may be relevant for safe operation. The dynamic model was built with Dymola using the programming language Modelica. In the field of transient power plant modeling, Dymola is a proven simulation software. Dymola offers a graphical development platform and corresponding equation solvers. The DASSL (Differential-Algebraic System Solver) has been used for all simulation scenarios. Most models for the components of the power plant come from the noncommercial software ClaRa library (Clausius-Rankine Cycle). Important material data are from the TILMedia library. As with the block arrangement in the real plant, the dynamic model consists of several components involving a diversity of different physics. The general approach for all models involves the balance equations for mass and energy as well as a simplified momentum equation to calculate pressure drops. Using these equations as well as specific heat transfer assumptions for conduction, convection, and radiation and the fluid properties for the involved mediums (flue gas and water), a power plant process can be described on a fundamental basis.

A detailed explanation of physical backgrounds for all the basic models used here can be found in Refs [9,10] In addition to the model approach, all geometry data, material characteristics, characteristic fields for pumps and turbines, and the entire control system of the reference power plant are incorporated into the model. To reflect the reality as precisely as possible, the model is calibrated at the end of the parameterization by using measurement data. The result is a fully physical 0D-/1D power plant model that is individually tailored to the respective power station. The model components are usually discretized one-dimensionally if the temperature gradients are relevant. This is important, for example, when calculating the lifetime consumption. Detailed information can be found in Ref. [11]. Similar models for other conventionally operating power plants have already been used in the past to optimize control power products or to consider start-up and shutdown processes.

The reason for the development of such models is changing requirements for thermal power plants. In Germany, these power plants were mostly built in the 80s and 90s. Since then their operation has changed fundamentally. As you can read
in Ref. [15], the number of start-ups has increased dramatically, at the same time the number of full load hours has decreased. These effects are accompanied by a more frequent provision of control services.\textsuperscript{16} This is not least due to the growth of renewable energies.\textsuperscript{17} One response from power plant operators is to make power plants more flexible.\textsuperscript{18} To this end, various measures are tested and optimized in dynamic models prior to testing in the power plant. These include improvements for the supply of control power, as can be seen in Refs [16, 19–22]\textsuperscript{23,24} improvement of the start-up process,\textsuperscript{25,26} and the reduction of the minimum power.\textsuperscript{25,26} In addition, as\textsuperscript{27} shows, dynamic models can be used for analysis in case of changes in the power plant infrastructure, for example in the integration of thermal storages.

### 3.3 Dynamic process model

The process engineering in the model reflects that of the real plant. Physical phenomena are represented by model approaches. However, in some components simplified approaches are chosen. For simplicity, for example, the regenerative air preheater was omitted. Instead, the air inlet temperature of the boiler is described by a load-dependent characteristic line. Furthermore, the coal mill is included in the model as a self-priming beater-wheel mill, but the grinding process is not described by physical effects, but only by mathematical surrogate models on the basis of characteristic curves. The fluid volumes and metal masses that are important for the dynamic consideration are largely given by the consideration of the pipe wall thicknesses of all vessels and the consideration of long pipelines. Volumes and metal masses, which were omitted for reasons of computing efficiency, are nevertheless contained in subsumed form. A special feature is the use of process heat, which is mainly taken from extraction 4. The necessary process steam pressure is ensured via a valve upstream of the industrial plant. In the model, the factory is represented by a constant temperature level to which heat from the process steam is transferred. The corresponding system diagram can be seen in Figure 2.

The input variables for the model are parameters that can also be seen as such in the real power plant. The boundary conditions given to the model are the ambient air temperature, the ambient air pressure, the composition of the air, and the temperature of the cooling water reservoir. In addition, further variables are defined. These include the setpoint value for the electrical output, the district heating output and the process steam mass flow as well as the grid frequency, and the setpoint value for the secondary control power.

### 3.4 Control system

In order to comprehensively replicate the real plant, the process model was combined with the control system. The control system was largely taken from the plant documentation, using the Clara Control Library. Input variables for the control system are taken from the process model. For this purpose, it is necessary for the model to offer sufficient accuracy so that all control loops can operate within their control range. All control loops necessary for the operation of the power plant have been implemented, from the unit control, to the feedwater pump control, fresh air controls and the level controls of the two-phase tanks. The only simplification was to omit the paths necessary for starting up and shutting down the plant and for operation at very low load with supporting oil firing. In the current state of the model, the turbine speed control is not included either. The turbines run with a constant 3000 rpm. Mass inertia and running characteristics of the turbines are not shown, so no statement can be made about the change in the turbine speed. The model includes both the path of the turbine fast shutdown and the switch over from pressure to power control. Figure 3 shows the time sequence of a load shedding, after the event which led to the load shedding, up to the point where the power control is taken over to regulate the remaining demand.

### 3.5 Lifetime consumption

The dynamic power plant model allows the calculation of spatially resolved temperature fields in components as well as the determination of the applied pressure. Of particular interest are thick-walled boiler components, such as collectors and manifolds of the heating surfaces. Geometrically, these are ball and cylinder shells with branches (e.g., nozzles). By means of these temperature and pressure curves, the current material stresses can be derived. In a second step, the stresses...
obtained in this way can be used to make statements on component loading and service life up to the technical crack in accordance with the technical guideline DIN EN 12952. The corresponding procedure is explained in detail in Ref. [13] and will be taken up again in the following chapter.

3.6 Validation of the model

An important point in the application of models is the validation of the simulation data. The validation is a test for plausibility. During model development, the fundamental physical equations have to be checked. Input values such as heat transfer coefficients and fouling factors must also be critically examined at all times. Special attention must be paid to the fulfillment of the mass and energy balances during the evaluation of the subsystems and of the overall system. The final validation of this model was based on measurement data on a day when phases at full load and at partial load were available. They are therefore suitable for the validation of different operating points and also for the validation of dynamics. In total, measurement data for 70 different process variables were available. The accuracy of the model is best demonstrated by measured data from the real power plant and not in contrast to other models for two reasons. First, to the best of our knowledge, no other equivalent dynamic model of the reference power plant exists, and second, dynamic models of other power plants are not suitable for comparison because they either do not describe the same scenario or have been designed for other use cases. Consequently, the level of detail can differ significantly. However, a maximum tolerable deviation of 10% between the measured value and the simulation value is specified in Ref. [23]. This deviation is clearly undercut in the present model at all evaluated measuring points. The validation for the most important process variables is shown below.

Even after careful validation, the validity of the model cannot be proven for the respective application. However, when considering the simulation results for different scenarios, a relatively precise estimation of the significance of the subsequent simulation studies for similar application cases can be made. It must be noted that the measurement data used also contain considerable measurement uncertainties that cannot always be precisely quantified. These can be caused by, for example, calibration that is no longer valid or by sensor wear due to aging. With regard to the dynamics of the measured values, the error estimation of the measurements is made even more difficult. Although it is known that, for example, temperature sensors that are in an envelope or already covered with deposition layers have a certain dynamic of their own, this cannot be precisely quantified.

The following diagrams show the simulation results as dashed lines and the measured values as solid lines. In this validation scenario, the schedule serves as the input variable. As can be seen from the comparison, the generator power in the model is largely identical to that in the power plant. In Figure 4, the timetable of the power plant and the measured and simulated generator power are compared. The comparison of the main input variable (schedule) and the essential output variable (generator power) allows a comparison of the overall system dynamics. It can be seen that essential dynamic processes can be reproduced very accurately by the model. Both the ramp increases and the order of magnitude of the major process fluctuations can be represented by the model. The differences between simulation and measurement data at 14.5 hours can be caused, for example, by a slightly delayed start-up of a coal mill. It can also be seen that the calculated power slightly overshoots or undershoots during load changes in the model (see the points in time at 12.5 hours and 13.25 hours). These overly large power amplitudes result from the intervention of the enthalpy correction of the feedwater flow, which in the real power plant reacts to strand imbalances. In the existing model, the strings are not resolved so this effect cannot be considered.

Figure 5 shows the feedwater mass flows as a comparison of measurement and simulation. The graph also includes the precontrol value specified by the feedwater control. Here, the effect of the control loop is shown in relation to the previously discussed simplification with regard to the line imbalances. It could be shown in Ref. [25] that these can also be proven by means of 0D/1D simulations. Here, too, it can be seen that the
fundamental dynamics of the process can be reproduced and that the components involved were correctly modeled.

Figure 6 shows the pressure curves of the water-steam cycle when entering the boiler after the evaporator and of the live steam. Again it can be stated that the simulated data largely agree with the measured data, especially with regard to the boiler inlet and outlet. In partial load, a nearly constant offset can be determined, which amounts to approximately 4% of the nominal pressure. This can be caused by a slightly different absorption capacity of the turbines or by a discrepancy in the pressure loss models.

The validation data in Figure 7 concern a completely different area of the power plant. The oxygen content in the flue gas can be seen here. This depends on the combustion air ratio and thus on the air inflow into the combustion chamber. This parameter is controlled via the lambda control in the secondary air control loop.

In addition to the variables shown, temperatures, valve positions, injection mass flows, and various enthalpies were also compared in a comprehensive validation. In order to statistically record the results obtained, the operating modes were divided into five categories: Full load, medium load, partial load, low load, and load change. This showed that the greatest deviations always occurred during load changes. The largest deviations occurred in the hot reheat pressure, but the deviations in 95% of the load cycle times were less than 11% compared to the nominal hot reheat pressure and less than 4.6% in 50% of the time. All other state variables showed minor deviations even during load changes.

The power plant was able to prove its island operational capability in a test run in 2004. Since the load shedding is a very complex scenario in which many parameters change very quickly and are partly outside the normal ranges, a validation according to this scenario makes sense. However, only a few process variables are available for this purpose. Process steam decoupling was not active at this point. At the time of load shedding, the unit control reacts and goes from the usual pressure control to power control. The upper available load is reduced to 50% as a result of the load shedding with a very high gradient. HP and MP turbine valves close and as a result both the high- and the low-pressure bypass valves open and prevent an inadmissible pressure increase in the boiler. Another consequence is the very rapid reduction of the generator power to 5% of the nominal power. This process can also be described very well with the model, as Figure 8 shows.

Figure 9 shows the pressures at the inlet and outlet of the HP turbine valve. Shortly after the load shedding is triggered, the live steam pressure rises and then drops by more than 50% within 15 minutes. In view of its complexity over time, this effect can be reproduced very well in the model. Both the pressure peak and the stationary value—measured after 30 minutes—can be displayed with very small deviations by the model. With regard to the HP turbine inlet pressure, a stationary offset is noticeable. This can be explained by an
evacuation of the turbine stage, which is not implemented in the model.

Figure 10 shows the live steam temperature as well as the hot reheat temperature. Both temperature curves cross during the scenario. This trend and the steady-state temperatures are also reproduced very accurately by the model. Temperature peaks can only be read in the model but not in the measurement data. As already described, this can be related to the inertia of the temperature measurements but can also be caused by inaccurate parameterization of the high-pressure turbine bypass injection cooler.

4 | RESULTS

With the help of the model, a number of investigations were carried out regarding the load-shedding scenario. The starting point is the deactivation of the process steam decoupling during the load-shedding test. At the core of the simulations shown here is the question at which level process steam can be decoupled during the described scenario. Three scenarios are compared with each other. 1. A load shedding to 9% of the nominal power and 2. A load shedding to 4% of the nominal power. The third scenario is a load shedding to 4% of the nominal power with simultaneous further throttling of the flap to 10% instead of the minimum opening degree of 21.5% specified in the control system. The generator power is congruent with Figure 8. The load shedding takes place after five minutes as in the validation. In contrast to the validation calculation, the generator power was 75% of the nominal power at the beginning of the scenarios. This has no effect on the qualitative course of the variables.

Figure 11 shows the feedwater flow in the three scenarios. Due to the reduction of the upper available load to 50%, there is also a reduction of the feedwater mass flow. In the course and the values, the three scenarios hardly differ. The simulation shows the lowest mass flow, with the simulation of the load shedding at 4% of the nominal power. The highest value can be determined in the scenario with the highest output.

There are two reasons for the slightly varying feedwater mass flows. First, due to the required output, a higher steam mass flow in the IP and LP turbine section is required, and second, the process steam decoupling is influenced by the varying degree to which the throttle flap closes. Closing the throttle flap strongly increases the pressure in the IP turbines and more process steam is decoupled. Figure 12 shows this effect. The possible decoupling of process steam is almost linearly dependent on the turbine mass flow. Thus, the decoupling in the scenario with 9% of the nominal power with otherwise unchanged boundary conditions is in any case higher than the decoupling with a lower output. This trend can only be broken by additional interventions in further control variables such as closing the throttle flap. In Figure 12, it can even be seen that with a minimum opening degree of the throttle flap of only 10%, the decoupled mass flow can be significantly increased. However, it should also be noted that break-ins at the time of the load shedding, even down to 0 kg/s cannot be completely excluded, but the stronger closing of the throttle flap also has a positive influence here.

Although the stronger closing of the throttle flap leads to positive effects in terms of process steam decoupling, it has a negative influence on operational safety. During the scenario, there is a risk of plant shutdown due to high exhaust steam temperatures in the turbine stages, initiated by the safety control system. These result from insufficient heat transfer due to low steam mass flows. By closing the throttle flap, the steam
mass flow through the LP turbines is further reduced, which in turn leads to higher exhaust steam temperatures, as can be clearly seen in Figure 13 using the example of the LP turbine 3. It is valid that a high steam mass flow in the corresponding turbine area leads to a lower increase in exhaust steam temperatures. In this respect, a high output, after a load shedding, is also an advantage.

5 | LIFETIME CONSUMPTION

Since this scenario represents an exceptional situation, a plant-friendly operating mode, which avoids lifetime consumption, can be the aim. However, due to the fast switching and control of many valves and process variables in a short time, this scenario will inevitably have an influence on the lifetime of many components. The turbines are protected from excessively high exhaust steam temperatures by control systems, so there is a risk of a complete shutdown especially with large process steam decoupling, but no direct damage to the turbine blades is to be expected. It is also true that the vast majority of power plant components are capable of withstanding the stresses during load shedding. Critical component stresses are to be expected for thick-walled components. Ref. [29] gives an overview of the occurring damage mechanisms. The focus of this consideration is the evaluation with regard to the lifetime consumption resulting from the low-cycle fatigue according to DIN EN 12952.28

The dynamic power plant model allows the calculation of spatially resolved temperature fields in components as well as the determination of the applied pressure. The current material stresses can be derived from these temperature and pressure curves. In a second step, based on DIN EN 12952, these can be used to make statements about the component stress and lifetime. The differences between internal and external pressure as well as the mean wall thicknesses and mean diameters are decisive for the calculation of mechanical stresses; for thermal stresses, the temperature differences within a component must be taken into account.

Finally, the total stress of a component is determined and classified. According to the guideline, this is associated to and compared with the material-immanent SN-curve. The result is, on the one hand, the ratio of the stress range with the fatigue strength and, on the other hand, the low-cycle fatigue in equivalent operating hours.

Figure 14 shows the occurring pressure amplitudes relative to the nominal live steam pressure during the scenarios. By the reduction of the upper available load, the heat output of the boiler and thus the load are reduced. In the sliding pressure method, these are directly proportional to the pressure amplitudes. Pressure amplitudes of up to 44% are reached by undershoots. The absolute pressure amplitudes or the relative pressure amplitudes shown in the diagram compared to the nominal live steam pressure are rather low in the case of the throttle flap due to the already low-pressure level. However, this is where the highest wall temperature differences occur.

In addition to the fact that the pressure amplitudes are at the same level in all scenarios, no clear trend can be identified in the scenario comparison. The largest differences can still be seen in the MP turbine valve. On this component, the pressure amplitudes are particularly high with low output power.

The ratio of stress range and fatigue strength, shown in Figure 15, results from the pressure amplitudes shown and the temperature amplitudes not shown here, taking into account many other parameters (eg, surface roughness, weld seams, etc).

As a general rule, if the stress level exceeds the fatigue strength, the components will be damaged. This is the case in the diagram for values above 100%. Thus, component damage to the HP preheaters 6 and 7, the deheater, and the throttle flap can be detected, with clear differences. The HP preheater 6 and the deheater are subjected to the highest stresses, while the HP preheater 7 and the throttle flap are exposed to significantly lower stresses. The simulation data show no fatigue stresses above the fatigue strength in the entire boiler as well as on the HP and MP turbine valves and the bypass valves which are not shown here.

This information leads to the representation of the lifetime consumption in equivalent operating hours (EOH) in Figure 16, where the total lifetime of a component was assumed to be 200 000 hours. Due to the geometry data of the HP preheater 7, the damage occurring at this point is relatively small. The preheater has a lifetime loss of approx. 10 hours. The deheater and the HP preheater 6 have to endure significantly greater lifetime consumption, with a lifetime loss of approx. 62 and 80 hours respectively.

In a comparison of the three scenarios, the variant with 4% of the nominal output and a minimum permissible throttle flap opening degree of 21.5% has to accept slightly lower lifetime losses. However, these differences are only small, and therefore, it appears unnecessary to make any changes because of them.
A very comprehensive dynamic model of a lignite-fired power plant has been developed as presented in this paper. The model allows a diversity of applications focusing on dynamic operation, for example, analysis of a load-shedding scenario and the corresponding calculation of lifetime consumption. It has been shown that when evaluating the load-shedding scenario with simultaneous process steam decoupling, two effects must be reconciled. On the one hand, the height of the turbine exhaust steam temperatures rises due to low mass flows through the turbine stages; this effect is represented by the model and can be quantified. On the other hand, the continuous supply of process steam to the industrial plant during load shedding is not ensured at all times. The stationary level of decoupling and the temporal behavior of the process steam mass flow can be influenced by the throttle flap. Further closing of this valve, however, has a negative influence on the flow through the turbine stages after the decoupling.

For future investigations, a compromise has to be found in this respect: It is conceivable to accept a lower degree of opening of the throttle flap for a certain period of time in order to decouple process steam at any point in time independently of the power output. The most important criterion must be operational safety; therefore, even in such scenarios, the maximum exhaust steam temperatures should not be reached at any turbine stage. The presented results should be applied especially in different transmission networks, and the load-shedding algorithms should be examined without considering the restrictions of the connected producers. Thus, further improved algorithms could be implemented by a combination of network control and generator control. First points of contact can be found in Refs [6,7].

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REFERENCES
1. Bittner M, Bagert M, Emmerich J, et al. Elektrischer Eigenbedarf, 3 Auflage. Berlin, Germany: VDE Verlag; 2012.
2. Berndt H, Hermann M, Kreye H, Reinisch R, Scherer U, Vanzetta J. Transmissioncode. 2007.
3. Usoro PB, Rouhani R, Mehra RK, Varaiya P. Power system modeling for emergency state simulation. Math Model. 1983;4:143-165.

FIGURE 14 Pressure Amplitudes, during a load shedding on 9% respectively 4% of nominal power, and a minimum Throttle Flap Opening of 21.5% respectively 10%.

FIGURE 15 Stress Range in Relation to Fatigue Strength, during a load shedding on 9% respectively 4% of nominal power, and a minimum Throttle Flap Opening of 21.5% respectively 10%.

FIGURE 16 Load Cycle Fatigue in Equivalent Operating hours, during a load shedding on 9% respectively 4% of nominal power, and a minimum Throttle Flap Opening of 21.5% respectively 10% (1 EOH = 1/200 000 of total Lifetime).
4. Maslo K, Hruska Z. Control strategies for power system in Island operation. *J Energy Power Sources*. 2015;2(3).
5. Sapar AF, Gan CK, Ramani AN. Modelling and simulation of Islanding detection in microgrid. *IEEE Innov Smart Grid Tech*. 2014.
6. Malikowski R, Niznanski J. Underfrequency load shedding: an innovative algorithm based on fuzzy logic. *MDPI Energies*. 2020;13(6):1456.
7. Choi Y, Lim Y, Kim H-M. Optimal load shedding for maximizing satisfaction in an Islanded microgrid. *MDPI Energ*. 2017;10(1):45.
8. Neumann P, Maslo K, Sulc B, Jarolimek A. Power system and power plant dynamic simulation. *IFAC Proc Volumes*. 1999;32(2):7294-7299.
9. XRG GmbH: ClaRa Documentation. XRG GmbH, 2019.
10. Effenberger H. Dampferzeugung, Dresden, 1999.
11. Richter M, Berndt A, Mutschler P, Hübel M, Nocke J, Weber H, Hassel E. Regelleistungsverschleißmodell für primär- und sekundärgeregelte thermische Kraftwerke im ENTSO-E Netz. Rostock, 2015.
12. Hübel M. Verbesserung des transienten Betriebsverhaltens und der Systemdienstleistungsbereitstellung thermischer Kraftwerke mittels dynamischer Simulation. Dissertation, Rostock, 2016.
13. Kuhn B, Fischer T. Ermittlung von Kennwerten zur Bewertung des thermischen Ermüdungsrisswachstums. TIB, 2017.
14. Hübel M, Ziems C, Berndt A, Richter M, Gierow C, Nocke J, Hassel E, Weber H. Effects of integrating large amounts of wind and solar energy on conventional power plants and optimisation strategies for this new challenge. 13th Wind Integration Workshop November 11th-13th, Berlin, pp. 14-19., 2014.
15. Ziems C, Huber M, Weber H. Combining lp and mip approaches to model the impacts of renewable energy generation on individual thermal power plant operation, Power and Energy Society General Meeting (PES), IEEE, 2013.
16. Nassar I, Al Ali S, Weber H. Effects of increasing intermittent generation on the frequency control of the European power system, 19th World Congress The International Federation of Automatic Control, 2014.
17. Richter M, Möllenbruck F, Obermüller F, Knaut A, Weiser F, Lens H, Lehmann D. Flexibilization of steam power plants as partners for renewable energy systems, Power Systems Computation Conference (PSCC), IEEE, pp. 1-8, 2016.
18. Hentschel J, Babi U, Spliethoff H. A parametric approach for the valuation of power plant flexibility options. *Energy Rep*. 2016;2:40-47.
19. Hübel M, Meinke S, Berndt A, Richter M, Mutschler P, Nocke J, Hassel E, Weber H, Funkquist J, Sander M. Modelling a lignite power plant in modelica to evaluate the effects of dynamic operation and offering grid services, 10th International Modelica Conference, Lund, 2014.
20. Hübel M, Nocke J, Hassel E, Meinke S. Identification of energy storage capacities within largescale power plants and development of control strategies to increase marketable grid services, ASME PowerEnergy Conference, San Diego, 2015.
21. Gottelt F. Werkzeuge zur Bewertung von Kraftwerkseinspruchungen bei windbedingt gesteigerten Dynamikanforderungen. Dissertation, Rostock, 2010.
22. Hentschel J, Zindler H, Spliethoff H. Modelling and transient simulation of a supercritical coal- ed power plant: Dynamic response to extended secondary control power output. *Energy*. 2017;137:927-940.
23. Hübel M, Meinke S, Andren M, et al. Modelling and simulation of a coal-fired power plant for start-up optimisation. *Appl Energy*. 2017;208:319-331.
24. Meinke S. Modellierung thermischer Kraftwerke vor dem Hintergrund steigender Dynamikanforderungen aufgrund zunehmender Windenergie- und Photovoltaikleistung. Dissertation, Rostock, 2012.
25. Prause J H, Hübel M, Holtz D, Nocke J, Hassel E. Local steam temperature imbalances of coal-fired boilers at very low load. *Energy Proc*. 2017;120:439-446.
26. Gierow C, Hübel M, Nocke J, Hassel E. Mathematical model of soot blowing inuences in dynamic power plant modelling, 11th International Modelica Conference, Paris, 2015.
27. Richter M, Oeljeklaus G, Görner K. Improving the load flexibility of coal-fired power plants by the integration of a thermal energy storage. *Appl Energy*. 2019;236:607-621.
28. DIN EN 12952, Wasserrohrkessel und Anlagenkomponenten Teil 3: Konstruktion und Berechnung für drucktragende Kesselteile, 2011.
29. Richter, M, Berndt, A, Mutschler, P, et al. Regelleistungsverschleißmodell für primär- und sekundärgeregelte thermische Kraftwerke im ENTSO-E-Netz. Rostock: University of Rostock; 2015.

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