

Abstract

To keep our planet livable, hundred and seventy-five nations worldwide, including Europe, have committed to drastically reducing greenhouse gas emissions. The work at hand participates with the energy transition toward decarbonized electricity production by providing a method to analyze the incentives for the thermal fleet to contribute. Given the liberalized economic environment Europe and other countries have put in place, the work at hand analyzes the signals set by the energy markets to investors and power plant operators regarding flexible power plant operation and the future requirement of power plant flexibilisation, with improvement suggestions.

This work contributes to the field of energy system analysis and operations research. First, a methodological framework for quantitative, long-term, high-resolution techno-economic assessments of an individual power plant's operational flexibility is put in place. Instead of relying on single metrics, this method uses the power plant's unit commitment and economic dispatch for flexibility valuation. Depending on the desired insight, different metrics might be derived from the plant dispatch. The single unit, self-scheduling problem of a merchant power plant solved from a price-taker perspective developed in this work includes the intraday and frequency control markets, as well as a parametric power plant model suited for operational flexibility assessments. The model accounts, among others, for the degraded power plant efficiency at part-load. In addition, significant aspects, like the variation of start-up costs as a function of the market prices are included. Improved opportunity cost calculation methods including part-load efficiency degradation for the optimization of capacity reservation in the frequency control market are developed. Quantitative analyses demonstrate that comprehensive flexibility studies should include intraday and frequency control markets. The developed concepts might also be implemented in models solving other types of unit commitment problems than the single unit self-scheduling problem. The proposed formulations are suited for the state-of-the-art mixed integer programming approach. The work at hand, however, introduces an alternative approach. Acknowledging that the power plant operation is a controlled process with a finite number of states and transitions, the concept of events is used to overcome uniform time discretization. This event-based approach requires less computation

time than time-discrete approaches when simulating long time horizons.

The work's practical relevance is illustrated in the retroactive observation of how the merchant power plants react to the markets in their operation strategies. The case studies show that the day-ahead markets incent a conventional power plant's flexible operation at increased shares of renewables, but currently do not compensate for the profit difference resulting from this system-friendly dispatch. The analyzed frequency control and intraday markets help in improving the day-ahead profit and monetary value of power plant flexibilization. The design of the frequency control capacity reservation market is shown to benefit more power plants (renewables as well as conventional ones) when the capacity reservation duration is short. The value of operational flexibility improvements is quantified using various metrics, for different technologies and market environments. These case studies indicate that if investors further expect a three to five-year return on investment, the existing conventional fleet is unlikely to experience a significant flexibilization.

Kurzfassung

Um den Planeten lebenswert zu halten, haben sich weltweit hundertfünfundsiebzig Nationen, und insbesondere die Europäische Union, dazu verpflichtet, die Treibhausgasemissionen drastisch zu reduzieren. Die vorliegende Arbeit untersucht den Beitrag thermischer Kraftwerke zum Aufbau einer dekarbonisierten Stromerzeugung. Vor dem Hintergrund der Liberalisierung der Energiewirtschaft in Europa und anderen Ländern werden die bestehenden Anreize der Energiemärkte für Investoren und Kraftwerksbetreiber zum flexiblen Betrieb der Kraftwerke, sowie ergänzende Maßnahmen zur Kraftwerksflexibilisierung analysiert und Optimierungen vorgeschlagen.

Es wird ein methodischer Rahmen für eine quantitative, langfristige und hochaufgelöste technoökonomische Bewertung der betrieblichen Flexibilität eines einzelnen Kraftwerks vorgeschlagen. Anstatt sich auf eine Metrik zu konzentrieren, verwendet die hier vorgeschlagene Methode eine Kraftwerkseinsatzplanung zur Flexibilitätswertung. Abhängig von der gewünschten Erkenntnis können unterschiedliche Metriken aus dem Kraftwerkseinsatz abgeleitet werden. Das in dieser Arbeit entwickelte, aus einer Preisnehmerperspektive herausgelöste Problem des Einsatzes eines Kraftwerks, umfasst die Intraday- und Regelleistungsmärkte sowie ein parametrisches Kraftwerksmodell, das für betriebliche Flexibilitätsanalysen geeignet ist. Das Modell berücksichtigt unter anderem den reduzierten Kraftwerkswirkungsgrad bei Teillast. Darüber hinaus sind wesentliche Aspekte wie die Veränderung der Anfahrkosten in Abhängigkeit von den jeweiligen Marktpreisen enthalten. Verfeinerte Verfahren zur Berechnung der Opportunitätskosten, einschließlich einer Verschlechterung des Teillast-Wirkungsgrads für die Optimierung der Kapazitätsvorhaltung auf dem Regelleistungsmarkt, werden vorgestellt. Quantitative Analysen zeigen, dass Berechnungen ohne Intraday- und Regelleistungsmärkte gegebenenfalls den Wert der betrieblichen Flexibilität unterschätzen würden. Die in der vorliegenden Arbeit entwickelten Konzepte sind für alle Betrachtungsweisen der Kraftwerkseinsatzplanung geeignet. Diese Konzepte sind in der üblichen zeitdiskreten Formulierung der gemischt-ganzzahlige Kraftwerkseinsatzoptimierung implementierbar. Ein darüberhinausgehender Ansatz wurde vorgeschlagen. Da der Kraftwerksbetrieb ein kontrollierter Prozess mit einer endlichen Anzahl von Zuständen und Übergängen ist, wird ein ereignisbasierter Ansatz verwendet, um die Notwendigkeit einer einheitlichen Zeitdiskretisierung

rung zu überwinden. Der hier gewählte Ansatz erfordert gegenüber dem zeitdiskreten Ansatz weniger Rechenzeit bei der Simulation langer Zeiträume.

Die praktische Relevanz der vorliegenden Arbeit liegt in der auf historischen Datensätzen basierten Simulation, wie Kraftwerke in ihren Betriebsstrategien auf die Märkte reagieren. Fallstudien zeigen, dass die Day-Ahead-Märkte den flexiblen Betrieb eines konventionellen Kraftwerks bei erhöhten Anteilen erneuerbarer Energien fördern, aber derzeit die Gewinndifferenz, die sich aus diesem systemfreundlichen Betrieb ergibt, nicht kompensieren. Die analysierten Regelleistung- und Intraday-Märkte tragen dazu bei, den Day-Ahead-Gewinn und den Geldwert der Flexibilisierung von Kraftwerken zu verbessern. In der vorliegenden Arbeit wird gezeigt, dass der Regelleistungsmarkt mehr Kraftwerke (sowohl erneuerbare als auch konventionelle Kraftwerke) nutzt, wenn die Kapazitätsreservierungsdauer kurz ist. Der Wert der Verbesserungen der betrieblichen Flexibilität wird anhand verschiedener Metriken für verschiedene Technologien und Marktumgebungen quantifiziert. Diese Fallstudien deuten darauf hin, dass der bestehende Park konventioneller Kraftwerke wahrscheinlich keine signifikante Flexibilisierung erfahren wird, wenn die maximale Amortisationszeit der Investoren weiterhin drei bis fünf Jahre betragen darf.

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Part A

Theoretical work foundation





1 Motivation

1.1 Energy system decarbonization

1.2 The operational flexibility challenge

1.2.1 Overview of flexibility definitions

1.2.2 The operational flexibility providers

1.3 Liberalized market environment

1.4 Research question

To keep our planet livable, hundred and seventy-five nations worldwide, including Europe, have committed to limiting the global temperature increase by drastically reducing anthropogenous greenhouse gas emissions. The current resource we are relying on globally to produce electricity and heat is the most carbon-intensive one: coal. In 2015, coal accounted for 39.3% of the world's electricity production and for 44.9% of the world's CO₂ emissions from fuel combustion[1]. Electricity and heat accounted for 42% of the global CO₂ emissions in 2015 [2]. The energy sector's logical contribution to climate protection targets is thus to reduce, and ultimately eliminate, the use of greenhouse gas emitting fuels for electricity production in favor of clean ones. This transition is a very challenging (and crucial) one. The author wishes to concur to the success of this transition by providing a method to analyze the incentives for the thermal fleet to contribute.

The most apparent challenge raised by the energy transition when relying on variable renewable energy sources is the intermittency they introduce in the system, and thus the increasing need for operational flexibility. Given the liberalized economic environment Europe and other countries have put in place, the work at hand analyzes the signals set by the energy markets to investors and power plant operators regarding flexible power plant operation and the future need for plant retrofitting. The author aims to put in the hands of everyone (either the ones who believe that there should be absolutely no incentive for these plants to remain or the ones who believe that we will need them for a long time) a method to quantitatively assess the incentives for flexible operation.

This thesis is divided into three parts: the theoretical work foundation, the development of the methods and concepts and finally