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Increasing energy flexibility of manufacturing systems through flexible compressed air generation

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Abstract

A continuing increase in energy supply from variable renewable energy (VRE) sources requires new strategies to match energy supply and demand. Demand response (DR) strategies focus on flexibilizing energy demand. In this context, manufacturing systems can be designed and controlled to achieve a better fit between energy demand and volatile supply. To maximize energy flexibility, not only manufacturing processes but also auxiliary systems such as compressed air (CA) supply offer opportunities for DR actions. Nonetheless, dynamic behavior and dependencies between manufacturing processes, auxiliary services and resulting overall energy demand requires an integrated approach. This paper presents a method to control production systems and CA supply to increase energy flexibility while maintaining manufacturing system throughput and considering dynamic system dependencies. A production system with several processes, buffers and CA supply system is modeled and simulated in a mixed continuous-time and discrete-event environment. Energy control strategies are implemented and their effectiveness is evaluated. A case study is used to demonstrate that VRE integration can be improved through process and CA supply control without compromising throughput. A focus is set on CA supply and its influence on energy flexibility: the effect of increased CA system volume and additional compressor capacity is investigated.

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Keywords: Manufacturing system simulation; energy flexibility; demand response

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1. Introduction

In 2010, industry was the largest contributor of direct and indirect annual greenhouse gas emissions of all sectors. Industrial emissions summed up to 28.6% of the global 49.5 $GtCO_2eq/yr$ emissions, of which 18% were direct emissions and 10.6% indirect emissions through electricity and heat production [1]. As a result, reducing emissions from industry plays a vital role for mitigating climate change. Aside from enacting measures addressing energy intensity and efficiency of industry, low carbon energy and electricity supply such as renewable energy (RE, e.g. biomass, solar/wind energy) are regarded as central strategies for reducing overall carbon emissions and increasing energy independence [2]. Some of these RE sources are so called variable renewable energy (VRE) sources (e.g. wind). VRE sources are characterized by temporarily changing availability, non-dispatchability and largely decentralized generation capacities (both RE and VRE) [2].

A special challenge emerges when VRE sources start to supply a substantial share of electricity within a power system (e.g. in Denmark or Germany) or if locally generated VRE ought to be directly consumed (decentralized generation) to avoid transportation requirements. As VRE output can change significantly and electricity demand can be relatively inelastic, solutions have to be found to overcome local and temporal demand-supply mismatches. In the context of high VRE penetration, two general strategies are (1) storing electricity for later demand or (2) reshaping demand to better match supply, also known as demand response (DR) [3]. Storing electricity for later use generally reduces efficiency due to conversion inefficiencies or might simply be unavailable (i.e. pumped hydropower requires suitable geological characteristics). Reshaping demand can be a viable strategy as inefficiencies might be lower. Further, a flexible demand enables additional strategies such as pricing arbitrage (shifting electricity demand from high prices to times with low prices), control and reduction of peak demand or participation in reserve capacity markets. In the context of unstable or unavailable grid supply, energy flexibility can contribute to an energy-autarkic production. However, restrictions need to be considered (i.e. fulfilling production targets, area illumination if

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people are present).

In the light of the above, this paper suggests a methodology to increase use of decentralized VRE generation by re-shaping electricity demand of a typical manufacturing system. Strategies include controlling manufacturing and auxiliary services, in this case compressed air (CA) generation, to match limitedly available VRE supply. A special focus is set on the impact of different CA system set-ups, such as CA generation capacity and CA storage.

2. State of research

Utilization of compressed air to store (electrical) energy during off-peak demand periods has been known and implemented for several decades. Compressed air energy storage (CAES) plants use electricity to compress air into an underground cavern, which can be discharged through a gas turbine and thus converted back to electricity when required. Integration and economic feasibility in a renewable energy system has been investigated e.g. in [4] and [5]. An implemented solution is the first CAES plant in Huntorf, Germany (290 MW turbine output), built in 1978 [6]. The plant was initially planned to store energy from nuclear and fossil fuel base load plants, but can also be used to store energy from VRE. A second plant built in McIntosh, Alabama, USA (110 MW plant) started operation in 1991. Conversion efficiency and therefore economic feasibility are major challenges for CAES, which has led to technology improvements. Currently, advanced adiabatic compressed air energy storage technology (AA-CAES) is ready for large-scale testing, with an expected conversion efficiency of approx. 70% [7–9]. Another lead are isobaric conversion cycles, namely the isobaric adiabatic compressed air energy storage plant with combined cycle (ISACOAST-CC), which can reach a conversion efficiency of 80% [9,10].

In contrast to above mentioned technologies, industrial CA generation can be used to store electricity by producing CA, storing the air and utilize the stored energy e.g. in manufacturing machines. The inherent difference is the avoidance of an additional conversion cycle and related losses. Assuming that industrial applications require CA independent of CA availability, CA generation is mandatory to sustain operations. As such, shifting CA generation to periods with e.g. low energy prices or high VRE availability results in only one electrical conversion cycle, which would have been also required without shifting CA production. In a broader context, the described strategy falls under demand side management (DSM), in particular DR. DSM strategies aim at influencing customers' electricity use (amount and time of use), while DR, as part of DSM, aims at shifting electricity demand (without necessarily reducing total energy demand). For an overview and classification of DSM and DR see e.g. [11] or [12].

Within the area of DSM, a special focus has been set on energy efficiency of CA supply rather than electricity demand shifting of compressed air supply systems. For a comprehensive literature review on energy used for CA generation and saving opportunities see e.g. [13]. An example for demand shifting (DR) of CA generation can be found in [14]. Electricity price arbitrage is enabled through shifting CA production. Different pressure levels and tank sizes are evaluated against total energy demand and energy costs. A static price threshold is used to control the compressor, the CA demand profile is taken from measurements, and the main focus is on thermodynamic modeling.

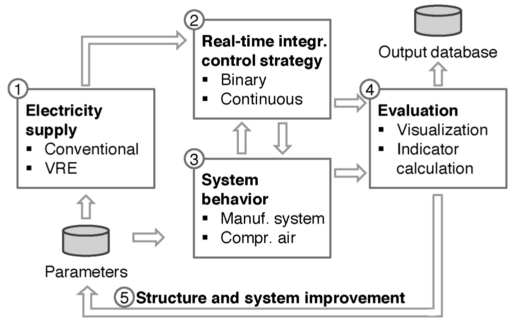

Fig. 1: Structural overview of proposed control and improvement concept.

In order to provide an integrated method to utilize manufacturing systems with connected CA generation for DR purposes under (decentralized) VRE generation, a real-time control for energy demand of processes and compressors under dynamic electricity availability is proposed. The concept is an integrated method which considers electricity demand from CA generation and processes together with variable CA demand from processes. A real-time control strategy has been chosen as planning and optimization approaches require forecasting of VRE availability. Forecasting errors and short-term supply changes are unavoidable, which constitutes the requirement of a real-time method to enable implementation into a manufacturing execution system.

3. Real-time control simulation and system improvement concept

The proposed concept has the goal to foster integration of VRE through flexible electricity control of manufacturing processes and a connected CA supply system. A structural overview of the concept can be found in figure 1. To improve integration of VRE, two main methods are proposed: (a) a real-time integrated control strategy and (b) structural and system optimization to support the control strategy. The concept utilizes recorded VRE supply data and grid supply parameters (*1. Electricity supply* in figure 1) as input for the control strategy (*2. Real-time integrated control strategy*). The control algorithm controls manufacturing processes and compressors according to available own VRE generation. Dynamic system evolution and behavior is determined depending on initial parameters and control signals, and system information is fed back to the control module (*3. System behavior*). Both the control module and system behavior provide input for evaluation of the system and its energy control (*4. Evaluation*). Alteration of input parameters, control method and system set-up is used to improve integration of VRE by evaluating indicators for different input factors and set-ups (*5. Structure and system improvement*). In the following, the different elements are described. Further detail on proposed control strategy (without CA generation) can be found in [15] (submitted paper).