Applied Energy 205 (2017) 210–224

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Model-based investigation of residual load smoothing through dynamic electricity purchase: The case of wastewater treatment plants in Germany

Maximilian Seier*, Liselotte Schebek

Technische Universität Darmstadt, Institute IWAR, Franziska-Braun-Straße 7, 64287 Darmstadt, Germany

HIGHLIGHTS

- Wastewater treatment plants (WWTPs) residual load smoothing potential was assessed.
- WWTP-site-specific, individual restrictions were acquired and used.
- Transferable residual load smoothing indicators were defined.
- German WWTPs residual load smoothing potential reaches significant dimensions.

ARTICLE INFO

Keywords:
Load shifting
Demand side management
Electricity price modeling
Residual load smoothing

ABSTRACT

Energy systems with a high share of renewable electricity generation face a challenge associated with surplus electricity generation. Flexibility options may help to integrate renewable electricity and reduce the need for electricity from fossil fuels. Load shifting is one of the flexibility options that lead to residual load smoothing in energy systems. In this paper, the effects of load shifting by dynamic electricity purchase on future residual load smoothing was assessed using wastewater treatment plants (WWTPs) in Germany as a case study. As dynamic electricity purchase is motivated economically, a consumer's demand for supplying flexibility options needs a price signal. Therefore, electricity wholesale prices on an hourly basis were modeled for 2030 using a merit order simulation for two scenarios. Relevant data for WWTPs was obtained from primary data suppliers, which was then aggregated. The effects on residual load smoothing were assessed by optimizing WWTPs electricity purchase costs on a daily basis. Our results show that German WWTPs have a potential to integrate 120 MW_{el} of surplus electric power. The developed methodology has a high potential to be applied to other potential load shifting actors when assessing the potential of residual load smoothing and renewable electricity integration. This can be achieved by adapting boundary constraints to other electricity consumers.

1. Introduction

Power from wind energy and photovoltaics is an important pillar of mitigation policies for climate change worldwide. In contrast to conventional, fossil fuel fired power plants, wind power and photovoltaics are fluctuating energy sources that are not controllable in terms of the time when electricity is produced. Therefore, high shares of wind power and photovoltaics lead to a discrepancy between electricity supply and electricity consumption in the temporal dimension. This discrepancy is known as residual load, which defines the current electricity consumption minus the current feed-in of renewable electricity. In conventional energy systems, the compensation of residual loads is usually performed by fossil fired power plants, pumped storage power plants or by export and import between different grids, respectively. However, with rising shares of fluctuating renewables these capacities are limited. Today, in case of positive residual load, i.e. a lack of electricity supply by renewables, electricity is increasingly produced by gas- but also coal-fired power plants [1]. In case of negative residual loads, the surplus electricity from wind or photovoltaics is lost by curtailment of the plant [2–7]. The use of surplus electricity through storage but notably further flexibility options in the power system is therefore of economic interest and is currently strongly targeted by science and politics [8–14]. Here, flexibility means to shift surplus energy of renewables from periods of low demand to periods of high demand, in other words from periods of negative residual load to periods of positive residual load [11]. This strategy is termed as the so-called *residual load smoothing* (RLS).

* Corresponding author.
E-mail address: m.seier@iwar.tu-darmstadt.de (M. Seier).

http://dx.doi.org/10.1016/j.apenergy.2017.07.116
Received 19 May 2017; Received in revised form 13 July 2017; Accepted 26 July 2017
0306-2619/

Table 1
Examples for constraints limiting the load shifting for several applications.

Electric vehicles	Industry	Households
• Battery Capacity • Desired (user-required) maximum charging time • Initial charging status • Desired final charging status	• Start-up/shut-down times of processes • Warehouse capacity/current warehouse stock • Production electricity demand	• Electricity demand of device for load shifting • User behavior: maximum acceptance for the delay of a service, e.g. a washing machine

1.1. Technological background of load shifting

One flexibility option for RLS is *load shifting* (LS) on the consumer side, which is embedded in the concept of demand side management (DSM) [15]. DSM in general comprises different measures to "influence the time pattern and/or amount of electricity demand in ways that will increase customer satisfaction, and coincidentally produce desired changes in the utility's system load shape" [16]. LS means the temporary shift of electricity demand of a consumer, e.g. an industrial production process, which contributes to RLS of the grid LS, and is seen as a feasible and economically advantageous alternative to energy storage systems since it uses the existing technology and infrastructure of the consumer [11].

As LS uses capacities of plants or processes not intended explicitly as storage systems of the grid, it is restricted by constraints set by the respective technology and application (Table 1). These technology-specific restrictions necessarily have to be considered in order to estimate potentials of RLS from a specific type of consumer.

Various studies have investigated potentials and penetration barriers for LS and RLS, respectively, in different countries [17–22] as well as for different consumer types, e.g. electric vehicles [23–29], industrial applications [30–35] or households [36–42]. While some studies consider potentials as rather minor [17,18], others state that LS bears significant contributions to RLS if the economic framework sets the necessary incentives [43]. As a general insight, studies concluded that the benefit from LS for RLS is highly depending from the respective grid and consumer type under consideration. However, methodology of previous studies did not include two important issues which describe the interaction of grid and consumer and thus are most important for the assessment of RLS potentials from LS: first, previous studies used a static approach for the investigation of the LS capacity of a consumer which means the simplified assumption that the full capacity of the consumer is provided at one point of time. Obviously, this approach neglects the site-specific, dynamic characteristics of the specific constraints of load shifting users. Second, studies did not model the temporal explicit distribution of demand and supply in a specific power system. Consequently, the need of the grid for RLS is not be matched with the temporally changing ability of a specific consumer to provide LS.

In this paper, we present a novel approach for a dynamic assessment of the contribution of LS on the consumer side to RLS in the grid, represented by so-called RLS indicators we defined. Our paper aims at a quantitative assessment of RLS from specific consumer types taking into account technical constraints of the plant as well as the temporal explicit distribution of demand and supply in the surrounding power system. For our investigation we used the case study of waste water plants in Germany; however, our methodological approach is applicable also to LS from other consumer types and to other national power systems if the necessary data can be provided.

1.2. The case of Waste Water Plants (WWTP) in Germany

1.2.1. The framework of the German energy system

Based on the 2030 Energy Strategy of the European Commission [1], the German energy policy adopts the expansion of renewable energy sources as the main pillar to achieve a low carbon society and a goal for the share of renewable electricity for gross electricity consumption. The two main focused technologies are wind power and photovoltaics [2]. These technologies contribute already 19.4% of the total electricity production in Germany [44]. For the time horizon of 2030, the demand for flexibility options is forecasted to grow significantly [11].

Consequentially, the increase of storage capacities and RLS have become a crucial issue. LS options for Germany have been investigated by several studies [15,45,46,47]. Klobasa et al. assessed the potential for LS of several industrial electricity consumers like pumps, ventilation, cooling and pressurized air [47] in southern Germany (Bavaria, Baden-Wuerttemberg). This study can be considered to use the most advanced approach up to now as it uses a temporarily partly explicit approach, defining certain time periods for LS to be investigated. Constraints in terms of user's willingness and technical ability to modify the load profile of production processes were obtained from a company survey. Technical ability means the duration of a load shedding event or the deactivation time of a process. They concluded that the load that may be deactivated through shutting down processes depends strongly on the shutdown time. For example, the load shifting potential of all considered processes in southern Germany was estimated to is approximately 200 MW_{el} in the case of a four hour shut-down. Therefore, Klobasa et al. is regarded be seen as a good first step towards a dynamic assessment. However, this approach does not take into account the demand from the grid for RLS.

1.2.2. LS from Waste Water treatment plants (WWTP)

Wastewater treatment plants (WWTP) have been identified as one possible player for load shifting [48,49]. Depending on the WWTP's capacity and infrastructure, methane (biogas) can be produced from the anaerobic digestion of sewage sludge. It is then stored in on-site biogas storage tanks and combusted in combined heat and power plants (CHP) to enable a decrease in external electricity and heat purchase. By loading the gas storage in times when residual load is low and carrying out combustion of biogas in times when residual load is high, RLS is achieved by using gas storage capacities as energy storage. Consequently, technical, plant-specific characteristics that limit the load shifting potential of a wastewater treatment plant are gas storage capacity, biogas production and therefore biogas availability, nominal capacity of CHP (maximum on-site electricity generation) and the hourly electricity demand. From the economic perspective, the power production cost of an WWTP operator is low compared to the supply through externally produced electricity. As a consequence, feed-in of electricity is not attractive for WWTP operators since self-consumption of biogas to lower electricity purchase is always economically advantageous in comparison to purchase from the grid [50]. The case of LS from WWTP is focused on the goal to reduce negative residual load, i.e. the targeted consumption surplus electricity.

The first assessment of the load shifting potential of German WWTPs was done by Apel et al. [15]. Based on a static approach, the study states that German WWTPs may have gas storage capacities of 1.2 GW h_{el}. A recent study has updated this figure indicating that the maximum shiftable load amounts to 1.9 GW h_{el} [51].

2. Materials and methods

2.1. Approach

For the assessment of RLS_{LS} we developed a dynamic approach, taking into account the technical constraints of a specific consumer type