Applied Energy 177 (2016) 500–514

Contents lists available at ScienceDirect

Applied Energy

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

The effect of distributed electricity generation using natural gas on the electric and natural gas grids

Cara R. Touretzky, Dana L. McGuffin, Jena C. Ziesmer, Michael Baldea *

McKetta Department of Chemical Engineering, The University of Texas at Austin, 200 East Dean Keeton St., Stop C0400, Austin, TX 78712, United States

HIGHLIGHTS

- Gas-fueled distributed generation increases dependency of electric grid on gas grid.
- Optimal operation of group of 10 kW and 50 kW electric generators for load flattening.
- Consider effects of centralized vs. decentralized decision making and seasonality.

ARTICLE INFO

Article history:
Received 27 February 2016
Received in revised form 6 May 2016
Accepted 14 May 2016

Keywords:
Natural gas grid
Electric grid
Distributed generation
Load flattening
Demand response

ABSTRACT

The efficient and economical design and operation of individual small-scale distributed generation (DG) units has received considerable attention. It is now plausible to envision a future scenario where a large number of such units, spanning capacities from the kW to the MW scale, are deployed in a region. As distributed electricity generation using natural gas becomes more widespread, the dependency of the electric grid on the natural gas grid will increase. This concerns multiple interaction points along the two networks, and reaches beyond the natural gas demand of large-scale load following or baseload gas-fired powerplants. More specifically, a better understanding is required of the potential changes in the dynamic behavior and interaction of the electricity and natural gas grids at or close to residential use sites (neighborhoods), where the small-scale DG infrastructure is likely to be located. In this paper, an optimization-based framework is developed for analyzing the operation of an ensemble of small-scale natural gas fueled DG units, and quantify their ability to flatten the electric grid load (i.e., reduce the peak demand) of the neighborhood that they serve. Our analysis relies on realistic energy use data and takes into account capacity limitations of the current natural gas distribution infrastructure, centralized vs. decentralized control of the DG unit operation, equipment durability considerations, heating preferences of home users, and seasonal effects. There is a substantial increase in natural gas consumption near consumers for all scenarios considered, which has implications for the control of the natural gas grid. We demonstrate the importance of having a centralized decision-making scheme when multiple distributed generation resources are present, and make recommendations for the optimal sizing of generators.

1. Introduction

Electricity and natural gas (NG) are supplied to residential, commercial, and industrial customers using complex networks that are in many ways interconnected. For example, natural gas fired power plants are used for load following on the electric grid [1]. Alternate methods for efficient electricity generation (e.g., CHP, microturbines, or fuel cells) have a range of operating capacities and can rely on NG as a primary energy source. It is possible to envision a future scenario (e.g., [2,3]) where a large number of these units, ranging from the kW to MW production scale, are deployed in a region, thereby creating an increased dependency of the electric grid on the NG grid at multiple points along the transmission and distribution supply chains. This scenario appears as an attractive option for planning future residential or mixed-use communities under the assumption that natural gas prices remain low [4]. However, the potential changes in the interactions between the electricity and NG grids that arise in this situation should be carefully evaluated.

In this work, we focus specifically on this issue, and address the question "*What is the consequence of tighter interdependency between the electric and NG grids at intersection points spanning utility-scale electricity generation through residential use of*

* Corresponding author.
E-mail address: mbaldea@che.utexas.edu (M. Baldea).

http://dx.doi.org/10.1016/j.apenergy.2016.05.098
0306-2619/

distributed generation?" Several case studies are developed which illustrate the local requirements of both the electric and NG grids for a small neighborhood model, considering multiple configurations of NG-based generators and various weather conditions and operating restrictions. Data for customer energy demands are based on national energy surveys and information provided by the Electricity Reliability Council of Texas (ERCOT). We formulate and solve the model for the operation of the ensemble of consumers and generators as a mixed-integer linear program, and analyze the resulting optimal energy usage profiles in terms of the ability to flatten the load placed by the host neighborhood on the electric grid.

2. Background

2.1. Overview of the electric and natural gas grids

The electricity and natural gas grids are both comprised of a transmission and distribution system, with components (e.g., substations for electricity and compression stations for NG) which ensure the safe and efficient delivery of energy to consumers. However, the similarities stop here. The dynamic characteristics of the electric grid are very different from those of the natural gas grid. The electric grid must operate with the supply and consumption of electricity in perfect balance; large imbalances of electricity supply and demand lead to changes in voltage and frequency which cause (potentially catastrophic) failures [5]. On the other hand, natural gas is compressible and can therefore be stored in underground facilities or "linepacked." Linepacking is the temporary increase in pressure in the distribution pipelines to act as a buffer for daily demands larger than the base load [6,7]. Because of this the natural gas grid has slower dynamics than the electric grid.

Planning for both short and long-term future production and demand is an important aspect of the operation of both grids for safety, reliability, and economic reasons [8]. It is particularly important for the electric grid because of the lack of cost-effective grid-scale storage (see [9] for a review of grid-scale battery technology). Consequently, the planning mechanisms for the two grids are structured differently.

The need to balance supply and time-varying demand on the electric grid has influenced the technology portfolio used by generation facilities and utility companies. Base load power generation (i.e., plants that run 24/7 and produce a constant amount of power) relies on hydro-electric, nuclear, coal, and natural gas combined cycle (NGCC) plants [10], while load-following power generation relies almost exclusively on natural gas-fired plants because of their ability to be ramped up and down quickly [1,10,11]. Natural gas-based electricity generation has lower greenhouse gas emissions than coal-fired power plants [12], so natural gas is a preferable fuel source for centralized electricity production for environmental reasons. In the US, the fraction of electricity produced using NG has been steadily increasing over the past decade due to decreasing natural gas prices (attributed to the development of hydraulic fracturing of shale). In fact, approximately 35% of natural gas consumed in the US in 2014 was used for electricity generation, and 31% for industrial processes, while the remainder was used by residential and commercial consumers [13].

The variability of demand poses special challenges to grid operations. When the load on the grid is too high to be satisfied by typical generation resources, special "peaking plants" may be brought online for brief periods to meet the extreme demand level [10,14]. In many cases, these are inefficient and tend to produce more CO_2 emissions than base load power plants. The desire to lower the peak load on the electric grid has lead to the development of demand response (DR) and demand management (DM) programs, which encourage consumers to curtail or shift their electricity use from peak times [15,16]. These programs are typically based on a time-dependent price schedule (e.g., time-of-use pricing) which penalizes consumers for electricity consumption during peak demand times. As a consequence, there has been a significant amount of research in how consumers should (or do) behave in such a scenario. For example, optimal scheduling of appliance usage [17] and the control of thermal energy storage in residential and commercial buildings [18–20] have been investigated as load-shifting strategies. Flattening the electric grid load using batteries has been examined at both the grid scale [21] and locally at individual homes [22].

Another difficulty in operating the electric grid is the increased variability and uncertainty in supply introduced by the increase in use of renewable generation technology, since their production levels are weather and season dependent [23,24]. Natural gas based electricity generation can be used to mitigate the uncertainty of supply associated with the increased presence of renewable sources of electricity. This is – again – due to the flexibility natural gas provides for production to be ramped up or down quickly to satisfy short term load balancing needs. Distributed generation (discussed in the next section) can also aid in the effort to balance the uncertainty in the supply of electricity from renewable sources such as wind and solar power.

2.2. Distributed generation technology

Distributed generation (DG) describes small-scale electricity generation technology located close to consumers, which leads to minimal losses associated with transmission (which can be up to 6% [25]). DG is a broad term and can refer to units producing from a few kW of electricity up to the MW scale [26]. In a similar vein, microgrids [27,28] comprise a set of DG units and consumers, and have the ability to operate independently from the traditional electric grid. These are elements of the so-called 'smart grid' [14,29] and aim to address the peak demand and intermittency issues associated with the incorporation of renewable energy sources in the generation mix at the grid level. DG can also be used as an ancillary service, which helps increase the reliability of the electric grid [30]. There is a large body of literature dedicated to the design and operation of DG technology in this context but, true to the scope of our paper, we will briefly review the NG-fired DG area.

Combined Heat and Power (CHP) and Combined Cooling Heating and Power (CCHP) refer to electricity generation systems which also recover and use waste heat, increasing the overall efficiency. A detailed review of CCHP strategies is provided in [31], along with representative system designs – classified as micro-scale (under 20 kW), small-scale (20 kW–1 MW), medium-scale (1–10 MW), and large-scale (over 10 MW). Micro-CHP can be used by residential customers [32], while commercial customers may employ small-scale CHP [33]. Large-scale designs for planned communities and microgrids should also account for the presence of other energy sources, like photovoltaics (PV) [34,28]. The "prime mover" for electricity generation in CCHP tends to be natural gas-based combustion turbines [31]. Solid Oxide Fuel Cells (SOFC) and Molten Carbonate Fuel Cells (MCFC) using natural gas as their fuel source are a promising technology for the small to large scale because of their high efficiencies and low environmental impacts [35,36]. Hybrid micro-turbine and SOFC systems have also been proposed [37]. Micro-turbines (defined by [38] as under 500 kW in size) are well-suited for DG applications because of their small size, high (greater than 80%) efficiencies, and flexible startup/load following capabilities [38]. In addition to being used for CHP, they can operate as a baseload or peak-shaving unit, or as a standby power source in case of emergencies [38]. Both micro-turbine based