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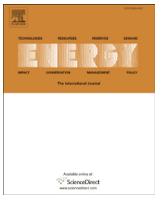

The potential benefits of widespread combined heat and power based district energy networks in the province of Ontario

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ABSTRACT

In this work, an assessment is conducted of the potential primary energy savings and CO_2 reductions associated with converting a conventional energy system comprising high thermal power plant penetration to one of two configurations. The first configuration consists of widespread DE (District Energy) grids equipped with CHP (Combined Heat and Power) plants, and the second includes wind energy. A model is constructed and five scenarios are evaluated with the EnergyPLAN software taking the province of Ontario, Canada as the case study. Scenario optimization results show that reductions in fuel utilization and CO_2 emissions of up to 8.5% and 32%, respectively, are possible when switching to an energy system comprising widespread CHP based DE grids. A sensitivity analysis reveals that widespread CHP based DE systems have lower fuel utilization and CO_2 emissions than large-scale wind systems for relative installed capacities below approximately 25% of the total generation mix. Differences in fuel utilization and CO_2 emissions of up to 6.4% and 10%, respectively, are observed when comparing outputs from energy systems made up of two distinct CHP technologies, demonstrating the importance of accounting for heat to power ratio in large-scale energy planning studies that incorporate CHP generation.

1. Introduction

DE (District Energy) and wind power are both capable of reducing fossil fuel utilization and CO_2 emissions. The efficiency of wind conversion depends on the wind resource at the site as well as the turbine equipment used [1]. As wind power is intermittent, ancillary services must be provided to the electricity grid at all times to stabilize potential imbalances between supply and demand and maintain voltage and frequency to acceptable levels [2,3]. This is especially true for energy systems with high levels of wind energy penetration. A DE system is an integrated system in which energy is generated locally and is distributed to individual buildings within a network. High energy efficiencies can be achieved in DE systems as loads are aggregated and managed simultaneously, thereby, reducing waste energy streams [4]. Other advantages of DE include increased flexibility, reduced energy costs, increased security of energy supply, and reduced reliance on large-scale conventional generation and transmission infrastructure [5]. A DE system may consist of a single central energy plant, or a series of smaller plants interconnected by pipes that provide steam, hot water, or chilled water to the clients connected to the network. Typical DE system components include boilers, chillers and/or heat pumps for providing heating and cooling services, as well as CHP (Combined Heat and Power) units for supplying both heat and power simultaneously [6]. Depending on location, thermal storage infrastructure may also be added to increase overall efficiency [7].

Various national level modeling studies have been conducted to examine the impacts of expanding CHP-based DE grids on a large scale. Danestig et al. [8] incorporate Stockholm's DE network into a broader national scale model which was used to study the potential for CHP capacity growth in the city. This study showed that when CHP plants with high electricity to heat ratios are used, up to 15% of Sweden's total electricity load can be met by CHP resulting in CO_2 emission reductions of up to 5 million tons per year. Lund et al. [9] modeled the Lithuanian national energy system for a scenario in which one of its largest nuclear power plants is decommissioned. To replace the missing generation capacity, they proposed replacing all boilers in the existing district heating systems with CHP plants. Simulation results show that compared to using new thermal power stations, this strategy would lower both fossil fuel consumption and CO_2 emissions by up to 70%. Münster et al. [10] developed a model of the Denmark energy system and showed that CHP and district heating can contribute to the sustainability and security of supply of future energy systems and that it is cost effective to

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increase the district heating share up to 57% of the total national heat demand.

A number of national level modeling studies have also been conducted to assess the impacts of high penetrations of wind energy. Connolly et al. [11] constructed a model of the Irish energy system to identify maximum feasible levels of wind penetration. They found that a wind penetration of approximately 30% was optimal from both a technical and economic standpoint. Bjelic et al. [12] assessed the large-scale integration of wind power in the Serbian energy system for a number of scenarios. They demonstrated that 2500 MW of installed wind capacity is feasible given that the existing pumped storage hydro capacity is used for balancing purposes. Le and Bhattacharyya [13] modeled the British energy system to assess the optimal wind power integration in 2020 based on the total cost of supply. For the two scenarios considered, they concluded that integrating 80 TWh of wind is preferable from both a technical and economic perspective. Liu et al. [14] developed a model of the Chinese energy system and showed that the maximum feasible wind power penetration is approximately 26%. A similar type large-scale wind integration study was conducted by Hong et al. [15] focusing on the province of Jiangsu in China. The study presents impacts with respect to technical limitations, total fossil fuel consumption, and total emissions from implementing a number of different regulation strategies to the province's energy system.

As described above, the majority of case studies found in the literature focus on the impacts of expanding a particular technology solution (i.e. CHP-based DE grids or wind energy generation) on a nation's energy system. No studies have been identified that compare these two technologies in the context of a large-scale system.

The objective of this research is to compare the impacts from widespread switching to CHP-based DE grids versus widespread switching to wind power in an energy system having significant installed thermal power capacity. The province of Ontario, Canada is chosen as the jurisdiction of study. The current ratio of thermal power plant capacity to peak load in Ontario is approximately 0.42. Models corresponding to a reference scenario and a WDE (Widespread District Energy) scenario are constructed. Reference year energy system components and capacities are considered in the reference model. Boilers, and absorption chillers are considered in the WDE model. Data from 2007 (the reference year) is used to formulate the reference scenario primarily because this is the most recent year for which Canada census data is available. Three WDE scenarios are constructed and compared with the reference scenario on the basis of CO_2 emissions and fossil fuel consumption. An additional scenario is constructed to assess the impacts of expanded wind generation capacity relative to the expanded DE infrastructure scenarios.

The EnergyPLAN analysis tool is used to construct all models and to conduct the simulations. EnergyPLAN was specifically developed for the purpose of planning and designing energy systems consisting of intermittent energy sources and DE networks. The main advantage of EnergyPLAN relative to other energy modeling tools is that it is capable of optimizing an energy system based solely on the technical operation of its components. The model has been used extensively for case studies of large scale wind integration and CHP for Denmark, Ireland, Italy, Germany, Spain, Serbia, China, and the UK [7,11–20].

2. Methodology

2.1. The EnergyPLAN model

EnergyPLAN was originally developed by the Sustainable Energy Planning Research group at Aalborg University, Denmark in 1999. The latest version (i.e. V-10.0) is programmed in Delphi Pascal and provides a user friendly interface consisting of tab sheets. The model utilizes a deterministic, bottom-up approach and incorporates hourly distributions of energy generation and loads for a one year period. If longer time horizons are required, multiple one year blocks may be combined to shape a desired scenario. Model input data comprises energy loads, energy sources, power plant and transmission capacities and related economic data. Outputs are energy balances, fuel consumption, imports/exports as well as total costs including income from the exchange of electricity. The primary purpose of the model is to assist in the design of national or regional energy planning strategies. It is also appropriate for analyzing future energy systems in which the integration of fluctuating energy sources may be an issue [21].

EnergyPLAN encompasses the three primary sectors of an energy system; electricity, heat and transportation. This allows technologies such as CHP, heat pumps, electric vehicles, and hydrogen to be used to balance electricity production and load [22]. The model can be used to optimize an energy system from a technical perspective or from a market perspective. The technical analysis utilizes an optimization algorithm aimed at lowering CO_2 emissions while balancing loads and maintaining a stable electricity grid. The market analysis considers individual generator marginal production costs, internal market prices as well as trade opportunities with neighboring electricity markets. The optimization is based on the fundamental assumption that each plant will generate to maximize profit, taking into consideration any taxes and CO_2 emission costs.

In the current study, EnergyPLAN is used to model the 2007 Ontario energy system from a technical perspective. The energy pathways considered in the model are shown in Fig. 1. All energy flows are load-driven and stem from multiple generation sources. Among the end-use technologies, buildings whose heating and cooling needs are met by DE systems and buildings whose needs are met by individual systems are identified separately.

2.2. Scenario description

Five scenarios are developed in EnergyPLAN, independent of any existing provincial energy plan or strategy. As the focus of the study is purely technical, political and economic constraints are not considered. For each scenario, Table 1 summarizes total heating/cooling loads, conversion technologies, component efficiencies and fuel types for individual buildings and DE grids. Identical conversion technologies and fuel types are used in all scenarios for heating and cooling in individual buildings. Relative contributions and efficiencies of individual building conversion technologies are assumed to follow the distribution shown in Table 2 for all scenarios. Table 2 shows heating/cooling system efficiencies by fuel type as well as the heating to cooling load ratio for individual buildings. In all scenarios, district CHP plants and district boilers run solely on natural gas. All district boilers are assumed to have thermal efficiencies of 85%.

Scenario I is the reference scenario and is based on historical data from 2007 for all sources and loads. Hourly electricity system generation data by type (i.e. Wind, Hydro, Nuclear, Thermal) is obtained from the IESO (Independent Electricity System Operator) [23]. Power plant efficiencies, fuel mix ratios, and CO_2 fuel intensities are procured from Statistics Canada [24]. Electricity generation data is summarized in Table A.1 of the Appendix. Total individual building and DE heating/cooling loads are estimated to be 161 TWh and 6 TWh, respectively. No cooling takes place in the DE networks. The total CHP installed capacity is estimated to be 441 $MW_{(e)}$ with an average thermal efficiency, average electrical efficiency, and a heat-to-power ratio of 50%, 40%, and 1.25,