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Potential for increased wind-generated electricity utilization using heat pumps in urban areas

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HIGHLIGHTS

- Large-scale wind power and increased electric heat pumps were evaluated.
- A deterministic model of wind power and electricity demand was developed.
- Sub-models for space heating and domestic hot water demand were developed.
- Increased use of heat pumps can improve the viability of large-scale wind power.
- Larger wind power capacity can meet a target utilization rate with more heat pumps.

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ABSTRACT

The U.S. has substantial wind power potential, but given wind's intermittent availability and misalignment with electricity demand profiles, large-scale deployment of wind turbines could result in high electricity costs due to energy storage requirements or low utilization rates. While fuel switching and heat pumps have been proposed as greenhouse gas (GHG) emissions and energy reduction strategies at the building scale, this paper shows that heat pump adoption could have additional system-wide benefits by increasing the utilization of wind-generated electricity. A model was developed to evaluate the effects of coupling large-scale wind power installations in New York State with increased use of electric heat pumps to meet a portion of space heating and domestic hot water (DHW) demands in New York City. The analysis showed significant increases in wind-generated electricity utilization with increased use of heat pumps, allowing for higher installed capacity of wind power. One scenario indicates that 78.5% annual wind-generated electricity utilization can be achieved with 3 GW of installed wind power capacity generated electricity equal to 20% of existing NYC annual electricity demand; if 20% of space heating and DHW demands are provided by heat pumps, the 78.5% utilization rate can be achieved with an increase of total wind power capacity to 5 GW. Therefore, this integrated supply–demand approach could provide additional system-wide emissions reductions.

1. Introduction

Dense urban areas are often considered energy efficient because individuals tend to use less energy than residents of suburban and rural areas [1]. However, the cumulative effect in New York City (NYC) and other urban areas is a large, concentrated energy demand. The potential for in-zone renewable energy is limited in urban areas due to high energy demands relative to geographical size and land area; shading and microclimate effects from buildings and infrastructure; and limited space for equipment installations. NYC is projected to require 33% of the total annual electricity demand (excluding transportation) for New York State (NYS) in 2022 with NYC renewable energy resources representing only 16% of the statewide technical potential and only 2.2% of what is deemed economically viable statewide [2]. Therefore, integration of renewable energy into the larger electricity grid serving NYC will be required to offset urban fossil fuel usage.

Renewable energy resources, such as wind and solar, are intermittent: supply profiles do not necessarily align with demand profiles. As such, the need for energy storage to increase the utilization of electricity generated has been widely accepted [3]. This can be costly and render large-scale renewable energy deployments infeasible [4]. Further, these considerations ignore the dominant energy

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Nomenclature

A	total NYC floor area for a particular building type (m^2)
COP_{DHW}	domestic hot water heat pump coefficient of performance
COP_{SH}	space heating heat pump coefficient of performance
D_{base}	base electricity demand (MW h)
D_{EOB}	existing electricity demand over base load (MW h)
D_{DHW}	electricity demand for additional DHW heat pumps (MW h)
D_{NYC}	New York City electricity demand (MW h)
D_{SH}	electricity demand for additional SH heat pumps (MW h)
E_{grid}	existing grid electricity utilized to meet demands (MWh)
$E_{grid,DHW}$	existing grid electricity utilized for DHW through additional electric heat pumps (MW h)
$E_{grid,EOB}$	existing grid electricity utilized for existing electricity demand over base load (MW h)
E_{gridSH}	existing grid electricity utilized for SH through additional electric heat pumps (MW h)
$E_{gridtot}$	total annual grid electricity utilized to meet demands (MWh)
E_{wind}	wind-generated electricity utilized to meet demands (MW h)
$E_{windDHW}$	wind-generated electricity utilized for DHW through additional electric heat pumps (MW h)
$E_{windEOB}$	wind-generated electricity utilized for existing electricity demand over base load (MWh)
E_{windSH}	wind-generated electricity utilized for SH through additional electric heat pumps (MW h)
$E_{windtot}$	total annual wind-generated electricity utilized to meet demands (MWh)
EHP_{SH}	electric power draw of space heating heat pump (kW)
$ESUP_{SH}$	electric power draw of supplemental space heating (kW)
e_{total}	total annual carbon dioxide equivalent emissions from building electricity and heating fuels (kg CO2e)
F_{tot}	total annual heating fuel usage (MWh)
f_{DHW}	fraction of total fuel usage attributed to DHW
f_{SH}	fraction of total fuel usage attributed to SH
G_{wind}	wind-generated electricity summed across all sites (MW h)
$G_{windtot}$	total annual wind-generated electricity (MW h)
g_{wind}	electricity generated per wind turbine (MW h)
H_{DHW}	domestic hot water demand (MW h)
H_{SH}	space heating demand (MW h)
HD	heating degrees under an 18 °C basis (°C)
HHP_{SH}	heating capacity of space heating heat pump (kW)
$HSUP_{SH}$	heating capacity of supplemental space heating (kW)
N	total number of wind turbines
n	number of turbines at an individual site
n_{max}	maximum number of turbines allowed at an individual site
p_{DHW}	penetration of domestic hot water heat pumps as a percentage of the total space heating demand currently from fossil fuels
p_{SH}	penetration of space heating heat pumps as a percentage of the total space heating demand currently from fossil fuels
RHP_{SH}	rated nominal heating capacity of space heating heat pump (kW)
r_{fuel}	GHG emissions rate for in-building fossil fuel combustion (kg CO2e/MW h)
r_{grid}	GHG emissions rate for existing electricity grid (kg CO2e/MWh)
T	outdoor air temperature
T_{design}	space heating heat pump exterior design temperature (°C)
U_{wind}	wind-generated electricity utilization (%)
η_{DHW}	thermal efficiency of existing fossil fuel-burning domestic hot water equipment
η_{SH}	thermal efficiency of existing fossil fuel-burning space heating equipment
η_{SUP}	thermal efficiency of supplemental space heating
$\boldsymbol{\Phi}_{DHW}$	total annual domestic hot water fuel demand (MW h)
φ_{DHW}	DHW fuel demand of a DOE Commercial Reference Building model
$\boldsymbol{\Phi}_{SH}$	total annual space heating fuel demand (MW h)
$\boldsymbol{\Phi}_{total}$	total annual fuel demand (MW h)

Subscripts

h	hour of simulation
i	index of wind power site
j	index of building type

demands in many cities: Space heating (SH) and domestic hot water (DHW), particularly in residential buildings, which typically depend on natural gas and other fossil fuels. The use of heat pumps to meet significant greenhouse gas (GHG) emission reduction targets is typically recognized in broad renewable energy policy studies – including global [5], regional [6] and local [7] – but where the potential effects on the overall feasibility of such integrated approaches have been investigated, the curtailment of wind-generated electricity that occurs when large scale deployments are added to an existing grid have not been realistically predicted [8]. Metrics have been developed to evaluate the changes to the alignment of supply and demand profiles with intermittent resources, distributed generation and heat pumps [9], but the resulting effects on wind-generated electricity utilization at different levels of technology penetration warrant investigation. Further, the performance of heat pumps, particularly air-source heat pumps, is highly sensitive to exterior conditions [10]. Analyzing these effects requires a temporal analysis that incorporates weather data.

Strategies to better align supply and demand profiles and to reduce the need for additional storage are desired. The annual heating demand profile better aligns with the wind-generated electricity profile than does the electricity demand profile. At the individual household level, better correlation has previously been identified between wind availability and heating demands than between wind availability and electricity demands; this supports the viability of a distributed system for individual households that combined a wind turbine with a ground-source heat pump (GSHP) [11]. Due to the limited in-zone renewable energy potential in urban areas, this solution is likely limited to rural applications. However, control strategies have been identified to integrate utility-scale wind turbine deployments and electric heating loads into electricity grids for both frequency control [12] and demand response [13].

This paper discusses the analysis of approaches to shift heating demands from on-site fossil fuel to electricity to improve the utilization of utility scale wind power, reduce the cost of wind-generated electricity and reduce overall system GHG emissions. The

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