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Economic analysis of using excess renewable electricity to displace heating fuels

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HIGHLIGHTS

- Excess electricity from 100% renewable scenario can replace most of heating fuels.
- Heat production cost is comparable or lower than heating with fossil fuels.
- Heat pumps based district heating is less expensive than resistive heating.
- Fossil fuels are used only as backup and consumption can be reduced by almost 100%.
- Energy storage can inexpensively reduce gas consumption and CO_2 emissions.

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ABSTRACT

Recent work has shown that for high-penetration renewable electricity systems, it is less expensive to install higher capacity of renewables and to allow generation to exceed load during some hours, rather than to build so much storage that all electricity can be used to meet electrical load. Because excess electricity appears to be cost-optimum, this raises the question as to whether the excess electricity, which in the case of wind power is predominately produced in colder weather, might displace other fuels for purposes such as heat. This study models using excess electricity for heating, based on an analysis of electricity and heat use in a TSO in the North-Eastern part of the United States (PJM Interconnection). The heating system was modeled as heat pump based district heating (HPDH) with thermal energy storage (TES). Thus, excess electricity is transformed into heat, which is easy and cheap to store near the point of use. As an alternative to HPDH, the use of distributed electrical resistive heating coupled with high temperature thermal storage (HTS) was also assessed. In both cases, a natural gas fired boiler (NGB) was modeled to be installed in the building for back-up heat. An algorithm that calculates the total cost of a unit of heat was used to determine the economically optimal size of the system's main components and the influence that natural gas (NG) and electricity prices have on this optimum. It was found that a system based on heat pumps (HP) and centralized thermal storage supplies building heat at a lower or similar cost than conventional systems. In most cases electric resistive heating with HTS was found to be less cost-effective than HPDH. The consumption of natural gas can be reduced to as little as 3% of that used by an entirely NG-based heater. Also, thermal energy storage was found to be crucial when it comes to reducing the need for fossil fuels for heating (in this model, as backup heat).

1. Background

The theoretical potential of renewable resources (RES) on earth is consistently higher than the energy requirement for human related activities (the solar radiation alone on the earth's surface is more than three orders of magnitude larger than the global energy demand [1]). However, these resources, which are also non-carbon based, are not available in the required form and have to be converted–the expense of conversion and integration with existing power systems thus sets the parameters of today's economic completion between RES and transitional fuels. A comprehensive approach to meet the global energy requirements for all purposes (electric power, transportation, heating/

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Nomenclature

$€_{el}$	cost of electricity
$€_{MW\ h,th}$	average cost of a unit of heat supplied
$€_{NG}$	cost of natural gas
$€_{year}$	yearly production cost of a unit of heat
NG4, NG8, NG16	scenarios based on different price of natural gas (one, two, and four times the current price)
EL0, EL5, EL10	scenarios based on different price of excess electricity (free of charge, 5 $kW h^{-1}, and 10 $kW h^{-1})
COP	coefficient of performance
DH	degree hours
DHW	domestic hot water
E	energy content of the thermal storage
E_{max}	total size of the thermal storage units
HP	heat pump / scenarios with HP technology
HPDH	heat pump based district heating
HTS	high temperature thermal storage
i	index for each single state entirely or partly belonging to PJM
I	investment cost
k	index for the four cost centers (heat pumps, thermal storage, distribution network and natural gas fired boilers)
LHV	lower heating value
m	index representing the months from January 1999 and December 2002
NG	natural gas
NGB	household natural gas fired boiler
OM	yearly operations and maintenance cost
P_{ex}	excess electricity
PJM	is an electricity supply area in the North-Eastern United States
P_{max}	total size of the heat pump fleet
Q_{BP}	heat bypassing the thermal storage that goes directly to the end user
Q_{in}	heat from the heat pump
Q_{load}	aggregated thermal load
Q_{month}	monthly heating demand
$Q_{NG,month}$	monthly natural gas consumption
$Q_{s,i}$	heat into the thermal storage
r	interest rate
R	resistive heating unit, in scenarios with resistive heating technology
RREEOM	regional renewable electricity economic optimization model [7]
SH	space heating
t	index representing the hours from January 1999 and December 2002
TES	thermal energy storage
z	lifetime of the individual component
α	proportionality factor between the degree-hour values and the space heating requirement
γ	ratio between the population of a state that is served by PJM and the total state population
η_d	efficiency of the district heating distribution network
η_s	loss rate of the thermal storage
φ	share of natural gas in space heating and domestic hot water
ψ	percentage of natural gas used for space heating and domestic hot water

cooling, etc.) by means of renewable resources is proposed in [2,3], which proposes a future scenario in 2050 with a mix of RES providing all energy needs at costs similar to today's. Scenarios like this with very high penetration of renewables (equal or close to 100%) for the electricity sector have been studied in recent years by several authors [4–7]. In [8], the authors study a total renewable electricity scenario based on a combination of RES and pumped hydro as storage. The outcomes of the research is that the total electricity consumption worldwide can be met exploiting only green energy. Recently, Budischak et al. found that a mix of different and geographically distributed renewable sources coupled with transmission and energy storage could provide almost all the electrical requirements in a large interconnection [7].

When analyzing the integration of renewable electricity, the time mismatch between fluctuating production and demand has to be considered. Inevitably, when the share of RES reaches a certain level, there will be moments when more energy is available than needed and vice versa. The most common approaches to deal with excess electricity are:

- Reducing fossil fuel generation: this is the traditional approach and works well as long as these units are fast enough in changing their power output. Base load generators (typically nuclear and coal) are too slow for following RES fluctuations, whereas intermediate and peaking units (hydro and gas turbines) are fast enough. Fluctuating generation, like fluctuating load, also reduces efficiency, because the power plant is forced to work away from optimum design conditions.
- Load shifting: part of the electricity consumption can be shifted for increasing the demand during a certain period of time. This is practically implemented through energy market policies and requires the presence of shiftable loads.
- Storage to shift production: Energy storage can be introduced both at production and consumption sites. Similarly to load shifting, production shifting is motivated by the energy market framework.
- Introduction of new loads: Substitution of electrical loads for end-uses traditionally met by other energy carriers, such new loads include heating and electric vehicles.
- Power spill: excess power is not utilized at all. This is done when none of the above methods are applicable because of technical or economic constraints.

Many studies of high-penetration renewables assume that generation should never exceed load [4,6]. This may be expressed as never having excess at any one moment, or, in models with storage, that the yearly total generation should not exceed the yearly total load, storage being used to transfer energy from times of excess to times of deficit. However, such constraints on maximum generation do not consider whether this limit is cost effective. More recently, a few studies have recognized that excess renewable generation can be used to reduce the need for energy storage capacity [5,7,9], and because loss of revenue from excess generation may be less expensive than the cost of storage, the excess generation configurations can reduce electricity costs [7,9]. Heide [5] obtains figures for a fully renewable electricity scenario in Europe by studying how the amount of excess generation relates to the need for expensive storage capacity. Budischak [7] performed