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Electrification of residential space heating considering coincidental weather events and building thermal inertia: A system-wide planning analysis

Steve Heinen [a, *], William Turner [a], Lucy Cradden [b], Frank McDermott [b], Mark O'Malley [a]

[a] *Electricity Research Centre, School of Electrical & Electronic Engineering, University College Dublin (UCD), Belfield, Dublin 4, Ireland*
[b] *School of Earth Sciences, University College Dublin (UCD), Belfield, Dublin 4, Ireland*

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ABSTRACT

The increasing deployment of variable renewables and parallel residential space heat electrification using heat pumps poses two significant challenges for electricity systems: First, coincidence of certain weather events can stress the power system due to the increasing weather-dependence on both supply and demand side; Secondly, increased net load demand requires large capacity expansion unless heat and electricity can be partially decoupled. This paper proposes a planning methodology to explore these challenges by integrating a 'Resistance-Capacitance' representation of building thermodynamics into an integrated planning model. This enables analysis of coincidental weather effects which drive system adequacy and of the potential to utilise building thermal inertia to pre-heat the building and effectively store electricity in the form of heat according to system conditions. The model was tested with a case study for the Irish energy system in 2030. It was found that different weather patterns considerably influence investment and planning choices. Also, coincidental effects of different weather variables — in this case, low temperatures and low wind speed - define the most critical situations in terms of adequacy. By utilising building thermal inertia, total system costs of residential heat electrification can be reduced to the level of the benchmark technology, gas boilers.

1. Introduction

Variable renewable energy (varRE) deployment and space heat electrification (e.g. shifting heat from fossil fuel combustion in boilers to energy-efficient heat pumps (HP)) are essential elements in the decarbonisation strategies of many countries. Deploying these two technologies could pose some new integration challenges mainly due to the increased weather dependence and variability this introduces on both supply and demand sides of the energy system. Coincidental impacts of different weather variables such as temperatures and wind speed are rarely considered in a planning analysis, but it is important to understand how system adequacy can be stressed by simultaneous occurrence of low temperatures and low wind speeds. A potential strategy to efficiently manage the increased net variability from varRE deployment and heat electrification could involve utilising the building thermal inertia for shifting electricity demand. This paper proposes an integrated methodology for the electricity-residential heat system to analyse both coincidental weather impacts and the ability of building thermal inertia to store heat according to system-wide conditions in an integrated framework.

VarRE deployment increases the need for operational flexibility in order to maximise the use of the renewable resource whenever it is available [1]. Shifting residential space heat demand from gas to electricity potentially requires large electricity infrastructure expansion [2], given that space and water heating demand represents, for example, roughly 80% of final energy use in residential buildings in Europe, and 60% in the United States (US) [3]. Efforts to reduce space heat consumption through building insulation and heater efficiency improvements could partially offset additional generation requirements, but will not suffice to completely offset

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Abbreviations: BER, building energy rating; CCGT, combined cycle gas turbine; ERH, electric resistance heater; B, gas boiler; HP, heat pump; ewo, external wall outside; ewi, external wall inside; i, indoor air; iw, internal walls; OCGT, open cycle gas turbine; varRE, variable renewable energy.

* Corresponding author.

E-mail address: steve.heinen@ucd.ie (S. Heinen).

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increased peak demand [4,5]. Heat demand tends to vary considerably over days, seasons and years mainly due to its sensitivity to ambient air temperature variations [4,6,7]. Furthermore, a cold winter event can coincide with a period of low renewable energy output in a system with high varRE penetration [8], which would increase adequacy requirements and exacerbate investment needs [2]. Under-investment in electricity capacity could lead to extended periods of human exposure to cold indoor environments which pose a serious health risk, especially to vulnerable groups such as the young and elderly [9,10]. The impact of weather on building heat demand is considered in Refs. [4,6,7,11–13], but the implications on infrastructure needs are not analysed. Heat and renewable electricity planning studies typically ignore the sensitivity of the results to different weather years [14–19]. Petrović and Karlsson [20] capture only the impact of ambient temperatures on HP efficiency, but not on space heating demand.

Electrifying residential space heat could also open up new integration opportunities [21]. The building envelope has a thermal mass that adds thermal inertia to a building's thermodynamics since it takes time to heat up and cool down. This inherent thermal storage capacity could be utilised to pre-heat the building and store heat at times of high energy supply and is available at no extra capital cost, as opposed to other storage technologies. If real-time or smart control is enabled, then a HP or another electric heater could be operated in a flexible manner according to power system conditions without impacting the thermal comfort of building occupants [22]. In the short term this could help maximise varRE penetration and reduce peak loads by increasing or decreasing electricity consumption. In the long-term, utilising building thermal mass could provide generation capacity expansion savings and reduce heating system investments. Other power system planning assessments for space heat electrification do not consider planning benefits of utilising building thermal inertia, but only focus thermal water tanks as storage options [14,16,23]. Integrated electricity-residential heat operational assessments that capture the building storage capabilities do not consider investment benefits [15,24–26].

Cost-effective infrastructure deployment for large-scale space heat electrification has not been fully studied from a central-planner perspective. The least-cost planning model developed in this study endogenously takes into account building thermodynamics, which enables coincidental weather events to be captured and building thermal storage capabilities to be utilised. The building dynamics are modelled using a thermal network or RC (Resistance-Capacitance) circuit representation that is commonly used in reduced-order building simulations [27–31]. Based on weather inputs, the planning model endogenously optimises electricity and heat system investments and operation. The planning methodology also represents the interdependence between short-term dispatch decisions and long-term portfolio expansion.

The explicit representation of thermal building dynamics in a planning model highlights the two main research contributions of this paper:

- First, the RC representation of the buildings allows the model to capture the weather sensitivity of space heat demand and the consequent impact on electricity system planning, such as peak demands and investment needs. Apart from modelling the dependence of ambient air temperature on space heating demand, the system-wide planning model also enables the modelling of critical, low-probability, high-impact weather events that affect different parts of the energy system coincidentally. Of particular interest are, for example, coincidental and sometimes extended periods of low wind speeds and low temperature which drive system adequacy. In terms of varRE supply, the Irish case study presented in this paper is limited to wind due to the vast resource in Ireland, but the methodology can be applied to solar PV.
- Secondly, the system-wide planning and operational benefits that occur by using thermal inertia to shift peak loads and integrate excess varRE can be assessed in an integrated electricity-residential building perspective. A multi-node building model is used in this work so that both fast (air temperature) and slow (thermal mass) building thermodynamics are suitably captured. Hedegaard and Balyk [15] only use a single node building Resistance-Capacitance (RC) representation (i.e. one capacitor), which according to Bacher and Madsen [31] does not suffice to represent the building thermodynamics. The system-wide impacts of electrifying buildings with different levels of insulation can also be assessed.

The remainder of this paper is structured as follows. Section 2 gives an overview of the importance of weather impacts on electricity system planning. Section 3 presents the planning methodology including the RC building sub-model, Section 4 presents the case study used to test the methodology. Section 5 presents and discusses the results. Section 6 highlights further research needs before the conclusions are presented in Section 7.

2. Weather and impacts on electricity system planning

The objective of electricity planning is to develop economic, robust and reliable solutions to a variety of future scenarios, including primarily different fuel prices, technology costs, demand levels and policies. Weather is rarely considered as part of the risk or sensitivity analysis [32], but is increasingly important in a system with both weather-dependent supply in the form of renewable energies, and weather-dependent loads such as electric heating. A complete planning methodology needs therefore, to assess the weather impacts on electricity systems.

Weather affects energy system reliability which is typically divided into adequacy and security. The focus of this paper is on system adequacy and how it is affected by weather variability and coincidental weather impacts. Adequacy can be defined as the requirement for sufficient capacity within the system to satisfy the consumer load demand at all times [33]. System security relates to the energy systems' ability to withstand sudden disturbances (such as storms, hail or frost) [33], but is out of the scope of this analysis.

2.1. Temperature and wind

The relationship between wind speed and temperature is not straightforward and depends on complex weather patterns. However, weather patterns where low temperature and low wind speed coincide occur (Fig. 1 [34]) can stress the power system with high shares of wind generation [8,35]. Such events need to be considered in planning studies to provide adequate system capacity. Several of these types of weather pattern were identified by Brayshaw et al. [36] and tend to be associated with high pressure systems at certain locations around Europe. A climate phenomenon known as the North Atlantic Oscillation (NAO), which relates to pressure differences between a location near Iceland and a location around the Azores, has been shown to influence both air temperature and wind speeds in the mid-latitudes (e.g. Ireland and Great Britain) [37].

2.2. Temperature, wind and electricity demand

Heating demand in Northern Europe is predominantly determined by ambient air temperature, although other variables such