NUCLEAR COGENERATION IN DISTRICT HEATING: PATHWAYS TO DECARBONIZATION

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Overview

The decarbonization of the space-heating sector is a critical element in the global effort to transition to low-carbon energy systems [1]. District heating (DH) systems are recognized as an effective way to combine low-carbon sources to provide heat for residential and tertiary sector buildings. As a proven technology for decarbonized electricity generation and with experience in coupling with DH networks, the hybridization of nuclear plants appears to be a promising technology to contribute to the low-carbon mix for space heating [2].

However, considering the substantial investment required for this technology [3] and the development of alternative low-carbon sources, such as biomass and large-scale heat pumps, the role of nuclear cogeneration in DH systems must be critically evaluated. This paper aims to identify key factors influencing the optimal transition pathways to low-carbon DH systems with the potential to include nuclear cogeneration plants. We seek to understand the advantages of nuclear cogeneration in a local context compared to alternative low-carbon heat production technologies. This paper contributes to the literature on the use of nuclear cogeneration for district heating ([4], [5], [6]). It conducts a comprehensive study of economic scenarios for optimal decarbonization of district heating networks, and includes heat transport aspects in the modeling and economic evaluation.

Methods

We develop a multi-period Generation Expansion Planning problem for a local DH system. The model incorporates three sub-systems whose sizing is optimized: a nuclear cogeneration plant (based on the Pressurized Water Reactor technology) with heat extraction capacities, a heat transmission network from the nuclear cogeneration plant to the DH network, and alternative heat production capacities (gas boilers, large scale heat pumps, etc.) with detailed technical constraints and economic parameters.

The Generation Expansion Planning problem is formulated as a Mixed-Integer Linear Programming (MILP) model. To ensure computational feasibility, the model operates in a two-phase setup: an investment phase and an operation phase. The investment phase divides the horizon into 5-year periods, representing short-term system operations with representative weeks for each block at an hourly timestep. New capacities for heat production and transmission can be installed, and existing ones decommissioned between the 5-year blocks. The operation phase optimizes system operations for the full duration of each block at an hourly timestep, based on the capacities determined in the investment phase.

Representative weeks for each year block of the investment phase are selected using a custom k-means algorithm based on the one developed in [7]. The week closest to the centroid of each cluster is chosen as the representative week for this cluster. Additionally, the heat extraction and heat transmission sub-systems are modeled by physics-based non-linear equations, with the heat transmission system's piping including binary variables. To represent the entire system as a MILP, we linearize these sub-system equations for each configuration of the binary variables in the heat transmission system.

Results

Multiple scenarios are designed to assess the interest of nuclear cogeneration in such setting for different system configurations. The scenarios vary in terms of the following characteristics: the initial existing heat production and transmission capacities, the new capacities available for installation, the heat demand profile, and fuel and CO2 prices. We find that district heating systems initially using a mix of geothermal plants and gas boilers are those for which nuclear cogeneration has the highest share in the 40-year optimal mix. On the opposite, for DH systems using solid waste and biomass, the model only invests in nuclear heat transport infrastructures half into the modeling horizon, after biomass units and peak gas plants arrive at the end of their lifetime. In addition, we find that nuclear heat is relatively more used in systems with a higher heat demand. For instance, in the case of a DH network with initial capacities of gas boilers and geothermal units, the nuclear cogeneration plant, provides 55% of the heat needed in the 6TWh case over the full simulation horizon, wheareas it only provides 12% of the demand in the 600GWh case, the rest being supplied by gas units (in the first years only), geothermal units and large scale heat pumps.

In addition, sensitivity analyses are carried out to assess the robustness of our results. The most important components are the distance between the NCP and the distribution network, the unit cost of the pipeline and the discount rate.

Finally, we compare our empirical results with those from district heating systems based on either gas, large scale heat pumps, or solid biomass and waste. In addition to the cost saving brought by the use of nuclear cogeneration aside other heating technologies, we wish to evaluate the carbon savings of scenarios using nuclear cogeneration in comparison to those using exclusively non-nuclear technologies.

Conclusions

The objective of this study is to assess the key factors influencing the role nuclear cogeneration can play in decarbonizing a DH network, taking into account the initial state of heating production, as well as the evolution of economic parameters in the next decades. We show that the high investment costs associated with heat transport infrastructures limit the investment in nuclear cogeneration to fuel heat for a district heating network once the distance to be covered exceeds 30 km. Yet, even at long distances, nuclear cogeneration contributes to the decarbonization of heat production in most of the scenarios considered, with a share ranging from 15 to 50% of the total heat load, depending on the size of the DH network, the other units available and the electricity and CO_2 costs. We contribute to the literature on nuclear cogeneration applications for district heating by conducting a comprehensive study of economic scenarios for optimal decarbonization of district heating networks and by including heat transport infrastructures our the modeling of heat supply.

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