Decarbonization of district heating through the lens of the “energy trilemma”– review of current SD modelling approaches

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System dynamics modelling of district heating decarbonization overwhelmingly focuses on environmental sustainability - while energy security remains almost entirely unmodelled, representing a critical gap in balanced energy transition planning.

Environmental sustainability is the most comprehensively covered trilemma dimension, with well-established feedback loops around carbon intensity and technology choice. Energy equity is partially addressed through cost-based decision mechanisms but rarely framed as an explicit modelling objective. Energy security, despite being widely acknowledged as a core trilemma component, is almost entirely absent from existing SD model structures - no reviewed study explicitly captures supply diversity, resilience to disruption, or long-term capacity adequacy. As a result, none of the 25 reviewed studies simultaneously model the interactions and trade-offs between all three trilemma dimensions, representing a significant gap in current SD modelling of DH decarbonization.

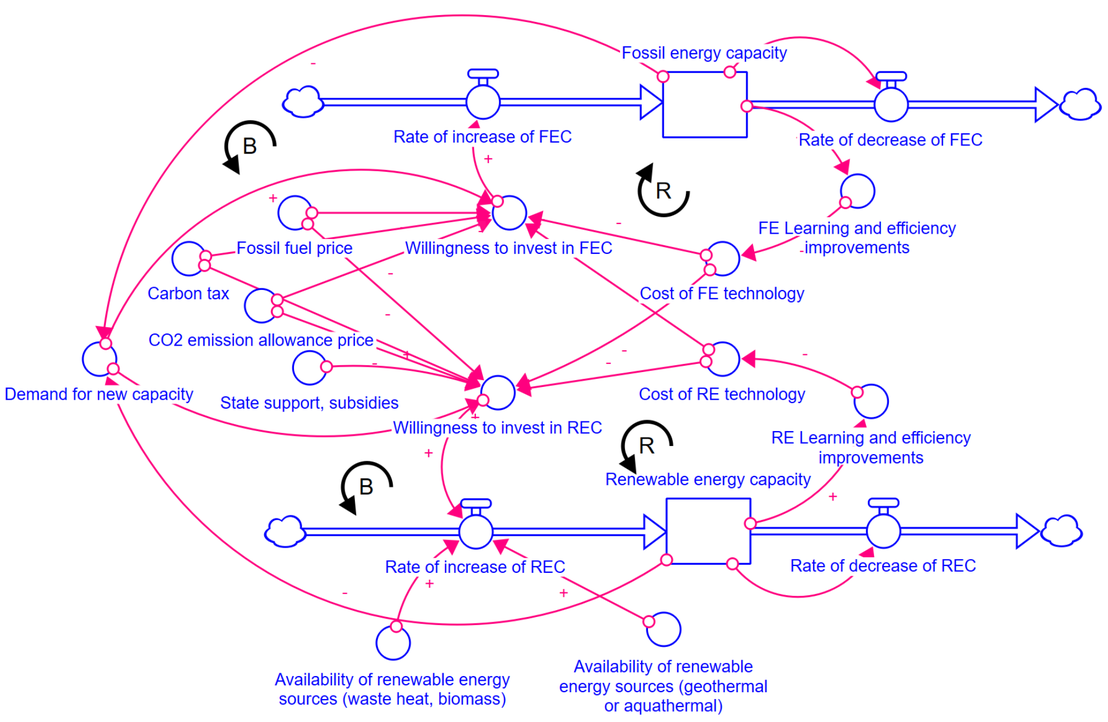
Introduction

District heating (DH) is a key tool for decarbonizing the urban heating sector and meeting EU 2050 climate targets. DH decarbonization involves three competing goals - the energy trilemma: environmental sustainability, energy equity, and energy security. System Dynamics (SD) modelling is well-suited for studying DH systems, capturing feedback loops, non-linear interactions, and time delays across interconnected subsystems. However, no study has systematically compiled SD feedback mechanisms across the literature, nor evaluated how well all three trilemma dimensions are represented in existing models. This paper fills that gap through a structured review of 25 SD modelling studies of DH systems.

Methodology

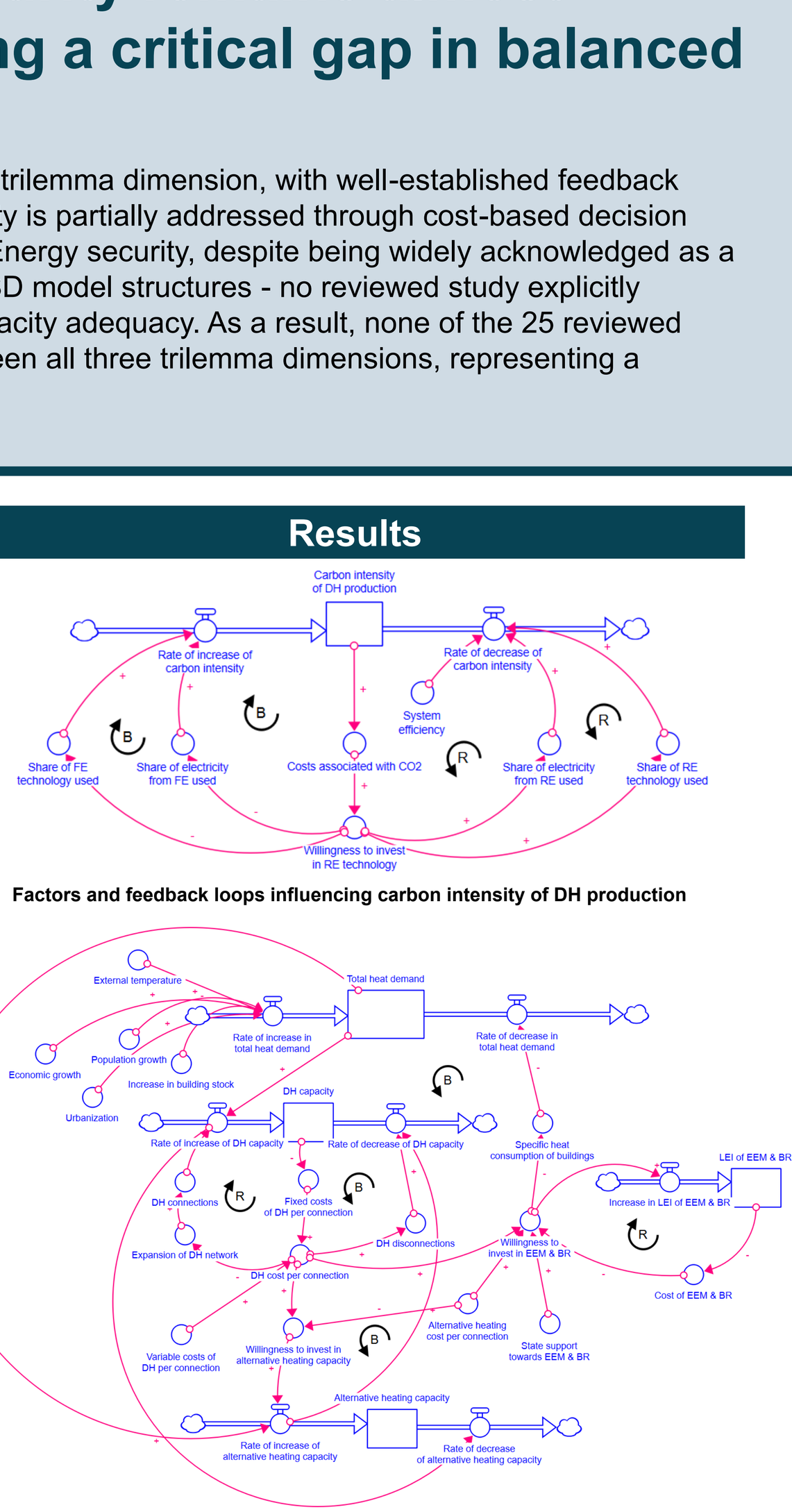
A structured literature review was conducted in Scopus using a predefined search string targeting SD modelling of DH systems. From 92 initial results, sequential filtering yielded 25 papers for final review. Each study was analyzed to extract causal relationships and feedback loops, yielding 131 total relationships, grouped into four thematic categories: renewable energy integration; carbon intensity of DH production; heating demand; and DH heating supply. **Findings for each group were then synthesized into consolidated SD diagrams.**

Results



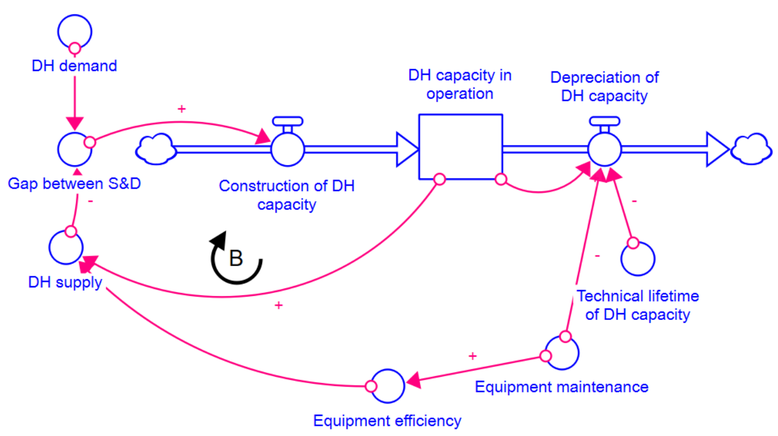
Factors and feedback loops influencing renewable energy integration

Results



Factors and feedback loops influencing carbon intensity of DH production

Factors and feedback loops influencing heating demand



Factors and feedback loops influencing DH heating supply