ABSTRACT

The present doctoral thesis sets out a comprehensive, data-driven methodological framework for evaluating and designing low-enthalpy geothermal solutions for heating and cooling applications in urban environments. This framework is systematically structured to address the fundamental challenges of energy transition implementation in complex urban settings. The research workflow, depicted in Figure 1, comprises an exploration of contemporary energy transition definitions. In this phase, the thesis examines how geothermal energy contributes to renewable energy systems and investigates the key challenges of integrating thermal energy sources within urban settings. The contemporary energy transition signifies a substantial structural transformation in energy supply and consumption systems, effecting a fundamental shift from fossil fuel reliance towards sustainable energy sources.

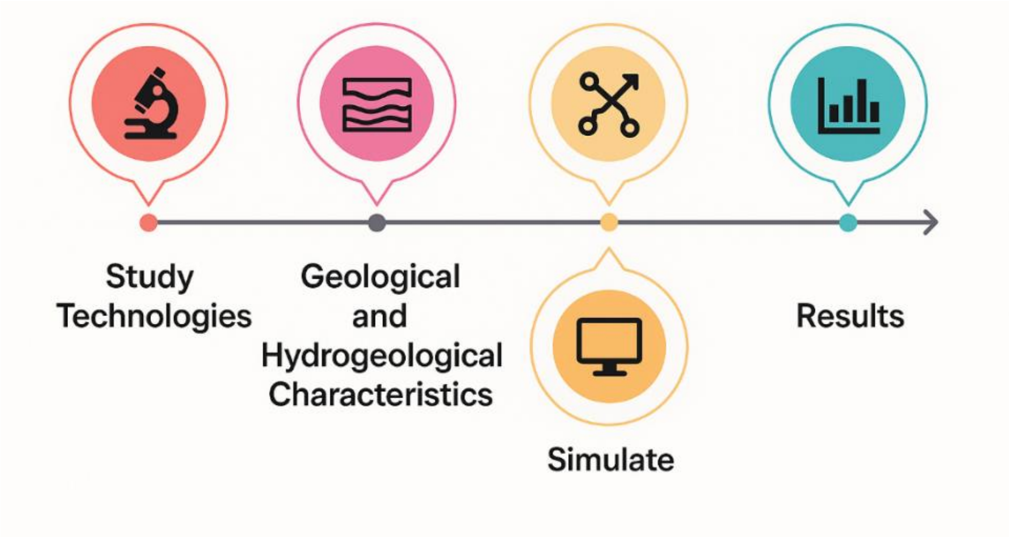

Figure 1. Schematic workflow of the thesis.

Geothermal energy is of particular significance in this transition, as it provides a constant power source that can offset the intermittent nature of other renewables, such as solar and wind energy. This contributes to the creation of more stable and dependable energy systems. However, integration in urban areas presents significant challenges due to thermal interference, spatial constraints, and regulatory frameworks, all of which must be carefully managed to ensure successful deployment. Subsequent to this exploratory phase, the thesis undertakes a comprehensive evaluation of low-enthalpy geothermal solutions, assessing their efficacy under diverse geological and hydrogeological conditions. The work specifically addresses which geothermal technologies are most effective by examining vertical borehole arrays, groundwater doublets, and subsurface thermal storage systems within the urban context of Turin. The influence of geological and hydrogeological conditions on technology selection is systematically investigated using publicly available datasets from regional geoportals, including stratigraphic profiles and piezometric data. The methodological steps essential for comprehensive evaluation are formalised through the integration of QGIS (©1989, 1991 Free Software Foundation, Inc.) for spatial data analysis, MODFLOW (U.S. Geological Survey Software) for groundwater flow modelling, FEFLOW (© DHI A/S) for coupled heat and mass transport simulations, and PEST for automated parameter calibration. This integrated approach facilitates the construction of spatially explicit conceptual models that capture the complexity of Turin's alluvial shallow aquifer system, which serves as a valuable resource for low-enthalpy geothermal energy exploitation.

The application phase of the thesis is centred on the maximisation of simulation accuracy through the implementation of advanced numerical methods and model calibration procedures. The research explores the potential of simulation methods to enhance the precision of results by implementing rigorous uncertainty quantification strategies. In this context, PEST is integrated within automated inversion loops to condition hydraulic and thermal parameters to observable data or literature benchmarks. In cases where observational constraints are limited, the calibration strategy prioritises the production of posterior parameter ranges as opposed to deterministic best-fit solutions.

The final phase of the research synthesises the key outcomes of the study and their implications for the deployment of geothermal systems in urban environments. The thesis presents spatial suitability maps for closed-loop versus open-loop solutions under documented stratigraphy and hydrogeology, operational guidelines for extraction and reinjection rates and borehole spacing requirements. The research implications for geothermal system deployment encompass practical guidance for urban implementation, including design heuristics for borefield sizing and layout, reinjection and monitoring requirements for piezometry and temperature, data standards for improving open databases, and policy measures to streamline permitting while protecting groundwater quality. The methodological framework is characterised by open datasets and numerical experimentation, ensuring transparency and reproducibility while positioning the approach as a transferable, low-cost decision-support tool for planners, utilities, and regulators. This comprehensive approach provides a pragmatic roadmap for the scaling of low-enthalpy geothermal solutions in urban areas. This is achieved by the use of reproducible, open-data modelling methods, which ultimately support the broader energy transition towards sustainable urban energy systems.