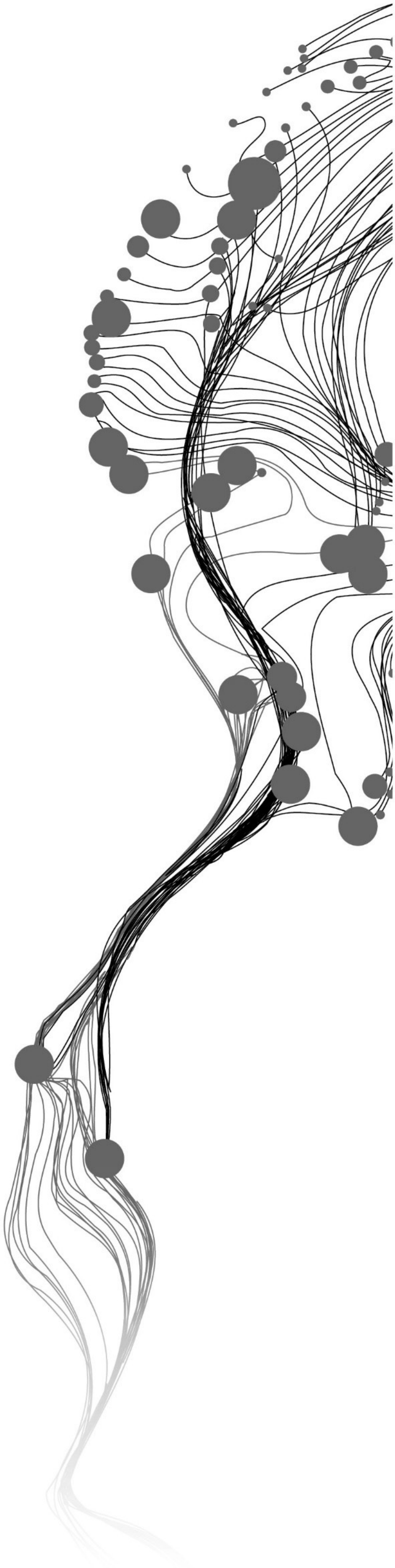
Exploring Planning Support Systems For Geothermal Resources In Enschede, The Netherlands

YONG BIN WONG
July, 2025

SUPERVISORS:
Dr. C.L. de Boer
Dr. C.A. Hecker



Exploring Planning Support Systems For Geothermal Resources In Enschede, The Netherlands

YONG BIN WONG
Enschede, The Netherlands, July 2025

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Spatial Engineering.

SUPERVISORS:
Dr. C.L. de Boer
Dr. C.A. Hecker

THESIS ASSESSMENT BOARD:
Dr. rer. nat. D. Reckien (Chair)
Dr. E.J. Aukes (External Examiner, UT BMS-CS)

ABSTRACT

Energy transition is a super wicked problem characterised by complex socioeconomic, technological and cultural considerations. Lack of community engagement contributes to low social acceptance and slow adoption of renewable energy projects, especially in subsurface developments, where public acceptability in the Netherlands is lowered following Groningen gasquakes. Participatory planning could mitigate local resistance to renewable energy development and, thus, could be valuable for the realisation of geothermal projects. However, there are only limited tools available to support the planning of geothermal energy projects. This calls for an investigation into Planning Support Systems (PSS) to support participatory planning processes of geothermal initiatives, facilitating knowledge exchange and consensus building among stakeholders within the Dutch city of Enschede. To examine the design of a PSS implemented for geothermal energy planning, we conducted a literature review of reported PSS applications and semi-structured interviews with identified key stakeholders who intend to use such applications for geothermal resource planning. This paper systematically reviews a total of 23 studies, gaining state-of-the-art knowledge about existing digital support technologies applied to renewable energy planning and geothermal infrastructure development. Based on an inductive thematic analysis of five interviews, major themes and factors concerning geothermal energy planning were identified. Agile user stories derived from interview responses, together with the use of design knowledge, conceptualise user requirements as PSS design criteria for geothermal energy planning. While these results provide a preliminary attempt at designing a PSS tool for professionals in geothermal energy planning, future work is needed to develop an effective tool for public engagement of citizen participation in the decision-making process.

KEYWORDS

geothermal energy, Low Unit Cost, planning support, neighbourhoods, stakeholder engagement

ACKNOWLEDGEMENTS

I express my deepest gratitude to my supervisors, Dr. C.L. de Boer (Cheryl) and Dr. C.A. Hecker (Chris), for your support, guidance and mentorship throughout my research journey. You guide me to think critically about taming wicked problems, but also to respect the non-linear process of conducting scientific research. Your constant encouragement during times of desperation, allowing light to shine through the cracks, instils in me a growth mindset and attitude that will continue to shape my academic and professional pursuits

I am thankful to the members of my thesis committee, the chairs Dr. rer. nat. D. Reckien (Diana) and Dr.Ir. L.G.J. Boerboom (Luc) for the constructive feedback and suggestions that enhanced the quality of my work. I am equally grateful to Dr. D. Kohli-Poll Jonker (Divyani) and A. Da Silva Mano (Andre) as procedural advisors for ensuring the journey runs smoothly. I express my sincere gratitude to my external examiner, Dr. E.J. Aukes (Ewert), for your valuable time and expertise in reviewing my thesis. I am grateful to all participants of this research for your generosity in sharing insights, and your contributions to this research are deeply appreciated.

I would like to thank my mentor, Dr. A.M. Pinto Soares Madureira (Mafalda), for your continuous support, since the first year of guiding me in developing my own personal development portfolio, till providing provisions in career search for the future. I also appreciate Sandy for your unwavering support and the willingness to discuss and provide feedback that allows me to always remain inspired.

My appreciation also goes to all the staff in the ITC Faculty and beyond, whose unconditional assistance, guidance and knowledge have been invaluable. I like to acknowledge my colleagues, from both M-SE and M-GEO, for your camaraderie and the stimulating discussions that inspired me throughout my master's programme. Your collective wisdom, encouragement and directness have been a cornerstone of my academic journey. My gratitude extends to all individuals with whom I have crossed paths, whether in small gestures or significant inspirations.

My heartfelt thanks and gratitude to my parents and brother for your incremental support and trust that is impactful to every phase of my life.

Last but not least, I shall not forget the bravery and courage to take to get out of thy country. I would like to pat myself on the back for not giving up, and also to remain faithful to myself. The luxury of being educated is simply to be grateful for, especially in these uncertain times.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

CAPEX	Capital Expenditure
DK	Design Knowledge
DSR	Design Science Research
DSS	Decision Support System
GIS	Geographic Information System
IS	Information System
LUC	Low Unit Cost
NIMBY	Not In My Backyard
OPEX	Operating Expenditure
PBL	Planbureau voor de Leefomgeving
PRISMA	Preferred Reporting Items for Systematic reviews and Meta-Analyses
PSS	Planning Support Systems
RES	Regional Energy Strategy
SDE++	Stimulering Duurzame Energieproductie en Klimaattransitie
SDGs	Sustainable Development Goals
TNO	The Netherlands Organisation for Applied Scientific Research
WEQ	Woningequivalent

1. INTRODUCTION

1.1. Energy Transition

Energy systems can be defined by two fundamental flows of energy resources. Energy provision includes natural sources of energy sustenance that are acquired by a community and the transformation of the primary energy into a secondary form, such as electricity, useful within the sociocultural settings (Bandh et al., 2023; Manzella et al., 2019). Energy consumption is closely associated with the characteristics of the community in meeting basic needs, desires and purposes at different geographical, environmental and societal scopes (Bandh et al., 2023). Therefore, energy systems have complex structures and properties (Bandh et al., 2023), which have profound implications on social and individual dimensions (Manzella et al., 2019). This makes energy vital for social and economic development, but also a source of environmental stress (Jakimowicz, 2022; Shortall et al., 2015a; Siksnelyte-Butkiene & Štreimikienė, 2023).

Energy consumption is by far the most significant contributor to total anthropogenic greenhouse gas emissions (Bandh et al., 2023), accounting for about 75% globally (WRI, 2022). As global energy demand has increased drastically with population growth and industrialisation over the past decade (Bandh et al., 2023), fossil-based energy sources remain a major part of the total energy consumption worldwide (Deshmukh et al., 2023; Devine-Wright, 2011; Sgouridis & Csala, 2014). Therefore, greenhouse gas emissions due to the combustion of fossil fuels have made climate change one of the pressing challenges in this century (Bandh et al., 2023; Deshmukh et al., 2023; Siksnelyte-Butkiene & Štreimikienė, 2023). Meanwhile, fossil fuel resources are finite and expensive (Bandh et al., 2023; Devine-Wright, 2011). With climate change being addressed in many international agreements, such as the Kyoto Protocol and the Paris Agreement, countries are committing to reduce their reliance on fossil energy sources and increase the use of energy from low-carbon sources, like renewable energy (Bandh et al., 2023; Devine-Wright, 2011; Manzella et al., 2019). This indicates that climate change mitigation requires significant changes in energy as well as policy systems, which are closely linked to the issue of sustainable energy (Ehrgott et al., 2010; Siksnelyte-Butkiene & Štreimikienė, 2023).

Fundamental changes in the energy system are often described as energy transitions, which involve integrating complex social and economic considerations (Bandh et al., 2023; Cha & Pastor, 2022). The concept of the energy transition is referred to as a temporary or extended period in which a change of energy sources by a particular community group is characterised by a socioeconomic, technological and cultural context (Bandh et al., 2023). Energy transition was initially focused on environmental pollution and energy security, but a transition towards sustainable energy systems has covered more problems lately related to social and economic development (Bandh et al., 2023; Siksnelyte-Butkiene & Štreimikienė, 2023). This includes using renewable and more domestic energy sources to achieve a decarbonised and low-carbon economy (Bandh et al., 2023; De Boer & Zuidema, 2015; Shortall et al., 2015a; Siksnelyte-Butkiene & Štreimikienė, 2023).

1.2. Societal Challenges of Energy Transition

Energy transition and technologies are subjected to the so-called trilemma (World Energy Council, 2019), namely energy security, energy equity and environmental sustainability. Energy security concerns the reliable availability of energy sources and supplies to meet current and future demands, whereas energy equity focuses on the accessibility and affordability of energy resources and services. The third dimension, i.e., environmental sustainability, emphasises minimising energy and emissions intensity by transitioning to renewable and low-carbon energy sources (World Energy Council, 2019). The energy trilemma concept indeed corresponds to the dimensions of sustainability by accounting for the current economic, social and environmental needs of future societies. However, characteristics of energy-related issues are bounded by high levels of complexity due to the combined and interconnected elements of technical, behavioural and institutional issues (Jakimowicz, 2022; Manzella et al., 2019; Siksnelyte-Butkiene & Štreimikienė, 2023). This causes the use of renewable energy to vary across different social, political and economic contexts (Devine-Wright, 2011; Manzella et al., 2019), creating a high level of uncertainty about future energy systems.

Energy is important in realising the idea of sustainable development, with energy transition closely intertwined with the United Nations' Sustainable Development Goals (SDGs) (Siksnelyte-Butkiene & Štreimikienė, 2023). Therefore, sustainable energy development has become a new paradigm in the twentieth century (Shortall et al., 2015b; Siksnelyte-Butkiene & Štreimikienė, 2023), helping to realise the role of energy in achieving the SDGs. However, accommodating such a paradigm shift is not easy. This is owing to the necessity for changing existing energy infrastructure and regulatory systems as well as the multitudinous involvement of decision-makers and stakeholders (Bandh et al., 2023; De Boer & Zuidema, 2015; Siksnelyte-Butkiene & Štreimikienė, 2023). Energy has important economic and social implications, such that the accessibility to commercial energy services directly affects poverty reduction positively (Siksnelyte-Butkiene & Štreimikienė, 2023). However, the lack of energy access has obstructed progress towards sustainable development. Therefore, sustainable energy development aims to account for the economic, social and environmental needs (Siksnelyte-Butkiene & Štreimikienė, 2023), while simultaneously ensuring efficient energy use by increasing energy access, affordability and security (Shortall et al., 2015a).

Renewable energy has become a priority for European nations (Georgiadou & Reckien, 2018), especially with the goal of the Green Deal to reach a climate-neutral continent by 2050 (Bandh et al., 2023). However, different social, political and economic factors cause the transition to a low-carbon energy system to be extremely variable (Devine-Wright, 2011). In the Netherlands, the implementation of renewable energy projects is slower than in other European nations as local decision-makers lack the institutional capacities to implement renewable energy policies (Flacke & De Boer, 2017; Georgiadou & Reckien, 2018). Moreover, limited opportunities for engaging local communities in decision-making processes have resulted in strong public resistance towards renewable energy implementation (Devine-Wright, 2011; Flacke & De Boer, 2017; Georgiadou & Reckien, 2018). The NIMBYism, or "Not in my backyard" phenomenon, also creates social gaps between the high levels of public support and the frequent local opposition to renewable energy projects (Devine-Wright, 2011; Flacke & De Boer, 2017; Georgiadou & Reckien, 2018). Furthermore, low levels of acceptance from the local community cause policymakers to remain sceptical about responding to public proposals for renewable energy locally (Devine-Wright, 2011). The NIMBY phenomenon, coupled with limited community engagement, leads to low levels of social acceptance of renewable energy projects.

Geothermal energy contributes a marginal share to the global energy source mix at just 0.3% (Nkinyam et al., 2025). With the abundance of natural reservoirs within the Earth (Bandh et al., 2023; Siksnelyte-Butkiene & Štreimikienė, 2023), geothermal is growing as a potential sustainable source to provide a stable and reliable supply of energy (Chouhan et al., 2024). However, like many other renewable energy alternatives, the development of geothermal energy can be hindered by its technical, socio-economic and environmental consequences (Anderson & Rezaie, 2019; Manzella et al., 2019; Raos et al., 2022; Solano-Olivares et al., 2024). To address and tame the wickedness of renewable-energy planning, early involvement of stakeholders and communities is needed to account for local particularities (Devine-Wright, 2011; Flacke & De Boer, 2017; Vargas-Payera et al., 2020). Collaborative strategies for decision-making strengthen common values (Aguilar et al., 2021; Devine-Wright, 2011; Flacke & De Boer, 2017), thereby ensuring the long-term growth of geothermal energy development (Manzella et al., 2019). This will require a public dialogue that enables local communities to play an active role in the development of geothermal energy technologies (Manzella et al., 2019). Furthermore, a sustained and reasoned societal dialogue is essential for accelerating or preventing geothermal energy development while avoiding unfair and technocratic decision-making processes (Manzella et al., 2019). However, limited collaborative dialogues have been practised to strengthen stakeholders' perceptions and knowledge of geothermal energy development.

1.3. Social Acceptance of Geothermal Energy

Environmental risks are one of the critical concerns affecting social acceptance of geothermal energy. The degree of impact varies according to the scale of geothermal exploitation and reservoir depth (Manzella et al., 2019). In the Netherlands, subsidy schemes facilitate large-scale geothermal development and exploitation for maximal heat production (De Groot et al., 2020; Mol et al., 2021). However, a deep geothermal project is restricted to areas with high-demand applications and high-quality aquifers (Mol et al., 2021). Moreover, a deep geothermal system, which can be installed up to a depth of 3000m, is susceptible to wear-and-tear (Mol et al., 2021), resulting in high operating costs and greater seismic risks that endanger social acceptance of geothermal energy technologies (Manzella et al., 2019; Renoth et al., 2023). On the contrary, shallow geothermal resources or low-enthalpy heat extracted from the ground or groundwater have lower environmental and induced seismicity risks than deep reservoirs.

Public acceptance and support of energy projects are subject to the perceived benefits, costs and risks of energy production. In the Netherlands, the pervasive phenomenon of land subsidence is a wicked challenge to the lowlands, yet this is further threatened by the exploitation of geo-resources (Pluymakers et al., 2023; Van Daalen et al., 2020). Subsurface operations are often associated with induced seismicity, which has substantial consequences for the densely populated nation of the Netherlands. One example is the exploitation of the largest European onshore gas field in the province of Groningen. The revenues from Groningen gas reserves were once considered a blessing, from post-war reconstruction to the funding of a welfare state, before falling victim to Dutch Disease[1] (Dekker & Missemer, 2024). Despite this resource crisis being curbed with a reduced extraction rate, extensive gas production brings costs and consequences to the local communities through a series of gasquakes that have led to negative social, psychological and economic impacts (Bieder et al., 2024; Palomo-Vélez et al., 2023). In particular, the infamous Huizinge and Zeerijp earthquakes have heightened public unrest and spurred local resistance towards gas extraction (Bieder et al., 2024; Boin et al., 2021; Palomo-Vélez et al., 2023). Salt mines have also been extracted since the early 1900s from the subsurface of the cities of Hengelo and Enschede in the Twente region. Empty salt caverns pose substantial risks, and the collapse of an old cavern in Hengelo resulted in a sinkhole in 1991 (Muntendam-Bos et al., 2022). In Enschede, undue risk management and stabilisation of abandoned caverns have caused a social and political uproar since the early 2000s, resulting in the public acceptance of salt mining being under pressure and the debate over mining initiatives being polarised (Roovers & Duijn, 2021). These cases can inform public planning and decision-making of subsurface operations, thereby mitigating local turmoil as well as resistance to geothermal extraction.

1.4. Research Gap

Social acceptance is a critical factor in determining the success of renewable energy projects. This leads to different theoretical frameworks being developed to recognise, understand and address factors influencing public acceptance of renewables (Devine-Wright et al., 2017; Ellis et al., 2023; Karytsas et al., 2019; Upham et al., 2015; Wüstenhagen et al., 2007). Among the many, the three-perspective model (Figure 1) is the most referred to for conceptualising social acceptance, and community acceptance is a crucial factor for energy-related infrastructure projects (Onencan et al., 2024; Renoth et al., 2023; Upham et al., 2015). There are geothermal projects that have failed in the past due to a lack of social acceptance (Manzella et al., 2019; Renoth et al., 2023). However, there is currently no established research on community perspectives on the realisation of geothermal projects. Despite the social acceptance framework by Wüstenhagen et al., (2007) serves as a heuristic framework for renewable energy innovation and a boundary object for framing energy as a socio-technical system (Ellis et al., 2023), there are only a few tools available to support the planning of geothermal energy projects. Therefore, planning support tools for collaborative and participatory processes of geothermal initiatives at Enschede are going to be explored in this study. Designing such tools could support stakeholder participation and interest in the planning process of renewable and geothermal energy projects.

[1] Coined by The Economist in 1977, the expression of Dutch Disease characterises the industrial fragility of the Dutch economy after the oil shock in the mid-1970s (Dekker & Missemer, 2024). In the Netherlands, the natural gas discovered from Groningen post-Second World War was able to cover a majority of the Dutch energy market, reconfiguring the Dutch economy from traditional manufacturing to energy-intensive industries (Dekker & Missemer, 2024). However, the 1973 Oil Embargo caused fossil fuel prices to skyrocket, penalising energy-intensive industries and weakening the newly structured Dutch economy. This led to a spike in unemployment and destabilised the Dutch currency (guilder). Hence, the term 'Dutch Disease' is substantiated by economic research to understand the mechanisms of why and how a natural resource boom can result in de-industrialisation (Dekker & Missemer, 2024).

Figure 1. A conceptual framework of social acceptance in a three-perspective model by Wüstenhagen et al. (2007).

1.5. Research Problem

Social acceptance is crucial for the success of renewable energy projects. Neglect of social acceptance could lead to ill-informed policymaking and practice, which creates local resistance towards renewable energy technologies (Devine-Wright et al., 2017). The absence of early engagement with local stakeholders and communities also results in complex trade-offs in the renewable energy decision-making and planning process (Flacke & De Boer, 2017; Manzella et al., 2019). On top of that, inadequate public dialogue discourages local communities from playing an active role in the development of geothermal energy technologies (Manzella et al., 2019). Therefore, a societal dialogue supported by participatory planning could be valuable for geothermal energy development by addressing unfair and technocratic decision-making processes.

A systematic review by Renoth et al., (2023) identifies a lack of community knowledge about geothermal energy as one of the main reasons for low levels of social acceptance, leading to public reservations or rejection of geothermal projects. Moreover, public participation and community engagement with geothermal energy are fragmented and underexplored in the governance of energy systems (Manzella et al., 2019). This is then coupled with limited community engagement opportunities and predominantly top-down decision-making processes (Devine-Wright, 2011; Flacke & De Boer, 2017), thereby creating a destructive cycle of local opposition to renewable energy technology. Therefore, a collaborative dialogue for social learning could be useful to facilitate the perceptions and knowledge co-production of stakeholders for renewable and/or geothermal energy planning. This can be achieved using planning support systems (PSS) as "*geoinformation technology-based instruments that incorporate a suite of components that collectively support some specific parts of a unique professional planning task*" (Geertman, 2008, p. 217).

1.6. Research Objective and Questions

This study aims to better understand the potential contribution of geospatial collaborative tools for geothermal resource planning in the municipality of Enschede, by constructing a preliminary design of a planning support systems (PSS) to support participatory planning. Two research questions are as follows:

(1) What does a conceptual design of PSS tools dedicated to supporting renewable energy planning need to be composed of to meet stakeholder needs?
(2) What are the design criteria describing the PSS tool for geothermal energy planning?

2. BACKGROUND

2.1. Geothermal Energy Technology

Geothermal energy is, by definition, the energy in the form of thermal heat stored beneath the surface of the Earth, originating from the residual heat of planetary formation or the decay of radioactive isotopes within the Earth's mantle and crust (English et al., 2023; Rybach, 2022). Additionally, the ground thermal energy conserved close to settlements can be regarded as having urban geothermal potential (Bayer et al., 2019). Geothermal energy is potentially inexhaustible, subject to the cooling of the planet over geologic time (English et al., 2023), and a non-intermittent sustainable source that provides a consistent and continuous energy supply independent of weather conditions and diurnal or seasonal cycles (Geothermie Nederland, 2018). The transfer of heat spatially from the hot core to the cool surface of the Earth creates geothermal gradients that could range from 20 to 40 °C km^{-1} (English et al., 2023). This vertical heat transportation via conduction and convection describes geothermal resources across subsurface strata or plays (Anderson & Rezaie, 2019; Geothermie Nederland, 2018). Seven strata in the Netherlands are potentially suitable for geothermal energy production, namely the Rotliegend, Triassic, Jurassic/Cretaceous, Upper Carboniferous, Chalk, Tertiary, and Zechstein plays (Geothermie Nederland, 2018). An understanding of geothermal play types assists in defining the vertical variation of ground thermal characteristics and properties, thereby aiding the evaluation of geothermal energy potential and the exploration strategies of reservoirs (Geothermie Nederland, 2018).

Like many sustainable energies, harvesting geothermal energy is not equally possible in all locations (De Boer & Zuidema, 2015). Areas with active tectonism and volcanism have higher geothermal gradients and heat flow (English et al., 2023). These areas, therefore, have traditionally been used by human societies to access and exploit geothermal heat near tectonic plate boundaries (Bleicher & Gross, 2015). Thermal energy at a localised geothermal system can be extracted from natural or induced fluid circulation. Geothermal fluids exist at high-permeability hydrothermal reservoirs are dependent on local geological characteristics and quality aquifers with suitable water flows (Ruef et al., 2020). On the contrary, low-permeability petrothermal reservoirs may have limited or no natural fluid content and, thus, require fluid injection that is associated with greater induced seismic risks (Bleicher & Gross, 2015; English et al., 2023; Ruef et al., 2020). Geothermal systems in the Netherlands are classified as hydrothermal and porous reservoirs (Mijnlieff, 2020). Accessible geothermal resource base is location-dependent, with local mean annual temperature measured at a specific area and depth below the Earth's surface (Dickson & Fanelli, 2005). Furthermore, geothermal energy as a useful and economic resource should be extracted at a cost competitive with other commercial energy sources (Dickson & Fanelli, 2005; English et al., 2023; Muffler & Cataldi, 1978).

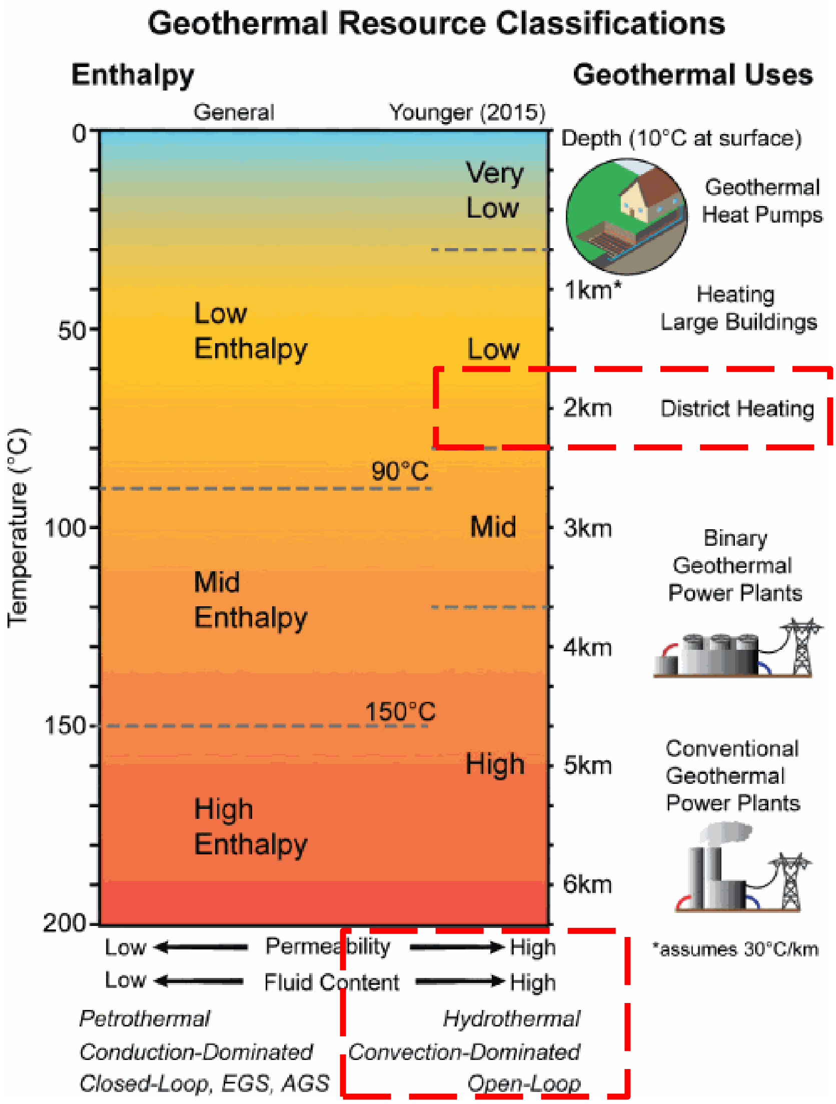


Figure 2. Tripartite classification scheme of geothermal resources, based on temperature and associated forms of utilisation described in Banks (2012) and Dickson & Fanelli (2005). A refined categorisation of geothermal resources, based on temperature and reservoir pressure, is proposed in Younger (2015). Sourced from English et al. (2023). This study focuses on Dutch hydrothermal and porous geothermal reservoirs for the use of district heating.

There is no universal standard terminology for classifying geothermal resources (Dickson & Fanelli, 2005). One common classification scheme is based on the heat content of the geothermal fluid, which is divided into low, medium, and high enthalpy. Enthalpy is proportional to temperature, and Muffler & Cataldi (1978) use 90°C and 150°C as threshold values for the enthalpy classification system of geothermal resources. However, no consensus is reached on the boundaries between classes, with the temperature values or ranges being ambiguous and meaningless on a case-by-case basis (Banks, 2012; Dickson & Fanelli, 2005). On the other hand, geothermal systems can be better classified based on the characteristics and potential use of fluids extracted from the subsurface reservoir. Liquid and vapour are fluid phases that frequently make a distinction in geothermal systems. Widely distributed worldwide, liquid-dominated geothermal systems may have temperatures ranging from <125 to >225 °C, with hot water and/or steam mixtures as the pressure-controlling fluid phases and wet steam being produced (Dickson & Fanelli, 2005). On the contrary, vapour-dominated geothermal systems are rarer, with the coexistence of liquid water and vapour as well as the production of dry and superheated steam (Banks, 2012). This study focuses on Dutch geothermal reservoirs for the use of district heating (see Figure 2). The circulation of fluid and the mechanism of heat transfer at the reservoir equilibrium state is another division between geothermal systems (Dickson & Fanelli, 2005). Dynamic systems are permeable reservoirs with fluids continually recharged, and the heat is transferred through convection, thus being considered the convection-dominated play (Anderson & Rezaie, 2019). Static systems or conduction-dominated play have minor or no recharge to the reservoir, and the heat is transferred only by conduction. The classical Lindal diagram (Lindal, 1973; Figure 3) showcases the possible uses of liquid and vapour-dominated geothermal fluids at different temperatures. Depending on the depth and the technologies used, subsurface geothermal energy can be used in various ways, from heat production to cooling and electricity generation (DiPippo, 1991; Geothermie Nederland, 2018; Romanov & Leiss, 2022). Deep and shallow are two geothermal technological families that have been developed for energy extraction, and there is no universal definition and classification that distinguishes between these two (Romanov & Leiss, 2022). The deep geothermal system is the focus of this study and is elaborated in the section below, while shallow geothermal is reviewed in Appendix 1.

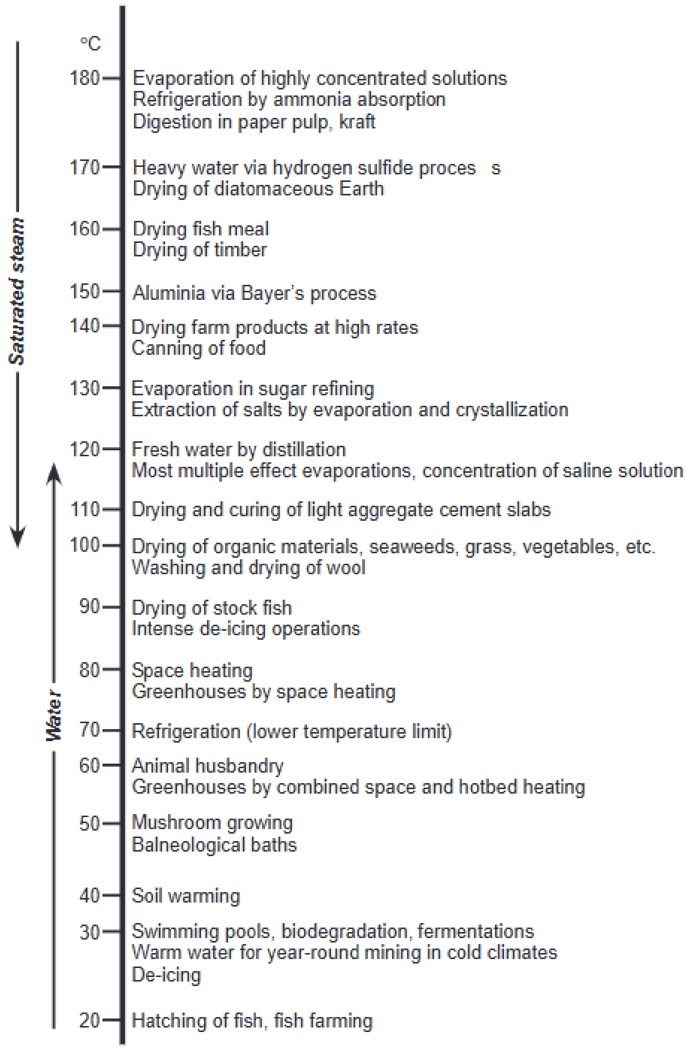


Figure 3. The Lindal (1973) diagram shows how geothermal energy resources of different temperatures can be applied for a range of applications. Sourced from Dickson & Fanelli (2005).

2.2. Deep Geothermal and Low Unit Cost

Deep geothermal refers to "t*echnologies developed to access great depths to retrieve and use temperatures above the annual mean air temperature*" (Manzella et al., 2019, p. 2). In a deep geothermal system, the geothermal production well is drilled up to several kilometres beneath the surface to extract heat from high-temperature reservoirs (Shah et al., 2024). For example, Romanov & Leiss (2022) consider deep geothermal with fluid temperatures of more than 90 °C, whereas Bertani (2016) describes deep fluids mainly as high (>180 °C) and medium (>100 °C) temperature resources. The Netherlands Organisation for Applied Scientific Research (TNO) defines deep geothermal with a depth between 1,500 to 4,000 m (Mijnlieff, 2020). There are currently 28 functioning deep geothermal doublets in the Netherlands that deliver six petajoules of heat yearly (Pluymakers et al., 2023). Techniques have also been developed to enable deep geothermal exploration in less suitable subsurface conditions, like the Low Unit Cost concept.

The concept of Low Unit Cost (LUC) has been introduced by Geothermie Groep Nederland B.V. as a relatively safe and cost-efficient alternative to conventional geothermal energy production for areas with less suitable subsurface properties, such as the Eastern part of the Netherlands. LUC methodology combines innovative project management and best practices in geothermal well engineering as well as production technology (De Groot et al., 2020). Operating at a restricted flow rate and low pressures, a LUC project implements a pilot hole as a de-risking methodology for well-testing to reduce up-front development costs and seismic risk (De Groot et al., 2020; Mol et al., 2021). The geothermal doublet is also designed with a slanted production well and a slanted injection well, which can be adjusted dynamically according to the reservoir characteristics. Moreover, LUC development requires a low production rate and modest temperature for moderate heat demand (Mol et al., 2021), which enables geothermal energy development to be economically feasible from shallower or lower-quality aquifers (De Groot et al., 2020). Hence, the LUC method allows safer and more cost-efficient harvesting of geothermal energy, posing potential wider applicability globally (Mol et al., 2021). The parallel-designed LUC doublet also optimises aquifer potential to match local heat demand. Therefore, the LUC development can serve as a source network on a local and small-scale heat supply, creating a low-temperature heating network that connects buildings within a neighbourhood.

The LUC development has been explored in the Eastern Netherlands at the cities of Emmen and Enschede. Within the portfolio project at Emmen, the LUC installation targets an aquifer of the early Cretaceous coastal marine Bentheim Sandstone at a 1,500 m true vertical depth (Mol et al., 2021). With an aquifer temperature of 61°C and a return temperature of 26 °C, this LUC project is estimated to harvest a geothermal potential of 1.5 MW_{th} for heating commercial greenhouses (De Groot et al., 2020; Mol et al., 2021). The net present value (NPV) of this project was calculated at €6 million over 30 years (De Groot et al., 2020; Mol et al., 2021). The LUC project in Enschede aims to establish the potential of the Late Carboniferous Tubbergen Formation as a geothermal source for domestic heating (Veenstra et al., 2020). An engineering feasibility study was conducted for developing a 3.6 MW_{th} geothermal installation that is capable of heating 600 houses (Veenstra et al., 2020). Prospective reservoirs were located at 1,500 – 2,200 m true vertical depth (Mol et al., 2021), with the reservoir temperature estimated at 63 °C and the return temperature set at 33 °C (Veenstra et al., 2020). A positive NPV of €12.7 million over 20 years (Veenstra et al., 2020) (see Table 1 below). Furthermore, the LUC project was estimated to supply energy consumption of 1,040,000 gigajoules (GJ) within the 20-year lifespan (Veenstra et al., 2020), corresponding to approximately 32 million m^3 of natural gas (31.6 m^3 per GJ) and a district heating cost of €45 million (€43.79 per GJ in 2025) (Schlagwein, 2025). This study explores LUC as a deep geothermal system for district heating, aligning with the Dutch Master Plan for Geothermal Energy (Figure 4) (Geothermie Nederland, 2018).

Table 1. Expected parameters of a LUC geothermal project in Enschede. Sourced from Veenstra et al., (2020).

	LUC Installation In Enschede
Estimated Life Span (years)	20
Net present value (€)	12.7 million
Heat Potential - Medium (MW_{th})	1.5 – 4
Heat produced Over Life Span (GJ)	1,040,000
Number Of Houses To Be Heated	600
Equivalent Volume of Natural Gas (m^3) [a]	32 million
Equivalent District Heating Cost (€) [b]	45 million

[a] Calculated as one GJ corresponds to 31.6 m^3 of natural gas (Schlagwein, 2025)
[b] Measured based on the district heating rate 2025 as one GJ at € 43.79 (Schlagwein, 2025)

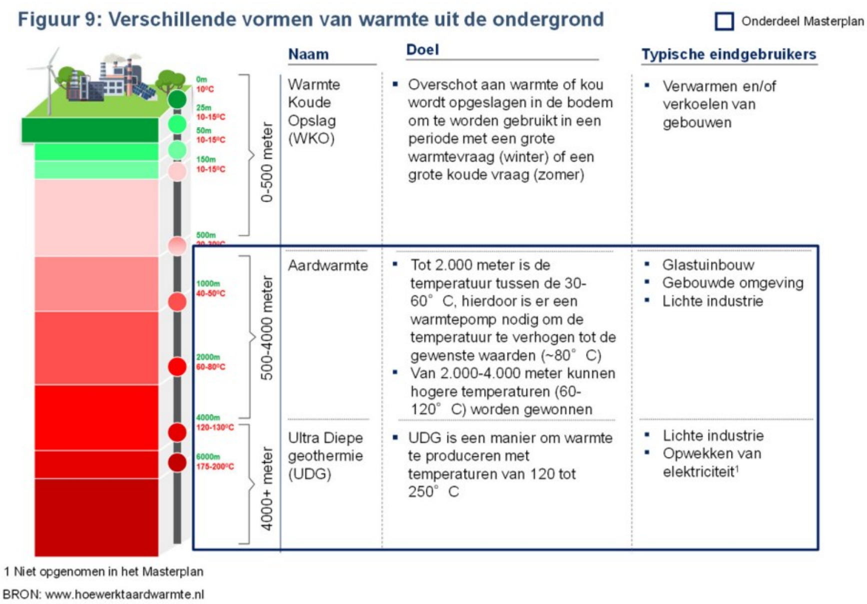


Figure 4. Different technologies and depths are being used for extracting heat from the subsurface in the Netherlands. Only geothermal energy and Ultra-Deep Geothermal energy are being discussed in the Master Plan. Sourced from Geothermie Nederland (2018).

3. RESEARCH DESIGNS AND METHODS

A Planning Support System (PSS) is a decision model that reflects a decision problem in a simplified real world. The building of a model is a process of formulating perspectives on a set of issues, uncertainties, values and possible policies (Bayley & French, 2008). Traditional conceptualisations assume perfect rationality from decision-makers, making traditional methods ineffective in offering solutions to unstructured and ill-defined problems, such as wicked problems. Thus, PSS that deal with wicked issues must embrace procedural rationality to systematically gather and analyse information through reasoning processes in finding acceptable alternatives (Mackenzie et al., 2006; Ritchey, 2011). The rational choice of solutions empowers the process of appropriate deliberation to be undertaken in a decision (Simon, 1976). In this study, the planning support system design consists of three steps: (1) Exploration; (2) Community Scouting; and (3) Model Design. These steps are designed to correspond to Simon's (1960) three-phase framework for planning and decision-making processes (Figure 5).

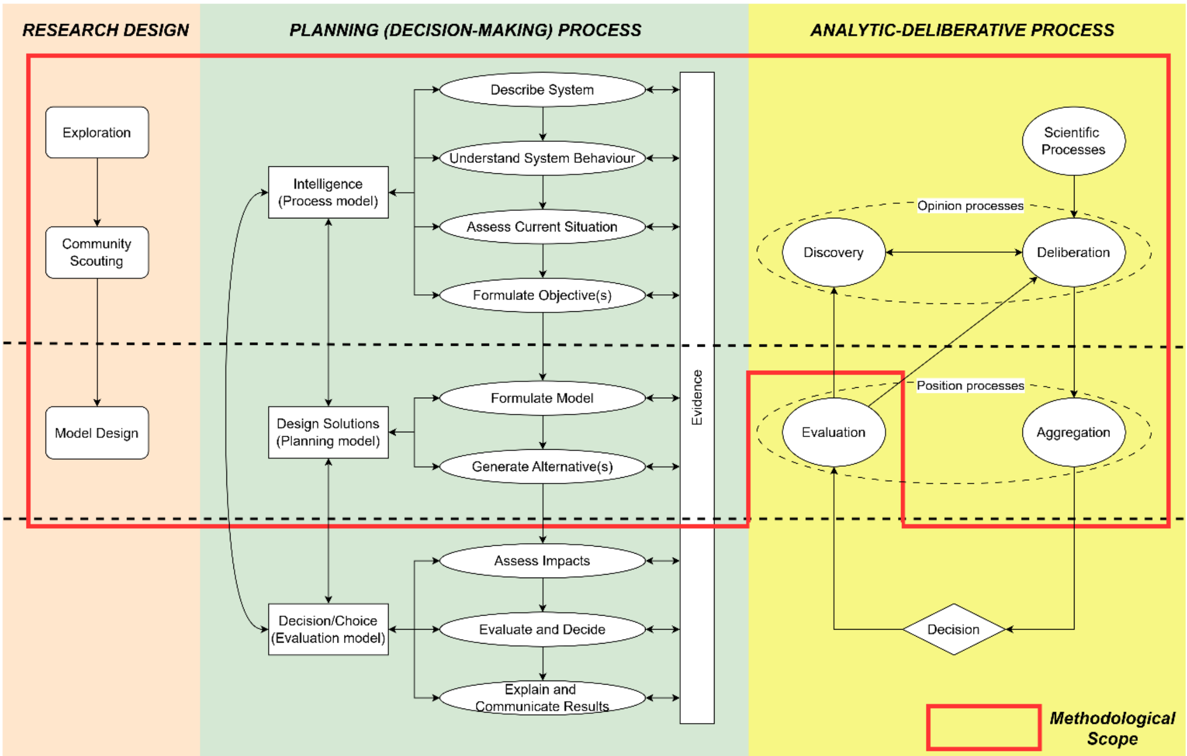


Figure 5. Conceptualisation of the research methodological steps in designing a planning support system. The research design is integrated with Simon's (1960) framework for planning and decision-making phase and the analytic-deliberative process from the National Research Council (1996).

Simon's framework presents the iterative movement between phases, i.e., *Intelligence*, *Design* and *Choice*, emphasising the procedural deliberation process as cyclical and evolutionary. Evidence in the form of facts, data, and knowledge is integrated throughout the planning process to "*capture perspectives, explore, analyse, simulate, and evaluate iteratively*" (Pretorius, 2017, p. 210). For example, the first step involves exploring facts and information in the local energy landscape, such as energy initiatives, interest groups, decision-makers and financiers. A stakeholder analysis can be incorporated to map the power and interest relations. This is then followed by scouting the community's social fingerprints, like housing units, heat demand and energy usage, which could help identify boundary conditions for PSS design and assess representativeness for addressing the decision problem. These two steps respond to Simon's *Intelligence* phase in identifying problem or opportunity situations by examining the local system and relevant behaviour. This is followed by assessing the existing situation that is needed for reaching a desired state, before formulating objectives and goals to be implemented into the support system.

Most public participation in renewable energy is a single-case focus without insights into the applicability to a variety of cases and contexts (Bouw et al., 2023). Therefore, the third step, Model Design, should address the need to develop options and scenarios. This involves developing socio-technical scenarios or providing information, e.g., questionnaires (Bouw et al., 2023), which allows PSS users to explore scenarios. Apart from avoiding the users being forced in targeted directions, this will also deal with problems within a spatial system boundary (elaborated in the section Stakeholder Analysis below), but having external influences from the environment where the system belongs (Champlin, 2019). This step corresponds to Simon's *Design* phase in initiating, developing, and analysing the possible courses of action (Jankowski & Nyerges, 2001; Sharifi et al., 2002), thereby assessing the feasibility and applicability of different options and alternatives. Simon's framework involves two steps, from formulating a planning model to identify ways that the current state of the system can be altered or improved (decision problem) to generating alternatives for simulating different states of system changes. Once the prototype is acquired, alternative options and courses of action for the PSS design can be evaluated in, for example, a public dialogue. This corresponds to Simon's Choice phase, which is not included in this study.

The proposed methodological step, as well as Simon's framework, is a recursive process that could be aligned with the systematic analytic-deliberative approach advocated by the National Research Council (1996). This process consists of four group categories: (1) Discovery, (2) Deliberation, (3) Aggregation, and (4) Evaluation. The exploration and community scouting steps, as well as Simon's Intelligence phase, focus on identifying facts and situations of the local system, in which the *Discovery* and *Deliberative* processes elicit the learning of issues, criteria and alternatives from prior discovery or available science. This information or facts is then aggregated to determine the model design by evaluating trade-offs for achieving the objectives. Once the prototype is acquired, the model is forwarded for making decisions. The feedback or alternatives received during the *Decision* process are evaluated for appealing design options on the planning support system. In response to possible adverse evaluation, the process is reiterated to *Discovery* and *Deliberative* processes for gathering information, thereby re-initiating the cyclic analytic-deliberative process. The cyclic approach could also happen within each individual process (Balint et al., 2011), or a divergence-convergence dynamic could be implemented within each process to elicit information useful for planning support system design (Champlin, 2019). This iterative approach facilitates social learning about ill-defined decision problems, and the knowledge acquired could raise awareness and clarity of participants about the trade-offs and complexity inherited in a particular planning scenario.

3.1. Study Area

3.1.1. City of Enschede, The Netherlands

Located in the east of the Netherlands, Enschede is a municipality in the Twente region of the province of Overijssel (Figure 6). Enschede is a medium-sized city with around 161,000 inhabitants (CBS, 2024a), comprising 10 districts and 70 neighbourhoods. In compliance with the National Climate Agreement, the municipality of Enschede is actively contributing to heat transition to achieve a natural-gas-free and climate-neutral city by 2050.

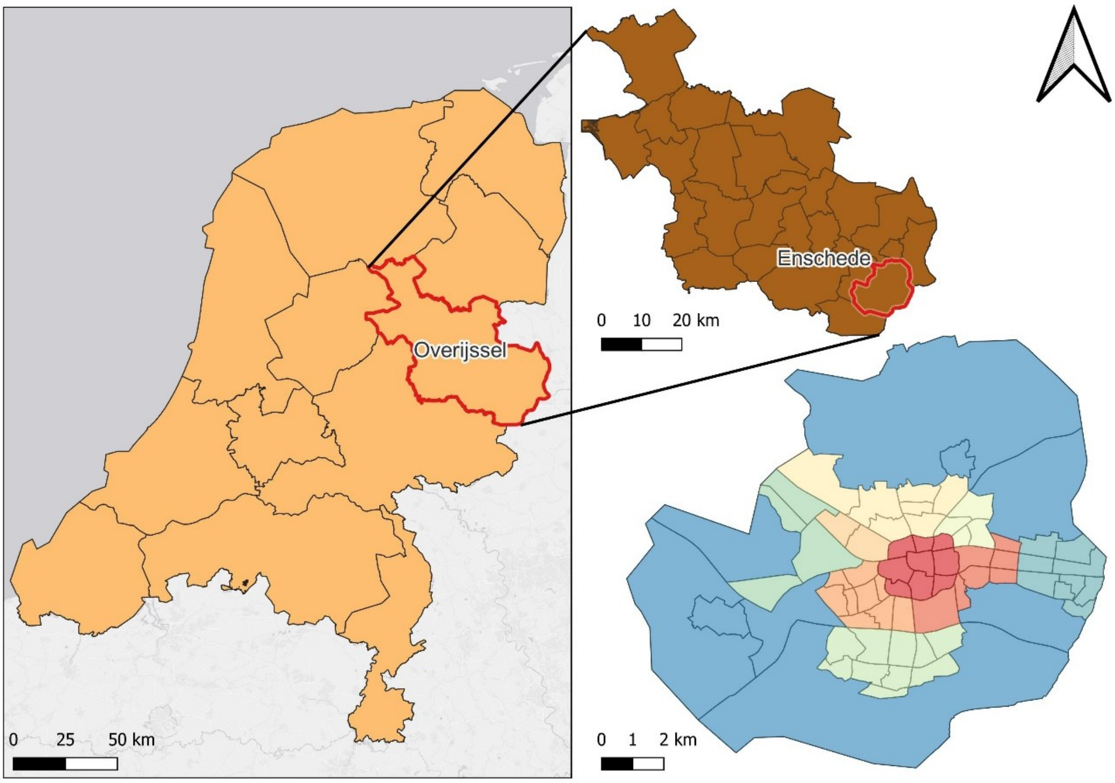


Figure 6. The Netherlands and the focus area, Enschede Municipality. Sourced from Author.

In accordance with the European climate and energy targets, the Netherlands has established ambitious climate goals to halve its emissions of greenhouse gases by 2030 and reduce as much as 95% by 2050 (Netherlands Enterprise Agency, 2020). Building on the Regional Energy Strategy (RES), the Energy Strategy Twente aims to produce more than 20% of energy sustainably by 2030 (Twente, 2020). Enschede is part of a Regional Heating Network within this strategic plan and one of the most sustainable in the Netherlands (Twente, 2019). As natural gas is the primary source for generating electricity and heat nationally (CBS, 2023; Netherlands Enterprise Agency, 2020), Enschede has created a heat transition vision to phase out natural gas district heating incrementally.

The Heat Transition Vision comprise short- and long-term objectives in 2030 and 2050, with recalibration every five years. A transition path (Figure 7) is mapped to identify the most feasible and affordable options for each district to replace natural gas (Gemeente Enschede, 2021). Along with residents and partners, the municipality also creates an implementation plan in several pilot districts, including Twekkelerveld (no. 31 in Figure 7), Roombeek (no. 42) and Varvik (no. 13), to investigate different heating alternatives and the costs involved (Gemeente Enschede, 2021). In the search for sustainable heat sources, geothermal energy is identified as one of the potential sources for small local heating and cooling networks in the long term. Therefore, the municipality closely monitors and investigates the possible development of geothermal energy nationally and regionally.

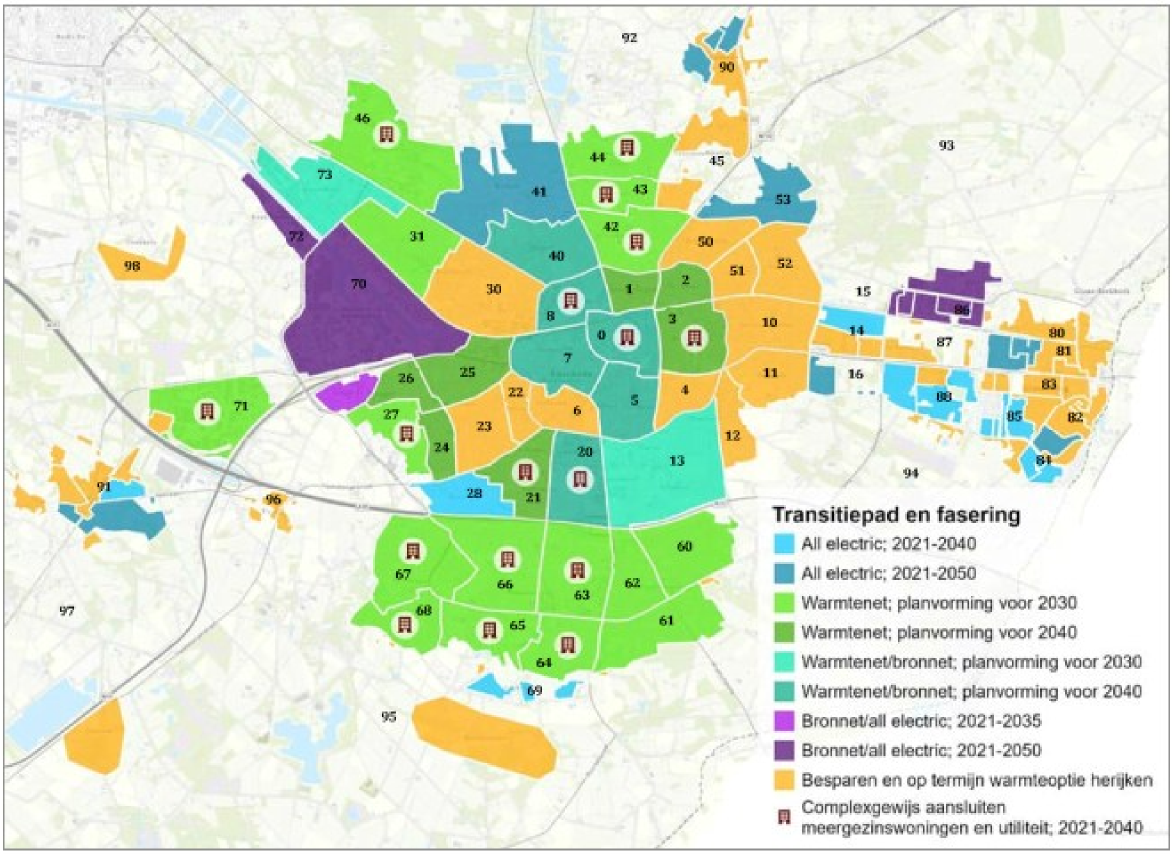


Figure 7. Transition map with a transition path and phasing per district in Enschede. Sourced from Gemeente Enschede (2021).

3.1.2. District Heating Network

The transformation of the heating and cooling networks to be more sustainable and climate-friendly requires a reduced carbon footprint from the heat supply systems. This led to the use of district heating systems, "*a technology that incorporates heat-generating units, transmission and distribution networks, substations, and heat consumers*" (Romanov & Leiss, 2022, p. 4). One common way is to utilise waste heat from different industrial processes to reduce the carbon footprint of heating and cooling supply systems. This facilitates the use of waste and renewables as lower-temperature heat sources in the urban districts and buildings that have multi-generation energy systems (Romanov & Leiss, 2022). With temperatures ranging between 30 and 70 °C, low-temperature heat networks in the Netherlands are still in their infancy (Acheilas et al., 2020). Therefore, the multi-faceted geothermal energy systems can have the potential to be an integral part of energy hubs and multi-energy systems.

Enschede has continuously been titled as having the most sustainable heating network in the Netherlands. The heat produced by the waste energy industry, primarily from Twence, is supplying more than 480,000 GJ every year to more than 9,000 households and 150 businesses. This waste energy company supports 95% of the district heat using bio-energy and waste incineration plants, achieving a 90% CO_2 reduction compared to natural gas-dependent central heating systems. In 2020, the heating network expanded with the construction of the Warmtebaan. This 8-kilometre-long pipeline connects three existing gas-fired heating networks to the more sustainable heat from Twence, supporting more than 2,000 households in the Tattersall, Roombeek and Deppenbroek districts and saving five million m^3 of natural gas per year. With the ambition of reaching CO_2 neutrality by 2040, the construction of Warmtebaan proves there is space for the future growth of sustainable heat in Enschede. Therefore, geothermal energy is one of the possibilities currently being explored for new heating sources.

Space heating can be sourced from converting gas and electricity to heat energy. However, the implementation plan of natural gas-free heating within the Heat Transition Vision will lead to the reliance on electricity demand for heat transition (Figure 8). This requires reinforcing the existing electricity grids or building new ones, which can impact the subsurface and surface for additional linear infrastructure. Furthermore, the additional electricity demand must be generated from other sustainable energy infrastructures, such as installing more wind turbines and solar panels, which are subjected to community opposition due to NIMBYism. With the recent extension of the district heating network in Enschede, connecting geothermal infrastructure to local heating systems is made more feasible. Therefore, geothermal systems could serve as a new energy source for district heating and an alternative to electric heating, allowing electricity to be used directly for household appliances. Therefore, the LUC development has the potential to support district heating with local source networks. This highlights the need to define the structure of local energy systems in Enschede, which is elaborated through a conceptual framework in the following section.

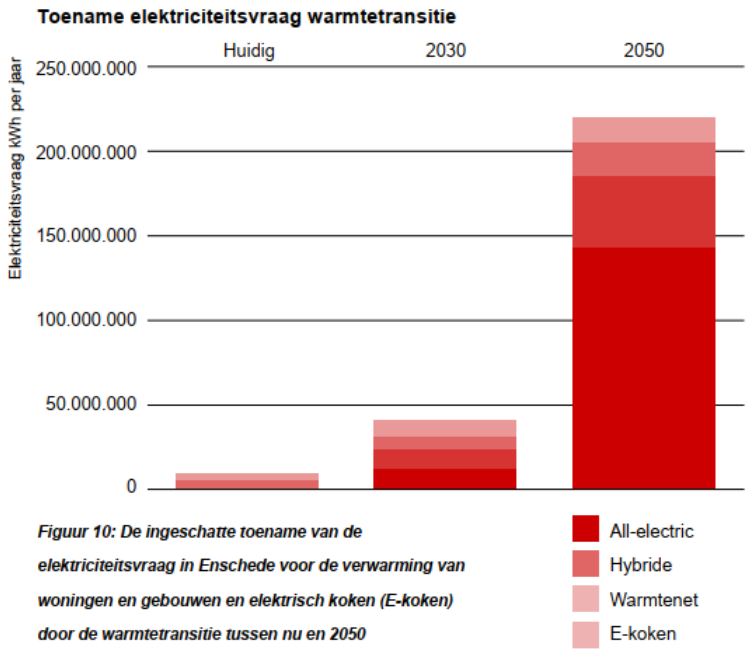


Figure 8. Estimated increase in the electricity demand in Enschede for heating homes and buildings and electric cooking (E-cooking) due to the heat transition for 2050. Sourced from Gemeente Enschede (2021)

3.2. Conceptual Framework

A conceptual framework offers a theoretical overview by mapping the functions and relationships between variables of the research topic (Leshem & Trafford, 2007). The use of PSS as a decision model for spatial planning is influenced by four interrelated and dynamic systems (Couclelis, 2005) (Figure 9). This study investigates geothermal energy development in Enschede. Therefore, the local energy landscape of the municipality is a spatial system that is subjected to the influence of external forces, like the National Climate Agreement. In response, the municipality created a heat transition vision to inform implementation plans needed to achieve the national climate goals and targets.

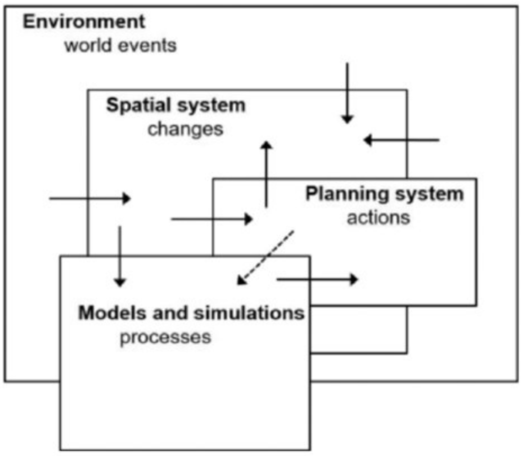


Figure 9. Four interrelated domains of change with a superimposed arrow indicating the potential contribution of planning actors to model building. Sourced from Champlin (2019), Adapted from Couclelis (2005)

Spatial planning of local energy sources requires an understanding of the processes and stakeholder groups within the urban energy landscape (Acheilas et al., 2020). The spatial system of geothermal energy landscape is governed by different actors (see Figure 10), consisting of the municipality, civil society (e.g., residents, housing corporations, energy cooperatives), operators (e.g., district heating and grid network), industries, and energy experts (further inspected in the section Stakeholder Analysis below and Appendix 2). These stakeholders possess different values and needs, interacting with the existing institutional and regulatory instruments, from legislations (e.g., the National Climate Agreement, Wet Collectieve Warmte Act), policies (e.g., Mining Act and Regulation, Environmental Activities Decree) and other arrangements involving subsidies (e.g., SDE++), compensation and financial incentives. In return, energy transition strategies are formulated to steer the heat transition vision of the municipality in developing energy technologies and infrastructure (like geothermal systems), facilitated by policy instruments and initiatives like the Wet gemeentelijke instrumenten warmtetransitie [2] and Programma aardgasvrije wijken [3]. These strategies are implemented to shape the urban energy system, in which the development of renewable energy is underpinned by institutional, socio-technical, environmental and financial factors. Having been applied in many urban planning and management contexts, a PSS can be designed to facilitate discussions and to

---

[2] Nationaal Programma Lokale Warmtetransitie (NPLW) (2024). *Wet gemeentelijke instrumenten warmtetransitie* [online]. Available at https://www.nplw.nl/wet-en-regelgeving/wet-gemeentelijke-instrumenten-warmtetransitie-wgiw
[3] Nationaal Programma Lokale Warmtetransitie (NPLW) (2023). *Programma Aardgasvrije Wijken (PAW)* [online]. Available at https://www.nplw.nl/warmteprogramma/ondersteuningsaanbod

include the knowledge and interests of various stakeholders in the planning processes of geothermal energy development.

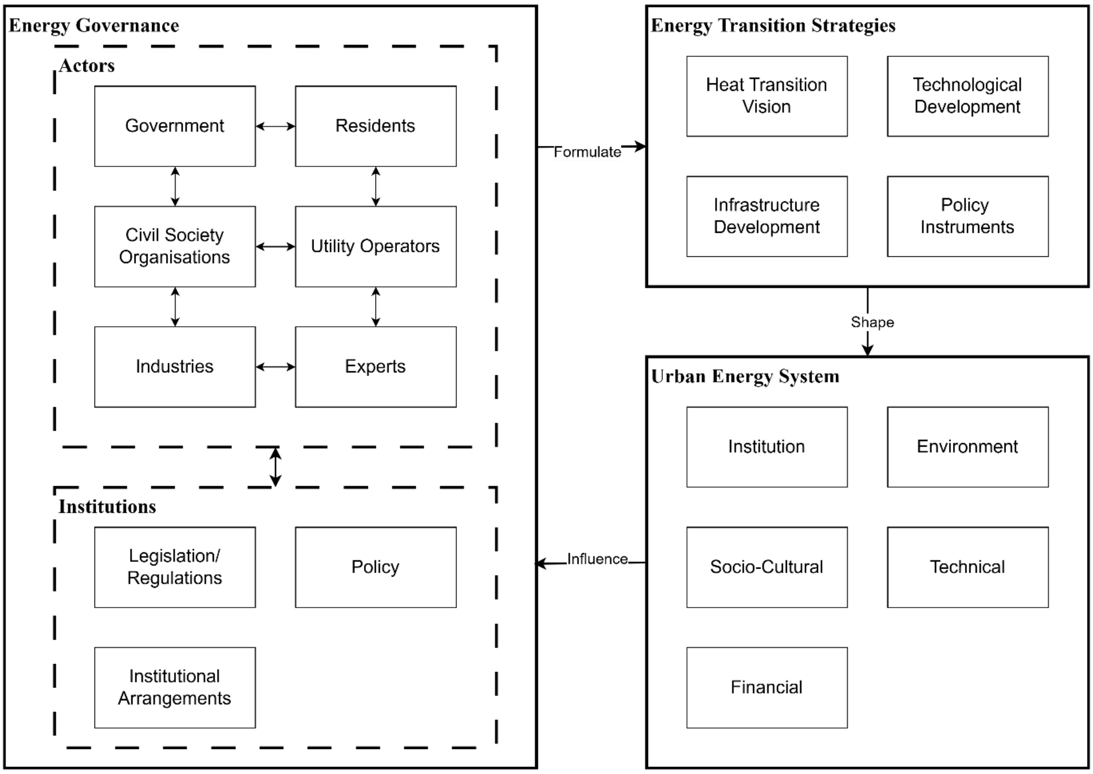


Figure 10. Conceptual framework of the spatial system boundary, i.e., the energy landscape of the municipality of Enschede. Sourced from Author.

3.3. Decision Problem

The development of decision-making frameworks for the selection of renewable energy sources in district heating systems has become an emerging topic of research (Acheilas et al., 2020). While a consensus is that the involvement of public participation in renewable energy planning is highly relevant (Radtke & Renn, 2024), methods for participatory planning are limited. Therefore, this study includes the design of planning support systems for integrating with a participatory planning process to address the decision problem, i.e., LUC geothermal development in Enschede, from the present state of not knowing the sociotechnical constraints of this geothermal energy technology to a desired state of gaining insights into the opportunities and barriers of geothermal initiatives locally. Adapting the phases of decision analysis by Regan & Holtzman (1995), the participatory planning process requires a decision scenario to identify the planning objectives at hand (Figure 11).

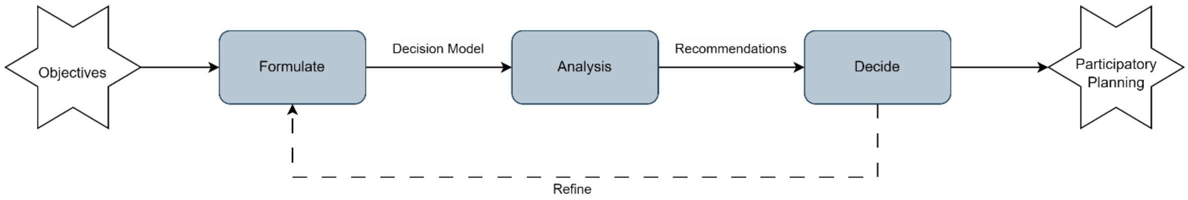


Figure 11. Framework for designing participatory planning processes. Adapted from the three-phase decision analysis by Regan & Holtzman, (1995), the participatory process begins with identifying objectives of a real decision situation on, for example, LUC geothermal development. This is followed by the formulation stage, in which one or more decision models are formulated to reflect the decision problems and objectives. The next stage is the analysis of the decision model(s) on likely consequences and uncertainties for achieving objectives. Recommendations interpreted from the analysis stage help decide on models to be used for participatory planning, or there is a need to re-assess decision models through a feedback or refinement path. Sourced from Author.

With 95% or 480,000 GJ of district heat per year already generated from the waste energy sector, geothermal energy technologies show promising potential to support the heat needed to achieve a more sustainable heating network in Enschede. However, this requires the planning of geothermal systems in parallel with urban development and the transformation of sociotechnical systems (Acheilas et al., 2020; Romanov & Leiss, 2022). Understanding the connections between the supply of geothermal energy and heat demand is, therefore, appropriate to overcome the technical, spatial and socioeconomic barriers in district energy planning. The heat supply-demand matching helps inform the expansion of the district heating network. This involves the analysis of heat-demanding areas and geothermal heat supply, together with their interactions and influences on each other. Moreover, the planning of surface and subsurface infrastructure is to be included in deciding the location for geothermal exploration. Furthermore, energy production and consumption levels should be balanced to meet the energy targets and associated investment costs.

Aligning with the long-term objectives of the Heat Transition Vision, neighbourhoods that would opt for local heat source networks are to be decided on regarding the extent to which renewable technologies, such as geothermal, can reduce natural gas and/or electricity consumption (Figure 12). In Enschede, there are about 15,000 housing equivalents (Woningequivalent or WEQ) connected to the heating network supplied from Twence, with each house every year accounting for a heat demand of 27 - 36 GJ and an average natural gas consumption of 1,420 m^3 (Gemeente Enschede, 2021). In addition, the Housing Vision anticipates that an estimated 3,225 and 9,300 houses will be built by 2030. To avoid the need for additional wind turbines and solar panels to meet increasing electricity demand, a reliable and sustainable heat source is to be optimally sourced. Therefore, spatial planning for efficient and sustainable energy strategies is to be shaped by integrating geothermal development into local source networks.

	All-electric	Warmtenet	Gasnet
Isolatie	Op natuurlijke momenten naar een basisniveau.	Op natuurlijke momenten naar een basisniveau.	Op natuurlijke momenten naar een basisniveau.
Techniek in de woning	Laag-temperatuur afgiftesysteem en een warmtepomp. Relatief veel impact in de woning.	Midden-temperatuur afgiftesysteem en een afleverset. Relatief weinig impact in de woning.	Midden-temperatuur afgiftesysteem en een hybride warmtepomp. Relatief veel impact in de woning.
Infrastructuur	Verzwaring elektriciteitsnet is in de meeste gevallen nodig. Impact op zowel onder- als bovengrond voor extra infrastructuur.	Relatief veel impact in de ondergrond.	(Bestaande) gasnet. Relatief weinig impact in de ondergrond.
Bovengrondse impact	Geluid- en zichtimpact door warmtepompen buiten in de tuin of op het dak. Plaatsing zonnepanelen en windturbines om tot een aanvaardbare duurzame energiemix te komen.	Warmte-overdracht-stations in de openbare ruimte.	Beperkt.
Bronnen	Landelijke, op termijn duurzame elektriciteitsmix.	Mix van duurzame, lokale bronnen. Bij lage temperatuur bronnen hoort nog een collectieve warmtepomp op duurzame elektriciteit.	Op termijn duurzaam gas (groen gas of waterstof).
Opt-out[14]	Lokale bronnetten.	All-electric en lokale bronnetten.	All-electric en lokale bronnetten. Opt-out is wenselijk aangezien dan al direct de stap naar aardgasvrij wordt gemaakt.

Tabel 1: Samenvatting van verschillende warmteopties

14) Opt-out: met opt-out bedoelen we dat niet 100% van de woningen en gebouwen in een wijk aangesloten zullen worden op de voorkeurswarmteoptie (de warmteoptie met de laagste maatschappelijke kosten). Voor een deel van de panden ligt een andere warmteoptie meer voor de hand omdat er binnen een wijk bijv. vaak een variatie is in het type en bouwjaar van woningen. Ook zullen niet alle inwoners kiezen voor de oplossing die als technische voorkeur naar voren komt.

Figure 12. Alternative heating options of transitioning different energy infrastructures to natural-gas-free districts in Enschede. Sourced from Gemeente Enschede (2021).

3.3.1. Scenario Development – Integrating Local Source Heating with Geothermal Energy

Geothermal energy is one potential source for the local source network or bronnet in the Heat Transition Vision of Enschede. This source network is a local and small-scale heating solution, providing low-temperature heat sources to residential or non-residential buildings that need additional heat and cold demand. As of November 2024, there are approximately 88,900 dwellings for housing and non-residential functions in Enschede (CBS, 2024b), with about 1% recorded to be using district heating with natural gas consumption for space heating and hot water (CBS, 2024c). A 120 m² home in the Netherlands is estimated to consume about 13,000 kWh, equivalent to 46 GJ, for heating and hot water (Wassink, 2018). The installation of Low Unit Cost (LUC) as a low-enthalpy geothermal energy system can be applied for space heating and cooling, with an estimated 50,000 GJ of energy produced annually to support 1,000 houses.

Neighbourhoods that opt for local source networks as heating options include those with a transition path between a local source network and a district heating network (i.e., Kennispark and Varvik-Diekman) or all-electric (e.g., Josink Es, Industrie- en havengebied and Koekoeksbeekhoek) (Figure 13). Existing buildings in Enschede are mostly old and moderately insulated. Therefore, neighbourhoods that have transition paths for heating network districts and are already connected to the district heating network require only an upgrade of insulation measures for buildings. On the other hand, neighbourhoods that have yet to have a heat distribution network will take an area-based approach to connect a heating network in phases by 2040, in which an alternative local heat source like geothermal energy will be needed while constructing the heat network infrastructure (Figure 14). The lead time for connecting to a heating network and taking insulation measures is at least 8 years, with areas made easier if a distribution network is within or near the neighbourhood. Kennispark and Varvik-Diekman have an urban development plan that was drawn up before the Transition Vision. Therefore, these neighbourhoods have been prioritised for heating network districts before 2030, allowing the heat transition measures to be implemented integrally with the urban development plan. Due to the cooling demand in business parks like Industrie- en havengebied and

De Slank, these neighbourhoods will have individual and small-scale collective heat options by 2050. Josink Es is an independent industrial estate that has expressed a high ambition to pursue climate neutrality by 2030 (Bureau Buiten, 2020).

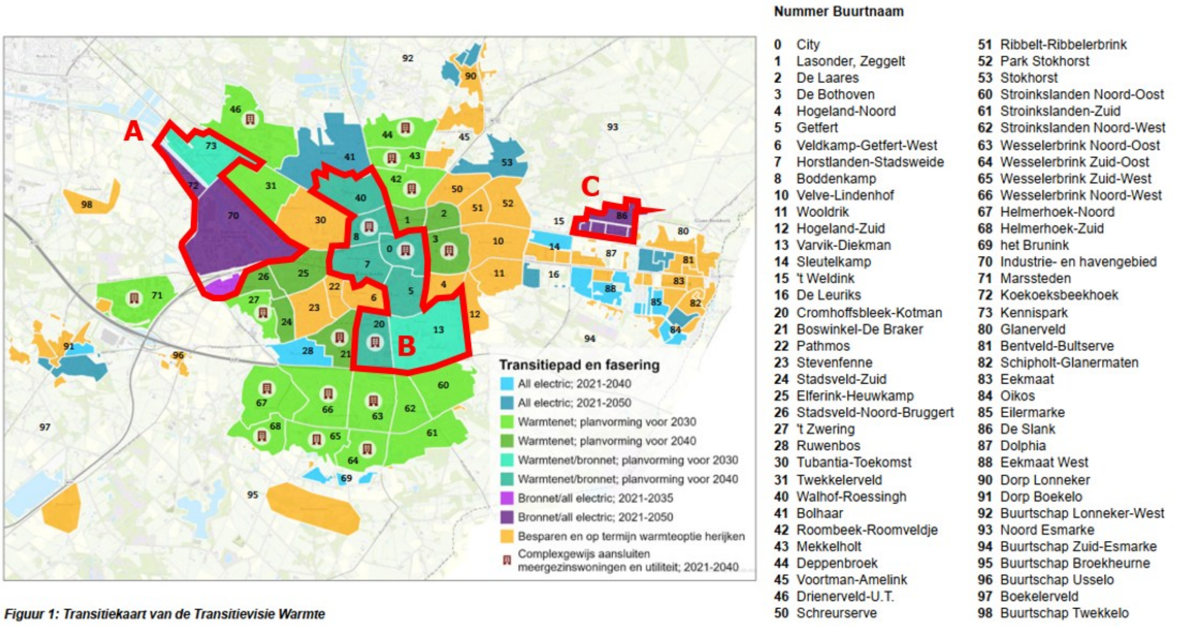


Figure 13. Heat Transition Vision map. Having the options for using local source networks as a heat transition path, red-bounded neighbourhoods are included in exploring the scenario of geothermal energy to support local source heating or bronnet. Sourced from Gemeente Enschede (2021).

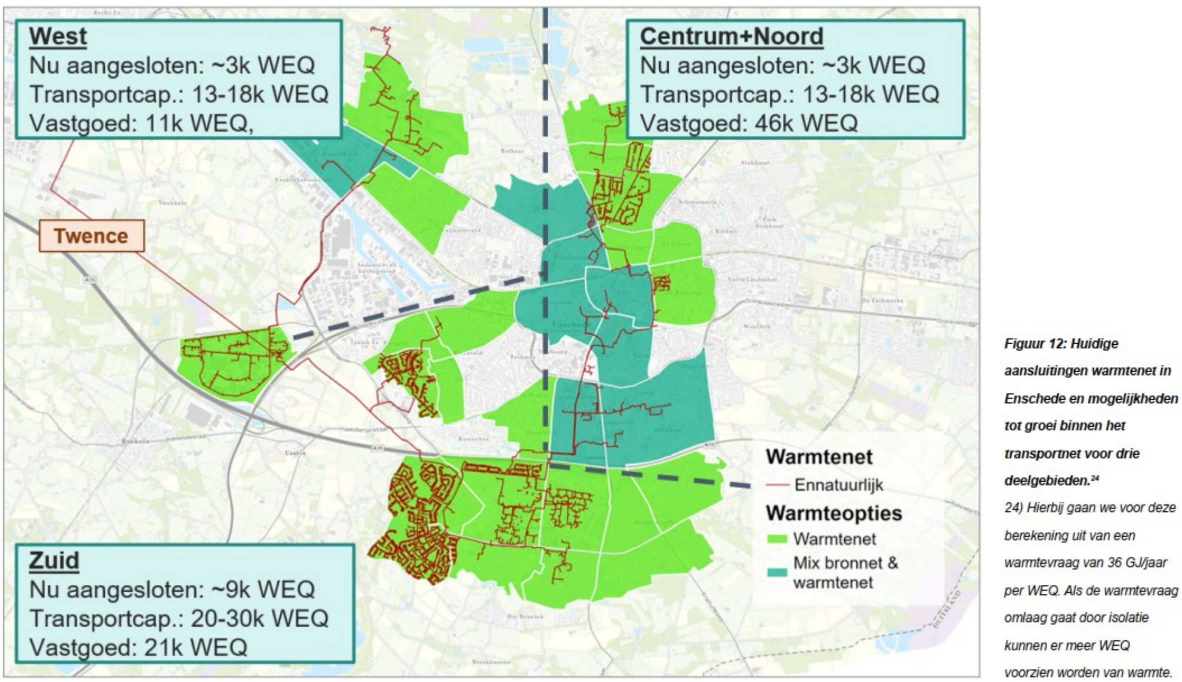


Figure 14. Current district heating network connections in Enschede and the possibilities for the growth of the heating network. Sourced from Gemeente Enschede (2021).

The Heat Transition Vision is designed using neighbourhoods as units. However, the boundary of neighbourhoods with different heating options is not restrictive, as a combination of area- and district-oriented approaches can be adopted for the heat transition plan. Furthermore, the heating options are not necessarily homogeneous within neighbourhoods due to social costs, the feasibility of solutions and other variables that make the decision problem wicked. For example, the amount of energy produced per LUC installation is dynamic and influenced by the subsurface conditions. Therefore, the number of geothermal plants needed and the strategic locations to be placed in Enschede are to be explored. Spatial constraint features representing ecologically sensitive zones and agricultural land are also included to analyse uncertainties in developing LUC projects.

This scenario prioritises LUC installation as an alternate heat supply for the local source network. The spatial extent of this scenario includes neighbourhoods where the heating option of bronnet is explicitly considered in the Heat Transition Vision. Therefore, industrial estates (e.g., Josink Es, Industrie- en havengebied and Koekoeksbeekhoek) and neighbourhoods that require connecting a heating network with the support of a local heat source are chosen, as outlined in Figure 13. The temporal scale adopted is according to the transition path indicated by the municipality for each district and the ambitions of different industrial estates, such as the business park Josink Es is pursuing climate neutrality by 2030. In this scenario, natural gas consumption is used as an indicator to provide direction in planning (Figure 15), with the existing 90 million m³ of gas demand as a target to visualise the amount of natural gas that could be reduced from LUC installations. This scenario will investigate the number of LUC installations needed to produce sufficient heat energy for space heating and replace natural gas in future expansion of heat/energy demand.

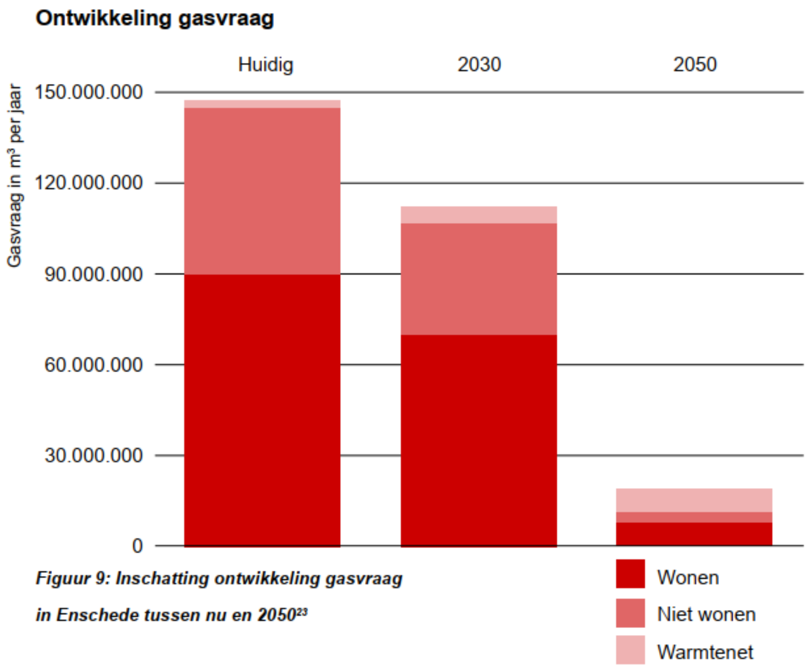


Figure 15. Estimation of gas demand development between 2021 and 2050 in Enschede. Sourced from Gemeente Enschede (2021).

Table 2. Neighbourhoods that are included in the scenario, with figures on the households and heat demand. The energy demand is calculated per household with 13,000 kWh for heating hot water (Wassink, 2018). The statistics are collected at best from CBS (2024b; 2024c), and the author recognises potential incomplete representation of the data. Josink Es is an industrial estate without a CBS boundary and, thus, respective statistics are not available.

Cluster	Heat Transition Vision Map Code	Buurtcode	Buurtnaam	Wijkcode	Number of Households	Proportion of households with district heating (%) [a]	Number of Households with District heating [b]	Energy demand (kWh) [c]	Total Energy Demand - per cluster (kWh)
A	70	BU01530700	Industrie- en havengebied	WK015307	130	0		0	**0**
	72	BU01530702	Koekoeksbeekhoek	WK015307	5	0	0	0	
	73	BU01530703	Kennispark	WK015307	5	8	0	0	
B	0	BU01530000	City	WK015300	2,820	2	0	728,000	**5,551,000**
	5	BU01530005	Getfert	WK015300	2,775	2	56	715,000	
	7	BU01530007	Horstlanden-Stadsweide	WK015300	2,120	0	55	0	
	8	BU01530008	Boddenkamp	WK015300	645	12	0	1,001,000	
	13	BU01530103	Varvik-Diekman	WK015301	1,675	4	77	871,000	
	20	BU01530200	Cromhoffsbleek-Kotman	WK015302	690	25	67	2,236,000	
	40	BU01530400	Walhof-Roessingh	WK015304	1,325	5	172	858,000	
C	86	BU01530806	De Slank	WK015308	65	0	66	0	**0**

[a] Percentage of homes that use district heating for space heating and possibly also hot water. This statistic is collected per neighbourhood (CBS, 2024c)

[b] Number of households using district heating is calculated by multiplying the number of households in each neighbourhood by the respective percentage of homes that use district heating

[c] Total energy demand is calculated by multiplying the number of households with district heating by the estimated 13,000 kWh energy used in a 120 m^2 home in the Netherlands

3.4. Literature Review on Planning Support

Design processes and needs are necessary to be considered to overcome the implementation gap of PSS development in renewable energy planning practice. This requires knowledge about various functionalities and characteristics of diverse PSS, including the added values and drawbacks of these applications. Therefore, an understanding of the potential role of PSS in planning practice is critical for supporting planning strategies and decisions. Reviewing existing research helps to synthesise the state of knowledge and technologies in the field of planning support systems, and the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) flow diagram provides a systematic methodology for research synthesis (Page et al., 2021). Hence, this study adapted the PRISMA approach to identify state-of-the-art development of planning support systems for renewable and geothermal energy strategies.

3.4.1. Energy Transition

A literature research was conducted on 16th November 2024, using the most established database, Scopus, to access a broader scientific literature (Visser et al., 2021), especially on the niche topic of geothermal energy. Multiple searches were reiterated beforehand to ensure that a rigorous methodology was applied in getting the relevant literature and that the review did not miss out on information useful for planning renewable and geothermal energy. The search string was composed of terms that expressed the topic of interest in planning support systems for renewable energies with a land-based system, such as solar, wind and bioenergy. This excludes offshore and other forms of renewables that have principles and considerations that differ from the planning support system design for geothermal energy. With this research focusing on planning tasks, decision support systems with multi-criteria approaches are, thus, not considered. The geoinformation technology-based methodology (i.e., GIS and geospatial) is included in the search terms to investigate the components of spatial planning for the energy transition (Figure 16). To acquire an overview of existing literature, the search was applied to publication Titles, Abstracts and Keywords in the Scopus database, as shown below:

> (TITLE-ABS-KEY ("planning support system" OR "planning support tool") AND TITLE-ABS-KEY ("energy transition" OR "renewable energy" OR "geothermal" OR "solar*" OR "photovoltaic" OR "wind*" OR "waste*" OR "bio*") AND NOT TITLE-ABS-KEY ("hydro*" OR "wave*" OR "tidal" OR "offshore") AND TITLE-ABS-KEY ("spatial" OR "GIS" OR "geospatial" OR "geographic information system") AND NOT TITLE-ABS-KEY ("decision support" OR "criteria"))

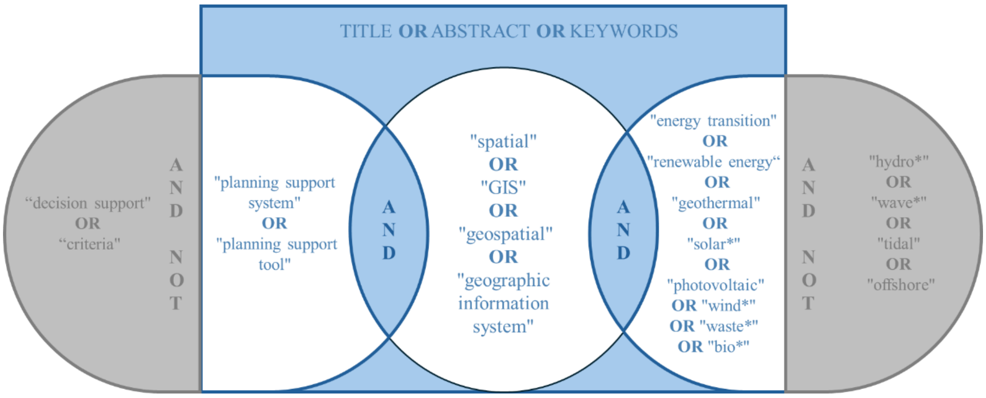


Figure 16. Graphical illustration of the literature review search query. The literature search string includes terms composed of the topic of interest in planning support systems (left area) for land-based renewable energies (right) and the spatially explicit methodology (middle). Sourced from Author.

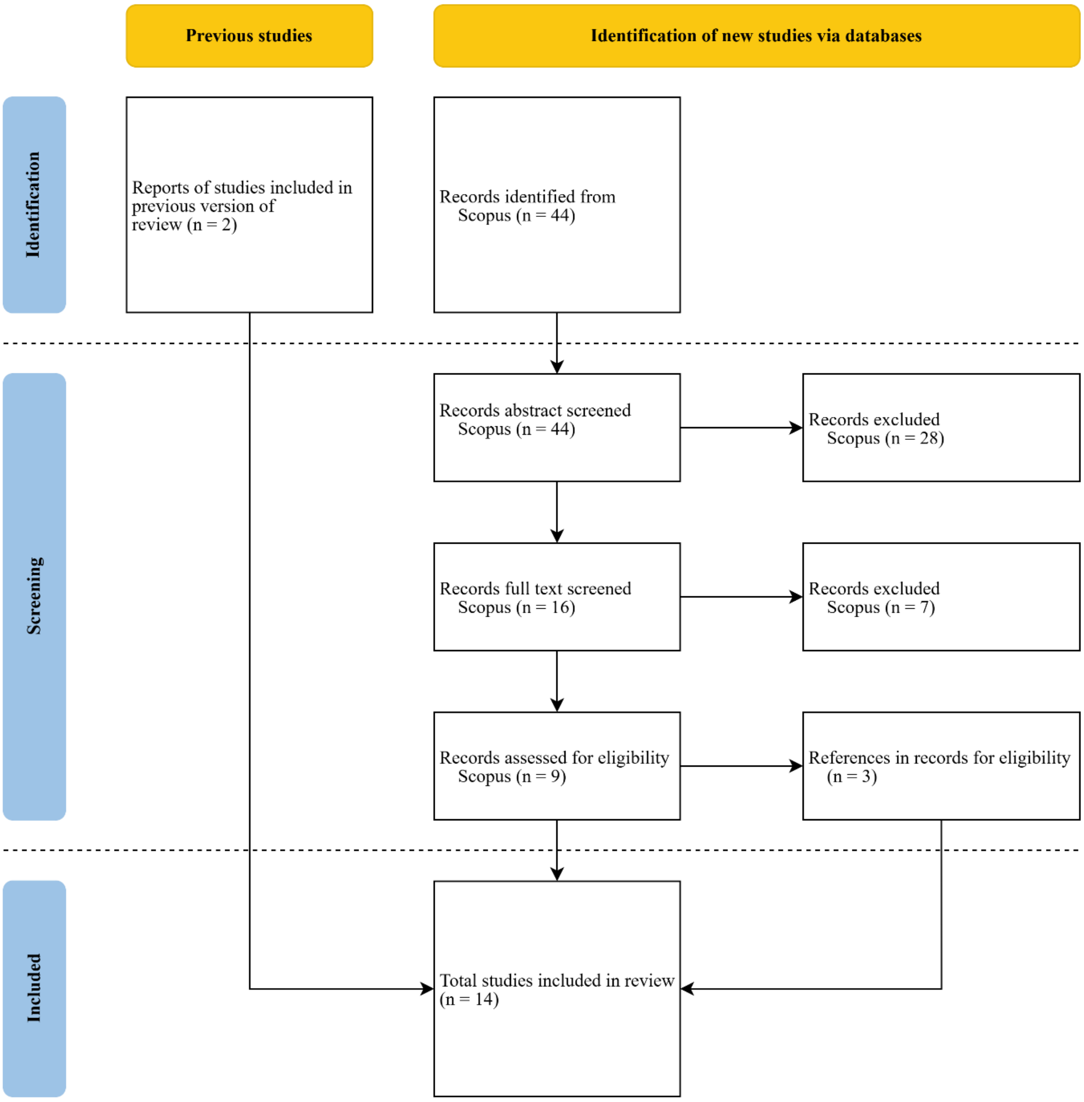


Figure 17. Adapting the flow diagram from PRISMA 2020 (Page et al., 2021), a step-wise process is used for the literature search and screening of articles. A three-phase process, i.e., Identification, Screening and Inclusion, is used to filter articles and to assess for relevancy. A total of 14 articles are included in this study to identify the state of knowledge and technologies in planning support systems for renewable energy. Sourced from Author.

The PRISMA approach consists of Identification, Screening and Inclusion phases, which were applied in this literature review to filter and assess the relevance of publications. The initial search returned a total of 44 articles, and the abstracts and titles of articles retained were examined to remove irrelevant literature and to identify potential articles. The abstracts were screened manually to include articles within the scope of this review based on the following guiding criteria:

- Studies explicitly include the phrase "planning support system" or "planning support tool", otherwise involve technologies designed for urban energy transition strategies as the main research subject.
- Developed modelling or interactive systems to establish planning support for renewable energy interventions.
- Utilised GIS-based methods, either as a major or part of the research approach.

The screening of abstracts and titles resulted in 16 articles, and the full text was then examined. Articles were excluded if PSS development is a recommendation solely for linking research output (Roth & Tilk, 2016), an ontology-based energy planning (Ouhajjou et al., 2014) or purely methodological or technological advancement for decision-support models (Forster et al., 2015; Grisiute et al., 2022; Tesfamichael et al., 2021; Yeo & Yee, 2014, 2016). The final list comprised nine articles from the initial literature search, with the addition of three articles through scanning references. Moreover, two articles were included that were not found through the search but from previous scanning of the literature. A step-wise flow diagram for the literature search and screening is displayed in Figure 17.

3.4.2. Geothermal Energy Technologies

In order to acquire an overview of the applications of planning support systems for geothermal energy development, a literature search was conducted using the Scopus database on the 1st of December, 2024. Opposed to the literature research on energy transition, the search string included support systems for both planning and decision processes as the topic of interest. This is mainly due to a limited amount of literature that has focused solely on the topic of planning support systems. Thus, including decision support systems could give a broader understanding of the development of geothermal-related digital supporting tools. Furthermore, urban planning and participatory development of digital tools are among the main topics of interest. The search string also focused on geothermal energy only, followed by the geoinformation technology-based methodology. The search was applied to publication Titles, Abstracts and Keywords:

> (TITLE-ABS-KEY ("support tool" OR "support system" OR "urban planning" OR "participatory") AND TITLE-ABS-KEY ("geothermal") AND TITLE-ABS-KEY ("spatial" OR "GIS" OR "geospatial" OR "geographic information system"))

Sorted from the newest publication date, the first 30 articles that were returned from the initial search were screened before the full text was reviewed and identified as potential articles within the scope of this review. The final list comprised three articles from the initial literature search, with the addition of six articles through scanning references and referring to previous literature searches.

3.5. Literature Analysis

The analysis of the reviewed literature was structured into three parts. The first part concerned the characteristics of PSS applications, such as the context of the applications, i.e., renewable energy types, case studies, the scale and the field of applications. The second part of the analysis aimed to understand the information collaboration systems and the support system tools, including the purpose of the PSS applications, the hardware and software details, the GIS functions and the spatial data used. In the third part, the design process of PSS applications and the participatory planning activities were reviewed. The attributes of the PSS design criteria based on an analysis of all reviewed papers are given below in Table 3.

Table 3. Design criteria and attributes of the reviewed planning and decision support systems. The description of design attributes is based on Flacke et al., (2020).

Design Criteria	Attributes	Description
Charac-teristic	Renewable Energy Type	Renewable energy technology that the tool has been used to address
	Case Study	Cities/regions and countries where the tool has been applied to
	Study Scale	The planning level at which the tool has been used, from continental and national to city and neighbourhood level
	Field of Application	The sector/field of application the tool is developed for and used in, within the domain of spatial planning in energy transitions and renewable energy planning
Support System Tool	Information Collaboration System	Tool used for collaborating on spatial information, i.e., paper maps, desktop computers, and interactive surfaces
	PSS/ DSS Tool	Tool used as a planning or decision support system
	Purpose	Purpose of the tool
	Hardware Setup	Hardware components of the tool
	Software Setup	Software used on the tool
	Main GIS Functions	Main GIS functions included in the tool, e.g., drawing, multi-criteria analysis, scenario analysis and 3D visualisation
	Data Layers	Spatial data used in the tool
Design Process	Stakeholder Involvement in PSS Design	Involvement of stakeholders in the development of the tool
	Goal of Planning Activity	Participatory planning activity, if any, and its goal
	Stakeholders/ Participants	Type of stakeholders involved in the participatory activity

3.6. Stakeholder Analysis

Public participation has become essential to achieve a democratic and sustainable energy transition (Metze et al., 2023; Radtke & Renn, 2024), emphasising the need for a stakeholder analysis to determine relevant actors and their relationships in the planning process. The stakeholder analysis conducted in this study is summarised in this section for the brevity of the research, while methodological details are included in Appendix 2. Stakeholders include all actors who are involved in or affected by the decision-making process of geothermal energy development directly or indirectly. Stakeholders were identified through desk research before being classified as primary, secondary, or external based on their roles and relationships in the planning process. A stakeholder interest table was then used to present the relative priorities of each stakeholder to achieve project objectives for facilitating the development of engagement and communication strategies. Insights acquired through this stakeholder interest table were used in the subsequent analysis on stakeholder attributes.

Attributes of different stakeholders are assessed to understand the interests, influence (or power), and potential impact of stakeholder classes on decision-making processes (see Appendix 2). The attributes of influence and importance were selected to derive a stakeholder classification matrix. The classification matrix was then used to identify assumptions and risks due to conflicting interests on the Heat Transition Vision and the LUC geothermal project. Moreover, stakeholders with high influence and/or importance over the project were determined to inform the project negotiations and design for multi-actor collaborations. The installation cost for an LUC is around €3 million, indicating that geothermal infrastructure resembles a megaproject. Given the rapid acceleration and implementation of technology that drives geothermal development at scale (European Commission: Directorate General for Research and Innovation, 2024; IEA, 2024), the causes for stakeholders to undertake geothermal development projects were analysed, with external stakeholders not directly involved in LUC planning excluded (see Appendix 2). This analysis allowed the motivations behind stakeholder support or opposition to the LUC development to be identified, ensuring that a coalition of stakeholders is formed with mutual benefits from the project.

3.7. Stakeholder Engagement

Participatory approaches function to better align geothermal energy planning with societal needs and values. This requires that societal norms, values, and concerns be included in planning procedures through the participation of stakeholders. In this study, stakeholder engagement through interviews was conducted to develop state-of-the-art knowledge about geothermal infrastructure development for district energy planning. With the stakeholder roles at a municipal level being more recognised as important in achieving national energy policy targets (Bouw et al., 2022; Martínez et al., 2022), interviews were conducted with stakeholders of Enschede to understand how decision-making takes place in local settings. Moreover, a PSS supports professionals in specific planning tasks and problems. Thus, only planning practitioners and researchers were interviewed to acquire dedicated information and knowledge related to geothermal infrastructure development.

3.7.1. Stakeholder Interview and Questionnaire

Qualitative studies of building and energy research are often practised with semi-structured interviews, to acquire data about users' perceptions, attitudes and behaviours on energy technology adoption (Galvin, 2015; Renoth et al., 2023). A 'semi-structured' approach composed of key starter questions or prompts, in which the interviewees could talk freely about themes or concepts relevant to research questions and possibly introduce ideas that the interviewer had not anticipated (Galvin, 2015). In this study, five semi-structured interviews were conducted with five stakeholders, consisting of individual(s) from dGB Earth Sciences, Cogas, Ennatuurlijk, the Municipality of Enschede and Enschede Energie. These interviews were carried out individually for each stakeholder via the meeting platform MS Teams (with Cogas and Ennatuurlijk) or in person (with the municipality, dGB Earth Sciences and Enschede Energie).

A questionnaire is designed to facilitate the semi-structured interview, with three parts: (1) Contextual information of Enschede's Heat Transition Vision; (2) Planning Support System Design; (3) Societal Impacts of Geothermal Energy Development. The purpose of the questionnaire is to gain knowledge and expertise from the stakeholders, with the interview responses to be transcribed and analysed to understand factors underpinning the decision problem and the planning support system for geothermal energy development. The first part of the questionnaire has two versions. The one for the municipality includes scoping questions to refine the understanding of the Enschede energy status and the Heat Transition Vision that defines the boundaries of the research. On the other hand, the questions for experts focus mainly on understanding stakeholders' knowledge, perceptions, and interest in the Heat Transition Vision. Table 4 below shows the key questions for the three-part questionnaire.

Table 4. Questionnaire for facilitating stakeholder interviews. The questionnaire consists of three parts: (1) Contextual information about Enschede's Heat Transition Vision; (2) Planning Support System Design; (3) Societal Impacts of Geothermal Energy Development.

No	Questions
Part I: Contextual Information about the Heat Transition Vision	
For gemeente:	
1	What is Enschede's current energy efficiency? How much energy is used for heating from renewable or non-renewable sources?
2	What is the role and interest of the gemeente in the energy value supply chain and the Heat Transition Vision?
3	Neighbourhoods are designed with heating options in the Heat Transition Vision. Can you describe the different heating options and mixed energy sources?
4	What is the implementation plan for exploring heating options connecting to the existing heat network? Is extending the district heating network an option?
5	What are the future heat or energy demands in Enschede? Would there be neighbourhoods where expansion of heat demand is expected?
For experts:	
1	Have you heard about Enschede's Heat Transition Vision? With your expertise, what are the drivers of this vision?
2	In the Heat Transition Vision, geothermal energy is considered a potential local heat source (or bronnet) for a few neighbourhoods. What do you think about the different heating options, such as bronnet?
3	Several neighbourhoods opt for a mix of bronnet and warmtenet or all-electric. How does your organisation support these mixed heating options?
4	What is the current implementation plan? In addition to heating options for connecting to the existing heat network, is an extension of the district heating network an option?
Part II: Planning Support System (PSS) Tool Design and Functionality	
1	Can you describe your experiences in using digital tools for professional planning tasks, like energy resource management?
2	Have you experienced using a decision or planning support tool for renewable energy planning, such as Global Wind Atlas and ThermoMap?
3	What functionality do you think would make a tool useful to support renewable or geothermal project planning, considering who the user(s) is and the usability and usefulness of a tool?
4	What kinds of spatial requirements are needed for installing a geothermal system or Low Unit Cost (LUC), e.g., spacing of doublets? How strongly does the placement of a geothermal well depend on the geology of the subsurface?
Part III: Societal Impact of Geothermal Energy Development	
1	What are the positive and negative societal concerns about geothermal development in Enschede? To what extent is public acceptance of geothermal energy in Enschede?
2	Despite the provincial government of Overijssel sees the potential of small-scale geothermal energy. What are the constraints that limit the applicability or adoption of geothermal energy in Enschede, e.g., investment costs and uncertainty of geothermal exploration?

3	To what extent do you think or feel that LUC development is feasible for geothermal harvesting in Enschede? Why?
4	What business model configurations on geothermal district heating are useful for creating value for investors, consumers and the environment?

3.7.2. Thematic Analysis

One of the most effective methods of analysing qualitative data is by employing thematic analysis (Mirza et al., 2024; Pope, 2000), which analyses classifications and presents themes or patterns related to the collected data. This qualitative framework approach generally involves understanding the data, identifying themes, and interpreting the identified data in an iterative and reflexive undertaking (Mirza et al., 2024; Sovacool et al., 2023). Figure 18 presents the qualitative framework approach to thematic data analysis. In this study, a data-driven inductive approach was undertaken where themes and codes were not pre-determined towards any analytical categories, but to allow themes to emerge directly from coding the collected interview responses. The data was mapped and arranged according to the thematic framework before being interpreted through user stories. A user story is an Agile technique to support the development of software or tools for collaborative planning processes (Aguilar et al., 2021, 2023). This agile approach follows a template of *Who*, *What* and *Why*, in which the Who indicates the intended user role or user group, the What denotes the software capability, and the Why provides the rationale or benefits of having such capability (Aguilar et al., 2020, 2023). Agile user stories were utilised to understand the context of use and elicit user requirements of a PSS tool for geothermal energy planning.

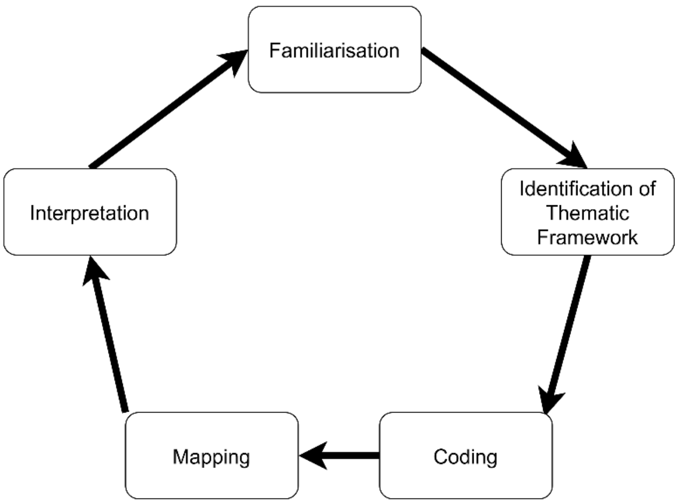


Figure 18. Stages of thematic data analysis in the qualitative framework approach (Mirza et al., 2024; Pope, 2000). Sourced from Author.

3.8. Participatory Process Objectives for Planning Support System Design

The classic ladder of participation by Arnstein (1969) illustrated a hierarchical stakeholder involvement, with higher rungs preferred over lower rungs for promoting citizen participation and power (see Appendix 3). The levels of public engagement needed depend on the objectives of the participatory process and the capacity of stakeholders to influence the outcomes (Reed, 2008). Having clear objectives is, therefore, important for determining the PSS design in support of the participatory process in building consensus while diversifying opinions and values (Balint et al., 2011; Reed, 2008). With consideration of the governance of energy transition in the Netherlands, possible objectives identified by Bayley & French (2008) were adapted for designing a PSS (Figure 19). A systematic review by Renoth et al. (2023) identifies a lack of community knowledge as one of the main reasons for low social acceptance of geothermal energy, leading to public reservations or rejection of geothermal projects. Therefore, the PSS design includes the objectives of *Information Sharing* and *Democratic Ideals* to convey factual information and to educate participants about district heating and LUC geothermal energy technologies, including potential impacts. These could build *Community Cohesion*, the third objective, with social learning useful to facilitate the perceptions and knowledge co-production of stakeholders for geothermal energy development. As trust is the most important factor influencing social acceptance of geothermal technology (Renoth et al., 2023), the PSS was designed in this study with the intention to alleviate the resistance and opposition from the public towards renewable and/or geothermal energy implementation. Moreover, the inclusion of stakeholders' knowledge in the design of planning support systems could improve the usefulness of the tools (Flacke et al., 2020; Vogt et al., 2023). The participatory process is also a means to receive viewpoints and perceptions from participants about geothermal. This helps decision-makers structure their thinking, thereby facilitating the third objective of improving *Decision Quality* to meet the needs and interests of developing geothermal resources.

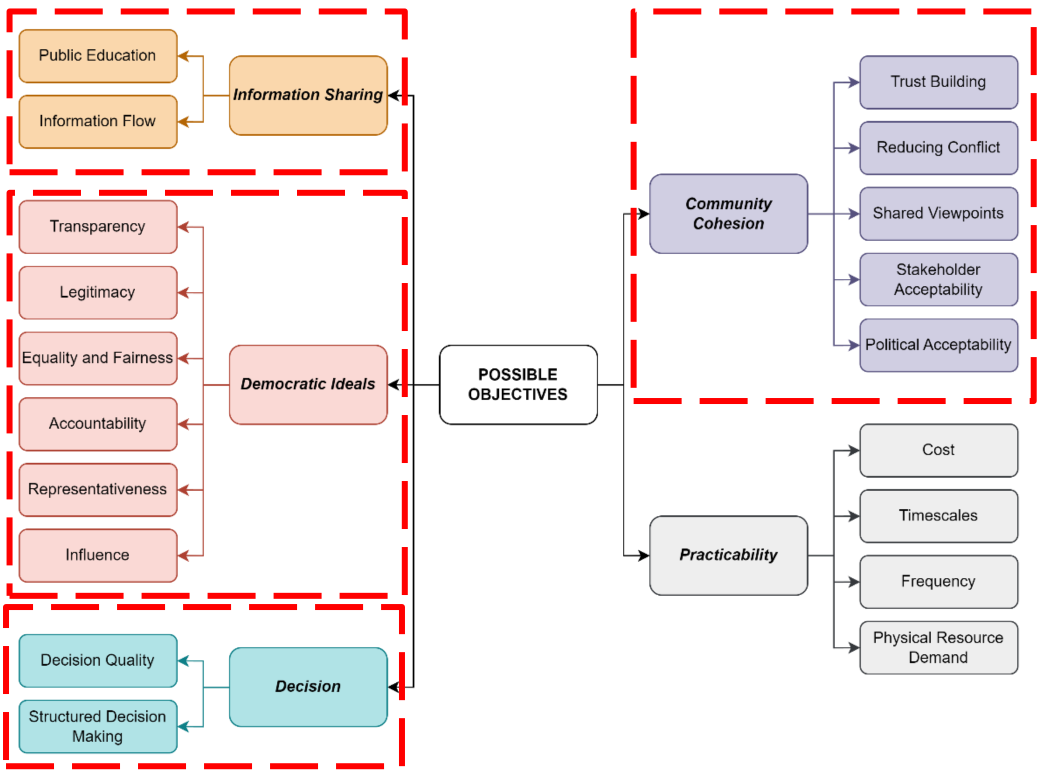


Figure 19. Possible objectives and attributes for designing a participatory process from the perspective of a public authority. *Information Sharing* is about exchanging of information to educate participants and explore decision issues thoroughly. *Democratic Ideals* are intended to explain what is being done and the reasons, as well as to gather information on the likely consequences. *Community Cohesion* contributes to social cohesion, while *Practicability* emphasises the process to be practicable without being costly and time-consuming. *Decision Quality* stresses stakeholder and public perceptions about the issues can widen and enrich authorities thinking, thus increasing the quality of the decision process. In this study, Information Sharing, Democratic Ideals, Community Cohesion and Decision (red brackets) are objectives that were considered when designing a planning support system. Sourced from Bayley & French (2008).

4. RESULTS

4.1. Planning Support System Attributes for Renewables And Geothermal Technologies

4.1.1. Renewable Energy Technologies

The literature search using Scopus yielded a total of 14 English-language peer-reviewed articles across five regions of the world Figure 20. All studies described the applications of PSS in supporting renewable energy planning steps. About two-thirds (n = 10) of these studies were conducted in the region of Europe, with half (n = 5) found to be Dutch case studies, aligning with the fact that various research groups in the Netherlands work on the topic of PSS (Flacke et al., 2020). Two studies were carried out in the United Kingdom, followed by one conducted in Australia in Oceania. Japan and South Korea each presented one study from the East Asia region. No study was found in the Americas.

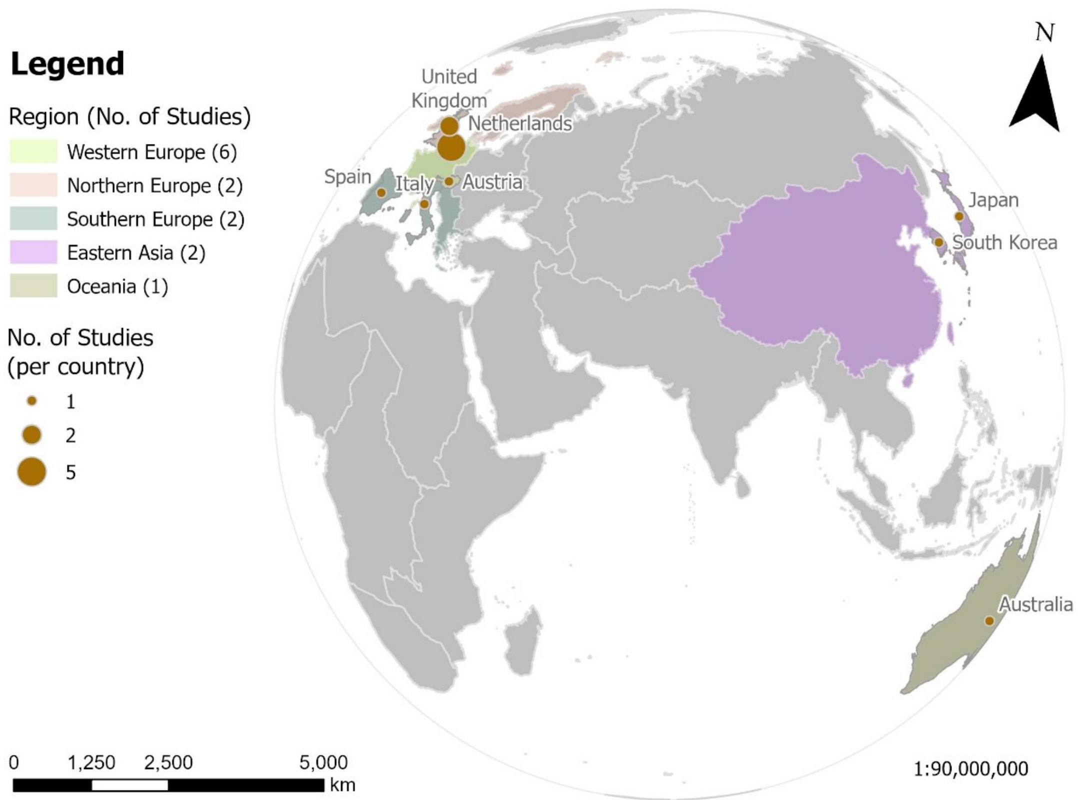


Figure 20. Spatial distribution of studies based on regions and countries (n = 14). The total number of studies conducted in each region is indicated in brackets, that is, Western Europe (n = 6). Study conducted by Kobayashi & Ikaruga (2015) is not mapped due to the use of virtual space (see Appendix 4). Sourced from Author.

The literature review results are divided into three parts. First, the overview of case studies and respective fields of applications for energy transitions and renewable energy planning. Second, the information systems and tools developed for planning purposes are detailed. Third, the design processes of PSS that were used are presented. In brief, PSS tools are predominantly used for planning solar and wind energy in cities, using mainly independent desktop computers but also maptables for collaborative mapping. Details of the literature are summarised in Appendix 4, with the main findings being elaborated in the section below.

PSS Applications

The development of PSS included in this review was published between 2003 and 2024, with the two studies conducted at the earliest in the city of Leicester, UK. These studies focused on solar energy planning, with one involving using PSS for deploying renewable technology (Gadsden et al., 2003), while the other was incorporated with the solar energy potential and the energy consumption of city dwellings (Rylatt et al., 2003). There were no other studies conducted until 2006, but after 2011, the use of such PSS applications became more widespread and common. The reviewed case studies on various PSS applications for renewable energy planning are given in Table 12 of Appendix 4.

The PSS applications taken into account in this review covered a wide range of renewable energy types. Solar and wind energy were being predominantly addressed, which reflects the typical foci of development in renewables. There was only one study applying PSS for biomass-based power generation. Being the main subject of this current research, the planning of geothermal energy using PSS did not occur once. Within the domain of spatial planning, most studies contributed to renewable energy planning at a city scale, and some focused on implementing PSS for sustainable urban development in neighbourhoods. There were studies that developed PSS for a national scale, with detailed work on energy planning applied at the regional and local levels (Hewitt et al., 2020).

The applications of PSS for energy transition emphasised various sectors of urban and regional planning. Most urban planning systems were developed for evaluating renewable energy potential and informing urban strategies (Gadsden et al., 2003; Ouhajjou et al., 2017; Rylatt et al., 2003). Sustainability development frameworks were adapted in a few of these studies to account for environmental and economic impacts (Ayoub et al., 2006; Yeo et al., 2013), thereby integrating information on urban and energy planning. A number of the reviewed studies also simulated land use modifications of renewable development by incorporating spatial modelling to investigate the impacts on energy transition processes (Hewitt et al., 2020; Marrone et al., 2023; Tripathy et al., 2024). Considerable studies developed PSS applications with communicative and analytical support capabilities to facilitate social learning among end users in exploring and exchanging ideas on energy plans (Flacke & De Boer, 2017; Ligtenberg et al., 2011; Pelzer et al., 2013, 2015; Sharma et al., 2011).

Collaborative Systems and Tools

Different information systems for collaborative situation analysis and planning have long been investigated. Consisting of a set of map printouts for scenario planning, large-scale paper maps involve the use of pins and paper as artefacts for unstructured annotations and sketching. In the literature search, none of the articles incorporated classical paper maps for renewable energy planning. Off-the-shelf desktop computers that support group work with a single-user utility were used noticeably, with two-thirds of the reviewed studies (see Table 13 in Appendix 4). Although intending to support group work, this single-user desktop-computer paradigm hampers the usability of desktop geographic information systems for collaborative planning practices (Vonk & Ligtenberg, 2010). Interactive surfaces, such as maptables and tabletop systems, were employed in other articles as a user-oriented interactive planning support tool. Bringing the advantage of interacting geographical data with a touch-enabled screen, this collaborative information system was exercised to create rooms for pulling together users from different backgrounds and disciplines to communicate and collaborate on renewable energy planning.

All desktop-based collaborative systems made use of computation models, primarily for estimating domestic energy demand to inform renewable energy efficiency planning. Other goals of the desktop-based modelling approach include simulating and visualising scenarios for the expansion of renewable energy. In contrast, maptables as interactive surfaces were commonly used for collaborative spatial mapping of future renewable energy design, improving communication and visualisation of alternative energy scenarios. Most interactive PSS tools were comprised of a similar hardware setup, using a maptable as a stand-alone system, with occasions having a second screen to visualise the planning scene and outcomes. Maptable uses a client-server-based PSS architecture operated on the software system of SimLandScape with various ESRI ArcGIS components. Most of the maptables combined the use of a similar ArcGIS extension, i.e., CommunityViz Scenario 360, which consisted of Scenario 3D displaying a real-time synchronised three-dimensional landscape and Scenario 360 as an integrated component for assessing impacts of simulated land use actions (Pelzer et al., 2013). There was only one study that did not incorporate any land-use planning software but used a visualisation software, i.e., SIEVE, to render a state-of-the-art 3D virtual environment.

The GIS functionality included in the PSS tools, both interactive maptables and desktop computers, comprised mainly of 2D and/or 3D visualisation, in support of other functions for drawing and sketching. Furthermore, urban development scenarios were explored to understand energy performance for future land-use planning. Other functions included calculating outcomes of energy interventions, often in the form of indicators to be visualised in charts. A variety of datasets were acquired in different studies for urban-scale energy modelling. Information on the building footprint and types formed the landscape typology useful for evaluating energy performance. Energy profile on the types of built-up areas was often used to estimate domestic energy consumption and to determine the potential use of renewable technologies for reducing energy demand. A land-use plan was included on some occasions for exploring alternatives and scenarios to modify the land-use functions for the addition of renewables. Most of the studies also included various weather-related data that brought meteorological information to analyse renewable energy potential. However, these data are less important for the current studies, as weather conditions exert a limited influence on the geothermal potential. The same is true for the elevation data on wind and solar energy, yet less applicable to geothermal production. This indicates existing renewable energy PSS tools are not transferable to geothermal planning, due to different factors to be considered for geothermal infrastructure development and subsurface operations.

Participatory Processes

Participatory processes in support of the PSS tools were often applied in the design phase. During the PSS tool design, stakeholders were engaged in acquiring user requirements and needs in developing tools that address given planning problems or challenges. In the scoping process, some studies utilised surveys or semi-structured interviews to gain a thorough understanding of the planning problems and the knowledge of stakeholders prior to the design of tools (see Table 14 in Appendix 4). Workshops and questionnaires were used to gather feedback on the prototyped tools and the additional functionality desired by stakeholders. Interactive development cycles with meetings also allowed developers and users to test the prototypes and discuss adaptations. The majority of the studies involved expert stakeholders, either local governments or practitioners from different domains. Only one study involved citizens through a questionnaire survey to analyse the awareness and interests of citizens in renewable energy technology.

Most of the studies that included participatory design processes also hosted activities for testing the PSS tools and evaluating the results and outcomes. In general, the goals of participatory activities were to explore energy planning scenarios collaboratively for assessing land management options. Some studies included targets, such as energy consumption and viable renewable installations, for exchanging ideas about current and future land-use planning. Moreover, the outputs of participatory activities, such as maps generated from PSS tools, were used to identify the impacts of renewable expansion on future land uses. However, the participatory activities were rarely used to assess factors of the usability of PSS tools and the usefulness of the participatory design process. Similar to the design process, most studies involved only academics or practitioners in the PSS planning activities.

4.1.2. Geothermal Technologies

A total of nine English-language literature were reviewed, all of which were located within the European region and in the United Kingdom. Most studies contributed to geothermal energy planning at a pan-European level, with the other literature focused on regional and neighbourhood planning. The majority of reviewed studies developed spatial information systems to support the decisions made to optimise the implementation of geothermal energy technologies, and only one study designed geoinformation support systems for the planning of the use of geothermal resources. The applications of DSS were applied to geothermal energy research on assessing the land suitability for geothermal technology installations. On the other hand, PSS was used for addressing planning issues involved in exploring geothermal potentials without interfering with different urban land uses. Results of the reviewed case studies on spatial support systems for geothermal energy are given in Table 5.

All studies used desktop computers as a hardware setup for information systems (Table 6). Unlike renewable energy technologies, most desktop-based geothermal information systems were based on built-in tools for land suitability assessment and geothermal potential mapping. Only one study made use of computational models to facilitate the planning of new geothermal installations (Baralis & Barla, 2024). Moreover, most studies incorporated web-based tools without the need for specific software. Only a few studies used ESRI ArcGIS components, while two studies took advantage of free and open-source software, specifically QGIS and CitySim Pro. Multi-criteria analysis and 2D visualisation were the main GIS functionalities implemented in DSS tools to assess the spatial suitability for geothermal technologies.

The reviewed studies acquired different datasets to analyse geothermal potentials. Critical for assessing underground heat resources, subsurface conditions, including geological characteristics and soil configuration, were obtained or surveyed to infer potential geothermal conditions. Hydrogeological properties with underground water sources were used to determine the quality of geothermal aquifers. Land cover and availability were investigated to determine restricted and permitted spaces for installing geothermal systems. A built environment was also mapped to acquire spatial compositions of urban fabrics and the thermal needs and efficiency of buildings for formulating urban energy strategies. Other urban form indicators, such as population density, building intensity and coverage, were useful in identifying spatial conditions optimal for geothermal interventions in district heating.

Table 5. Reviewed studies on the use of spatial support systems for geothermal energy research.

ID	Literature	Case Study	Study Scale	Support System	Research Aim
1	Bertermann et al., (2015)	Europe	Pan-European	PSS	Develop a European Outline Map (EOM) illustrating the thermal conductivity in W/m*K, considered as a property that controls heat flow through materials of different types
2	Tinti et al., (2018)	Europe	Pan-European	DSS	Assess the suitability of shallow geothermal systems at a maximum depth of 50 m
3	Galgaro et al., (2019)	Europe	Pan-European	DSS	Support the preliminary design of new geo-exchange systems
4	Acheilas et al., (2020)	Vreewijk neighbourhood of the Feijenoord district, Netherlands	Neighbourhood	DSS	Facilitate the implementation of smart thermal energy grids in local energy communities; Explore the network of actors in adopting the decision-support framework for steering the transformation of the thermal energy supply-demand system
5	Beriro et al., (2022)	Derbyshire, Nottinghamshire and West Midlands, England	Region	DSS	Assist with policy implementation and renewables deployment. Explore whether a prototype spatial decision support system can be developed to map the site-based feasibility of several renewable energy technologies as a solution to problems identified by potential end-users.
6	Ioannou et al., (2023)	Europe	Pan-European	DSS	Present a decision support tool for promoters/investors of geothermal energy projects, based on a decision tree (DT) structure
7	Ramos-Escudero et al., (2024)	Ciudad Lineal Neighbourhood of Madrid, Spain	Neighbourhood	DSS	Develop an optimised spatial tool for implementing renewable heating systems in urban areas, specifically combining geothermal heat pump technology (borehole depth of 100 m; single U-pipe) with on-site electricity production using photovoltaic panels.

ID	Literature	Case Study	Study Scale	Support System	Research Aim
8	Baralis & Barla, (2024)	Central district of Turin, Italy	Neighbourhood	PSS	Geothermal resources planning for managing interferences and optimising the use of underground heat resources. Plan the use of geothermal resources, accounting for the spatial and temporal variations of the site conditions due to the dynamics of the aquifers and the interactions with other subsurface users. Shallow geothermal at very low depths up to a few hundred meters
9	Bertermann et al., (2024)	Bavaria, Germany	Region	DSS	Estimate and illustrate very shallow geothermal energy potentials (vSGP) in rural areas of Bavaria based on the high-resolution digital German Soil Survey dataset

PSS = Planning Support System

DSS = Decision Support System

Table 6. Design of spatial support systems for geothermal energy research. ID for the corresponding literature is described in Table 5.

ID	PSS/DSS Tool	Purpose	Hardware Setup	Software Setup	Main GIS Functions	Data Layers	Stakeholder Involvement
1	ThermoMap	Provide an overview of the solar-driven very shallow geothermal energy resources in Europe	Desktop computer	- (Web-based tool)	Multi criteria analysis, Visualisation (2D), Search, Query	INSPIRE spatial data (Protected sites, Elevation, Geology, and Soil, Area management units, Meteorological geographical features, Habitats, and Energy Resources)	Experts of the ThermoMap consortium
2	GIS-based AHP–MCDA tool	Enhance the potential of an integrated package made up of drilling technique, borehole heat exchanger, and heat pump	Desktop computer	-	Multi criteria analysis	Bedrock depth, Thermal properties, Mechanical properties, Geological layer, Hydrogeology, Climate data, Land cover, Geothermal heat flow, Energy demand	No
3	Cheap-GSHPs DSS	Support the selection of the most suitable heat exchanger, the sizing of the borehole field as well as in the choice of the best installation and drilling technique	Desktop computer	- (Web-based tool)	Visualisation (2D)	Thermo-Geological Database, European geological map, Pan-European Climatic Database, Temporal heating and cooling profiles database, Heat pumps database	No

ID	PSS/DSS Tool	Purpose	Hardware Setup	Software Setup	Main GIS Functions	Data Layers	Stakeholder Involvement
4	Decision-support framework	Facilitate the multi-level decision-making process; Identify key parameters that influence the relationship between supply of geothermal energy and heat demand in DH systems; Spatial mapping of availability and demand for geothermal heat	Desktop computer	CitySim Pro	Multi criteria analysis	2D and 3D seismic profiles (porosity, permeability, thickness, depth, and temperature of the sandstone layer), 3D city block model (digital cadastre (DC), DSM, Energy consumption data (energy labels and gas consumption data), Urban form indicators (population density, dwelling density, building intensity, coverage, spaciousness, network intensity, and linear heat density)	No
5	Data4Sustain (D4S)	Assist with assessing where renewable energy might be feasible through the use of multi-criteria decision analysis, mapping and visualisation; Evaluates resource, constraints and feasibility for renewable energy technologies (RET)	Desktop computer	ESRI ArcMap, Web GIS client application	Multi criteria analysis, Drawing, Visualisation (2D), Dashboard, Reporting functions,	Bedrock Aquifer Potential, Depth to Groundwater, Groundwater Temperature, Resource and constraints summary maps	Technical and policy workshops; Using an agile software development approach for WebGIS; Multi-actor approach (researchers, the private sector and policy and decision makers)

ID	PSS/DSS Tool	Purpose	Hardware Setup	Software Setup	Main GIS Functions	Data Layers	Stakeholder Involvement
6	Decision tree framework	Assist stakeholders to select public engagement strategies, alternative financing solutions and risk mitigation measures (or options) for geothermal energy projects.	-	-	Multi criteria analysis	-	Consultation from supply chain stakeholders and experts (in social engagement and financing instruments for geothermal energy projects)
7	Multi-Criteria Decision Making (MCDM)	Perform an exhaustive geospatial analysis that considers technical, economic, and socio-environmental criteria, offering multiple alternatives prioritized through multicriteria evaluation methods.	Desktop computer	QGIS	Multi criteria analysis	Permitted zones (pedestrian pavement, spaces and recreational areas such as green spaces, sports facilities, and outdoor areas adjacent to buildings), Restricted zones (buildings and a 3 m buffer zone), URBAN3R database (building energy demand)	No
8	3D Thermo-Hydro numerical models	Assess optimal areas for the installation of new geothermal systems as well as manage actual interferences	Desktop computer	-	Scenario analysis	Hydrogeology, Entities producing thermal and hydraulic impact, Built environment, Hydro-thermal regime	No
9	vSGP maps	Provide a planning tool for dimensioning very shallow geothermal installations.	Desktop computer	Esri ArcGIS	Visualisation (2D)	Digital soil survey map (1:5000), Climate zones, DEM	No

4.2. Thematic Landscape into Perspective Inventory

To understand the values, needs and concerns of stakeholders to be included in the planning processes of LUC geothermal development, the thematic analysis extracted meaning from the interview responses and encompassed the pinpointing, sharpening, recording, and/or evaluation of recurring themes. The following sections are based on responses received during the stakeholder interview process. Codes and patterns from the thematic analysis were identified and grouped into three broad themes:

1. Challenges and barriers dealing with the Heat Transition Vision, including public engagement and geothermal infrastructure development.
2. Information collaborative systems focusing on the desired goals and features for supporting urban infrastructure planning.
3. Social and economic constraints revealing social acceptability, regulatory requirements and financial considerations.

4.2.1. Challenges and Barriers to Heat Transition Vision

Stakeholders involved in heat network development, such as the municipality, network operators and energy cooperatives, have regular meetings on heat planning and development plans. Recurring surveys are delivered by the municipality to collect public views on the Heat Transition Vision. Despite the public being viewed as the most important stakeholder group, public participation in the project remains challenging, especially reaching out to the inhabitants or residents of privately owned houses that are not represented by the housing corporations. While the local source heating options were planned together with citizens (i.e., freedom of choice), the exact heating options and phases for neighbourhoods are unknown, and the Heat Transition Vision is a first draft of reference for planning heat strategies at district and neighbourhood levels.

Unlike the Western part of the Netherlands, the heat demand and geological conditions in Enschede are not in favour of conventional geothermal systems. This makes LUC a possible heating option for creating a small local distribution network, which is still subject to barriers related to infrastructure development. While the installation of LUC required relatively less space than a conventional system, some areas are prohibited for subsurface operations, including faults, nature reserves, military areas, and water extraction areas (Waterwingebieden). Nitrogen emission is also a concern for geothermal infrastructure development or any construction projects. Moreover, the interviewee from Ennatuurlijk expressed that medium-temperature geothermal heat is yet to be suitable for connecting with the existing district heating network, which requires new distribution networks and housing connection pipelines to be constructed for LUC heat production and transportation. The spacing in LUC doublets can only be decided through a test drill to match the depth of drilling with the thermal energy needed at the surface, with considerations of technical costs (i.e., CAPEX and OPEX) and induced seismicity risks.

4.2.2. Collaborative Systems for Urban Planning

Stakeholders incorporate digital tools to facilitate project implementation and decision-making. For example, Cogas and the municipality refer to Startanalyse Aardgasvrije Wijken 2025[4] from Planbureau voor de Leefomgeving (PBL) for their planning practices to identify heating options for individual neighbourhoods with the lowest national costs. A suite of GIS technologies, including digital twins, had been used by Ennatuurlijk to optimise their heat transportation from the source network to the delivery units. As a research organisation, dGB Earth Science owns OpendTect, an open-source interpretation system for visualising and analysing seismic data.

[4] Planbureau voor de Leefomgeving (2025). *Startanalyse PBL 2025* [online]. Available at https://aisel.aisnet.org/cgi/viewcontent.cgi?article=1955&context=jais

Stakeholders experience the use of digital tools to various extents, with different GIS functions being expressed as desired PSS features. Data visualisation from a 2D planar view or digital maps is most useful for reporting and communicating information, while the visual capabilities of 3D visualisation allow monitoring subsurface layers and infrastructure assets to optimise investment needs. Feature drawing is useful for heat infrastructure development, such as installing pumps and pipes, and planning tasks of designing implementation plans for neighbourhoods and streets. Performance indicators for summarising information could be useful in monitoring the progress of the heat transition plan towards the energy target and fostering public perception about renewable energy options. This, however, could be challenging in practice as indicators are location-dependent and location-specific.

Uncertainty related to data and information limits digital tools to only internal use. Many models exist in facilitating energy planning, but these information collaborative systems often require an in-depth understanding and knowledge about the model and associated functions. Moreover, most tools are embedded with assumptions without localised parameters, leading to inconsistent information that is risky for sharing with external stakeholders. Data quality is yet another concern in ensuring that information is representative of the existing situation to support decision-making.

4.2.3. Social and Economic Constraints of Geothermal Development

In general, negative social perceptions of geothermal development are not observable in Twente, as no geothermal energy has been produced within the region. On the other hand, the perception of subsurface drilling is controversial among different social groups, especially on the NIMBY phenomenon, though private-public ownership of a geothermal facility is key for public acceptance. Public perception of district heating is important in transitioning away from natural gas-free heating, with the lack of trust in single heat suppliers being the bottleneck of public adoption of district heating. Public ownership of infrastructure is important in creating socially just and inclusive heating networks, allowing the public to have a greater stake in technical and financial choices. The newly proposed Wet Collectieve Warmte Act[5], that emphasises 50% or more control over the heat networks by public shareholders, creates uncertainty on the business case for geothermal development.

Without a pilot installation in the Netherlands, the willingness to fund and initiate is a challenge for LUC geothermal to be incorporated into energy planning in Enschede. A privately-owned LUC system is proposed as a bottom-up approach to expand according to heat demand, thus benefiting the local people in terms of heating and profits. At the other end, funding the entire LUC installation process through the community and the municipality is not a sustainable solution. The municipality considers partial crowdfunding or private-public co-ownership an interesting approach for this small-scale renewable energy system. Furthermore, funding models from European or NWO grants and possible subsidies (e.g., SDE++) are applicable for LUC geothermal development.

4.3. User Stories

In this section, the responses of the identified stakeholders were analysed and structured as user stories, following the *Who*, *What* and *Why* template, as shown in Table 7. Selected objectives of a participatory process were then used to relate the user stories to a) Decisions, b) Democratic Ideas, c) Information Sharing, and d) Community Cohesion.

[5] Nationaal Programma Lokale Warmtetransitie (NPLW) (2024). *Wet collectieve warmte* [online]. Available at https://www.nplw.nl/wet-en-regelgeving/wet-collectieve-warmte-wcw

The majority of responses had the intended planning purposes of improving the quality of decision processes. The capability or software functionality of a PSS should bring in more information about geothermal and heat planning, thereby widening and enriching the perceptions that may drive decision-making. For example, as a district heating supplier, Ennatuurlijk would like to identify weak spots in their heat network for optimising the energy efficiency of heat infrastructure. On the other hand, the municipality would find performance indicators useful for gathering information on the scale and progress of the heat development plan. Moreover, the functionality of feature drawing allowed assumptions to be tested or challenged, making the decision process more visible, structured and auditable. dGB Earth Science would like to map drilling wells and subsurface properties for their research in identifying ideal drilling locations.

Table 7. Examples of user stories extracted from the thematic analysis of stakeholder responses.

User Stories (Who, What, Why)	**Participatory Process Objectives**
As a municipal planning practitioner, I want to compile different information relevant to energy planning, so that I can facilitate project implementation and also provide justification for the decisions made.	Decision
As a municipal planning practitioner, I want to use performance indicators to summarise information about heat development plans so that I can monitor the progress of the heat transition towards the energy target.	Decision
As a municipal planning practitioner, I want to draw features at the residential and neighbourhood levels, so that I can develop implementation plans for specific streets and buildings	Decision
As a seismic interpreter for geothermal exploration, I want to study existing drilling wells and map subsurface structures and seismic coverage, so that ideal drilling locations can be better situated to reduce uncertainties about the aquifer, minimise seismicity and investment risks	Decision
As a district heating supplier, I want to optimise our heat network (with heat pumps or buffers being strategically placed), so that heat loss is reduced and overall energy efficiency can be improved	Decision
As a district heating supplier, I want to identify weak spots in our network and opportunities for optimisation, so that I can assess potential investment needs in the future.	Decision
As a social enterprise in community renewable energy, I want to summarise information about the potential of different energy alternatives through visualisation, so that I can plan whom I should approach for renewable energy installations	Decision
As an owner and operator of natural gas and electricity networks, I want to create a database or knowledge bank with facts and information about sustainable energy techniques, so that my stakeholders can understand the various heating system options and make informed decisions on choosing the most suitable system	Democratic Ideas
As a municipal planning practitioner, I want to communicate information through visual narratives, such as visualising underground infrastructure, so that I can improve consensus-building and planning efficiency with stakeholders	Democratic Ideas

As a knowledge and expertise partner with shareholding municipalities, I want to prepare information building blocks relevant and applicable to the region, so that we can share our knowledge and have a collective understanding of the pros and cons of the different sustainable energy techniques.	Information Sharing
As a district heating supplier, I want to share development plans for expanding the district heating network, so that the stakeholders can plan the different heating options and implementation phases for each neighbourhood	Information Sharing
As a public infrastructure company, I want to create socially just and inclusive district heating networks, so that public perception towards district heating can be improved.	Community Cohesion

The second most related participatory process objectives were democratic ideas and information sharing. The municipality would visualise and make information accountable for consensus-building and improving planning efficiency with stakeholders. As an operator of the district network, Cogas would like to create a knowledge database to make information more transparent and legitimate, allowing stakeholders to understand and decide on the various heating system options. Additionally, Cogas would build localised information blocks with shareholding municipalities to create a collective understanding of the trade-offs of different sustainable energy techniques. Similarly, Ennatuurlijk desired to share development plans with stakeholders to plan the district heating network expansion. Community cohesion was the least related, and Cogas would like to create a socially just and inclusive heating network using, for example, PSS to build public perception towards district heating.

4.4. Design Knowledge Problem and Solution Space

Information system (IS) research cycle between design-science and behavioural-science is at the confluence of people, organisations, and technology (Hevner et al., 2004). Concerning the creation and evaluation of information technology for solving behavioural and organisational problems, design science research (DSR) is intended to generate prescriptive knowledge about the design of IS artefacts, such as software, methods and models (Vom Brocke et al., 2020). As a means-end relationship between problem and solution spaces, design knowledge (DK) can be represented in designed artefacts like a PSS geo-information science instrument. The planning scenario in this study provides application context information, describing the planning problem in LUC installations for the Heat Transition Vision Enschede. The meaning and requirements of a design solution in addressing the problem in context are described as the goodness criteria (Vom Brocke et al., 2020), with four sociotechnical aspects (1) Technology; (2) Information Quality; (3) Human Interaction; and (4) Societal Needs. Guided by the information on goodness criteria, the PSS was designed through foundations of known theories and insights (e.g., literature findings, thematic landscape and user stories) with built activities, which are elaborated in the section below.

4.4.1. PSS Design Criteria

Guided by the goodness criteria for solution acceptance, societal needs regarding the accessibility and fairness of PSS tools were important for engaging stakeholders in collaborative planning for geothermal development. This implied that maptables or touch tables, as an interactive technology capable of keeping users actively engaging in group tasks, could be useful in facilitating stakeholders in expressing, exploring and reaching consensus for LUC development. Maptables with data maps as central for visioning and idea sketching, local knowledge co-production and geographical calculations were evident in a number of literatures on urban planning for renewable technologies (Flacke & De Boer, 2017; Geertman et al., 2013;

Ligtenberg et al., 2011; Pelzer et al., 2015; Sharma et al., 2011). Apart from reference topographic or aerial maps, thematic and administrative layers were included to provide an overview of the different urban landscape infrastructure and functions, such as neighbourhood boundary, building footprint and energy label (see Table 8). Additionally, resource and constraint layers were to assist professional planners in contextualising the feasibility of LUC technology in Enschede. A 2D object visualisation and manipulation would suffice in accommodating the diverse group of stakeholders with different digital capacities, but also manipulating 3D virtual objects through a 2D interface is challenging for users to translate 2D into 3D actions (Anslow et al., 2016). Furthermore, search and discovery functionalities would allow users with limited technical or GIS affinity to navigate and analyse background information, like neighbourhood attributes for prioritising heating options.

Sketch functionality is crucial at the initial planning stages for facilitating the creative design process and externalising the sharing of tacit knowledge (Ligtenberg et al., 2011). A sketch-based interaction was included in the PSS tool for stakeholders to annotate and comment during the exploration of LUC geothermal development, such as drawing potential neighbourhood clusters to be supported by geothermal heating. Predefined objects appended to a PSS tool would facilitate users in exploring the planning scenario. With new housing development anticipated in Enschede, different residential building features, with respective energy profiles, were included to assess energy typology and inform about heat demand for LUC geothermal development. Without referenced units and dimensions, a point feature could be dropped to represent an LUC geothermal plant in the PSS tool for users to visualise and examine opportunities as well as constraints and to explore where and when LUC installations can be made. Due to the undefined spacing between LUC geothermal units, a slider bar can be introduced as a distance measurement to create a buffer around individual LUC point features, determining the minimum spacing as required between neighbouring LUC units. The installation of LUC for household heating requires constructing or expanding the heating infrastructure. Therefore, pipelines with different diameters were designed as line features to investigate the heat distribution network and housing connection options. The cost per unit length of different pipeline diameters could also be calculated to optimise investment needs for heat network development and LUC installations. This could also be supplemented with the use of a chart to aggregate the total cost needed for establishing a local heating network with LUC installations. In addition, performance indicators could help in monitoring the progress of the heat transition plan in achieving the natural gas-free target. Spatial modelling and information database suggested by stakeholders were excluded from the PSS design.

Table 8. Proposed design criteria for a PSS tool for LUC geothermal planning in Enschede.

PSS Design	Goodness Criteria	Build Activities
MapTable	Societal Needs, Technology	Display data on an interactive maptable interface and support sketching and GIS functionalities.
Data, 2D Visualisation	Societal Needs, Information Quality	Include interactive maps of resources and constraints for geothermal and LUC development. Reference maps, like topography, land use, aerial photographs and road networks Thematic and administrative maps, like neighbourhood boundary, building footprint, energy label (per building), energy consumption patterns (per neighbourhood) Policy maps, like groundwater protected area (Grondwaterbeschermingsgebieden) and Natura 2000.

Search and discovery functionalities	Societal Needs	Enable each neighbourhood to be pointed or selected for showing background information like heat demand, housing units, % district heating, % gas consumption, etc.
Sketching functionality	Human Interaction	Create a sketch tool for planning and communicating a LUC design concept by simplifying a complex situation.
Predefined features (buildings)	Societal Needs	Create a reference design of energy typology that describes residential building types and respective energy profiles.
Predefined features (LUC geothermal plant)	Societal Needs	Create a default point feature for placing LUC installations.
Predefined features (pipelines)	Societal Needs	Create a reference design of the heating network and pipelines with different diameters for heat transportation and distribution.
Slider (distance between LUC units) (m)	Human Interaction	Create a slider template for an interval of distance to display the minimum distance between neighbouring independent LUC installations.
Cost measurement	Human Interaction	Assess the cost per unit length for pipe installations and construction. The cost per unit for the heating network varies between €100 per metre and over €2500 per metre, depending on material sources, distribution methods, temperature, etc.
Performance indicator	Human Interaction	Create a performance indicator to calculate the total natural gas savings from LUC installations, with the key performance indicator from the energy target, e.g., 90 million m^3 natural gas consumption from households.
Performance indicator	Human Interaction	Create a dynamic chart to calculate the aggregated investment cost for installing a LUC geothermal plant, new heat distribution networks and housing connection pipes. Reference price for installing heating network pipelines could be based on a middle value of €1000 per metre or could be connected to the dynamic cost measurement.

5. DISCUSSION

5.1. Wicked Planning Problems of Geothermal Development

5.1.1. Super Wicked Planning Problem

Policy planning often deals with ill-defined and unsolvable societal problems (Rittel & Webber, 1973). Involving different stakeholders and numerous avenues for development (Hewitt et al., 2020), energy transition is inherently a wicked planning problem. Especially in a pluralistic society, like the Netherlands, wicked policy problems entail unknown causes and effects, with high levels of disagreement among stakeholders concerning problems in context and no definite or optimal solution (Georgiadou & Reckien, 2018). Furthermore, energy transition is a super wicked problem, characterised by *"limited time for finding solutions, no central authority for solutions, those who solve are also causing the problem, and policy responses disregard the future irrationally*" (Jakimowicz, 2022, p. 21). This is reflected in the multilevel energy governance issue of Enschede, where the transition vision of 2050 requires the coordination among different actors, institutions and instruments. The wickedness of a planning problem can be reduced only when the issue is knowable, the knowledge is publicly shared or accessible, no deep conflicts of interest among stakeholders, and power is well distributed. Therefore, understanding the scale of wickedness in energy planning and geothermal development is critical to reducing the complexity of the energy transition issues, and a properly designed PSS could help in this regard.

5.1.2. (Un)Attractiveness of Geothermal Heating

"*Energy systems are constantly shaped by social and technical developments in cities*" (Gürsan et al., 2024, p. 2). The Netherlands initiates energy transitions through national and urban strategies, but "*the absence of a thorough understanding, such socio-technical interdependencies can lead to unintended consequences in terms of ineffective policies that can work against carbon-neutrality efforts in cities*" (Gürsan et al., 2024, p. 2). The national strategy is constructed through progressively phasing out natural gas infrastructure and scaling alternative heating options, in which affordable district heating should increase the attractiveness of alternative heating. However, district heating tariffs are currently linked to the average gas price, making the difference in energy cost between district heating and natural gas inconsiderable. For example, the average energy consumption of 42 GJ per year or 1,373 m^3 of gas for a two-person household in 2024 would cost approximately €1,960 with district heating (€43.79 per GJ) and €2,202 for natural gas (€1.604 per m^3 of gas). Furthermore, the increased natural gas prices could deepen energy poverty, hindering households from investing in alternative heating systems. Although a new tariff model will be introduced in the Dutch Wet Collectieve Warmte Act, district heating based mainly on waste incineration is not a clean or sustainable heat solution, which makes geothermal energy an attractive alternative. While adopting district heating systems in social housing is considered an inclusive transition (Gürsan et al., 2024), private homeowners are equally important in fostering acceptance and trust for key actors and sustainable energy technology, especially for geothermal development. This is where a PSS could be designed to address the social-technical challenges of geothermal energy planning in cities.

5.1.3. Applicability of PSS at Scale

The geothermal industry offers possible solutions for future sustainable energy production. However, the planning of such future-oriented development is a dynamic process influenced by the flows and interactions of people, resources and information within distinctive urban contexts. Moreover, the uncertainties and complexity inherent in spatial planning are dependent on the spatial organisation and activities of people at various spatial scales. This implies that planning support and the process are context-specific, and that PSS cannot be adopted or transferable to other spatial contexts without adaptation. For example, countries like Indonesia and the Philippines harness geothermal resources for electricity production, which is different from the Netherlands, where geothermal is used for heating. This speaks to the necessity for a PSS to be designed with consideration for different geothermal applications and specific planning needs on surface and subsurface infrastructure of urban systems. On the other hand, the geothermal PSS designed in this study for Enschede may be applicable to other Dutch cities, due to similar policy, culture and institutional settings. However, these scale-dependent factors remain pertinent for minimising the PSS implementation gap by considering the information, knowledge and planning practice to be included for designing a PSS.

5.1.4. Scale of Heat Supply-Demand

Domains and scales of actors, technological innovations and spatial development plans form institutional arrangements for local energy supply initiatives (Acheilas et al., 2020). Understanding the heat supply-demand matching on a local scale is important for strategising geothermal energy development to balance the investment cost and residential heat demand. Geothermal energy can be harvested almost anywhere in the Netherlands, but the intertwined technical, spatial and socioeconomic factors or barriers are often overlooked in the planning by stakeholders. For example, the small-scale LUC installation is suitable for areas with limited alternative options to meet local heat demand. The high energy demand in Enschede, which is currently supplied by the massive waste heat from Twence, does not make geothermal a desirable or only choice for alternative heating. This contrasts with rural municipalities, where connecting to a district heating network is not economically viable, making LUC geothermal an attractive and possible solution to replace natural gas. This could also be why Dutch rural neighbourhoods favour geothermal energy more than urban areas (European Geothermal Energy Council, 2024). The case of Dinkelland[6] provides valuable insight into how a rural municipality with a smaller population and, thus, lower heat demand may leverage LUC as a local small geothermal heating network. However, the planning challenge remains in funding the investment locally, especially with the low-level financial autonomy of rural municipalities, to enforce co-ownership and shared responsibility for improving social acceptance of geothermal technology. Social ownership can also embrace prosumer capitalism, allowing the heat price to be determined locally and transitioning away from a centralised and monopolised energy system. A PSS hosting diverse data and tools to support information and knowledge sharing would benefit users in understanding any scale dependence factors of district heating and geothermal planning.

5.1.5. Wickedness of LUC Geothermal Planning

Local stakeholder constellations and policy conditions drive energy system innovation and public acceptance within cities (Bonfert et al., 2024). Understanding the geothermal project management in Enschede could be important in driving the scale and frequency of LUC installation, where individual stakeholders have different motivations. Therefore, contextualising the wickedness of LUC geothermal planning can be

[6] The rural municipality Dinkelland could be the first in Twente to establish a local small geothermal heating network. There is an ongoing financial investigation and a technical investigation of the test drilling in the municipality, the results of which will benefit other municipalities in considering geothermal for heating homes and businesses. See more information at https://www.tubantia.nl/dinkelland/dinkelland-maakt-als-eerste-in-twente-werk-van-warmte-uit-de-bodem~a3511d90/?referrer=https%3A%2F%2Fwww.google.com%2F

difficult without realising the motives that drive stakeholder participation, which is why Flyvbjerg's (2014) four sublimes[7], i.e., political, technological, economic, and aesthetic, are used in this study to identify the causes for stakeholders to undertake LUC geothermal megaproject. For example, the heat distribution system is owned by the private company Ennatuurlijk, whose decisions are mainly profit-oriented. Adopting LUC development would, however, require submitting partial control of their heat system assets and imposing costs to replace the existing high-temperature heating infrastructure, which might have led to their opposition to geothermal development. This contrasts with the general public, who is motivated by the financial and environmental benefits of localised LUC development and, more importantly, the co-ownership of a geothermal facility rather than depending on a single heat supplier of the district network. Public engagement has been carried out for the planning of the Heat Transition Vision. However, it is unexpected to hear from stakeholder interviews that some residents, especially private homeowners, do not favour the initial plan and have lost trust in the municipality. This could inform on the important role of social enterprise Enschede Energie, as an advisor to the local public on alternative energy options and an intermediary party in the sounding board group (klankbordgroep) for the energy vision. Cogas faces challenges in engaging private homeowners, which could be attributed to their relationship with shareholder municipalities. This, however, appears not to move their perception of the importance of citizen engagement for energy planning. Both the dGB Earth Science and GGN are driving geothermal technological innovations. However, the former focuses more on researching possibilities of LUC implementation, while the latter may focus more on political interests in promoting geothermal as part of the future energy mix nationwide. PSS applied to geothermal planning can help explore the underlying motivations and interests associated with local stakeholder roles, facilitating geothermal project delivery and management.

At first sight, the Heat Transition Vision adopted by the municipality may appear to bring clarity and a united direction for energy transition, making the energy planning in Enschede less evident as a wicked problem. As this study progressed in investigating geothermal resource development, the problem definition and knowledge of geothermal planning became apparent as ill-defined, reflecting the wickedness manifested by the uncertainty of knowledge and the dissensus among stakeholders. For example, most interviewed stakeholders foresee small-scale LUC installations as an interesting option for future energy needs in Enschede. However, seismic data that is openly sourced (e.g., NLOG and ThermoGIS) or interpreted by dGB Earth Sciences provides limited knowledge and confidence to invest in geothermal resources locally. Furthermore, the different motivations for geothermal development and the conflicts against primary interests could have resulted in stakeholders with diverging goals and values, leading to discordance for geothermal development. This could be seen from dGB Earth Sciences and GGN as advocates for LUC installations, contrasting to Ennatuurlijk as an operator of the district heating network and conventional geothermal energy production. As a problem recogniser tool, PSS could facilitate the communication between stakeholders with a collection of aggregated data that contextualises information to reduce knowledge uncertainty. Therefore, this research exploits PSS to frame the planning problem and information, taming the wickedness of geothermal development.

[7] Flyvbjerg (2014) identifies four causes or "sublimes" – political, technological, economic, and aesthetic – that attract decision makers to undertake megaprojects. These "sublimes" explain the increased size and frequency of megaprojects, understanding what drives the megaproject boom and why megaprojects are attractive to decision makers.

5.2. Critical Reflections on Qualitative Research

5.2.1. PRISMA Literature Review

The literature review conducted in this study is to obtain existing knowledge about PSS technologies applied in renewable and geothermal energy planning. The PRISMA approach provides a structure for the literature review process to be reproducible. Although PRISMA is debatable in management or social science-related research that focuses more on pinpointing knowledge gaps through a narrative literature review (Mishra & Mishra, 2023), this approach provides transparent reporting of a systematic literature review. This study may, therefore, demonstrate the feasibility of a systematic review for social and technical research clusters, particularly in the geo-information science domain. Possible constraints and biases contributing to evidence synthesis should be examined. For example, the methodological rigour and content validity towards addressing the review topic about renewable and geothermal PSS can be assessed using appraisal checklists like AMSTAR and CASP. In addition to the use of the Scopus database, which mainly includes English-language publications, recent published or grey literature can be retrieved better using Google Scholar to expand on the emerging topic of spatial planning for geothermal energy. Despite the present study having its limitations, the PRISMA flow diagram and the literature screening process are documented to ensure that the literature review is reproducible and transparently reported for future improvements.

5.2.2. Semi-Structured Interview

A semi-structured interview as an open-ended qualitative method offers flexibility and adaptability in agile research, which should also be appreciated along with challenges and weaknesses. Although questionnaire topics were identified and mock interviews were implemented in advance, this topic-centred approach lost the fluid and flexible semi-structured approach. This, however, can be a factor of an interviewer's strengths and experience in actively listening and probing main and follow-up questions. As the series of interviews was conducted within a short two weeks, maintaining a neutral data collector is challenging without assumptions of stakeholders' roles in energy planning, especially with the wickedness of stakeholder dissensus. Qualitative interviewing training can, therefore, be beneficial in developing non-cognitive skills for effective balancing between neutrality and effective probing. While the individual stakeholder may be underrepresented in drawing conclusions and making comparisons, this study engaged with key stakeholder groups from the public and private sectors and a social enterprise to discuss the topic of energy planning and digital tool applications in depth. This also helps in acquiring in-depth information and evidence from interviewees while maintaining the focus of this study on PSS design. To improve stakeholder responses, questions directed towards the design and functionality of PSS tools can be selected and followed up in-depth during the interview. Moreover, a sample geothermal PSS can be created and demonstrated prior to the interview to assist stakeholders in providing more targeted and informed responses.

5.2.3. Thematic Analysis and User Stories Writing

Thematic analysis is distinguished by its flexibility in interpreting and describing qualitative data applied to various study designs and sample sizes, and it is designed to search for common and shared meanings across datasets, often grounded in published analytical principles. There are preexisting methods for renewable energy research related to policy development (Sovacool et al., 2023) and decarbonisation (Mirza et al., 2024), but rarely on spatial planning and geothermal development in particular, at least unknown to the knowledge of the author. This makes thematic analysis accessible yet less suitable, particularly for inexperienced practitioners, within the research field of geothermal planning. This study applies a data-driven inductive process to code and identify themes without the use of any theory. However, this bottom-up approach could subject to the risks of a qualitative method being applied broadly and never consistently, resulting in a weak analysis where themes overlap or lack internal consistency, as mirrored in this current study, for example, in identifying codes to elucidate the broad themes between the challenges and barriers with the socio-economic constraints. In this regard, a hybrid deductive and inductive approach may be helpful, by including predefined codes and themes from renewable energy planning that can be adapted for geothermal development. One of the pitfalls of conducting thematic analysis is the inadequate interpretation of data extracts (Kiger & Varpio, 2020), in which user stories in this study are formulated with participatory process objectives to elicit interview responses for PSS tool agile development. The user stories generation can be improved with the involvement of potential PSS users in a co-creation process to conceptualise the tool for participatory activities for geothermal development.

5.3. Applications and Implications of PSS Design Knowledge and Design Science Research

5.3.1. PSS Design Foundation

The lack of conceptual and methodological models directs this study to use the design science research (DSR) framework as a goal-driven search of PSS design for geothermal development, with reference to existing digital tools for other renewable energy development. Multifaceted knowledge is produced in DSR projects to build solutions for a defined problem domain and stakeholders that would evolve across time and space (Vom Brocke et al., 2020), which is applicable in the current study of energy transition as a super wicked problem. This framework distinguishes the application context information and the goodness criteria for solutions within the problem space. However, these two are interrelated components critical for understanding user-friendliness and usefulness to bridge the PSS implementation gap. In addition, the DK model lists sociotechnical categories of goodness criteria without a description of how they can be sourced, measured and translated into design foundations of solution artefact. Therefore, this study used literature findings as ground-truthing data to systematically gather, assess, and synthesise existing knowledge about PSS design, followed by stakeholder interviews to acquire users' requirements and needs relevant to the design of a PSS for LUC geothermal planning. By combining the DSR framework with findings from the literature review and stakeholder interviews, this study builds a conceptual and methodological foundation for designing a PSS to support LUC geothermal development.

5.3.2. Projectability and Fitness of PSS

Designing a PSS involves balancing the trade-offs between the projectability and the fitness of designed artefacts (Vom Brocke et al., 2020), depending on the scale of the application context and the planning problem. Unlike decision support systems, which are designed to aid decision makers in making particular decision tasks (e.g., identifying feasibility or optimum locations for renewable energy installations), PSS tools focus on planning scenarios to explore, visualise, discuss and raise awareness about issues associated with the need to plan. This enables PSS to attain high projectability that can accommodate different dimensions of geothermal planning and apply to other geothermal developments, such as the case in Dinkelland. Although this may lead to lower levels of fitness in problem-solving, the PSS tool designed in this study is intended to facilitate stakeholder discussions and knowledge exchange, enabling lower normative power as an approach to energy planning. Despite the usefulness of spatial modelling being recognised in several energy planning studies (Gadsden et al., 2003, 2003; Hewitt et al., 2020; Jiang et al., 2020; Yeo et al., 2013), stakeholders in this study are concerned about the in-depth knowledge required to interpret the model and associated functions, as well as the dependency on quality data input. Therefore, modelling tools are excluded from the PSS design to reduce the complexity and smartness of PSS, allowing the design with lower levels of fitness. PSS as a knowledge database can only meet individual needs without facilitating group planning, and thus is excluded from the design solution. In essence, designing a PSS requires managing the trade-offs between the projectability and the fitness of the application for achieving planning goals.

6. CONCLUSIONS

Energy transition is a super wicked problem that requires the consideration of complex socioeconomic, technological and cultural factors, and an array of renewable energy technologies are known to moderate these societal and environmental challenges to varying extents. As limited stakeholder consensus and knowledge undermine social acceptance of renewable energy projects in the Netherlands, participatory planning could facilitate the mutual learning and understanding of complex trade-offs in the decision-making and planning process of geothermal development. The purpose of the current study was to identify the potential design of a PSS tool to support participatory geothermal resource planning in the municipality of Enschede.

This study provides a comprehensive and transparent literature review of the existing research concerning geospatial collaborative tools for renewable and geothermal energy planning. A dataset of 23 scholarly articles was compiled and examined for the conceptual design of PSS tools according to three major aspects – characteristics of planning applications, information collaborative systems and PSS design process. On the one hand, research about the development of PSS for renewable energy planning has been established for over two decades. These studies were mostly focused on energy planning at a city scale, with mainly solar and wind renewables, to evaluate energy potential for informing urban strategies. On the other hand, the potential implementation of PSS was rarely directed towards the planning for geothermal energy development. The present study takes a step further towards the advancement in the research field of PSS conceptualisation. To the best of the author's knowledge, this could also be the first literature review bringing new insights into PSS design targeted for geothermal development. Therefore, this study provides a base for encouraging future research attempts to explore the extent to which a PSS can be usable and useful in supporting geothermal collaborative planning.

The systematic literature review was then combined with a stakeholder interview to develop state-of-the-art knowledge about district energy planning and geothermal infrastructure development in Enschede. An inductive thematic analysis was applied to responses collected from the interviews to understand the values and needs of stakeholders that are influential in LUC geothermal energy development. Three themes were identified as (1) Challenges and barriers to the Heat Transition Vision, (2) Information collaborative systems for urban planning (3) Social and economic constraints of geothermal development. Agile user stories extracted from the interviews conceptualise a PSS tool that addresses the user requirements for geothermal energy planning. This research provides a starting point for identifying the PSS design attributes and characteristics to support geothermal energy planning. This has laid down the foundation for PSS tool development to support future geothermal planning with citizen participation.

This study presents a novel or, if not, initial design of a PSS to support its usability for collaborative planning of geothermal development. The literature review demonstrates the wealth of planning support systems for land-based renewable energies. However, this geoinformation technology-based instrument, designed mainly for wind and solar energy, is less applicable to geothermal planning due to the different information needed for subsurface exploration and geothermal infrastructure development. Through combining thematic landscape and user stories, this study contributes to the broader literature by reporting a preliminary design for the development of geothermal PSS applications. A feedback path of refinement can be implemented to evaluate and improve the attributes and characteristics of PSS tangible in reducing the degree of wickedness in geothermal planning.

6.1. Future Research and Recommendations

Relatively few studies and limited real-world experience exist regarding PSS design for geothermal energy development. To balance the complexity of wicked planning problems and the simplicity needed for improving usability within the planning profession, some recommendations for further research can be made about the PSS development process and application.

This study shows that designing a geothermal PSS is practically challenging and fuzzy, revealing the need to conceptualise components relevant for the PSS design process. Therefore, a conceptual and methodological discourse of PSS design would be valuable to better connect the geothermal planning problem and the PSS solution artefact. Goodness criteria are used in this research to translate sociotechnical aspects for design innovation and to guide the foundations and build activities for geothermal PSS. However, the PSS should also be designed as an integral part of a planning process, to stay attuned to specific characteristics related to policy context and technology used. Future work should, therefore, improve coordination between developers or researchers and stakeholders, enabling all involved in PSS adoption and implementation in the PSS design journey and the subsequent planning decisions.

Secondly, related to the first recommendation, a design science research project emphasises iterative build-evaluation cycles to create, assess and refine design processes and build activities (Vom Brocke et al., 2020). Thus, the performance of the PSS tool in supporting the planning activities and goals should be evaluated for the fitness for use, together with the ability of PSS to adapt to changes in planning problems over time. Further research should also undertake the design of PSS as an iterative development and evaluation process to assess the impacts of planning scenarios or alternatives, followed by evaluating and deciding on the design options to improve usefulness and usability. Co-design activities, such as user interviews, story-writing workshops, and focus group meetings (Aguilar et al., 2020; Akbar et al., 2020), could also be incorporated into the evaluation process to balance creativity and control, allowing the PSS tool to be agile in deployment while maintaining user-friendliness for end users.

In support of the above suggested improvements, more stakeholders can be engaged in future research to acquire a more comprehensive view of users' requirements and needs, ensuring cohesion of PSS design. The conducted semi-structured interview only engaged key stakeholders in the public and private sectors of energy planning. However, this limits the viewpoints to only the upstream heat producer and distributor, without accounting for the downstream consumers or end users, as well as the provincial and central governance bodies. This could have important implications for energy governance locally, especially with public acceptance being a key factor for successful geothermal project implementation.

Finally, future research should be directed towards designing a PSS that could involve citizens in geothermal energy planning. This can be approached by either identifying a new design using a similar methodology in this study or evaluating the proposed design through the cyclic analytic-deliberative process. A PSS that enables citizen participation could help build public trust in emerging LUC development in the Netherlands, realising the growing potential of geothermal energy in the energy mix. Public participatory process should also consider the space and time settings for a PSS workshop, in which group work collaboration usually happens in a co-located and synchronous environment. Furthermore, community engagement should account for the demographic and socioeconomic representation of the public, paving the way for a secure and inclusive energy transition.

REFERENCES

Acheilas, I., Hooimeijer, F., & Ersoy, A. (2020). A Decision Support Tool for Implementing District Heating in Existing Cities, Focusing on Using a Geothermal Source. *Energies*, *13*(11), 2750. https://doi.org/10.3390/en13112750

Aguilar, R., Calisto, L., Flacke, J., Akbar, A., & Pfeffer, K. (2021). OGITO, an Open Geospatial Interactive Tool to support collaborative spatial planning with a maptable. *Computers, Environment and Urban Systems*, *86*, 101591. https://doi.org/10.1016/j.compenvurbsys.2020.101591

Aguilar, R., Flacke, J., & Pfeffer, K. (2020). Towards Supporting Collaborative Spatial Planning: Conceptualization of a Maptable Tool through User Stories. *ISPRS International Journal of Geo-Information*, *9*(1), 29. https://doi.org/10.3390/ijgi9010029

Aguilar, R., Flacke, J., Simon, D., & Pfeffer, K. (2023). Stakeholders Engagement in Noise Action Planning Mediated by OGITO: An Open Geo-Spatial Interactive Tool. *Journal of Urban Technology*, *30*(3), 23–46. https://doi.org/10.1080/10630732.2023.2190705

Akbar, A., Flacke, J., Martinez, J., Aguilar, R., & Van Maarseveen, M. (2020). Knowing My Village from the Sky: A Collaborative Spatial Learning Framework to Integrate Spatial Knowledge of Stakeholders in Achieving Sustainable Development Goals. *ISPRS International Journal of Geo-Information*, *9*(9), 515. https://doi.org/10.3390/ijgi9090515

Anderson, A., & Rezaie, B. (2019). Geothermal technology: Trends and potential role in a sustainable future. *Applied Energy*, *248*, 18–34. https://doi.org/10.1016/j.apenergy.2019.04.102

André, P., B. Enserink, D. Connor, & P. Croal. (2006). *Public Participation International Best Practice Principles. Special Publication Series 4*. Fargo, USA: International Association for Impact Assessment.

Anslow, C., Campos, P., & Jorge, J. (Eds.). (2016). *Collaboration Meets Interactive Spaces*. Springer International Publishing. https://doi.org/10.1007/978-3-319-45853-3

Arnstein, S. R. (1969). A Ladder Of Citizen Participation. *Journal of the American Institute of Planners*, *35*(4), 216–224. https://doi.org/10.1080/01944366908977225

Ayoub, N., Wang, K., Kagiyama, T., Seki, H., & Naka, Y. (2006). A planning support system for biomass-based power generation. In *Computer Aided Chemical Engineering* (Vol. 21, pp. 1899–1904). Elsevier. https://doi.org/10.1016/S1570-7946(06)80325-1

Balint, P. J., Stewart, R. E., Desai, A., & Walters, L. C. (2011). Participatory Processes. In P. J. Balint, R. E. Stewart, A. Desai, & L. C. Walters, *Wicked Environmental Problems* (pp. 103–127). Island Press/Center for Resource Economics. https://doi.org/10.5822/978-1-61091-047-7_6

Bandh, S. A., Malla, F. A., & Hoang, A. T. (Eds.). (2023). *Renewable Energy in Circular Economy*. Springer International Publishing. https://doi.org/10.1007/978-3-031-42220-1

Banks, D. (2012). *An Introduction to Thermogeology: Ground Source Heating and Cooling* (1st ed.). Wiley. https://doi.org/10.1002/9781118447512

Baralis, M., & Barla, M. (2024). rOGER: A method for determining the geothermal potential in urban areas. *Geothermics*, *124*, 103148. https://doi.org/10.1016/j.geothermics.2024.103148

Bayer, P., Attard, G., Blum, P., & Menberg, K. (2019). The geothermal potential of cities. *Renewable and Sustainable Energy Reviews*, *106*, 17–30. https://doi.org/10.1016/j.rser.2019.02.019

Bayley, C., & French, S. (2008). Designing a Participatory Process for Stakeholder Involvement in a Societal Decision. *Group Decision and Negotiation*, *17*(3), 195–210. https://doi.org/10.1007/s10726-007-9076-8

Beriro, D., Nathanail, J., Salazar, J., Kingdon, A., Marchant, A., Richardson, S., Gillet, A., Rautenberg, S., Hammond, E., Beardmore, J., Moore, T., Angus, P., Waldron, J., Rodrigues, L., & Nathanail, P. (2022). A decision support system to assess the feasibility of onshore renewable energy infrastructure. *Renewable and Sustainable Energy Reviews*, *168*, 112771. https://doi.org/10.1016/j.rser.2022.112771

Bertani, R. (2016). Deep geothermal energy for heating and cooling. In *Renewable Heating and Cooling* (pp. 67–88). Elsevier. https://doi.org/10.1016/B978-1-78242-213-6.00004-7

Bertermann, D., Klug, H., & Morper-Busch, L. (2015). A pan-European planning basis for estimating the very shallow geothermal energy potentials. *Renewable Energy*, *75*, 335–347. https://doi.org/10.1016/j.renene.2014.09.033

Bertermann, D., Schwarz, H., Rammler, M., & Jocic, N. (2024). Mapping of very shallow geothermal potentials in rural areas of Bavaria. *Glasnik Srpskog Geografskog Drustva*, *104*(1), 363–382. https://doi.org/10.2298/GSGD2401363B

Bieder, C., Grote, G., & Weyer, J. (Eds.). (2024). *Climate Change and Safety in High-Risk Industries*. Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-56995-1

Bleicher, A., & Gross, M. (2015). User motivation, energy prosumers, and regional diversity: Sociological notes on using shallow geothermal energy. *Geothermal Energy*, *3*(1), 12. https://doi.org/10.1186/s40517-015-0032-6

Boin, A., Ekengren, M., & Rhinard, M. (Eds.). (2021). *Understanding the Creeping Crisis*. Springer International Publishing. https://doi.org/10.1007/978-3-030-70692-0

Bonfert, B., Nielsen, H. Ø., & Pedersen, A. B. (2024). Taking first steps so that others can run – functions and limitations of governing the local energy transition. *Journal of Environmental Policy & Planning*, *26*(6), 608–622. https://doi.org/10.1080/1523908X.2024.2380277

Bouw, K., Wiekens, C., Elbert, S., & Faaij, A. (2022). How to plan for success? An exploration of social context factors in neighbourhood energy planning. *Energy Research & Social Science*, *92*, 102761. https://doi.org/10.1016/j.erss.2022.102761

Bouw, K., Wiekens, C. J., Tigchelaar, C., & Faaij, A. (2023). Involving Citizens in Heat Planning: A Participatory Process Design for Informed Decision-Making. *Sustainability*, *15*(3), 1937. https://doi.org/10.3390/su15031937

Bureau Buiten (2020). *Gebiedsagenda Josink Es* [online]. Available at https://www.parkmanagementjosinkes.nl/wp-content/uploads/Gebiedsagenda-Josink-Es-23-10-2020.pdf [Accessed: 24 Feb, 2025]

CBS (2023). *Electricity; production and means of production* [online]. Available at: https://opendata.cbs.nl/#/CBS/en/dataset/37823eng/table [Accessed: 20 Apr, 2025]

CBS (2024a). *Dwellings and non-residential stock; changes, utility function, regions* [online]. Available at https://opendata.cbs.nl/#/CBS/en/dataset/81955ENG/table?dl=B4A4E [Accessed: 22 Feb, 2025]

CBS (2024b). *Regional key figures in the Netherlands* [online]. Available at: https://opendata.cbs.nl/statline/#/CBS/nl/dataset/70072NED/table?fromstatweb [Accessed: 25 Feb, 2025]

CBS (2024c). *Woningen; hoofdverwarmingsinstallaties, wijken en buurten, 2022* [online]. Available at https://opendata.cbs.nl/statline/#/CBS/nl/dataset/85677NED/table?dl=B4A5B [Accessed: 26 Mar, 2025]

Cha, J. M., & Pastor, M. (2022). Just transition: Framing, organizing, and power-building for decarbonization. *Energy Research & Social Science*, *90*, 102588. https://doi.org/10.1016/j.erss.2022.102588

Champlin, C. (2019). *Contextualizing Planning Support (Systems): Co-designing to fit the dynamics of spatial strategy making* [Doctoral thesis, University of Twente]. University of Twente, Enschede.

Chouhan, A. K., Kumar, R., & Mishra, A. K. (2024). Assessment of the geothermal potential zone of India utilizing GIS-based multi-criteria decision analysis technique. *Renewable Energy*, *227*, 120552. https://doi.org/10.1016/j.renene.2024.120552

Couclelis, H. (2005). "Where has the Future Gone?" Rethinking the Role of Integrated Land-Use Models in Spatial Planning. *Environment and Planning A: Economy and Space*, *37*(8), 1353–1371. https://doi.org/10.1068/a3785

De Boer, J., & Zuidema, C. (2015). Towards an integrated energy landscape. *Proceedings of the Institution of Civil Engineers - Urban Design and Planning*, *168*(5), 231–240. https://doi.org/10.1680/udap.14.00041

De Groot, P., Mol, A., & Veenstra, E. (2020). Harvesting geothermal energy with low unit cost installations. *The Leading Edge*, *39*(12), 901–908. https://doi.org/10.1190/tle39120901.1

Dekker, H.-J., & Missemer, A. (2024). Resource booms and the energy transition: What can we learn from Dutch economists' response to the discovery of natural gas reserves (1959–1977)? *Energy Economics*, *134*, 107636. https://doi.org/10.1016/j.eneco.2024.107636

Deshmukh, M. K. G., Sameeroddin, M., Abdul, D., & Abdul Sattar, M. (2023). Renewable energy in the 21st century: A review. *Materials Today: Proceedings*, *80*, 1756–1759. https://doi.org/10.1016/j.matpr.2021.05.501

Devine-Wright, P. (Ed.). (2011). *Renewable energy and the public: From NIMBY to participation*. Earthscan.

Devine-Wright, P., Batel, S., Aas, O., Sovacool, B., Labelle, M. C., & Ruud, A. (2017). A conceptual framework for understanding the social acceptance of energy infrastructure: Insights from energy storage. *Energy Policy*, *107*, 27–31. https://doi.org/10.1016/j.enpol.2017.04.020

Dickson, M. H., & Fanelli, M. (Eds.). (2005). *Geothermal energy: Utilization and technology* (Online-Ausg). Earthscan.

DiPippo, R. (1991). Geothermal energy Electricity generation and environmental impact. *Energy Policy*, *19*(8), 798–807. https://doi.org/10.1016/0301-4215(91)90050-X

Ehrgott, M., Naujoks, B., Stewart, T. J., & Wallenius, J. (Eds.). (2010). *Multiple Criteria Decision Making for Sustainable Energy and Transportation Systems* (Vol. 634). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-04045-0

Ellis, G., Schneider, N., & Wüstenhagen, R. (2023). Dynamics of social acceptance of renewable energy: An introduction to the concept. *Energy Policy*, *181*, 113706. https://doi.org/10.1016/j.enpol.2023.113706

English, J. M., English, K. L., Dunphy, R. B., Blake, S., Walsh, J., Raine, R., Vafeas, N. A., & Salgado, P. R. (2023). An Overview of Deep Geothermal Energy and Its Potential on the Island of Ireland. *First Break*, *41*(2), 33–43. https://doi.org/10.3997/1365-2397.fb2023009

European Commission: Directorate General for Research and Innovation. (2024). *Embedding anticipatory governance in Europe's transitions.* Publications Office. https://data.europa.eu/doi/10.2777/3778181

European Geothermal Energy Council. (2024, April 24). Report: Geothermal lessons from Germany, Denmark and France for the Dutch Market. *EGEC - European Geothermal Energy Council.* https://www.egec.org/report-geothermal-lessons-from-germany-denmark-and-france-for-the-dutch-market/

Flacke, J., & De Boer, C. (2017). An Interactive Planning Support Tool for Addressing Social Acceptance of Renewable Energy Projects in The Netherlands. *ISPRS International Journal of Geo-Information*, *6*(10), 313. https://doi.org/10.3390/ijgi6100313

Flacke, J., Shrestha, R., & Aguilar, R. (2020). Strengthening Participation Using Interactive Planning Support Systems: A Systematic Review. *ISPRS International Journal of Geo-Information*, *9*(1), 49. https://doi.org/10.3390/ijgi9010049

Flyvbjerg, B. (2014). What you Should Know about Megaprojects and Why: An Overview. *Project Management Journal*, *45*(2), 6–19. https://doi.org/10.1002/pmj.21409

Forster, J., Fritz, S., Schleicher, J., & Rab, N. (2015). *Developer Tools for Smart Approaches to Responsible-Minded Planning Strategies*. 545–551. https://doi.org/10.52842/conf.ecaade.2015.1.545

Freeman, R. (1984). *Strategic Management: A Stakeholder's Approach*. Pitman, Boston, MA.

Gadsden, S., Rylatt, M., Lomas, K., & Robinson, D. (2003). Predicting the urban solar fraction: A methodology for energy advisers and planners based on GIS. *Energy and Buildings*, *35*(1), 37–48. https://doi.org/10.1016/S0378-7788(02)00078-6

Galgaro, A., Dalla Santa, G., De Carli, M., Emmi, G., Zarrella, A., Mueller, J., Bertermann, D., Castelruiz, A., Noye, S., Perego, R., Pera, S., Poletto, F., Pasquali, R., & Bernardi, A. (2019). New tools to support the designing of efficient and reliable ground source heat exchangers: The Cheap-GSHPs databases and maps. *Advances in Geosciences*, *49*, 47–55. https://doi.org/10.5194/adgeo-49-47-2019

Galvin, R. (2015). How many interviews are enough? Do qualitative interviews in building energy consumption research produce reliable knowledge? *Journal of Building Engineering*, *1*, 2–12. https://doi.org/10.1016/j.jobe.2014.12.001

Geertman, S. (2008). Planning support systems: A planner's perspective. In R. Brail (Ed.), *Planning support systems for cities and regions* (pp. 213–230). Cambridge, MA: Lincoln Institute for Land Policy.

Geertman, S., Toppen, F., & Stillwell, J. (Eds.). (2013). *Planning Support Systems for Sustainable Urban Development* (Vol. 195). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-37533-0

Gemeente Enschede (2021). *Transitievisie warmte Enschede* [online]. Available at: https://enschede.bestuurlijkeinformatie.nl/Agenda/Document/e1d71573-c779-4ba5-ab07-61c0a0a77b4d?documentId=87a9f53d-5ea9-4ea6-ae5c-9e7596112d7d&agendaItemId=be1f1763-84c2-4933-8175-d47e2abef70b [Accessed: 12 Mar, 2025]

Georgiadou, Y., & Reckien, D. (2018). Geo-Information Tools, Governance, and Wicked Policy Problems. *ISPRS International Journal of Geo-Information*, *7*(1), 21. https://doi.org/10.3390/ijgi7010021

Geothermie Nederland (2018). *Master Plan Geothermal Energy in the Netherlands* [online]. Available at https://geothermie.nl/images/Onderzoeken-en-rapporten/20180529-Masterplan-Aardwarmte-in-Nederland.pdf [Accessed: 24 Feb, 2025]

Groenendijk, L. (2003). *Planning and management tools*. Enschede, the Netherlands: the International Institute for Geo-Information Science and Earth Observation.

Grisiute, A., Shi, Z., Chadzynski, A., Silvennoinen, H., Von Richthofen, A., & Herthogs, P. (2022). *Automated Semantic SWOT Analysis for City Planning Targets: Data-driven Solar Energy Potential Evaluations for Building Plots in Singapore*. 555–564. https://doi.org/10.52842/conf.caadria.2022.1.555

Gürsan, C., De Gooyert, V., De Bruijne, M., & Raaijmakers, J. (2024). District heating with complexity: Anticipating unintended consequences in the transition towards a climate-neutral city in the Netherlands. *Energy Research & Social Science*, *110*, 103450. https://doi.org/10.1016/j.erss.2024.103450

Hevner, March, Park, & Ram. (2004). Design Science in Information Systems Research. *MIS Quarterly*, *28*(1), 75. https://doi.org/10.2307/25148625

Hewitt, R. J., De Boer, C., & Flacke, J. (2020). Participatory development of digital support tools for local-scale energy transitions: Lessons from two European case studies. *Global Transitions*, *2*, 138–149. https://doi.org/10.1016/j.glt.2020.07.003

International Energy Agency (IEA) (2024). *The Future of Geothermal Energy* [online]. IEA, Paris. Available at: https://www.iea.org/reports/the-future-of-geothermal-energy [Accessed: 10 Mar, 2025]

Ioannou, A., Falcone, G., Baisch, C., Friederichs, G., & Hildebrand, J. (2023). A Decision Support Tool for Social Engagement, Alternative Financing and Risk Mitigation of Geothermal Energy Projects. *Energies*, *16*(3), 1280. https://doi.org/10.3390/en16031280

Jakimowicz, A. (2022). The Energy Transition as a Super Wicked Problem: The Energy Sector in the Era of Prosumer Capitalism. *Energies*, *15*(23), 9109. https://doi.org/10.3390/en15239109

Jankowski, P., & Nyerges, T. (2001). *GIS for Group Decision Making* (0 ed.). CRC Press. https://doi.org/10.4324/9780203484906

Jiang, H., Geertman, S., & Witte, P. (2020). Ignorance is bliss? An empirical analysis of the determinants of PSS usefulness in practice. *Computers, Environment and Urban Systems*, *83*, 101505. https://doi.org/10.1016/j.compenvurbsys.2020.101505

Karytsas, S., Polyzou, O., Mendrinos, D., & Karytsas, C. (2019). *Towards social acceptance of geothermal energy power plants*. https://europeangeothermalcongress.eu/wp-content/uploads/2019/07/136.pdf

Kiger, M. E., & Varpio, L. (2020). Thematic analysis of qualitative data: AMEE Guide No. 131. *Medical Teacher*, *42*(8), 846–854. https://doi.org/10.1080/0142159X.2020.1755030

Kobayashi, T., & Ikaruga, S. (2015). Development of a smart city planning support tool using the cooperative method. *Frontiers of Architectural Research*, *4*(4), 277–284. https://doi.org/10.1016/j.foar.2015.09.004

Leshem, S., & Trafford, V. (2007). Overlooking the conceptual framework. *Innovations in Education and Teaching International*, *44*(1), 93–105. https://doi.org/10.1080/14703290601081407

Ligtenberg, A., De Vries, B., Vreenegoor, R., & Bulens, J. (2011). SimLandScape, a sketching tool for collaborative spatial planning. *URBAN DESIGN International*, *16*(1), 7–18. https://doi.org/10.1057/udi.2010.17

Lindal, B. (1973). Industrial and other applications of geothermal energy. In: Armstead, H. C. H. (ed.), *Geothermal Energy*, pp. 135–148. Paris, UNESCO

Mackenzie, A., Pidd, M., Rooksby, J., Sommerville, I., Warren, I., & Westcombe, M. (2006). Wisdom, decision support and paradigms of decision making. *European Journal of Operational Research*, *170*(1), 156–171. https://doi.org/10.1016/j.ejor.2004.07.041

Manzella, A., Allansdottir, A., & Pellizzone, A. (Eds.). (2019). *Geothermal Energy and Society* (Vol. 67). Springer International Publishing. https://doi.org/10.1007/978-3-319-78286-7

Marrone, P., Montella, I., & Fiume, F. (2023). Technologies and proximity spaces: Tools for conscious choices in ecological transition. *TECHNE - Journal of Technology for Architecture and Environment*, *25*, 101–115. https://doi.org/10.36253/techne-13719

Martínez, S. H., Harmsen, R., Menkveld, M., Faaij, A., & Kramer, G. J. (2022). Municipalities as key actors in the heat transition to decarbonise buildings: Experiences from local planning and implementation in a learning context. *Energy Policy*, *169*, 113169. https://doi.org/10.1016/j.enpol.2022.113169

Metze, T. A. P., Van Den Broek, J., Van Est, R., & Cuppen, E. H. W. J. (2023). Participatory repertoires for aligning policy and society: An analysis of Dutch stakeholder views on deep geothermal energy. *Energy Research & Social Science*, *98*, 103019. https://doi.org/10.1016/j.erss.2023.103019

Mijnlieff, H. F. (2020). Introduction to the geothermal play and reservoir geology of the Netherlands. *Netherlands Journal of Geosciences*, *99*, e2. https://doi.org/10.1017/njg.2020.2

Mirza, Z. T., Anderson, T., Seadon, J., & Brent, A. (2024). A thematic analysis of the factors that influence the development of a renewable energy policy. *Renewable Energy Focus*, *49*, 100562. https://doi.org/10.1016/j.ref.2024.100562

Mishra, V., & Mishra, M. P. (2023). PRISMA for Review of Management Literature – Method, Merits, and Limitations – An Academic Review. In *Advancing Methodologies of Conducting Literature Review in Management Domain* (world; Vol. 2, pp. 125–136). Emerald Publishing Limited. https://doi.org/10.1108/S2754-586520230000002007

Mol, A., Veenstra, E., Hout, M., & de Groot, P. (2021). *LUC concept: A game-changer for low-enthalpy geothermal developments* [online]. Available at: https://dgbes.com/images/PDF/Mol_etal_LUC_Game_Changer_DEW_Jan_2020.pdf [Accessed: 9 Apr, 2024]

Muffler, P., & Cataldi, R. (1978). Methods for regional assessment of geothermal resources. *Geothermics*, *7*(2–4), 53–89. https://doi.org/10.1016/0375-6505(78)90002-0

Muntendam-Bos, A. G., Hoedeman, G., Polychronopoulou, K., Draganov, D., Weemstra, C., Van Der Zee, W., Bakker, R. R., & Roest, H. (2022). An overview of induced seismicity in the Netherlands. *Netherlands Journal of Geosciences*, *101*, e1. https://doi.org/10.1017/njg.2021.14

National Research Council (1996). *Understanding Risk: Informing Decisions in a Democratic Society*. Washington, DC: National Academy Press.

Netherlands Enterprise Agency (2020). *Heating and Cooling Potential Analysis – An assessment of the potential for an efficient heating and cooling supply in the Netherlands* [online]. Available at: https://energy.ec.europa.eu/document/download/e8ae7afa-d099-491f-b4d0-fad697652238_en?filename=nl_ca_2020_en.pdf [Accessed: 15 May, 2024]

Nkinyam, C. M., Ujah, C. O., Asadu, C. O., & Kallon, D. V. V. (2025). Exploring geothermal energy as a sustainable source of energy: A systemic review. *Unconventional Resources*, *6*, 100149. https://doi.org/10.1016/j.uncres.2025.100149

Onencan, A. M., Ou, J., & De Koning, J. I. J. C. (2024). Social acceptance of district heating: Evidence from the Netherlands. *Sustainability Science*, *19*(3), 815–830. https://doi.org/10.1007/s11625-023-01452-8

Ouhajjou, N., Loibl, W., Anjomshoaa, A., Fenz, S., & Tjoa, A. (2014). Ontology-based urban energy planning support building-integrated solar PV. In A. Mahdavi, B. Martens, & R. Scherer (Eds.), *eWork and eBusiness in Architecture, Engineering and Construction* (pp. 543–550). CRC Press. https://doi.org/10.1201/b17396-89

Ouhajjou, N., Loibl, W., Fenz, S., & Tjoa, A. M. (2017). Stakeholder-oriented energy planning support in cities. *Sustainable Cities and Society*, *28*, 482–492. https://doi.org/10.1016/j.scs.2016.08.006

Palomo-Vélez, G., Contzen, N., Perlaviciute, G., & Steg, L. (2023). Trust in institutions and public acceptability of risky energy production: Testing the causal relationships in the context of Groningen earthquakes. *Energy Research & Social Science*, *96*, 102927. https://doi.org/10.1016/j.erss.2022.102927

Pelzer, P., Arciniegas, G., Geertman, S., & De Kroes, J. (2013). Using MapTable® to Learn About Sustainable Urban Development. In S. Geertman, F. Toppen, & J. Stillwell (Eds.), *Planning Support Systems for Sustainable Urban Development* (Vol. 195, pp. 167–186). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-37533-0_10

Pelzer, P., Arciniegas, G., Geertman, S., & Lenferink, S. (2015). Planning Support Systems and Task-Technology Fit: A Comparative Case Study. *Applied Spatial Analysis and Policy*, *8*(2), 155–175. https://doi.org/10.1007/s12061-015-9135-5

Pluymakers, A., Muntendam-Bos, A. G., & Niemeijer, A. (2023). Induced seismicity: A global phenomenon with special relevance to the Dutch subsurface. *Netherlands Journal of Geosciences*, *102*, e2. https://doi.org/10.1017/njg.2023.2

Pope, C. (2000). Qualitative research in health care: Analysing qualitative data. *BMJ*, *320*(7227), 114–116. https://doi.org/10.1136/bmj.320.7227.114

Pretorius, C. (2017). Exploring Procedural Decision Support Systems for Wicked Problem Resolution. *South African Computer Journal*, *29*(1). https://doi.org/10.18489/sacj.v29i1.448

Radtke, J., & Renn, O. (2024). Participation in Energy Transitions: A Comparison of Policy Styles. *Energy Research & Social Science*, *118*, 103743. https://doi.org/10.1016/j.erss.2024.103743

Ramos-Escudero, A., Magraner, T., & Gil-García, I. C. (2024). Optimized spatial tool for the implementation of ground source heat pump coupled with photovoltaic panels heating systems in urban areas. *Energy and Buildings*, *323*, 114752. https://doi.org/10.1016/j.enbuild.2024.114752

Raos, S., Hranić, J., Rajšl, I., & Bär, K. (2022). An extended methodology for multi-criteria decision-making process focused on enhanced geothermal systems. *Energy Conversion and Management*, *258*, 115253. https://doi.org/10.1016/j.enconman.2022.115253

Reed, M. S. (2008). Stakeholder participation for environmental management: A literature review. *Biological Conservation*, *141*(10), 2417–2431. https://doi.org/10.1016/j.biocon.2008.07.014

Regan, P. J., & Holtzman, S. (1995). R&D Decision Advisor: An interactive approach to normative decision system model construction. *European Journal of Operational Research*, *84*(1), 116–133. https://doi.org/10.1016/0377-2217(94)00321-3

Renoth, R., Buchner, E., Schmieder, M., Keim, M., Plechaty, M., & Drews, M. (2023). Social acceptance of geothermal technology on a global view: A systematic review. *Energy, Sustainability and Society*, *13*(1), 49. https://doi.org/10.1186/s13705-023-00432-1

Ritchey, T. (2011). *Wicked Problems – Social Messes: Decision Support Modelling with Morphological Analysis*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-19653-9

Rittel, H. W. J., & Webber, M. M. (1973). Dilemmas in a general theory of planning. *Policy Sciences*, *4*(2), 155–169. https://doi.org/10.1007/BF01405730

Romanov, D., & Leiss, B. (2022). Geothermal energy at different depths for district heating and cooling of existing and future building stock. *Renewable and Sustainable Energy Reviews*, *167*, 112727. https://doi.org/10.1016/j.rser.2022.112727

Roovers, G., & Duijn, M. (2021). Interventions in the Subsoil in the Netherlands
—Tension between Central Planning and Local Acceptance. *Open Journal of Political Science*, *11*(01), 1–11. https://doi.org/10.4236/ojps.2021.111001

Roth, M., & Tilk, C. (2016). *Here Comes the Sun: A Prototypical GIS-based 4-dimensional Rooftop Solar Potential Analysis to Support the Energy Turnaround*. Wichmann Verlag. https://doi.org/10.14627/537612016

Ruef, F., Stauffacher, M., & Ejderyan, O. (2020). Blind spots of participation: How differently do geothermal energy managers and residents understand participation? *Energy Reports*, *6*, 1950–1962. https://doi.org/10.1016/j.egyr.2020.07.003

Rybach, L. (2022). Shallow Systems—Geothermal Heat Pumps. In *Comprehensive Renewable Energy* (pp. 197–219). Elsevier. https://doi.org/10.1016/B978-0-12-819727-1.00105-9

Rylatt, M., Gadsden, S., & Lomas, K. (2003). Using GIS to Estimate the Replacement Potential of Solar Energy for Urban Dwellings. *Environment and Planning B: Planning and Design*, *30*(1), 51–68. https://doi.org/10.1068/b12931

Schlagwein, T. (2025). *Stadsverwarming* [online]. Available at https://www.overstappen.nl/energie/stadsverwarming/ [Accessed: 21 May, 2025]

Sgouridis, S., & Csala, D. (2014). A Framework for Defining Sustainable Energy Transitions: Principles, Dynamics, and Implications. *Sustainability*, *6*(5), Article 5. https://doi.org/10.3390/su6052601

Shah, M., Prajapati, M., Yadav, K., & Sircar, A. (2024). A comprehensive review of geothermal energy storage: Methods and applications. *Journal of Energy Storage*, *98*, 113019. https://doi.org/10.1016/j.est.2024.113019

Sharifi, M. A., Van Den Toorn, W., Rico, A., & Emmanuel, M. (2002). Application of GIS and multicriteria evaluation in locating sustainable boundary between the tunari National Park and Cochabamba City (Bolivia). *Journal of Multi-Criteria Decision Analysis*, *11*(3), 151–164. https://doi.org/10.1002/mcda.323

Sharma, S., Pettit, C., Bishop, I., Chan, P., & Sheth, F. (2011). An Online Landscape Object Library to Support Interactive Landscape Planning. *Future Internet*, *3*(4), 319–343. https://doi.org/10.3390/fi3040319

Shortall, R., Davidsdottir, B., & Axelsson, G. (2015a). Geothermal energy for sustainable development: A review of sustainability impacts and assessment frameworks. *Renewable and Sustainable Energy Reviews*, *44*, 391–406. https://doi.org/10.1016/j.rser.2014.12.020

Shortall, R., Davidsdottir, B., & Axelsson, G. (2015b). Geothermal energy for sustainable development: A review of sustainability impacts and assessment frameworks. *Renewable and Sustainable Energy Reviews*, *44*, 391–406. https://doi.org/10.1016/j.rser.2014.12.020

Siksnelyte-Butkiene, I., & Štreimikienė, D. (2023). *Sustainable Energy Development: A Multi-Criteria Decision Making Approach* (1st ed.). CRC Press. https://doi.org/10.1201/9781003327196

Simon, H. A. (1976). From substantive to procedural rationality. In T. J. Kastelein, S. K. Kuipers, W. A. Nijenhuis, & G. R. Wagenaar (Eds.), *25 Years of Economic Theory* (pp. 65–86). Springer US. https://doi.org/10.1007/978-1-4613-4367-7_6

Solano-Olivares, K., Santoyo, E., & Santoyo-Castelazo, E. (2024). Integrated sustainability assessment framework for geothermal energy technologies: A literature review and a new proposal of sustainability indicators for Mexico. *Renewable and Sustainable Energy Reviews*, *192*, 114231. https://doi.org/10.1016/j.rser.2023.114231

Sovacool, B. K., Iskandarova, M., & Hall, J. (2023). Industrializing theories: A thematic analysis of conceptual frameworks and typologies for industrial sociotechnical change in a low-carbon future. *Energy Research & Social Science*, *97*, 102954. https://doi.org/10.1016/j.erss.2023.102954

Tesfamichael, B., Montastruc, L., Negny, S., & Yimam, A. (2021). Designing and planning of Ethiopia's biomass-to-biofuel supply chain through integrated strategic-tactical optimization model considering economic dimension. *Computers & Chemical Engineering*, *153*, 107425. https://doi.org/10.1016/j.compchemeng.2021.107425

Tinti, F., Kasmaee, S., Elkarmoty, M., Bonduà, S., & Bortolotti, V. (2018). Suitability Evaluation of Specific Shallow Geothermal Technologies Using a GIS-Based Multi Criteria Decision Analysis Implementing the Analytic Hierarchic Process. *Energies*, *11*(2), 457. https://doi.org/10.3390/en11020457

Tripathy, A., Koeva, M. N., Cardenas Leon, I. L., & Nourian, P. (2024). Planning Support System Development for analysing environmental performance of form-based design decisions: Case Study of Enschede. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XLVIII-4/W11-2024*, 137–144. https://doi.org/10.5194/isprs-archives-XLVIII-4-W11-2024-137-2024

Twente (2019). *Enschede's district heating most sustainable in the Netherlands* [online]. Available at: https://twente.com/en/global-goals/7-affordable-and-clean-energy/enschedes-district-heating-most-sustainable-in-the-netherlands [Accessed: 15 May, 2024]

Twente (2020). *Strong ambition RES-Twente: generate half of the current electricity consumption sustainably by 2030* [online]. Available at: https://twente.com/en/global-goals/7-affordable-and-clean-energy/forse-ambitie-res-twente-helft-huidig-elektriciteitsverbruik-in-2030-duurzaam-opgewekt [Accessed: 15 May, 2024]

Upham, P., Oltra, C., & Boso, À. (2015). Towards a cross-paradigmatic framework of the social acceptance of energy systems. *Energy Research & Social Science*, *8*, 100–112. https://doi.org/10.1016/j.erss.2015.05.003

Van Daalen, T. M., Fokker, P. A., Bogaard, P. J. F., & Van Der Meulen, M. J. (2020). Why we urgently need a public subsidence information service in the Netherlands. *Proceedings of the International Association of Hydrological Sciences*, *382*, 821–823. https://doi.org/10.5194/piahs-382-821-2020

Vargas-Payera, S., Martínez-Reyes, A., & Ejderyan, O. (2020). Factors and dynamics of the social perception of geothermal energy: Case study of the Tolhuaca exploration project in Chile. *Geothermics*, *88*, 101907. https://doi.org/10.1016/j.geothermics.2020.101907

Veenstra, E., De Groot, P., De Lange, J., Mol, A., & Van Den Heuvel, P. (2020). Geothermal potential of the Tubbergen Formation in the Twente region of east Netherlands. *Interpretation*, *8*(4), SQ93–SQ103. https://doi.org/10.1190/INT-2019-0277.1

Visser, M., Van Eck, N. J., & Waltman, L. (2021). Large-scale comparison of bibliographic data sources: Scopus, Web of Science, Dimensions, Crossref, and Microsoft Academic. *Quantitative Science Studies*, *2*(1), 20–41. https://doi.org/10.1162/qss_a_00112

Vogt, A., Flacke, J., Pfeffer, K., Hoefsloot, F. I., Strugar Kolesnik, J., & Schnell, J. (2023). Development of an inclusive Mapping Application in a Co-Design Process. *AGILE: GIScience Series*, *4*, 1–8. https://doi.org/10.5194/agile-giss-4-48-2023

Vom Brocke, J., Winter, R., University of St. Gallen, Switzerland, Hevner, A., University of South Florida, USA, Maedche, A., & Karlsruhe Institute of Technology, Germany. (2020). Special Issue Editorial –Accumulation and Evolution of Design Knowledge in Design Science Research: A Journey Through Time and Space. *Journal of the Association for Information Systems*, *21*(3), 520–544. https://doi.org/10.17705/1jais.00611

Vonk, G., & Ligtenberg, A. (2010). Socio-technical PSS development to improve functionality and usability—Sketch planning using a Maptable. *Landscape and Urban Planning*, *94*(3–4), 166–174. https://doi.org/10.1016/j.landurbplan.2009.10.001

Wassink, J. (2018). *How sustainable is electric heating?* TU Delft. https://www.tudelft.nl/en/delft-outlook/articles/how-sustainable-is-electric-heating

World Energy Council (2019). *World Energy Trilemma Index 2019* [online]. Available at: https://www.worldenergy.org/publications/entry/world-energy-trilemma-index-2019 [Accessed: 10 May, 2024]

World Resources Institute (WRI) (2022). *Climate Watch Historical Country Greenhouse Gas Emissions Data*. Washington, DC [online]. Available at: https://www.climatewatchdata.org/ghg-emissions [Accessed: 5 June, 2024]

Wüstenhagen, R., Wolsink, M., & Bürer, M. J. (2007). Social acceptance of renewable energy innovation: An introduction to the concept. *Energy Policy*, *35*(5), 2683–2691. https://doi.org/10.1016/j.enpol.2006.12.001

Yeo, I.-A., & Yee, J.-J. (2014). A proposal for a site location planning model of environmentally friendly urban energy supply plants using an environment and energy geographical information system (E-GIS) database (DB) and an artificial neural network (ANN). *Applied Energy*, *119*, 99–117. https://doi.org/10.1016/j.apenergy.2013.12.060

Yeo, I.-A., & Yee, J.-J. (2016). Development of an automated modeler of environment and energy geographic information (E-GIS) for ecofriendly city planning. *Automation in Construction*, *71*, 398–413. https://doi.org/10.1016/j.autcon.2016.08.009

Yeo, I.-A., Yoon, S.-H., & Yee, J.-J. (2013). Development of an Environment and energy Geographical Information System (E-GIS) construction model to support environmentally friendly urban planning. *Applied Energy*, *104*, 723–739. https://doi.org/10.1016/j.apenergy.2012.11.053

APPENDICES

During the preparation of this work, the author used ChatGPT in order to (1) acquire background knowledge, such as that related to geothermal energy technologies, (2) explore methodological concepts of qualitative research, and (3) review written content, specifically the methodology of Stakeholder Analysis, for writing a summary. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the work. The author also acknowledges the use of Grammarly in helping to review the English writing, and the feedback generated by this tool was critically reviewed by the author before the writing was revised.

Appendix 1 – Shallow Geothermal

The exploitation of geothermal sources at a commercial scale began in the twentieth century (Bleicher & Gross, 2015), and shallow geothermal is one of the two technological families that have been developed for energy extraction. Shallow geothermal refers to technologies that harness the thermal stability of the shallow underground for heating as well as cooling purposes (Manzella et al., 2019). Shallow geothermal energy is usually stored up to a few hundred meters deep beneath the subsurface layers (Rybach, 2022; Shah et al., 2024). However, geothermal energy with low temperatures ranging from 30-40 °C may still exist at greater depths (up to 1,000 metres) in the Netherlands (Geothermie Nederland, 2018). Although induced seismic risks are commonly less major for geothermal resources extracted through shallow systems (Bleicher & Gross, 2015), environmental concerns about ground and groundwater contamination persist in shallow geothermal (Ioannou et al., 2023). Exhibiting the advantage of maintaining a constant temperature all year round (Bleicher & Gross, 2015), low-temperature geothermal energy is capable of providing a robust, localised and renewable energy source for urban areas (Acheilas et al., 2020; Bayer et al., 2019), with space heating and cooling remain the major geothermal applications in the Netherlands (IEA, 2024).

Shallow geothermal resources are ubiquitous compared to deep and high-enthalpy resources that are often scarce and inaccessible. However, the low temperatures are not always sufficient for direct usage. This requires a geothermal heat exchanger or ground source heat pump (GSHP) to increase the temperature to a desired level for effective geothermal resource exploitation (Banks, 2012; Geothermie Nederland, 2018). The GSHP systems mostly exploit groundwater or ground-coupled temperatures at a shallow depth of 10–200 m (Manzella et al., 2019). Such ground source heat reserves are more prevalent than conventional geothermal resources globally and remain one of the fastest-growing applications of renewable energy and geothermal technology (Banks, 2012; Ioannou et al., 2023). A buffer technology is also used for heat and cold storage (HCS) in the ground of up to 500 m during periods of high demand for heat (in the winter) or cold (in the summer) (Bayer et al., 2019; Geothermie Nederland, 2018). Therefore, shallow geothermal energy could offer localised energy access up to neighbourhood levels and create energy communities (Acheilas et al., 2020).

Appendix 2 – Stakeholder Analysis

The super wicked problem of energy transition is enclosed with multidisciplinary and interrelated subsystems that require a transformation of the entire energy sector and market (Jakimowicz, 2022). In response to such complexity, energy policy and planning are increasingly emphasising public participation as one of the most promising approaches for sustainable energy transition (Metze et al., 2023; Radtke & Renn, 2024). Public participation may be defined as "*the involvement of individuals and groups that are positively or negatively affected by, or that are interested in, a proposed project, program, plan or policy that is subject to a decision-making process*" (André, 2006, p. 1). The involvement of participants at stake, or stakeholders, in energy governance shows promising strategies for fulfilling the democratic sustainability transition. Therefore, a stakeholder analysis is critical in providing data to help determine who is or should be involved in the planning process, revealing any concerns in the relationships among people that should be considered as the process moves forward. Moreover, the identification of stakeholders can better address the social impacts and relevance of designing a planning support system tool for this research.

Stakeholder Identification and Classification

Stakeholders include "*all actors or groups who affect and/or are affected by the policies, decisions and actions of a project*" (Groenendijk, 2003, p. 57). Therefore, the identification and selection of stakeholders takes reference to the direct or indirect affectees or beneficiaries of the decision-making process of geothermal energy development. The selection criteria are taken into consideration, and the objective of the stakeholder analysis focuses on people's participation, in which the public is a stakeholder group often underpowered in renewable energy planning. Stakeholder interests were identified based on desk research and further expanded during the following stakeholder engagement phase, where more information was acquired. Within a broader theoretical approach, stakeholders were classified based on the relationships in planning processes and the results of geothermal energy development. Stakeholders at the heart of the interest and the intended beneficiaries were classified as primary or secondary, whereas those who were not directly involved but are interested in the outcome of the development project are considered external (Freeman, 1984; Groenendijk, 2003). A stakeholder interest table was then used to classify the relative priorities of each stakeholder to achieve project objectives, facilitating the development of engagement and communication strategies. Low values were assigned to stakeholders with high priority for achieving the project objectives. Table 9 provides an overview of identified stakeholders and their classes and interests in the potential geothermal development project in Enschede.

Table 9. Stakeholder Interest Table. Primary and secondary stakeholders are beneficiaries and those interested in the geothermal development project in Enschede, while external stakeholders are those who are not directly involved but are interested in the outcome of the project. Project impacts on stakeholders' interests are classified into positive (+), negative (-), uncertain (+/-) and unknown (?). Relative priorities show how the project should prioritise meeting the interests of each stakeholder in relation to the other stakeholders (e.g., lower values are associated with higher priorities) to achieve project objectives for facilitating the development of engagement and communication strategies.

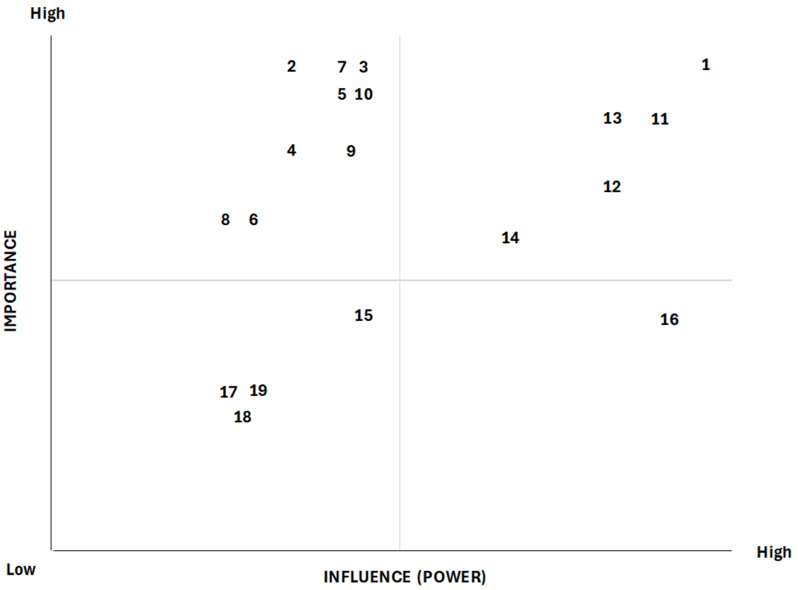
Stakeholders		Main Interest	Potential Project Impact	Relative Priorities Of Interests
<u>Primary Stakeholders</u>				
1	**Municipality of Enschede**	Submit the Heat Transition Vision for achieving natural gas-free heating in 2050 with transition paths outlined per neighbourhood	+	=1
		Reduce the cost of the heat transition with the cheapest alternatives to natural gas	+/-	
		Management role in the heat transition plans and timeline at regional, municipal and neighbourhood levels	+	
2	**Residents (of neighbourhoods within the Heat Transition Vision Enschede)**	Cost savings on utility bill	?	=1
		Freedom of choice of heat supplier	-	
		Environmental benefits and costs of geothermal development	+/-	
		Induced seismic risk with geothermal exploration	-	
3	**Housing Corporations (Domijn, De Woonplaats, SJHT, Vechtdal Wonen, etc)**	Own the majority of buildings and large flats to be connected to the heating network	?	=1
<u>Secondary Stakeholders</u>				
4	**General Public (not from neighbourhoods of the Heat Transition Vision Enschede)**	Benefits and costs of the pilot heat transition project	?	=2
5	**Energy Cooperatives**	A group of citizens who work on sustainable energy projects, a district heating network or energy-saving within neighbourhoods	+/-	=2

	Stakeholders	Main Interest	Potential Project Impact	Relative Priorities Of Interests
6	**Ennatuurlijk Aardwarmte**	Private heating company that operate the district heat network in Enschede. Manage the heat network infrastructure and distribute heating to households and businesses. The largest geothermal energy producer in the Netherlands.	+	=2
7	**Cogas**	Publicly-owned company as part of the Regional Heating Network Twente that provides consumers with affordable and sustainable heat	+	=2
		Develop plans for heating networks to facilitate the use of heat from sustainable sources such as biomass, biogas, geothermal heat and residual heat.	+	
8	**dGB Earth Sciences**	Provide seismic interpretation solutions	+	=2
		Advocate Low Unit Cost (LUC) installations as a cost-effective geothermal solution	+	
9	**Twence**	Publicly-owned company as part of the Regional Heating Network Twente provides consumers with affordable and sustainable heat	+	=2
		Provide sustainable heating from residual waste and biomass	-	
10	**Enschede Energie**	Local energy cooperative with a mission to generate sustainable energy in Enschede. Part of the consultation groups for the Enschede Heat Transition Vision	?	=3
11	**Provincial of Overijssel**	Develop energy vision for the province of Overijssel. The Energievisie Overijssel 2050 includes geothermal energy as one of the potential heat supply sources.	+	=3
		Geothermal Action Plan for Heat Development Path. Possible small-scale geothermal energy for supplying the local heating network in Twente and West Overijssel	+	
		Financial feasibility of geothermal energy and heat	-	
12	**Geothermie Groep Nederland (GGN)**	Advocate a regulatory framework for mining and extraction of geothermal resources	+	=3

Stakeholders		Main Interest	Potential Project Impact	Relative Priorities Of Interests
External				
13	**Waterschap**	Water pollution risks and mitigations associated with geothermal development	-	=4
14	**Netherlands Organisation for Applied Scientific Research (TNO)**	Independent statutory research organisation helps businesses and governments in decisions about land utilization, subsurface usage and groundwater stewardship	+	=4
		Innovation for underground technological applications for the energy transition	+	
15	**Rijksoverheid**	Provide subsidies for building owners to become natural gas-free; New financing instruments to be set up to make the pre-investment more feasible for the building owner.	+	=5
16	**Central Government Ministries (KGG, I&W, EZ, etc)**	Coordinate on the planning and environmental policy for the optimal use of the subsurface at the lowest possible social costs.	+	=5
17	**Energie Beheer Nederland (EBN)**	Invest in Dutch energy related projects	?	=5
		Advise the Ministry of Climate Policy and Green Growth on geothermal energy	+	
		Conduct seismic study into geothermal heat potential in the Netherlands (together with TNO)	+	
18	**Enexis Groep**	Develop and monitor the capacity of the electricity grid as a network operator. Enpuls Warmte Infra focuses on sustainable heating infrastructure for provinces and municipalities	?	=5
19	**Netherlands Enterprise Agency (RVO)**	Provide organisations with subsidies for sustainable heating, e.g., the Warmtenet investeringssubsidie (WIS) subsidy	+	=5

Stakeholder Attribute Assessment

Attributes of different stakeholders are assessed to understand the interests, influence (or power), and potential impact of stakeholder classes on decision-making processes. With the relative interest of different stakeholders in the geothermal development projects being identified (see Table 9), the attributes of influence and importance are selected and combined to derive a stakeholder classification matrix. Influence is the power of a stakeholder in making decisions for the project, while importance indicates the stakeholders' needs and interests to be prioritised for the project (Groenendijk, 2003). In addition to identifying assumptions and risks due to conflicting interests, the classification matrix helps to locate key stakeholders with high influence and/or importance over the project, thereby informing the project negotiations and design for multi-actor collaborations. The stakeholder matrix diagram, combining the information from the interest table, can be seen in Figure 21.



ID	Stakeholders
1	Municipality of Enschede
2	Residents
3	Housing Corporations
4	General Public
5	Energy Cooperatives
6	Ennatuurlijk Aardwarmte
7	Cogas
8	dGB Earth Sciences
9	Twence
10	Enschede Energie
11	Provincial of Overijssel
12	Geothermie Groep Nederland (GGN)
13	Waterschap
14	TNO
15	Rijksoverheid
16	Central Government Ministries
17	Energie Beheer Nederland (EBN)
18	Enexis Groep
19	Netherlands Enterprise Agency (RVO)

Figure 21. Stakeholder Classification Matrix for geothermal energy development in Enschede. The classification matrix identifies the influence and importance of each stakeholder in relation to other stakeholders. In addition to identifying assumptions and risks due to conflicting interests, the matrix helps to locate key stakeholders with high influence and/or importance over the project for informing the project negotiations and design for multi-actor collaborations. ID corresponds to the Stakeholder Interest Table in Table 9. Sourced from Author.

Geothermal Megaproject Management

Megaprojects have been used as the preferred delivery model for goods and services across many businesses and sectors, including energy and renewable infrastructure (Flyvbjerg, 2014). "Mega" in a scientific and technical unit of measurement means one million, and a megaproject would be, in economic terms, a million-dollar (or euro, pound, etc.) project. This applies to geothermal infrastructure, with LUC installations costing around €3 million or greater for conventional systems. With the decline in oil and gas demand encouraging the clean energy economy, the rapid acceleration and implementation of technology drives geothermal development at scale (European Commission: Directorate General for Research and Innovation, 2024; IEA, 2024). Therefore, systematic and valid knowledge about the causes or sublimes[8] of stakeholders for geothermal development are important to inform policy, practice, and public debate. Stakeholders identified in the previous step were analysed using the four sublimes of megaproject management (Table 10). External stakeholders identified in Table 9 are not at the core of planning and decision-making for LUC development, thus being excluded from the analysis.

Table 10. The four causes or "sublimes" that drive megaproject development. Sourced from Flyvbjerg (2014).

Causes of Driving Megaproject Development	Characteristic
Technological	The excitement engineers and technologists get in pushing the envelope for what is possible in "longest-tallest-fastest" types of projects.
Political	The rapture politicians get from building monuments for themselves and for their causes, and from the visibility this generates with the public and media.
Economic	The delight business people and trade unions get from making lots of money and jobs off megaprojects, including money made for contractors, workers in construction and transportation, consultants, bankers, investors, landowners, lawyers, and developers.
Aesthetic	The pleasure designers and people who love good design get from building and using something very large that is also iconic and beautiful.

The motives that drive stakeholders to participate in the LUC geothermal development project were identified within the four sublimes of megaproject development. With LUC installation as a new concept in the Netherlands, the excitement of establishing a LUC geothermal plant brought about the advocates and operators of LUC installations (e.g., GGN and dGB Earth Sciences) to be associated with the technological sublime (Table 11). The establishment of an innovative geothermal plant in the Eastern part of the Netherlands, where conventional geothermal harvesting is considered less possible, could bring attention to the public and media. This resulted in GGN, the provincial and municipal governments and the associated publicly owned heat infrastructure organisations (e.g., Cogas and Twence) gaining visibility and being ascribed to the political sublime. With the potential to become a sizable and profitable business, LUC geothermal could financially benefit organisations and corporations involved in heat production and

[8] Flyvbjerg (2014) identifies four causes or "sublimes" – political, technological, economic, and aesthetic – that seduce decision makers to undertake megaprojects. These "sublimes" are used to explain the increased size and frequency of megaprojects, understanding what drives the megaproject boom and why megaprojects are attractive to decision makers.

transportation. In addition, investors or heat customers could gain financial savings from long-term sustainable geothermal energy over the volatility of the gas price, thus also being subjected to the economic sublime. LUC installations are designed to be constructed locally and meet concentrated heat demand, suggesting that the urban residents and the public could be attributed to the aesthetic sublime.

Table 11. Stakeholders identified and their associated sublime(s) for LUC geothermal project development.

		Type of Sublime			
	Stakeholder	*Technological*	*Political*	*Economic*	*Aesthetic*
1	Municipality of Enschede		X	X	X
2	Residents			X	X
3	Housing Corporations			X	X
4	General Public			X	X
5	Energy Cooperatives			X	
6	Ennatuurlijk Aardwarmte			X	
7	Cogas		X	X	
8	dGB Earth Sciences	X		X	
9	Twence		X	X	
10	Enschede Energie			X	
11	Provincial of Overijssel		X		
12	Geothermie Groep Nederland (GGN)	X	X	X	

Appendix 3 – Arnstein's Ladder of Citizen Participation

Arnstein's (1969) Ladder Citizen Participation features eight "rungs" that distinguish low levels (like informing) and high levels (like co-creation) of public involvement in democratic decision-making. The ladder describes three general forms of citizen power in the participation processes, i.e., Nonparticipation Degrees of Tokenism, and Degrees of Citizen Power, and how the importance of the public in influencing these processes.

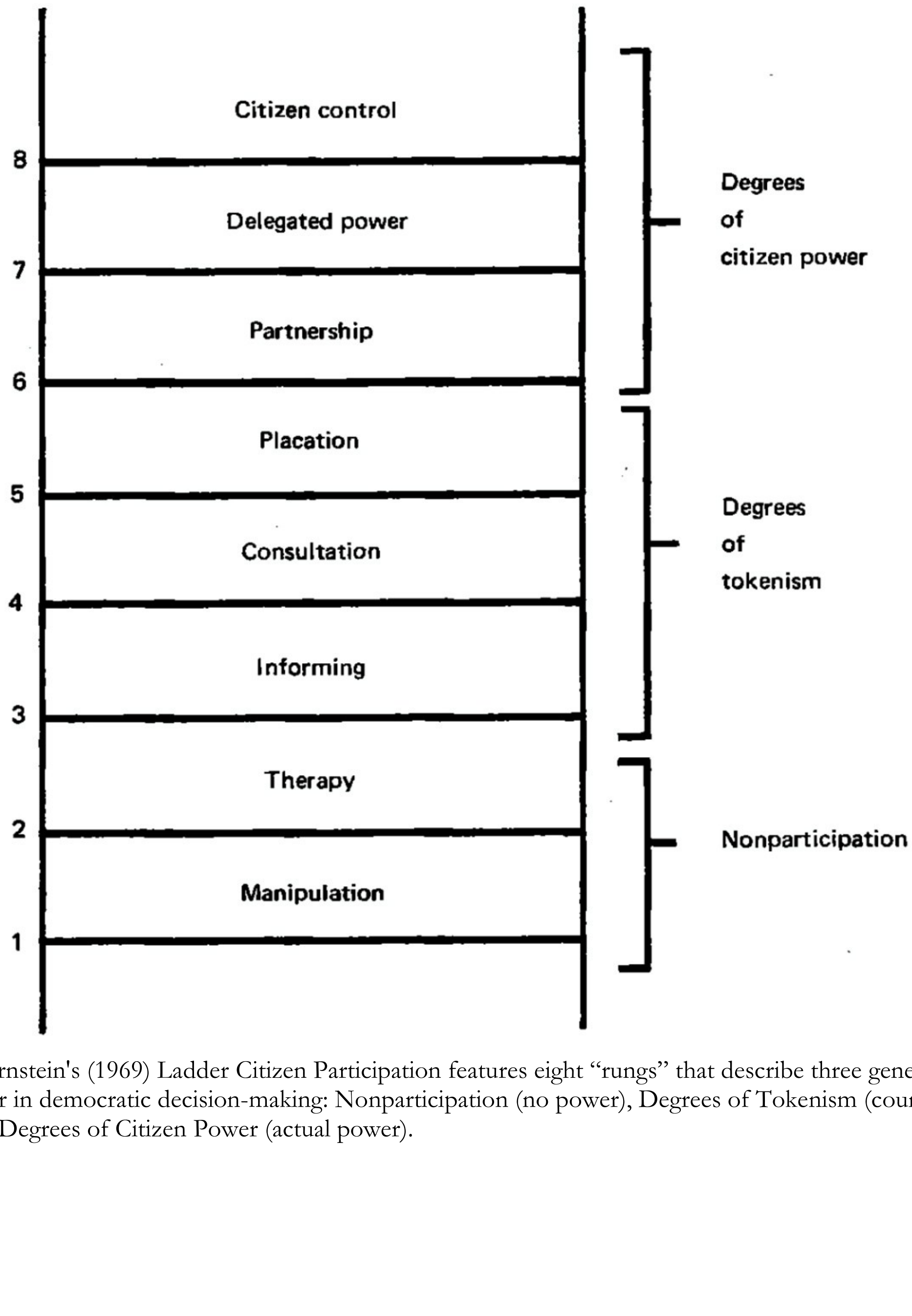


Figure 22. Arnstein's (1969) Ladder Citizen Participation features eight "rungs" that describe three general forms of citizen power in democratic decision-making: Nonparticipation (no power), Degrees of Tokenism (counterfeit power), and Degrees of Citizen Power (actual power).

Appendix 4 – Planning Support System Attributes for Renewable Energy Planning

The design criteria and attributes (i.e., characteristics, planning support system tool, design process) of the reviewed PSS applications for renewable energy planning are summarised in this section.

Table 12. Studies included in the literature review. The general characteristics of selected literature on various PSS applications for renewable energy planning.

ID	Literature	Renewable Energy Type	Case Study	Study Scale	Field of Application
1	Gadsden et al. (2003)	Solar	Leicester, UK	City	Solar energy planning (SEP) system for informing city planners on deploying solar energy technology
2	Rylatt et al. (2003)	Solar	Leicester, UK	City	Solar energy planning (SEP) system for predicting the solar energy potential and energy consumption of dwellings
3	Ayoub et al. (2006)	Bioenergy	Japan	National	Biomass-based power generation planning for accounting environmental and economical impacts of establishing the biomass systems
4	Ligtenberg et al. (2011)	Solar, Wind	Hypothetical area (in the Netherlands)	City	Social learning (energy balance of different layouts and compositions of housing and mixed use areas)
5	Sharma et al. (2011)	Wind	Grampian region, Southern Victoria, Australia	Region	Social learning (communicate and support the exchange of knowledge and farm planning scenarios)
6	Yeo et al. (2013)	Solar, Wind	Gwangmyeong-si, Republic of Korea	City	Renewable energy planning with integration of urban planning information and urban microclimate and energy information for supporting environmentally friendly urban planning
7	Pelzer et al. (2013)	Wind	Rijnenburg in Utrecht, Netherlands	Neighbourhood	Social learning (environmental issues in the windmill spatial planning; integrating area-based environmental values into spatial planning)

8	Pelzer et al. (2015)	Wind	Arnhem, Netherlands	City	Social learning (exploration tasks on energy consumption and energy plans; initiating a stakeholder dialogue)
9	Kobayashi & Ikaruga (2015)	Solar	Virtual Space	City	Renewable energy planning and consensus-building using cooperative housing development methods.
10	Flacke & De Boer (2017)	Solar, Wind	Enschede, Netherlands	City	Social learning (community engagement and awareness building on renewable-energy options)
11	Ouhajjou et al. (2017)	Solar	Vienna, Austria	City	Energy planning based on semantic web technologies to provide information for developing urban energy strategies
12	Hewitt et al. (2020)	Solar	Region of Navarre, Spain	National	Energy transition using spatial modelling for land use simulations to reveal how land use may change at future dates, in response to the input variables used to determine the transition rules
13	Marrone et al. (2023)	Solar	Five districts (Testaccio, Balduina, Tor Bella Monaca, Prima Porta, Piazza Mazzini) in Rome, Italy	Neighbourhood	Energy transition planning by guiding choices between effective and interdependent solutions for decarbonisation through renewable energy production
14	Tripathy et al. (2024)	Solar	Twekkelerveld neighbourhood of Enschede, Netherlands	Neighbourhood	Energy transition analysing the modifications in built urban form affecting environmental performance at the scale of the neighbourhood

Table 13. Information collaboration systems and PSS tools for renewable energy planning.

ID	Information Collaboration System	PSS Tool	Purpose	Hardware Setup	Software Setup	Main GIS Functions	Data Layers
1	Desktop computer	BREDEM-8 model	Predicting the baseline energy consumption of buildings to determine the potential of deploying the key solar energy technologies of passive solar design, solar water heating and photovoltaic (PV) systems; Physically-based modelling of the energy use of the UK housing stock	Desktop computer	-	Visualisation (2D)	Baseline energy consumption of buildings; Dwellings (type, age, tenure, etc); Digital urban map (heated ground floor area, total facade area, ratio of window area to wall area and the end area of the property)
2	Desktop computer	BREDEM-8 model Customised map-data derivation toolset	Deriving data useful for energy demand models directly from digital maps and aerial photographs	Desktop computer	-	Drawing, Feature selection	Dwellings (age, number of storeys); Plan built-form, Historical local street directories
3	Desktop computer	-	Visualising data attributes for viewing the city names and the potential power plant locations for forestry residue conversion	Desktop computer	-	Visualisation (2D)	Administrative boundary for cities

4	Interactive surface	MapTable	Collaborative spatial planning to find the optimal energy and CO2 balance of an area; Exploring scenarios of energy neutral housing areas with solar panels and windmills	Maptable, client-server architecture	SimLandScape, Esri ArcObjects, various libraries	Visualisation (2D), Sketching, Indicator Models (IMs) calculations	Residential building types (apartment building, terrace house, semi-detached house, detached house, farmhouse, country estate and a mansion) and energy profile
5	Interactive surface	MapTable	Collaborative planning to demarcate the location of wind turbines for whole farm planning; Visualising landscape objects in 3D virtual environments to communicate and understand landscape form, function and processes.	Touch table (NEC–LCD 5220)	ArcGIS, SIEVE (for 3D visualisation), object library in Oracle	Visualisation (2D and 3D), Drawing, 3D scenarios	Digital wind turbines objects; DEM data; Additional data (wind speed, altitude and consideration of environmental and aesthetic impacts)
6	Desktop computer	Energy Integrated Planning Support System (EnerISS) Modeler	Modelling urban space and generating a GIS mesh DB for the compact prediction of the urban energy demand	Desktop computer	-	Visualisation (2D and 3D)	DTM and DEM; Land registration; Land cover; Administrative boundary
7	Interactive surface	MapTable	Collaborative planning of windmills around the neighbourhood; Improve communication among planning actors	Mapsup MapTable, stand alone system	CommunityViz Scenario 360	Visualisation (2D), Drawing, SPL (Sustainability Profile of the Location) indicator calculation	Land-uses and sustainable functions (i.e., windmills)

8	Interactive surface	MapTable	Facilitate communication among stakeholders during different planning stages; Improve communication among stakeholders during different planning stages	Mapsup MapTable, stand alone system	CommunityViz Scenario 360	Visualisation (2D), Drawing, Indicator calculation	Energy consumption patterns, per postal code
9	Desktop computer	3D modelling	Understanding the virtual space for the construction of a residential area using renewable energy technology, such as solar panel service	Desktop computer	-	Visualisation (3D)	-
10	Interactive surface	MapTable	Collaborative allocating renewable energy projects in a city using a COLLAGE model	Maptable plus extra screen, stand alone system	CommunityViz Scenario 360	Visualisation (2D), Sketching, Indicator calculations	-
11	Desktop computer	Computation models	Computation modelling for generating data that supports stakeholder-oriented decisions made for the energy planning process	Desktop computer	-	Querying	Building footprint, Weather
12	Desktop computer	APoLUS model (cellular automata)	Simulating future land use under various scenarios of expansion of renewables (e.g., solar); Modelling actor dynamics	Desktop computer	-	Land use classification, Zoning for spatial planning, Scenario analysis	Digital land use map (urban, agricultural, forest, solar energy etc)

13	Desktop computer	Renewable Energy Communities (RECs) model	Modelling of the most effective renewable energy intervention for decarbonisation; Exploring electrification scenarios with renewable energy sources; Assessing the potential spaces and surfaces to accommodate distributed energy generation systems in relation to consumption	Desktop computer	-	Scenario analysis	Microclimatic conditions; In-situ environmental measurements; Irradiation
14	Desktop computer	Graphic Modeler	Determining approximate solar energy potential of rooftops with simplified workflows and open-source methodology	Desktop computer	-	Visualisation (2D and 3D), Scenario analysis	DSM and DEM (from LIDAR data); Building footprint (roof size, building orientation and roof slope); 3D building models; Weather

Table 14. Participatory process on the PSS design and planning activity.

ID	Stakeholder Involvement in PSS Design	Goal of Planning Activity	Stakeholders/Participants in Planning
1	No	Planning scenarios (by filtering and targeting viable dwellings for the installation of solar collectors; analysing proposed estate layouts to meet specific stringent energy consumption targets)	-
2	No	-	-
3	Decision information by planners at the national level and the regional executers and designers	-	-
4	Highly interactive development cycles, consisting of various development meetings; Involving software developers and spatial planners (and designers)	Explore energy reducing options and scenarios; Exchange ideas about the current and future spatial situation; Sketch potential interventions	Experts in the field of spatial planning and sustainable energy (both practitioners and academics)
5	Workshops to take feedback on incorporating additional functionality; A questionnaire to elicit feedback on the potential real world application of the geo-visualisation tools	Explore what if? Scenarios; Design and evaluate land management options and future collaboratively	End users (farmers, agricultural extension officers, scientists, information and technology experts, biodiversity experts, land and fire response teams, private consultants, urban and regional planners, and policy-makers.); Industries
6	No	-	-
7	No	Modify existing land-use functions; Include sustainability aspects into the urban development plan for the vision "Living in the Landscape"	Planning actors (environmental analyst and urban designers); Activities were facilitated by a GIS specialist

8	Semi-structured interviews were conducted with stakeholders of the project; Followed by questionnaires	PSS to the Arnhem case concerned primarily investigative tasks; Visualize and discuss spatial distribution patterns of energy consumption to explore its relationship to current land use; Monitor energy consumption over time based on the construction year of a building; Highlight and discuss areas of excessive energy consumption to explore its relationship to current land use.	Stakeholders of the project from the municipality of Arnhem, namely the city's project leader and the city's GIS office
9	A questionnaire survey among local citizens of Simonoseki City in the Yamaguchi Prefecture, Japan, on smart city planning, about awareness of a smart city, the interest in solar power service, the interest in electrical control service, the initial investable value of an energy conservation technology	-	-
10	Discussions of the model with the municipality	Discussing locations of renewable energy projects	Citizens; Councils (policy-makers)
11	Questions received from stakeholders (Building owners, City administration, Grid operator) during scoping phase; Competency questions about potential acceptance or rejection of integrating solar photovoltaics in buildings or refurbishing buildings	-	-
12	Semi-structured interview (according to sociogram); Two workshops (use timeline technique for actor interaction/dynamics; determine model parameters)	Produce future land use maps in the Navarre region for each of three scenarios of expansion of RE; Identifying impacts of RE on future land uses	Key actors in the region (e.g. cooperatives, environmental groups, policy-makers, and planners)
13	No	-	-
14	No	-	-

Appendix 5 – Ethical Considerations for Stakeholder Interview

This research was conducted within the geosciences domain, with the data collected through the stakeholder engagement activity, i.e., an interview using a questionnaire. Therefore, potential ethical issues of this research were identified using the ethics questionnaire available on the University of Twente Ethics Review web application, along with submitting a consent form, a project introduction document and the questionnaire on 28th February 2025. The UT ITC Geo Ethics Committee performed the ethics assessment, and the research received ethical approval on 10th March 2025 from the committee. Guidelines and recommendations provided by the committee were followed during the research, e.g., geospatial dataset granularity, anonymised data and encrypted files for digital sharing. No personal or any information leading to the identification of stakeholders is included in this published document. Any information collected during the research will be destroyed by the end of this research.