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Article

A Decision Support Tool for Implementing District Heating in Existing Cities, Focusing on Using a Geothermal Source

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Abstract: In the context of climate change mitigation strategies in urban environments and reducing reliance on carbon-based energy sources, the Netherlands is gradually taking steps towards modification of its thermal energy system. Geothermal energy, widely used in agriculture, has recently emerged as a local, clean, and sustainable energy source able to fulfil the residential demand for space heating and has received growing attention in district energy planning. However, failed attempts in the past and the lack of experience with direct application of this technology in district heating systems has increased uncertainty with respect to the technical, spatial, and socioeconomic barriers to be overcome between supply and demand. This calls for the application of decision support tools in order to remove these barriers and facilitate more appropriate decision making towards the implementation of smart thermal energy grids in local energy communities. This research explores how the network of actors, those who see opportunities in direct use of geothermal energy in the Netherlands, can work on the transformation of the current centralised carbon-based energy systems towards local sustainable energy communities.

Keywords: district heating; geothermal source; decision support tool; GIS; urban energy analysis; local energy community

1. Introduction

The Dutch Ministry of Economic Affairs and Climate Policy has a long-term goal to make the energy system carbon neutral by 2050. Currently, about 15% of the energy consumed in the Netherlands is used in the building stock for space heating (SH) and domestic hot water (DHW) [1]. However, the government of the Netherlands has recently decided to halt production of natural gas at the Groningen field as part of the efforts to reduce the risk posed by earthquakes and prevent depletion of this natural resource [2]. The Netherlands is thus becoming increasingly reliant on imports of natural gas. In addition, the emissions related to the combustion of natural gas contribute to climate change. The substantial reduction of the use of natural gas is therefore an urgent part of the route to the policy of a sustainable energy supply [3]. Local governments are constrained to make strategic decisions for the planning of heat supply, encouraging the energy transition towards a low-carbon future. An increasing number of stakeholders and policy makers have become aware of the district heating potential and possibilities it offers with regard to energy efficiency and climate mitigation objectives. To meet these targets, it has become necessary to assess the local demand for heat, and the potential for using different renewable energy sources. One should determine which renewable energy type, or mix, would be best suited in an urban area, as well as the impact these choices would have on existing energy systems.

Among renewable energy sources for DH, some studies have focused on the potential for utilising geothermal energy. Fox et al. [4] suggest how direct use of deep high-temperature geothermal energy (>100 °C) could provide a large fraction of heat that is currently mostly supplied by high grade fossil fuels. Geothermal energy is a local, untapped renewable energy resource that could offer decentralized energy access up to the neighbourhood level and create energy communities [5]. It has a small land area footprint and generates little to no CO_2 emissions. There is a need to assess the potential of this local energy source for urban districts and this requires a good understanding of the processes and techniques as well as identifying stakeholder groups within the existing urban energy landscape.

Direct use of medium enthalpy geothermal sources in traditional DH systems has received much less focus than biomass, solar thermal energy, and waste heat sources from industries. This could be explained by the fact that research for deep geothermal energy as a source for district heating systems is naturally limited to colder climates where geothermal reservoirs most often have higher temperatures. The spatial mapping of availability and demand for geothermal heat would help in the expansion of district heating networks on a local scale through an appropriate heat supply–demand matching. Overall, there is a lack of understanding of how different stakeholders organised by local governments can prioritise decisions when integrating renewable energy sources (RES), such as geothermal energy, into existing carbon-based energy systems.

This research explores the various actors who see opportunities in direct use of geothermal energy in the Netherlands and are working on the transformation of the current centralised carbon-based energy systems towards local sustainable energy communities. There is an increasing need to convince decision-makers and adopt the right decision-support framework towards the use of this technology. The aim is to overcome barriers in the implementation of geothermal projects in the residential sector by informing technicians, civil servants, and decision makers of regional and local governments so that they are well-equipped with the technical knowledge to steer the various stages of transformation of the thermal energy supply-demand system. To this end, it is important for the research to identify the key actors of the network, the different levels of influence and interest they have, and the dependency paths that determine the linkages between them.

2. Literature Review

2.1. Partnerships in Implementing Energy Systems

Energy systems in urban areas are complex, adaptive systems that consist of organisations, technology components, policies, and applications that involve dynamic interactions between numerous actors with varying roles and interests [6]. Organisations operate in the context of institutions, which define the rules, behaviours, and norms to which organisations must adhere [7]. Behaviours are enabled or enable regulative, normative, and cognitive rules embedded in social groups and technical elements, which support technological development by providing stability to sociotechnical configurations [8].

On a local level, energy supply initiatives call for new institutional arrangements and collaborations as well as the integration of different policy fields including the energy, spatial planning, and construction sectors. These institutional arrangements are formed and shaped by technological innovations, social networks across different domains and scales, and spatial development plans [5]. An important condition for new institutions to emerge in local energy systems is that organised actors have enough resources to transform the existing institutions or create new energy communities [7].

Energy communities are small neighbourhoods or districts that can effect change and contribute to a clean local production and supply of energy [9]. Network actors who shape these institutions are known as institutional entrepreneurs and are central for creating new connections across the public and private domain [7]. Furthermore, the different steps of transformation necessitate that sufficient capital, technical, land, skill, labour, and other resources are available to be allocated and mobilised among actors for the development of a project [6].

Hence, the new partnerships and interdependencies that are formed between individuals, organisations, and institutions, who transfer resources and knowledge to achieve a collaborative goal, create new models of network governance. These new forms of network governance can contribute to building trust, developing community capacity, and creating a collaborative advantage, such that the potential to collectively steer the energy system through the different steps of transformation is increased [6].

2.2. District Heating in Urban Planning

District heating (DH) plays an important role in an efficient thermal energy supply system. The high heating density in urban environments makes it more economically competitive to deploy DH, which is necessary for integration of renewable energy sources [10]. DH networks, which are currently fed by excess heat from industrial processes, power plants, and waste incineration facilities, allow access to local available heat resources that could not be used otherwise. Thus, expansion or construction of new DH networks is essential to make a transition from these fossil driven energy sources to renewable energy [5].

District heating (DH) networks are well-insulated pipes that transport hot water from a heat source to houses and utility buildings [11]. Depending on the temperature of the heat source, DH systems can be generally divided into high temperature heat networks and low temperature heat networks. In addition, heat sources can be described as either permanent or non-permanent. On one hand, permanent heat sources, such as cogeneration power plants, geothermal, and biomass, can constantly produce a higher supply than the demand of the system. On the other, non-permanent renewable heat sources, such as solar thermal energy, have a fluctuating seasonal supply profile and require the addition of other heat sources to fulfil the peak loads of the system [11].

The implementation of district heating (DH) networks in existing cities is characterised by a high level of complexity including multiple stakeholders; varying scales; long term consequences; and uncertainty in the different decisions, options, and methods; space for construction issues.

A conventional district heating (DH) network is generally fed by one centralised high temperature source from where heat is delivered to many houses and businesses. This large-scale network is usually supplied with hot water by carbon-based heat sources that include waste incinerators, power stations, and the chemical industry [12]. The structure of the network comprises two main pipelines: a primary or transport network and a secondary or distribution network. More often than not, heat sources and residential areas are located far apart, thus, the heat is first supplied to the primary network at a temperature of between 90 and 120 °C (depending on the season) and subsequently to a substation, also well-known as a heat transfer station (HTS) [13]. The heat is always delivered by means of heat exchange, in other words, there is a supply and a return flow, the latter ranging from 58 to 68 °C [14]. From the substations, the heat is pumped into the distribution network at a lower temperature in the range of 70 to 90 °C and delivered to the end consumers. The return temperature lies in the range of 40 to 60 °C [13]. An important disadvantage of high-temperature heat networks is that they require a substantial number of houses to be connected to the grid. Therefore, policy makers always need to balance the extent to which the investment costs outweigh the amount of homes that can be heated via the heating network as well as how these costs relate to the costs of retrofitting those homes [15]. Heat losses are also an important issue in these large-scale high-temperature heating networks. According to a study by the Central Agency for Statistics of the Netherlands (CBS) from 2015, on average, 25% of the heat entering a high-temperature heat grid is lost [1,16].

Low-temperature heat (LTH) networks, also referred to as fourth generation heat grids, have a supply temperature ranging between 30 and 70 °C [17]. In the Netherlands, the development of fourth generation district heat networks is still very much in its infancy [18]. To achieve high efficiencies in district heating systems it is important that the distribution temperatures are low. This is because low supply temperatures in DH networks indicate a higher electrical output from combined heat and power (CHP) plants, a higher heat recovery from industries and geothermal plants, and a higher coefficient of performance (COP) when heat pumps are utilised for the production of heat [12]. Furthermore, the application of most renewable heat sources in DH networks necessitates the implementation of a low-temperature distribution network. This creates opportunities for connecting many different sources and installing small-scale, carbon emission-free heat networks on a community level [19]. Another advantage of low distribution temperature is the reduced distribution losses. These subsequently result in economic benefits too for the many stakeholders involved in heat grids, since for every one-degree Celsius decrease in return temperature, the savings can reach up to 0.5 € per MWh [12]. Concerning the connection of the distribution network to the end users, it is crucial to highlight a distinct difference between LTH networks that have a supply temperature ranging between 50 and 70 °C (medium temperature) and LTH networks that have a supply temperature below 50 °C (low temperature). That is, low temperatures below 50 °C require that the heated surface be very large and the heat loss be very small. This entails that the buildings are well insulated and have a radiant underfloor heating system installed. In addition, a solar thermal water heater or an electric boiler is required to fulfil the needs for domestic hot water (DHW) because of the risk of legionella bacteria. For older houses, this usually means a substantial renovation, which may require an investment of tens of thousands of euros [15].

One of the major challenges to achieving savings in heat demand and the use of sustainable heat lies within the existing building stock. The consideration for insulation investments in the stock of buildings, the investments in sustainable generation at building level, or investments in area-oriented solutions is complex and full of contradictions. For example, making a large part of the housing sector energy neutral is not cost-effective because the post-insulation of existing buildings is relatively expensive. This is problematic in urban areas where a large part of the current stock of buildings is old. Recent research also shows that the expansion of a DH network in an area greatly depends on densification [3]. The heat demand for the less densely populated areas should be provided by decentralized individual facilities such as heat pumps and solar water heaters. This is because the heat demand is too low to compensate for the costs required to build the infrastructure for a DH network. Furthermore, focusing on energy systems acknowledges that organisations and technologies are embedded within a broader context of social and economic systems. In sociotechnical systems the supply of heat is fundamental and brings together different societal functions. Transformation in such systems calls for a parallel evolution of society and technology.

2.3. Decision Support Framework for District Energy Systems

The integration of various RE sources in district heating is a laborious task. Decision makers have to take into account multiple factors that are often conflicting due to the growingly complex spatial, socioeconomic, environmental, and technical considerations involved. Multiple stakeholders engage in the decision-making process, each introducing different factors and perspectives, that need to be settled within a framework of mutual commitment [20]. Over the past few decades, an emerging body of literature has focused on the development of frameworks that support decision-making in the selection of renewable energy sources in district heating systems. Haralambopoulos and Polatidis [21] developed a group decision-making framework based on multi-criteria analysis for a geothermal source in Greece using the PROMETHEE II outranking method. The proposed methodology aims at resolving conflict among different stakeholder groups and improving the development of RE projects. Shortal et al. [22] developed an indicator evaluation framework for geothermal energy projects in Iceland, utilising a Delphi survey as a sustainability assessment tool. Their study demonstrated that stakeholder groups prioritise among other factors, geothermal resource capacity, efficiency, expected lifetime of the reserve, as well as air and water quality. Oei [23] proposes a novel regulatory framework for district heating in the Netherlands, with the goal of increasing the attractiveness of district heating as opposed to conventional sources for space heating. He suggests that two new business models could be adopted by the Dutch district heating market, which could increase the share of renewable heat sources and promote more sustainable practices in the urban energy sector. Generally, many authors ([11,24-26]) emphasize the importance of utilizing local resources such as solar heat, biomass, and excess heat from fossil-driven sources to realise a sustainable heat supply with reduced carbon dioxide emissions. Much less focus has been placed on direct use of medium enthalpy geothermal sources in traditional DH systems. Furthermore, only a few international studies ([24,27,28]) have addressed the issue of expanding district heating systems, and research is mostly focused on a regional or urban scale. The present paper proposes a novel decision-support framework utilizing a Geographic Information Systems (GIS) model that can assess the link between efficient application of deep geothermal energy in district heating systems and urban energy planning.

3. Methodology

In urban planning, the integration of a geothermal source into a heat network is a problem inherently characterised by a high level of complexity including multiple stakeholders; varying scales; long-term consequences; and uncertainty in the different decisions, options, and methods. Such complicated problems require multi-level governance and can be supported by weighing alternative options against a set of selected indicators. In this paper a decision-support framework is developed by exploring the key parameters that influence the relationship between supply of geothermal energy and heat demand in DH systems.

Both qualitative and quantitative data is required to facilitate the multi-level decision making process. To develop this framework, an extensive literature review was conducted to identify qualitative parameters, and GIS techniques were applied to quantitatively analyse the energy consumption levels and the spatial distribution in a district. GIS technologies allow for the processing of large datasets and the exchange of information between specialised spatial data infrastructures and platforms.

First, geological survey data describing the potential for annual heat production from the geothermal source determined: (a) the spatial and temporal boundaries of the plan area; (b) the type of DH system required for heat transportation and distribution; and (c) the topographical data including building boundaries, manmade constructions, green areas, as well as road and underground networks for the GIS analysis. Second, data derived from different sources were processed and integrated to create a layered GIS model.

Third, a 3D block model of the city compatible with the building energy simulation software CitySim Pro was generated in order to estimate the heat demand on a high spatio-temporal resolution. In addition, energy labels and average gas consumption data were mapped to compare energy consumption indicators of the studied buildings on different levels of detail. Ownership data relating to energy producers, energy companies, housing corporations, and individual owners provided this study with qualitative data for the stakeholder analysis of the district heating sector. Fourth, a spatial analysis of urban context was performed to determine the morphology of the plan area and the technical impact on the distribution of geothermal heat.

To this end, the use of geospatial data at different scale levels can help inform stakeholders of the existing state of the districts, the potential for heat transition, as well as the implications of this transition. Based on the selected set of criteria, two scenarios were generated that primarily depend on the adaptability of buildings, the urban morphological conditions, and the organisational structure that defines how the involved stakeholders can impact different decisions in urban energy governance.

3.1. Geothermal Energy Source Assessment

For the application of geothermal heat in DH networks, it was first necessary to estimate the installed capacity of the reservoir. A detailed geological study was carried out by Hydreco in collaboration with the municipality of Rotterdam in order to map the deep subsurface and the potential for geothermal heat production from three different locations.

This was accomplished by combining 2D and 3D seismic profiles with drilling data including porosity, permeability, thickness, depth, and temperature of the sandstone layer. According to geologist van Campenhout, the geothermal source under study is located at the lower cretaceous sandstone below a former oil reservoir, at a depth of 1235 m in the deep subsurface of the Feijenoord district [29]. The geological survey showed that hot water is stored below the oil layer at a depth of 1760 m (Figure 1) at an estimated temperature of 54 °C. The key parameters describing the geothermal reservoir are listedin Table 1.

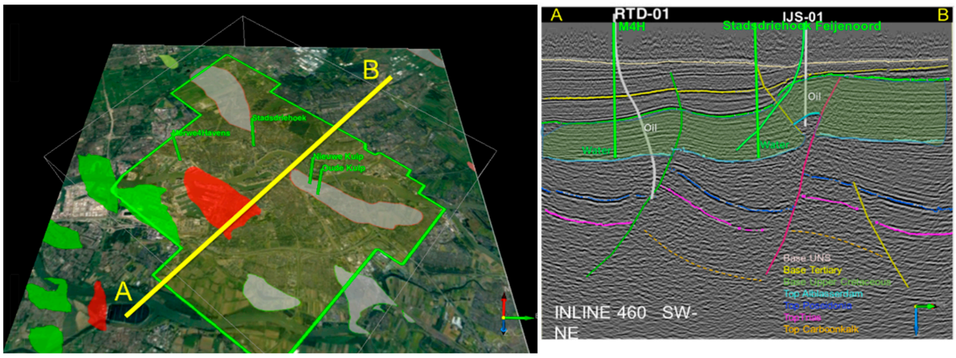

Figure 1. A 2D seismic profile of the subsurface under the studied area. Retrieved from van Campenhout [29].

Table 1. Geothermal source production characteristics. Retrieved from van Campenhout [29].

Parameter	Value	Unit
Supply temperature	54	°C
Return temperature	15–20	°C
COP	15	
Depth	1760	m
Thickness	100	m
Permeability	215	Md
Capacity	5.2–6.5	MW
Porosity	21.3	%

According to Bakema and Schoof [30], the capacity factor of deep geothermal doublets with an installed capacity between 5.5 and 7.4 MW in the Netherlands in 2015 was 0.662. Assuming the same capacity factor for the geothermal reservoir in the studied area, the potential of annual production for one geothermal doublet is:

$$\text{Annual production (MWh)} = C_f \cdot \text{Installed Capacity MW} \cdot 8{,}760\ \text{h}$$

$$= 0.662 \cdot 5.2\ \text{MW} \cdot 8{,}760\ \text{h} = 30{,}155\ \frac{\text{MWh}}{\text{year}}$$

3.2. Building Heat Demand Modelling

The methodology followed for the analysis of the thermal needs of the residential plan area involved the following steps: (i) generation of the 3D city block model in GIS; (ii) estimation of the heat demand in the urban energy simulation platform CitySim; (iii) quantitative statistical analysis of results, and (iv) assessment of the impact of the urban context on the potential to meet the heat demand.

The creation of a 3D city block model in GIS required the collection of geospatial data that contain information on the location and footprint of the buildings. The main sources of geospatial data are topographical maps showing the boundaries of properties in relation to adjoining properties and geographic features [31]. Additional sources for collecting heights of the geographic features are AHN3 point cloud data, which are created with satellite remote sensors and photogrammetry methods. By using GIS spatial operations and functionalities, these data can be transformed into usable information to infer heights of buildings and then calculate building volume.

In this case study, the aim was to assess the heat demand of tens of thousands of residential buildings, hence, the buildings were modelled in "Level of Detail 1" (LOD1)—that is, the simple volumetric representation of the geometry of a building (Figure 2). Choosing a higher level of detail would not be realistic since computation time would be much too long and collection of data would be impractical or infeasible. The 3D city block model is generated by combining two data elements:

- digital cadastre (DC), from which building footprint and corresponding building attributes are inferred;
- digital surface model (DSM), measured with LiDAR technology that captures both the natural and built features on the Earth's surface. Building heights are deduced from this layer with GIS processing.

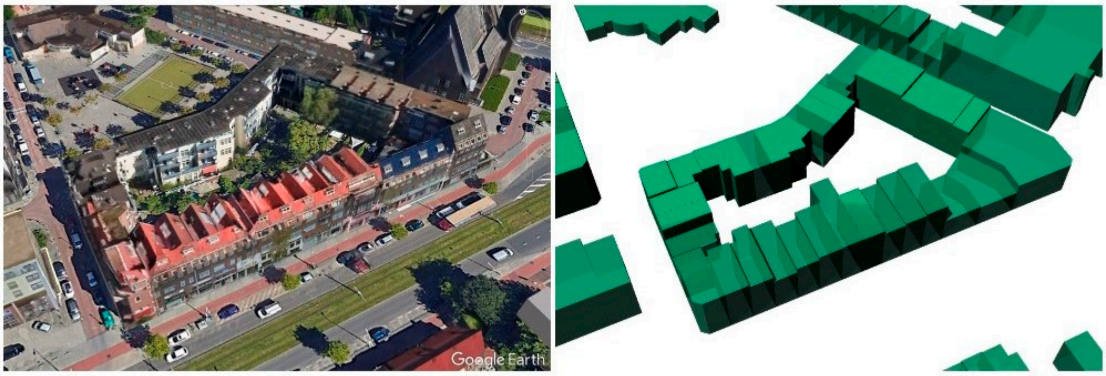

Figure 2. Satellite image from Google Earth of the Hilleshuis neighbourhood (left). "Level of Detail 1" (LOD1) model of multiple adjacent buildings (right).

Considering that urban energy simulation models commonly address districts with thousands of buildings, it would be unrealistic to collect exhaustive building data for every individual building. Hence, a common approach is to classify the building stock into archetypes that have similar attributes. This work used a deterministic archetype classification scheme based on the Dutch national reference home standard that distinguishes six dwelling types: detached house, semi-detached house, terrace house between, terraced house corner, gallery complex, and apartment complex [32]. The first pair are then grouped as a single-family house (SFH), the second as a terrace house (TH), and the third as a multi-family house (MFH) as shown in Figure 3. Furthermore, the dwelling types were divided into three construction periods (pre 1964, 1965–1990, and 1991–2018) based on the classification of the residential typology database, the European Typology Approach for Building Stock Energy Assessment (TABULA) [33]. Consequently, in total, the archetypes were classified into nine different classes, each associated with a sample building in TABULA and assigned with the corresponding physical construction parameters (i.e., U-values of wall, floor, etc.).

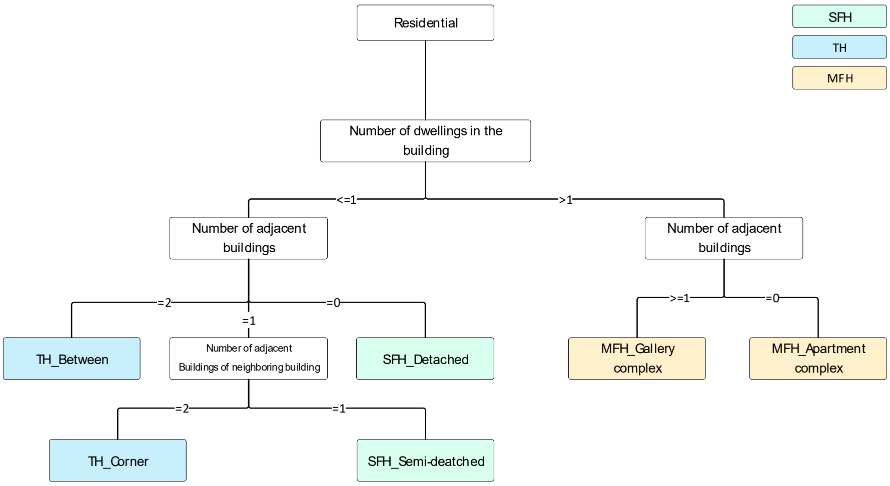

Figure 3. Dwelling typology classification based on topology relation and number of addresses per building unit. Retrieved from Wang [21].

The final implemented classification rules were construction period, number of addresses per building, and building footprint topology relations. After these processes, the 3D city block model contained LOD1 buildings within separate layers, each representing a unique dwelling type and construction period. To simplify the heat demand simulation in CitySim, each building was modelled as a single thermal zone.

With regard to weather data, hourly time-series of the meteorology of the study area was required by CitySim to run an energy simulation (Figure 4. These data were retrieved from the Royal Dutch Meteorological Institute (Koninklijk Nederlands Meteorologisch Instituut (KNMI)) [34] for Schiphol station, and converted into a CitySim compatible format.

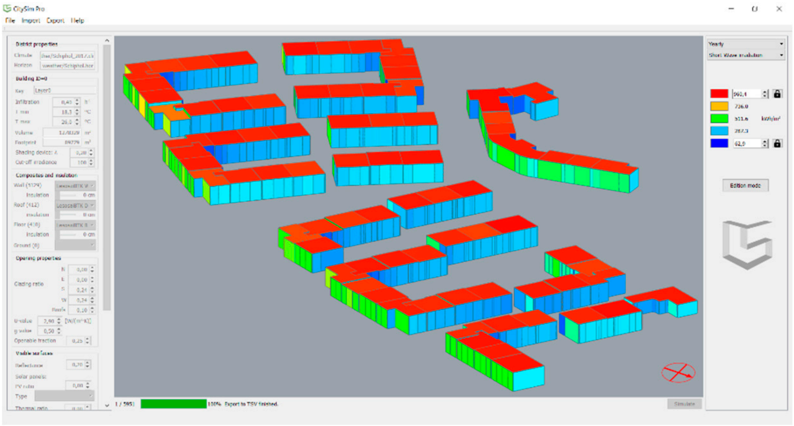

Figure 4. CitySim platform. Completion of energy simulation for an island.

3.3. Energy Consumption and Ownership Data

The energy consumption data included energy labels and gas consumption data. The energy labels were open source data found in *Rijksdienst voor Ondernemend Nederland* (RVO) [35]. Average annual gas consumption data were obtained from the Heath Atlas (Warmteatlas) of RVO. The latest dataset accessible was from year 2017 on postcode level 6 (PC6), which includes four digits and two letters. Although information on specific gas consumption data per individual address is known to energy companies, it is published on a higher spatial scale (PC6) due to privacy-related reasons. This also means that gas consumption data are less accurate than energy labels data for the studied buildings. Housing ownership data is also protected for privacy and was given by Veldacademie [36] in Rotterdam for the purpose of this research. This is a dataset providing detailed information on the ownership of the properties and the occupants, which can help determine how many people could be serviced by a DH system in a certain area and which stakeholders are involved in housing project developments.

3.4. Spatial Analysis of Urban Context

The spatial analysis was performed in GIS by means of a set of urban form indicators including population density, dwelling density, building intensity, coverage, spaciousness, network intensity, and linear heat density. After selecting which urban samples to include in the research, a boundary was drawn around the samples to define the area of the fabric. The urban fabric included built-up and non-built area of a residential neighbourhood. In addition, the non-built space consisted of islands—that is, private lots of buildings and other non-built space—and the street network that connects the islands [37]. These area-specific characteristics needed to be defined in order to derive urban form indicators.

The following step for each urban sample was to calculate their geometric attributes by using simple geospatial operations. These geometric attributes included the total land area of the fabric and the island (A), the gross floor area of all dwellings (FSI), the total building footprints (GSI), the length of the street network (N), and the total surface of the open space (OSR). After inferring these characteristics from the attribute fields in GIS, the final step was to calculate the urban form indicators. Figure 5 illustrates the urban fabric in the Vreewijk neighbourhood of the Feijenoord district for which a spatial analysis was performed to compare energy consumption levels in relation to urban density.

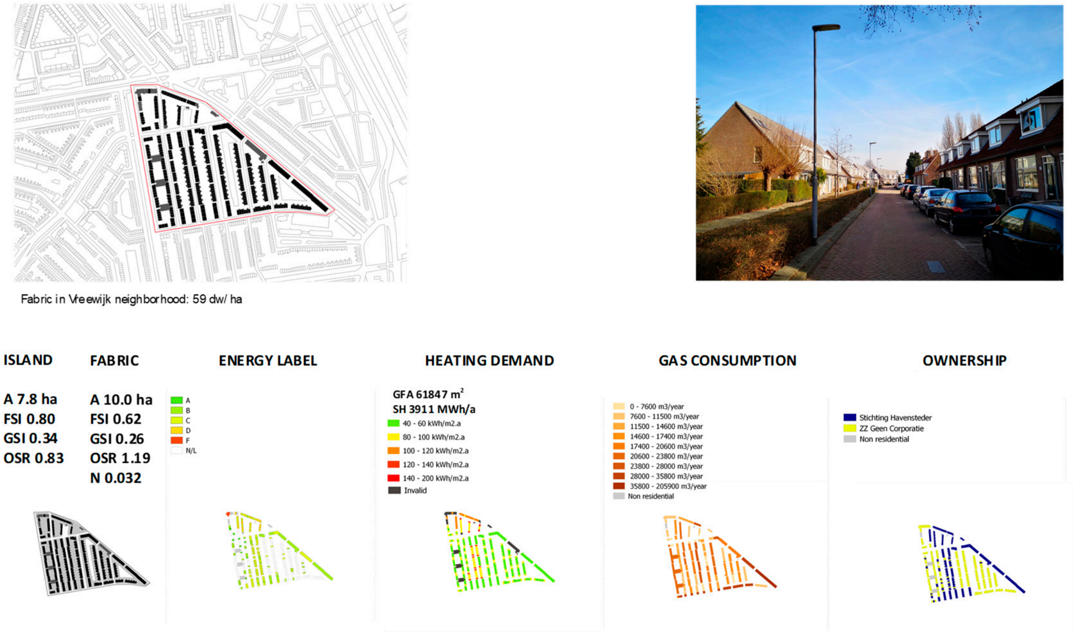

Figure 5. Mapping energy consumption levels and densification on the urban fabric of the Feijenoord district between 1990 and 2010.

4. Heat Network in Rotterdam

The DH network in Rotterdam is supplied with residual heat by a waste incineration plant and consists of a primary transport network and two main distribution networks on the north and the south of the Nieuwe Maas (Figure 6). The 26-km-long transport network comprises two pipelines: one conduit transfers heat to the city at a temperature of 90–120 °C and the other returns cooled water back to the starting point at a temperature of 58–68 °C [38] [14]. The distribution networks are connected to the primary network by means of a heat transfer station (HTS) and are operated by two different energy suppliers.

The selection of the research area was based on the location and capacity of the studied geothermal source as well as its proximity to an existing distribution network. Feijenoord and IJsselmonde districts are located in Rotterdam Zuid and are considered opportune for the heat transition because there are plans to redevelop many neighbourhoods, while most buildings are owned by housing corporations that govern the construction and maintenance of each dwelling; this means that a clean energy intervention can be planned hand executed here with fewer difficulties compared to an intervention in an area with individually owned houses.

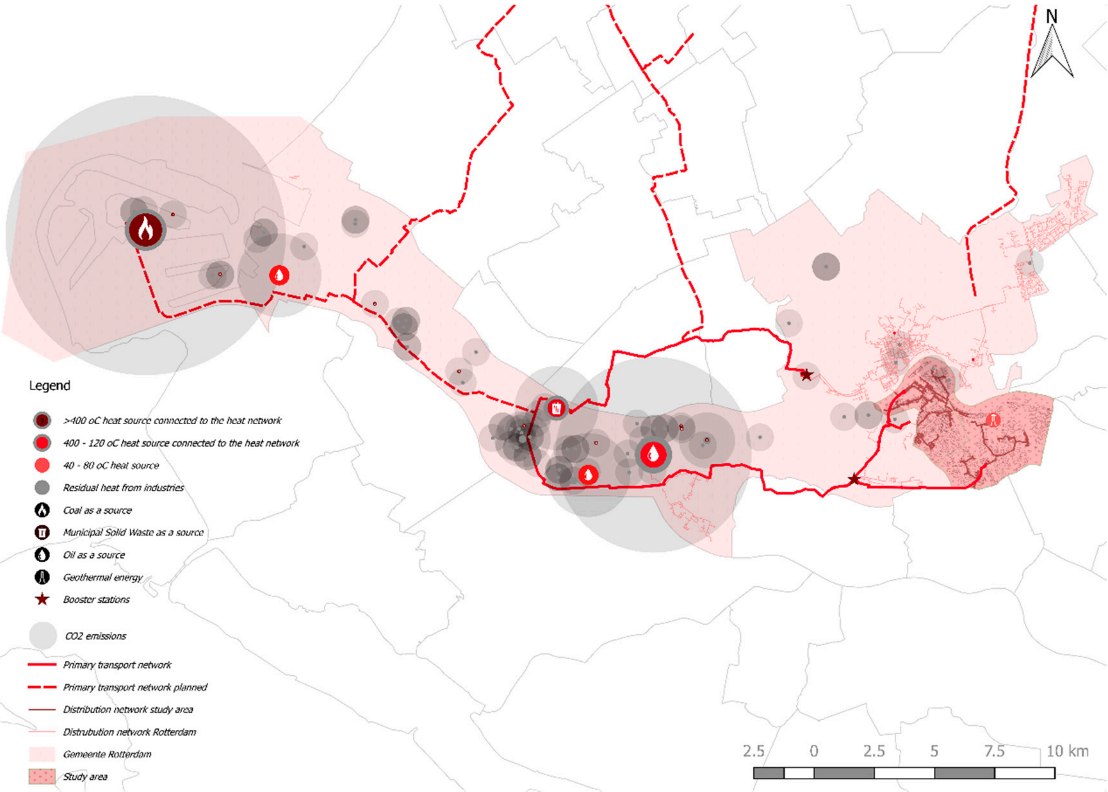

Figure 6. Heat network in Rotterdam and CO2 emissions from industrial heat sources.

4.1. *Heat Demand and Supply of Geothermal Energy*

The energy needs of a total of 23,641 buildings were simulated in CitySim Pro as shown in Figure 7. The results indicated a gross heat demand of 269 GWh/year including both space heating and domestic hot water.

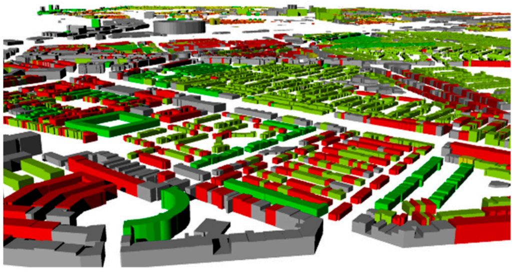

Figure 7. Rendered 3D close-up image of the Feijenoord district’s heat demand.

Combining the annual production data of the geothermal source with the aggregate heat demand in the area, it is obvious that only a limited percentage of the total heat demand in the area could be met by the geothermal source. However, even if the geothermal energy supply was sufficient for the thermal needs of the two districts, not all buildings would be well suited for district heating.

While aggregate results provide the research with an estimation of the total annual heat demand, hourly heat demand curves are modelled for each building separately. Hourly heat demand curves help identify peak loads and base loads when selecting suitable buildings for medium temperature geothermal heat. Nonetheless, the selection of buildings is not solely based on the specific heat demand (Figure 8) but also on other decision factors required to generate future scenarios.

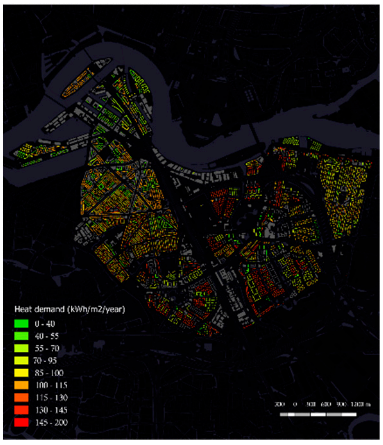

Figure 8. Heat demand map of Rotterdam Zuid in 2019.

For an efficient application of geothermal energy in DH networks, it is important to determine the temperature level of both the source and the heat transport and distribution infrastructure. Thus, high-temperature heat should be provided to consumers that have a high heat demand per surface area (kWh/m^2/year) and medium or low temperature heat should be provided to energy efficient buildings. This is also a well-known principle of a cascade system and steers decisions towards a rearrangement of DH networks through energy integration technologies [39]. Accordingly, DH networks should be planned with a design that increases the capacity and capability to connect local heat sources and to recycle low or medium temperature renewable sources and effluents from industrial processes and sewer networks.

From the GIS analysis and the building energy simulation, two scenarios were generated in the area for the utilisation of geothermal resource (Figures 9 and 10). Considering the two proposed scenarios, we identified a trade-off (Table 2). On one hand, centralisation would secure a constant supply of heat to dwellings because the residual heat from the AVR Rozenburg waste incineration plant (WIP) can be used as a back-up source for peak loads in the coldest season, and reduced costs in terms of piping needs because the existing infrastructure can be utilised for the distribution of hot water to houses. On the other, the significant temperature increase required for the geothermal source to reach the distribution temperature of a high temperature district heating (HTDH) network would substantially increase the costs for the heat pumps and lead to a much less efficient DH system. Furthermore, this scenario relies on the utilisation of traditional third generation heat networks that do not facilitate the use of medium or low temperature renewable energy sources, resulting in high distribution losses and CO_2 emissions.

With respect to the second hypothesis of adopting a decentralised scenario, the decision maker would be confronted with high upfront costs for a new pipeline installation and investments to retrofit existing houses. These networks are more suitable for new housing projects because the in-house heat delivery systems can be planned a priori without requiring the end user to invest in retrofitting strategies. However, from the 3589 dwellings that appear to be suitable for this scenario, only 320 dwellings are currently under construction, while the rest need refurbishment. This might either involve a simple replacement of the existing wall-mounted radiators with larger ones or in, cases where the geothermal source has a temperature below 50 °C, substantial costs for renovation.

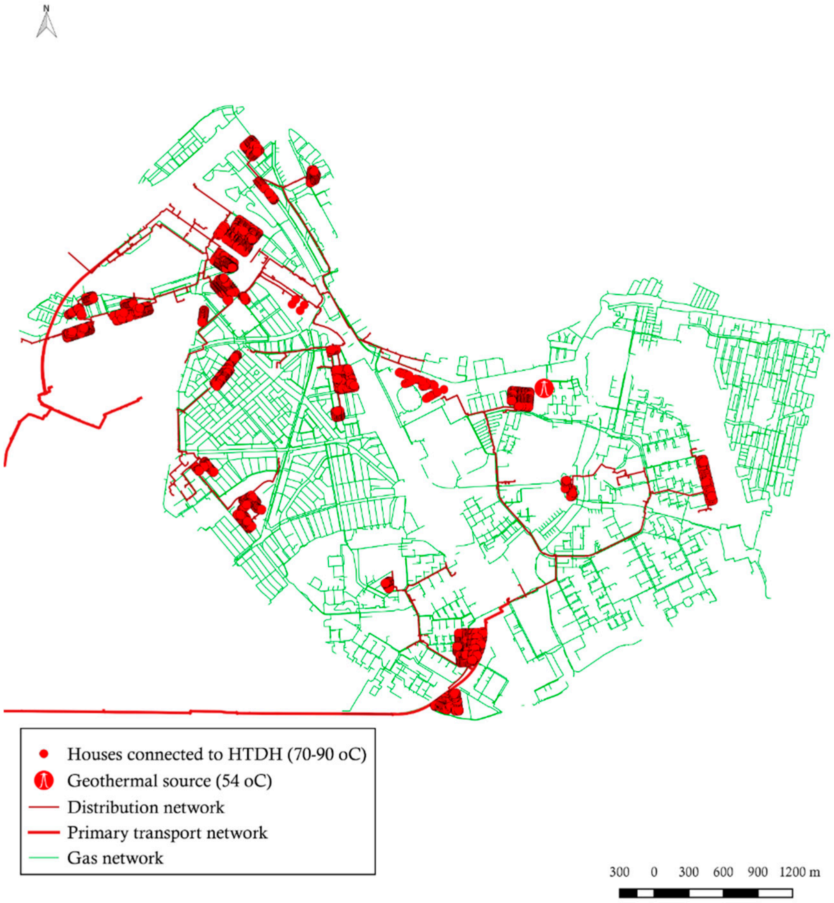

Figure 9. Centralised scenario.

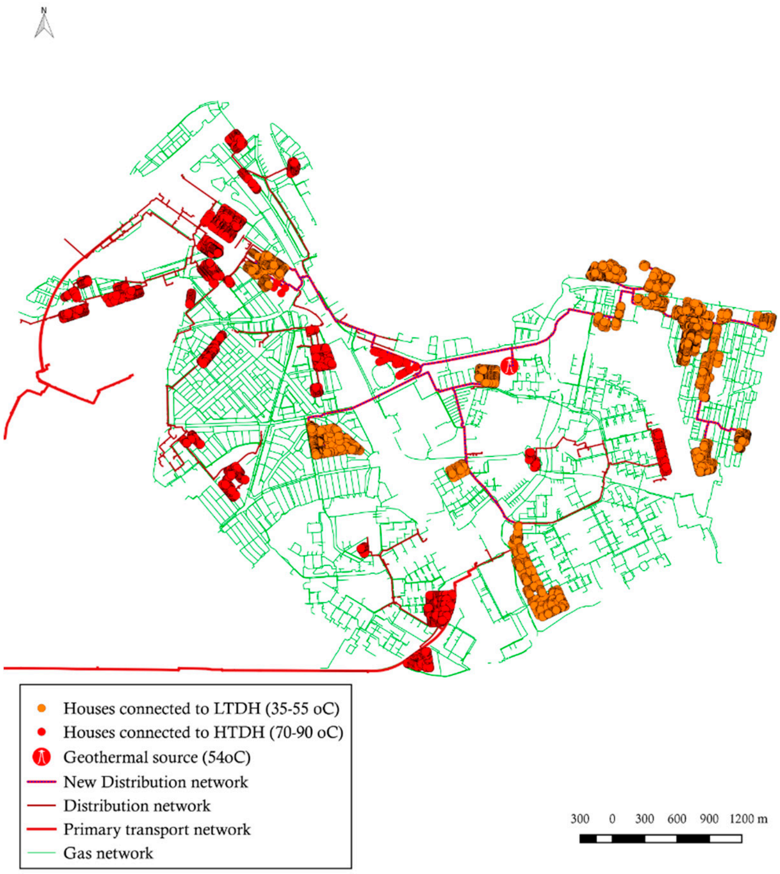

Figure 10. Decentralised scenario.

Table 2. Advantages and disadvantages of the two proposed scenarios.

Scenario	**Centralized HTDH**		**Decentralized LTDH**	
Phase	**Advantages**	**Disadvantages**	**Advantages**	**Disadvantages**
Heat supply	Opportunity to cascade heat from high heat demand sources and sinks to low heat demand sinks.	Difficult to integrate renewable energy sources.	Possibility to connect other renewable heat sources to fully decarbonize the heat sector.	Risks with legionella bacteria if the supply temperature drops below 50 degrees Celsius.
	The geothermal source can be used as a baseload. Peak heat loads can be met by using the residual heat from the WIP. This leads to reduced costs.	Sustains the utilisation of traditional heat networks that use fossil-based energy sources to operate. In addition, this leads to an increased need for waste in the future.	Combination with LTH sources if available in the area (such as biomass and solar thermal). Creation of a smart thermal grid. This leads to reduced GHG emissions.	Difficult to use the geothermal source as a baseload unless a hybrid system is installed with a combination of biofuel back-up boilers. Expensive to run on full capacity.
Connection to a heat network	Utilisation of the existing distribution network leads to reduced cost, no need for a new pipeline installation (except for De Kuip area).	Increased distribution losses and high CO_2 emissions deriving from industrial waste heat.	Energy efficient heat network with reduced distribution losses.	High costs for installation of a new DH pipeline configuration.
	The capacity of the source is large enough to add the new De Kuip housing project. The distribution network is in proximity to the stadium.	Very large temperature difference compared to the system. Massive energy input required by heat pumps to upgrade the temperature. This makes implementation of this scenario almost infeasible.	Temperature is high enough to supply DHW.	The linear heat density is within a suitable range (1.3 MWh/m/year).
Urban context	Urban form indicators of fabrics where an HTDH network exists are well-suited for a profitable DH operation.		Opportunity to co-ordinate activities of DH installation with sewer replacement projects that are planned in Reyeroord and Groenenhagen for the near future.	Gas and sewer replacement projects will create a nuisance in the area for a considerable amount of time.
	The street network in the De Kuip area can be designed beforehand taking into account the DH pipeline configuration.	Limited number of new houses will be connected to the grid (only de Kuip area, 1700 dwellings).	Opportunity to add many new housing projects in the heat network in Lombardijen, Katendrecht, and Groote IJsselmonde.	
			Opportunity to add existing housing in the heat network.	Adaptable houses are relatively scattered over the area.
Housing adaptability	No need for retrofit strategies. Most houses are already connected to the heat network.		Existing houses do not need major retrofit interventions. These activities can be co-ordinated by the housing corporations.	Slightly increased costs to make the selected houses compatible to an LTDH network.

	Supply of both domestic heating and DHW with a central HIU in each building.		Shift to more energy efficient houses.	Need to use substations without storage of DHW and pipes with a small volume flow rate between heat pumps and the taps to prevent legionella bacteria growth.
			Floor heating can be installed directly when constructing new houses.	
Heat demand	De Kuip new housing project is very close to the existing distribution network. The demand is about 7600 MWh equivalent to the remaining demand required to balance with the supply of geothermal energy.	No incentives to renovate houses. The supply temperature is high enough to heat less efficient houses too.	Many housing corporations own the houses that are eligible for DH. Easier to make arrangements on the end user side.	Less suitable for old houses unless substantial renovations are made in the houses.
		Sustains a system with a high temperature heat demand per m^2.	Creation of a new market with a low heat demand per m^2.	

4.2. Stakeholder Analysis

The stakeholder analysis aimed to identify and map the key stakeholders across different policy sectors, evaluate their interest and likelihood to influence the decision-making process of the geothermal project, as well as to illustrate the dependency ties between them. A structured four-step approach was developed based on a review of the literature sources, as shown in Figure 11.

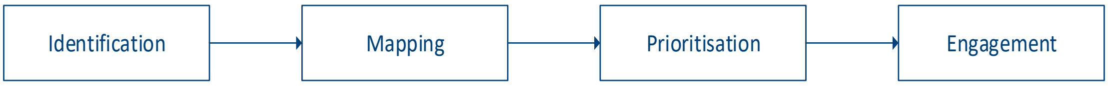

Figure 11. Structured four-step approach for stakeholder analysis.

First, a comprehensive list with the principal internal and external stakeholder groups of the district heating sector was created. Second, a stakeholder map was drawn to visualise the multi-level stakeholder landscape as illustrated in Figure 12. Following the mapping process, stakeholder prioritisation was used to distinguish the influence and interest among different groups on urban energy planning and ensure that resources are addressed effectively. This was achieved by the application of the power versus interest matrix, a common stakeholder prioritisation tool [40]. This tool is very effective for managing stakeholders and distinguishing their roles, level, and type of engagement in the project by positioning them in the matrix.

Lastly, a stakeholder engagement network was designed to identify the required actions by the involved players and the dependency paths between them. Stakeholder involvement is associated with interactions among different people, which can sometimes be unforeseeable and sometimes time-consuming. The geothermal energy project also requires an efficient allocation of resources and a proper ordering of activities to ensure that implementation is realised cost-effectively.

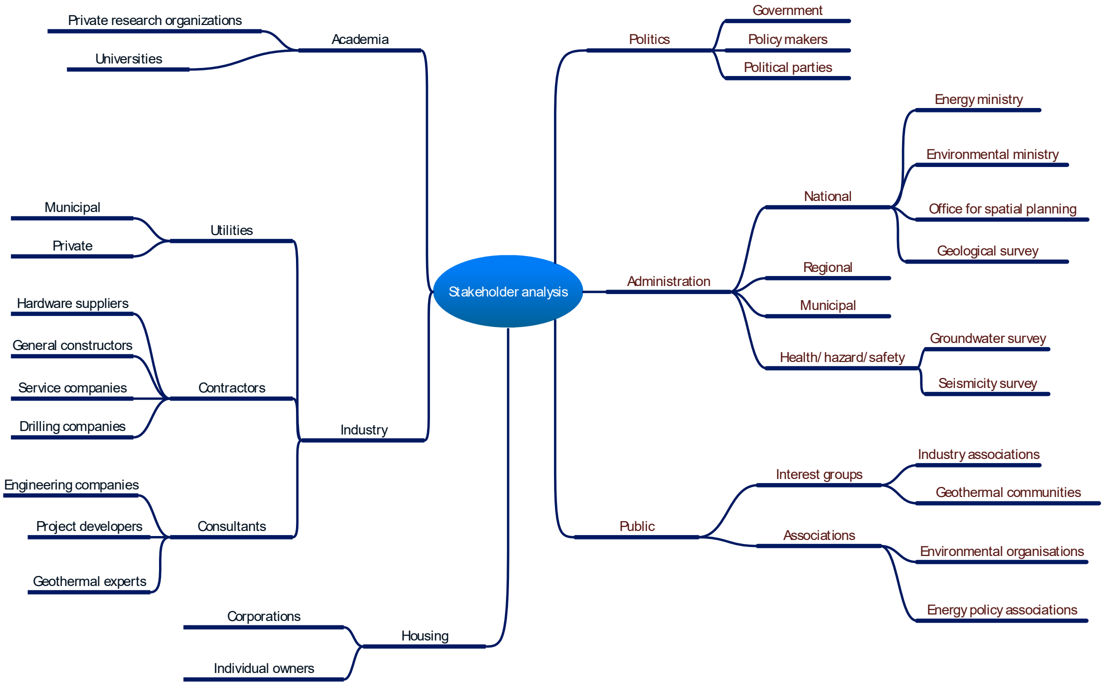

Figure 12. Multi-stakeholder mapping. Based on Minder and Siddiqi [41].

5. Decision Support Framework

The decision-support framework for geothermal application in local district energy systems was developed on the principle of iterative design, a cyclic process of gathering data and information described in the previous sections, analysing the involved stakeholders, and refining the results. During the analysis, decision variables were identified and classified in five thematic phases (Figure 13). The aim was to illuminate previously hidden issues in direct use of geothermal energy and provide a means for overcoming social, spatial, and technical barriers in decision making for sustainable urban energy planning.

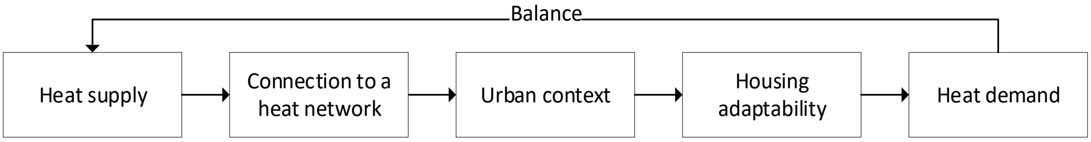

Figure 13. Abstract model of the five phases of the decision-support framework.

Figure 14 presents the decision tree from the supply of geothermal energy to the residential heat demand. This process is intended to be linked with the decision-support framework (Appendix A), allowing the decision-maker to make a simple assessment of different decision pathways during the project development phase.

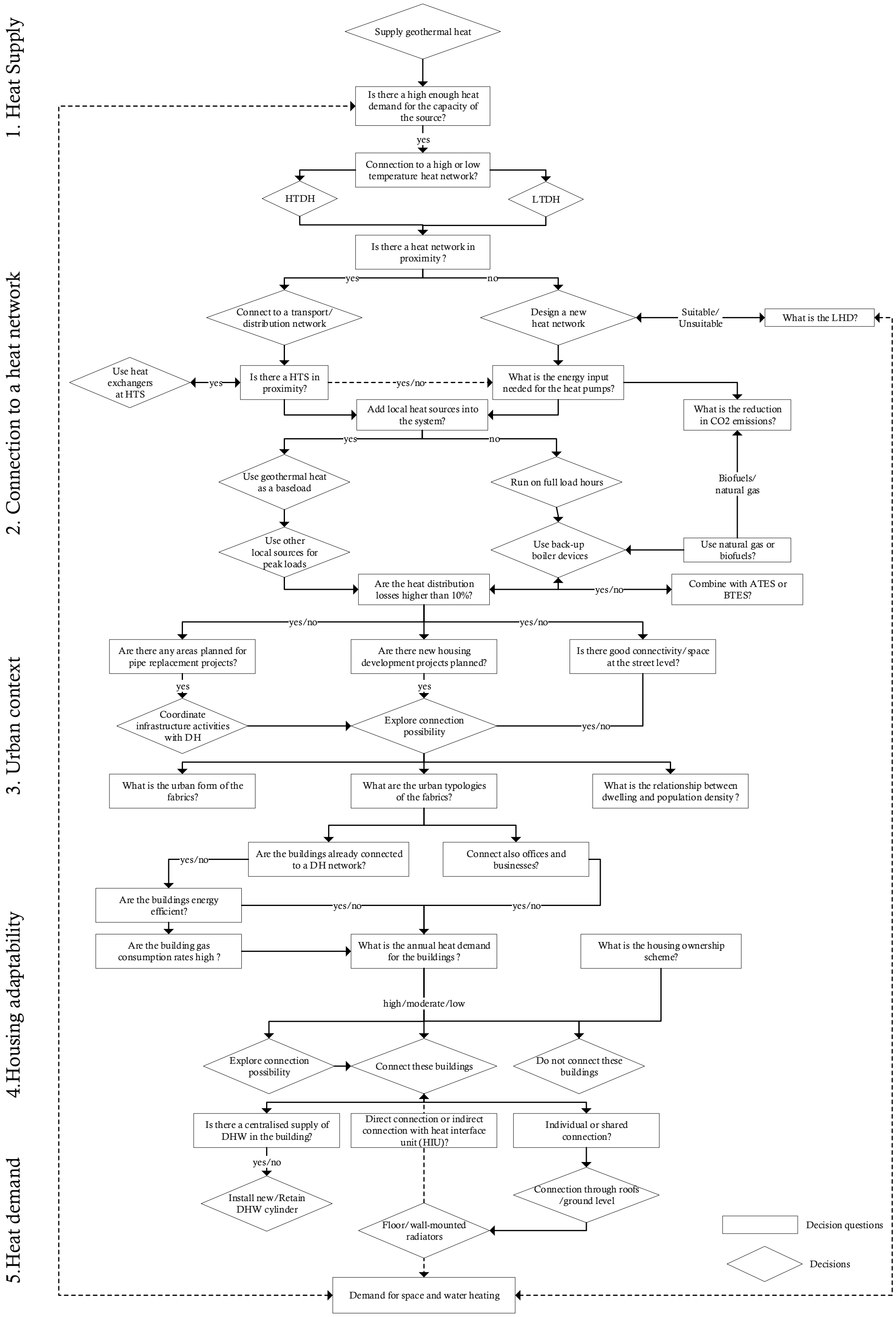

Figure 14. Decision tree linked to the framework.

5.1. Stakeholder Roles and Coordination

This section deals with identifying and prioritising stakeholders of the various sectors, who engage in the geothermal project development, and exploring dependency paths between them. These stakeholders are nested within larger stakeholder groups that form the sociotechnical regime of geothermal energy in the Netherlands. This sociotechnical regime is the platform through which institutional arrangements steer decisions to implement the geothermal project strategy.

The stakeholders can first be divided into two main domains: those who engage in the geothermal energy value chain and those who engage in the district heating value chain (Figure 15). The stakeholder groups within these two domains are not necessarily connected. On one hand, geothermal energy is a source for heating that requires a district heating network to couple production with consumption. On the other, district heating networks are multi-source systems that interact with more stakeholder groups than the geothermal energy value chain.

Each stakeholder plays a different role in the process. Stakeholders involve public and private institutions, researchers, producers, consultants, as well as firms that buy, transport, and distribute heat from the geothermal doublet to the end consumer. Umbrella organisations are key players in the chain because they coordinate the activities of geothermal energy projects and pool resources by working together with sustainable energy developers and industrial contractors. National and local governments develop and promote the policies, define the legislative and regulative context of the innovation, and consult about issues such as the provision of permits to new exploration applications. As regards the societal setting, residents, citizens, and the media will also have a central position in determining the demand side for geothermal energy and promoting the development of smart thermal grids [42].

Depending on the position of the stakeholders in the two value chains, their roles can be divided into high-level and coordinating. High-level roles will be either adopted by one actor responsible for keeping other actors informed or by multiple actors. In the latter case, activities will be coordinated either by one stakeholder in dialogue with other stakeholders or by many stakeholders that have the same influence individually on the decisions. Coordinating roles between stakeholders will be undertaken on the basis of their influence, interest, and previous experience.

Figure 16 illustrates the network of the stakeholders that exchange knowledge, mobilise resources, and make decisions in both value chains in the Netherlands. It is important to emphasise that the framework developed in this research only addresses stakeholders and decisions that need to be taken once the geothermal reservoir is available to provide hot water in the district heating network.

Depending on their influence and interest, the network of actors can be further classified into four categories: key player, keep satisfied, keep informed, and build awareness. This way, the various stakeholders involved in the project can be better positioned and mapped.

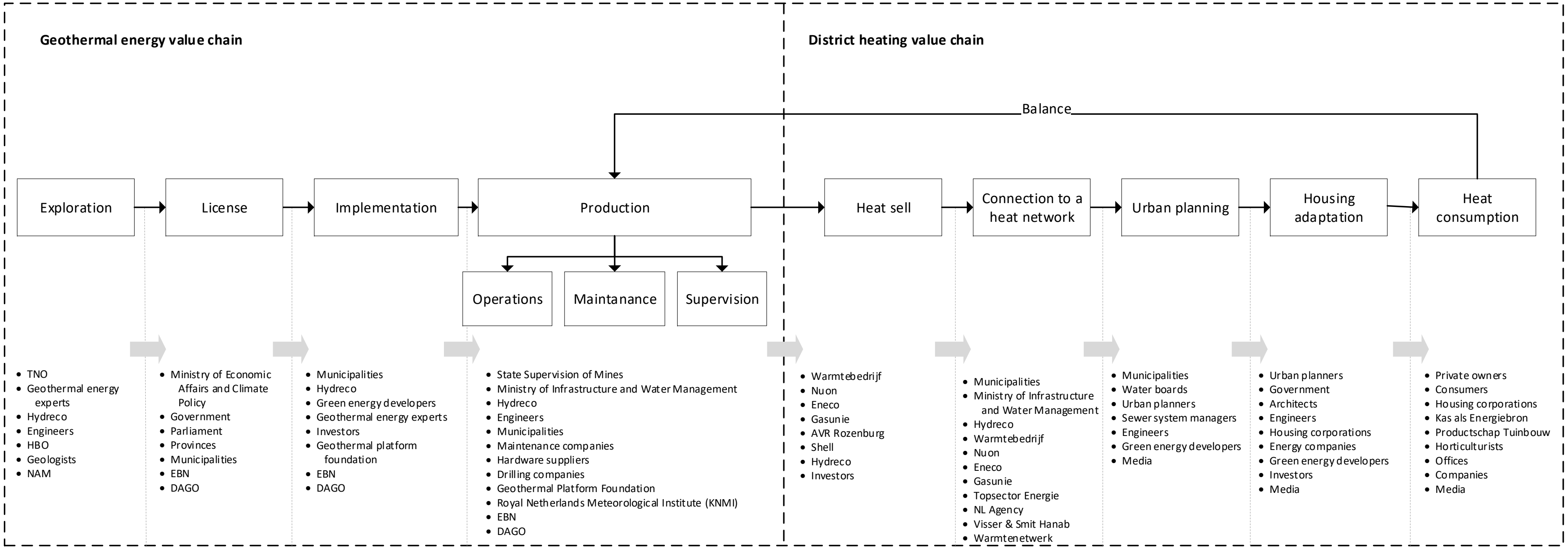

Figure 15. District heating and geothermal energy value chain.

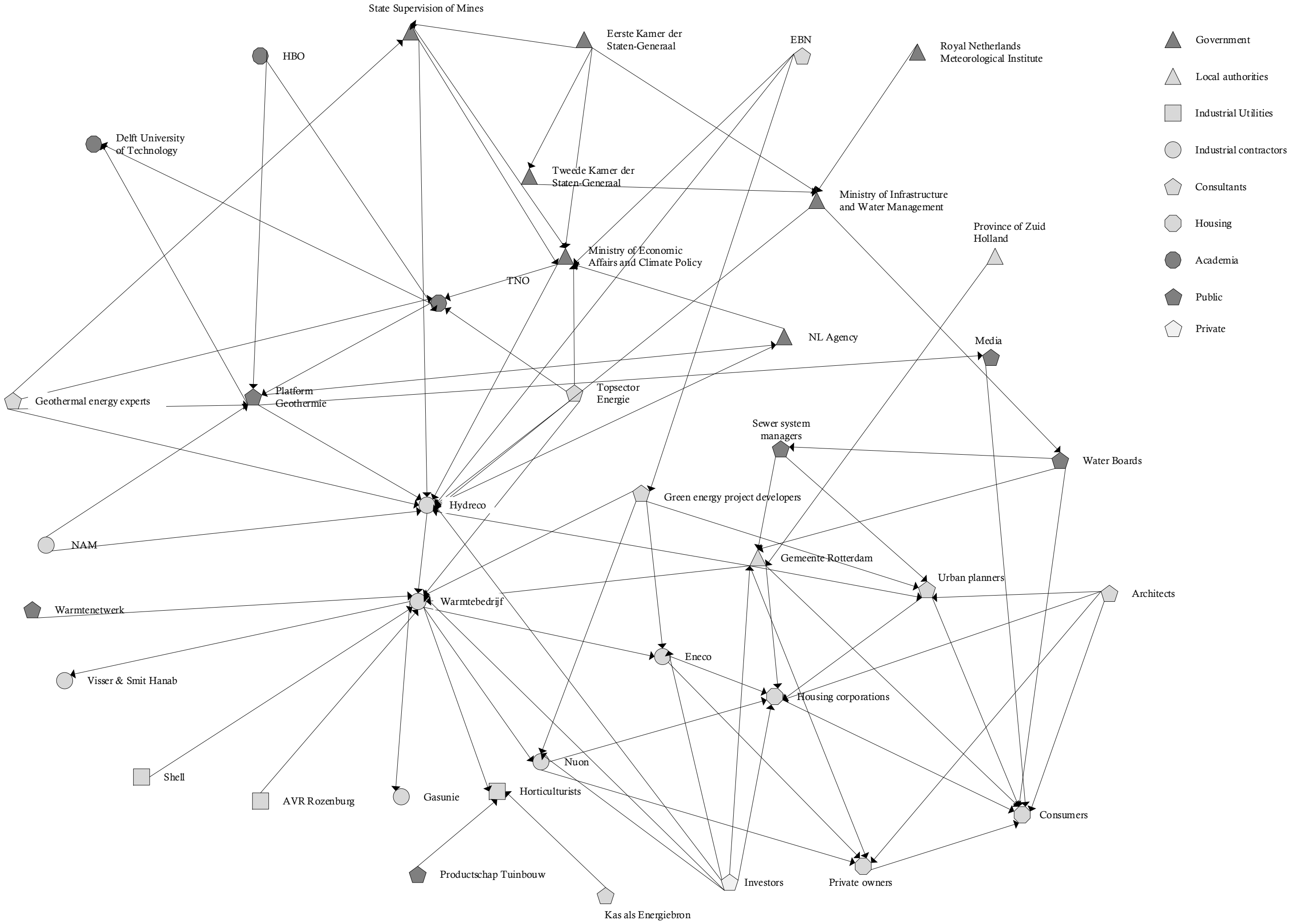

Figure 16. Network of information and resource exchange between stakeholders involved in the two value chains.

6. Discussion

To reduce greenhouse gas emissions in the built environment and dependency on carbon-based energy sources, we need to rethink how we prioritise decisions and adopt an integrated understanding of urban energy systems. Direct application of medium or low temperature geothermal energy in fourth generation DH systems is a radical innovation that occurs in protected spaces within a supportive framework that fosters the development of an alternative local emission-free regime. From supply to demand, each phase involves different questions that not only lead to alternative routes along the decision tree, but also to very different sets of stakeholders. Making this clear within the framework proposed in this paper supports decision makers and increases knowledge capacity. The framework connects different scales and supports decisions about aspects to the implementation of a new energy supply that are of very different natures.

At the building scale, it is crucial to classify the dwelling types and estimate their energy performance. When testing the developed framework on a residential area, the first step is to collect building energy consumption data and visualise the heat demand. At an early phase of the decision-making process, the creation of maps in GIS depicting energy labels and gas consumption rates provides a first estimation of the annual heat demand. This allows for identification of potential hot spots for district heating and scans large urban areas. If a high potential for district heating is detected, the heat demand must be analysed at a high spatio-temporal resolution to effectively balance supply and demand on an hourly basis. This can be achieved by coupling the GIS model with urban building energy simulation software.

At a district level, the heat demand modelling results show a positive correlation between a low annual heat demand per surface area (kWh/m^2/year) and a high energy label, with only a few exceptions. The same applies to the relationship between PC6 gas consumption data and annual heat demand per surface area, although the former is calculated on an aggregated level. Dwellings with a high energy performance have on average an annual heat demand per surface area lower than 75 kWh/m^2/year and are registered with an energy label of at least B. From an energy saving perspective, such dwellings are well-suited for a connection to low temperature district heating (LTDH) networks because they facilitate a system with reduced heat losses and investment costs for refurbishment.

When coupling the constant supply of the geothermal source with the fluctuating heat demand of buildings in the area, it was concluded that geothermal energy should serve as a source that covers the base load demand (3442 kW). Geothermal can be used to cover 40% of the maximum heat demand and 70% of the annual heat demand. The key prerequisite for this is to store excess heat in the summer months when the head demand is low. Similar rates for direct use of geothermal energy have also been reported by Björnsson [43]. Moreover, the geothermal source could potentially cover 11.2% of the domestic space heat and hot water demand of the entire plan area, thereby contributing considerably to greening the heat supply. A combination with other renewable sources such as biomass and solar thermal energy in an LTDH system would even further eliminate the use of natural gas and carbon-based heat sources.

Furthermore, assessing the suitability of different clusters in the plan area for integration into a heat network requires interdisciplinary work. While the space heat demand together with energy labels and gas consumption rates give an elaborate picture of the thermal needs and efficiency of buildings, morphological patterns of urban fabrics are critical in spatial planning. Urban form indicators were used in this work not only to evaluate the profitability of the DH network but also to assess whether there is enough space to make interventions at the street and district scale. The development of energy communities is a call for technical renovation assignments on the consumer side. As the framework suggests, the most critical factor for replacing a building's natural gas boiler with district heating is the supply temperature of hot water. Depending on the type of the heat network, different houses are adaptable to the system and alternative options are available to cover the needs both for space heating and for domestic hot water.

At the district scale, installing a new pipeline configuration for DH requires that the underground infrastructure will be modified. In Rotterdam the local legislation allows streets to be opened only once every five years. The municipality is making an agenda for the whole city by working together with urban planners and housing corporations in order to coordinate the gas and sewer network replacement, building refurbishments, and new housing projects. In this way, time intervals can be indicated for the entire city to optimally plan when to start the energy transition in neighbourhoods [44].

In addition, this research has shown that it is easier to connect houses owned by housing corporations rather than houses that are owned by individuals. Since the decision on retrofitting a building is made by a housing corporation, all occupants are represented by the housing corporation. This means that a reduced number of actors is involved in the guiding coalition to the heat transition in a neighbourhood and makes the decision-making process less complicated. Hence, a shared connection can be implemented at the street level that utilises one heat exchanger between the distribution network and the multiple adjacent houses that are owned by the same stakeholder. Furthermore, housing corporations can pool funds through subsidy schemes for building refurbishment and adaptation strategies, thereby facilitating decision making and reducing investment costs [45].

To fully outface the carbon-based regime, niche novelties must bridge the gap between producers, suppliers, and end users through community-based institutional arrangements. Thus, a collaborative and participatory governance process must be ensured that brings the various stakeholders together. This urban development participation involves local working groups at a city scale (political, administrative, industry, utilities, public, and private) that collaborate in the decision-making process and exchange opinions and information in order to find solutions for the entire community (Figure 17).

Such a participatory approach demands suitable spatial planning, policies that regulate district heating networks, and encouragement of policymakers and governments to mobilize resources for sustainable energy systems. In spatial planning there are many different processes and stakeholders involved that result in multiple considerations to account for in decision-making in addition to heat supply, such as social and environmental implications, land distribution, and the well-being of residents. Furthermore, local authorities should promote energy-neutral buildings designed for integration with smart thermal grids and establish new operation and maintenance processes that increase energy efficiency and reduce costs.

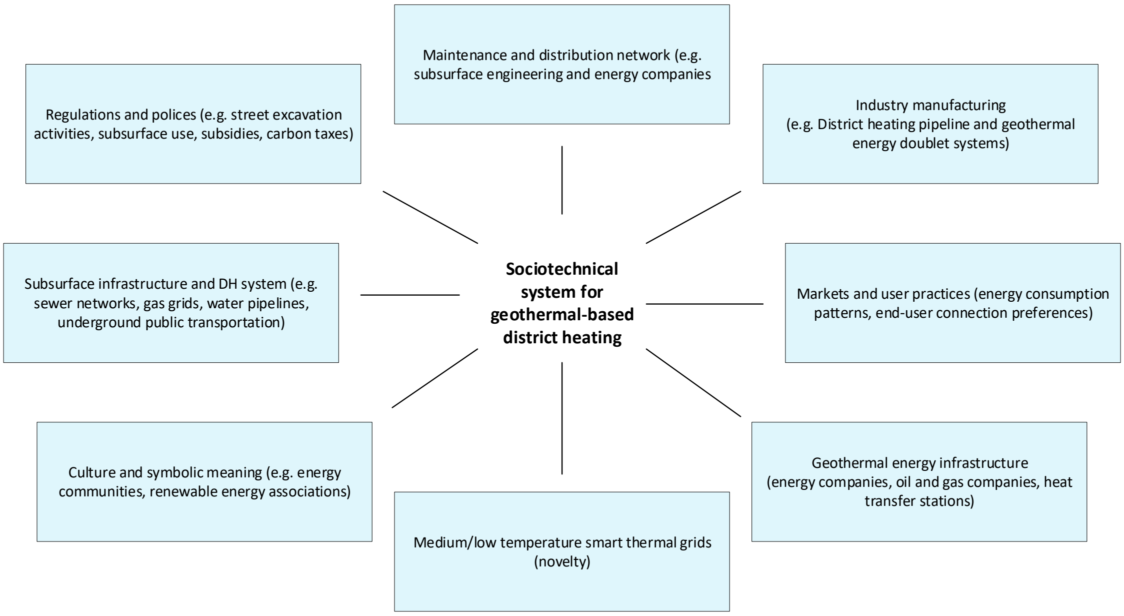

Figure 17. Sociotechnical system for geothermal-based district heating. Based on Geels [46].

To transform local energy systems, the community needs to create a shared vision and an urban master plan that can be achieved by means of physical interventions that comply with rules laid down in the legislative context. It will take at least a decade for the multiple stakeholders involved to articulate their early ideas, create visions, and transform the sociotechnical regime. Decision-support mechanisms are extremely important as there are dependency paths in the process of integrating technical components in urban planning.

Nevertheless, there are many institutional barriers that hamper a speedy transition. Institutional entrepreneurs and political leaders are central to encouraging the transition. Individual actors such as consumers overcome issues at the micro level with their decisions by implementing refurbishment and retrofit strategies on their dwellings, in consultation with architects, while urban developers have the knowledge capacity to guide their actions towards greening the neighbourhood. Energy companies can make a better use of resources in line with the fight against climate change. At the same time, efforts should be focused on disseminating information to residents in order to build community capacity and provide incentives.

7. Conclusions

This paper focuses on identifying critical decisions made by different stakeholders in order to overcome technical, spatial, and socioeconomic barriers in the supply-demand system of geothermal energy and DH networks. There is an urgent need to open up a platform for stakeholder engagement at a local level and to create opportunities for a face-to-face dialogue to respond to the complexities of the realities that the local governments are facing by adopting a multi-scale approach towards urban energy systems. The notion of platform highlights a broader sociotechnical system in which novelties such as smart thermal grids and medium or low temperature geothermal energy reservoirs need to be positioned and where individual initiatives create a guiding coalition.

Local authorities are showing a great agency and willingness to be protagonists in efforts to tackle the challenges related to greening the heat supply with renewable sources such as geothermal. To make the most of such agency, it is crucial to remove the biases that they face in terms of inadequate funding, lack of representation and voice, isolation, and difficulties in creating networks. These questions are crucial and difficult to address because they indicate how climate change mitigation relies on the capacity and capability of local governance.

Digital solutions (GIS) were used as a tool to link the digital and physical world and connect two different domains: energy planning and urban planning. A decision-support framework was gradually developed in an iterative process to indicate different decision pathways when connecting geothermal supply with demand for space heating and hot water. This way the framework contributes to shortening the distance between supply and demand and by highlighting the most pressing challenges facing connecting the supply of geothermal energy into existing or to-be-constructed district heating.

Location-specific urban samples in GIS enabled this work to identify important differences that affect decisions in district energy planning. This is innovative because it connects urban construction on a larger scale and shows potential to include district heating in the network. Thus, GIS gives a contextual assessment of costs and benefits of the implementation. The assessment is accomplished by comparing a range of urban typologies that vary in terms of building energy performance, heating demand, gas consumption, morphological characteristics (street width and network, building block footprints), and housing ownership schemes. When considering the expansion of a heat network in a neighbourhood, particular attention should be paid to the spatial context, as besides retrofitting buildings, interventions are necessary on the street level too. Urban form indicators are indispensable for the decision-making processes because they help identify spatial conditions that are optimal for district heating systems. These indicators combined with demographic indicators such as population density can help steer decisions towards neighbourhoods where a heat transition is worth the high costs of pipeline installation and where social benefits can be maximised.

On an urban level, stakeholders need to consider the proximity of houses to the local geothermal source and the heat network, the linear heat density as a measure of cost-effectiveness of the pipeline installation, and retrofit strategies required from the end user. The supportive framework is versatile and can be replicated in different case studies to steer decisions and indicate the most favourable conditions for a long-term application of geothermal energy in DH networks. Municipalities and urban planners can replicate the GIS-based model to assess the local heat demand and create climate-proof scenarios and heat transition pathways. The framework can also help in finding hot spots for building refurbishment, thereby assisting the involved actors to discover the most cost-saving renovation strategies.

On a positive note, interaction between academia and local authorities reveals a genuine interest in deepening of knowledge by trying to identify together long term-solutions to successfully develop a resilient, adaptive, and sustainable energy infrastructure in local communities. The focus should be put on understanding how macro processes like climate change emerge in urban environments, exploring how these processes are addressed by local authorities with the challenges they face, and identifying together a mechanism to support them.

8. Future Recommendation

This research calls for future development of the decision-support framework by filling in the knowledge and information gaps within the framework as well as by conducting supportive studies for geothermal energy projects including a cost-benefit analysis to evaluate the net social benefits in the long-term and an environmental impact assessment to determine the possible negative externalities on climate, groundwater, and soil. Furthermore, a life cycle analysis study would be very useful to emphasize the reduction of greenhouse gas emissions when comparing the future use of medium or low temperature geothermal energy sources in LTDH networks to the current application of carbon-based heat sources in HTDH networks.

As regards the network of actors, this project attempts to shed light upon the multiple stakeholders involved in geothermal energy projects in the Netherlands. However, this classification was only rationalistic since an empirical analysis of stakeholders involved in geothermal energy in the Netherlands is missing in the literature. There is no one single method for stakeholder analysis that is ideal. To this end, selecting a methodology depends on the time constraints, availability of resources, and the scope of the project. Combining both empirical and theoretical approaches and finding similarities among the analysis outcomes is the best practice to identify and map the various actors and decision makers.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A. Decision-support framework focusing on a geothermal energy source in district heating systems.

Decision Variables	Values/Characterisation	Decision Questions	Assessment	Decision Symbols	Key Issues/Recommendations
Phase 1. Supply of Heat					
Location	IJS-01	Is a DH system in proximity?	Yes	+	Explore the compatibility with the geothermal source
			No	−	High costs for DH pipelines if the DH network is located far from the source
		Is there enough space above ground for the installation of a geothermal doublet?	Yes	+	Even though geothermal doublet installations have a small land footprint, a minimum of 100 m^2 are needed for the installation
			No	−	Boreholes can be drilled diagonally, but the installation above-ground should be located as vertically to the reservoir as possible
Supply/return temperature	55/20 degrees Celsius	Connection to a high or low temperature heat network?	High	~	High temperature heat networks are efficient because they can cascade heat from high heat demand sources and sinks (e.g., industries) to low heat demand sinks (e.g., houses). However, it is difficult to integrate renewable heat sources
			Low	+	Optimal network for integration of other renewable heat sources to fully decarbonize the heat sector. Attention should be given to risks with legionella bacteria for DHW. Temperature needs to be higher than 50 degrees Celsius if DHW is supplied by district heating
Capacity	5.2 MW	Is there a high enough heat demand for the capacity of the source?	Yes	+	The heat demand of the area needs to be analysed. Not all houses are equally fit for DH connection. Heat demand profile depends on buildings
			No	−	The geothermal project is not economically viable
Peak heat load	12,547 kW	Use the source as a baseload?	Yes	~	Advantage: Reduced costs requirements: higher heat demand to distribute the supply and additional heat sources (not implementable without back-up sources)
			No	−	This means that the source will be used to cover the peak load demand. Very expensive at the moment
Full load hours	30,155 MWh/year	Operate on full load hours?	Yes	−	Expensive and need for back-up devices that run on biofuels for peak heat load
			No	+	Use as a baseload
Phase 2. Connection to a heat network					
Distance to transport network		Connect to a transport network?	Yes	~	If a transport network is in proximity, consider using a heat exchanger to mix and upgrade the temperature. However, the system will become less efficient the larger the temperature difference between source and heat transport
			No	~	Find a distribution network
Distance to distribution network		Connect to a distribution network?	Yes	~	If the temperature of the source is compatible to the temperature of the distribution network, then a connection with a heat exchanger in between is the best choice
			No	~	Explore the possibilities to install an independent DH installation
Local heat sources	Industries/CHP/WIP/Biomass/Solar thermal	Add local heat sources into the system?	Yes	+	Optimal if the heat sources are renewable. If there is a biomass plant and/or solar thermal energy, create a smart thermal grid using geothermal for the baseload. Residual heat from industries, cogeneration plants, and waste incineration plants are fossil-based.

			No	−	Expensive to fully operate the whole system solely on geothermal energy
Location of heat transfer stations (HTS)	- Maasstad Hospital - Groene Kruisweg	Is there an HTS in proximity?	Yes	+	Intersection of transport and distribution networks. The heat exchangers could be utilised from these booster stations
			No	−	There is a requirement to install new heat exchangers between houses and the distribution network
COP for heat pumps		What is the energy input needed?	High	−	Depending on the supply temperature of the DH network, the higher the temperature, the higher the electricity input required. This also translates to higher GHG emissions
			Low	+	Energy savings and lower CO_2 emissions
Fuel type for back-up boilers	Biofuels	Use natural gas or biofuels?	Yes	~	Increases the GHG emissions but secures stability in the system
			No	~	Decreases the GHG emissions but very expensive to operate on full load with geothermal energy
Peak supply	-	Use other heat sources for the peak supply?	Yes	?	Depends on availability of the sources, intermediacy and diurnal supply
			No		
Percentage of heat distribution losses		Are the heat distribution losses higher than 10%	Yes	−	HTDH have higher distribution losses
			No	+	4th generation DH systems have lower distribution losses
Heat storage	-	Is there a possibility to combine with Aquifer Thermal Energy Storage (ATES) or Borehole Thermal Energy Storage (BTES)?	Yes	+	Heat storage in aquifer reservoirs will increase the overall efficiency of the system. Attention: potential implications involve disturbing the hydrology balance
			No	−	Less efficient system
Linear Heat density (LHD)		Is the LHD for this scenario in a suitable range?	Yes	+	Target value is 1.8 MWh/m/year for distribution losses lower than 10% and reduced costs
			No	−	The geothermal energy project will most likely have increased costs
CHG emissions		What is the reduction in CO_2 emissions?	Significant	+	Combination of energy used for back-up boilers and heat exchangers. Depends on the previous decisions made for the system
			Moderate	~	
			Insignificant	−	
Phase 3. Spatial analysis of urban context					
Buildings construction period		What are the urban typologies of the selected fabrics?	New	+	Better to select relatively new buildings because they are better insulated. Best candidates for LTDH networks
			1990s	+	
			1970s	~	Expensive refurbishment strategies need to improve insulation and make these buildings adaptable to DH
			post-war 1950s	~	
			pre-war	−	Mostly unsuitable unless substantial renovation is done
Spaciousness (OSR)		What is the ratio between open space and gross floor area of the dwellings?	High	−	A balanced ratio between open space and gross floor area is recommended. On one hand, sufficient open space is good for the distribution. On the other, sufficient gross floor area indicates a high enough heat demand
			Balanced	+	
			Low	−	
Coverage (GSI)		What is the ratio between open space and built-up area of the urban fabric?	High	−	A balanced ratio between open space and built-up area is recommended for the same reasons as stated previously
			Balanced	+	
			Low	−	
Building intensity (FSI)		What is the ratio between gross floor area of the dwellings and area of urban fabric?	High	+	High FSI ratios indicate a larger gross floor area, which shows that a relatively higher heat demand is concentrated in less space
			Balanced	~	
			Low	−	

Dwelling density		How would the concentration of dwellings in the urban fabric be characterised?	High	+	High dwelling densities are beneficial for the project because the length of the DH network decreases. A minimum of 15 dw/ha is required for the operation to be economically viable
			Moderate	~	
			Low	−	
Network density		Is there a good connectivity of the street network?	Yes	+	High network densities indicate better connectivity of the street network, hence connection to end users is easier
			No	−	
Street width		Are the streets spacious enough?	Yes	+	Very narrow streets (below 4 m) should be avoided when designing the DH pipeline configuration because there is not enough space for DH pipelines
			No	−	
New housing developments	De Kuip, Lombardijen, Katendrecht, Groote Ijsselmonde	Are there new housing development projects planned in the near future?	Yes	+	Best candidates for implementation of LTDH networks. Easy to coordinate the DH network expansion with building construction activities and install radiant floor heating
			No	−	
Underground infrastructure replacement projects	Reyeroord and Groenenhagen	Are there any areas planned for pipe replacement projects?	Yes	+	Opportunity to install DH pipelines if applicable in the area and coordinate the two activities
			No	−	
Phase 4. Housing adaptability					
Energy label	Mostly A and B. Only a few have a C label	Are the selected buildings energy efficient?	Yes	+	An LTDH network requires that the houses have a high energy efficiency (higher than C) with reduced heat losses
			No	−	
Heating system	Natural gas/DH	Is the house already connected to a DH network?	Yes	+	Existing connections are suitable clients because the energy infrastructure is already installed. Shifting to LTDH operating at a medium temperature requires a replacement of the radiators with larger ones
			No	?	It should be examined whether the house is in proximity to a DH network
Domestic hot water (DHW)	Individual boiler/heat interface unit (HIU)	Is there a centralised supply of DHW in the building?	Yes	+	HIU are central boilers installed in apartment complexes that provide DHW to multiple dwellings. When DH is connected to the building at a temperature > 50 degrees Celsius DHW can be supplied along with spatial heating
			No	~	Usually individual gas boilers are used for DHW purposes. These should be replaced either by DH if temperature is above 50 degrees Celsius or with a solar thermal boiler on the roof
Radiant heating	Floor heating/wall-mounted radiators	What type of radiators will be installed?	Floor	?	For temperatures below 50 degrees Celsius, floor heating should be used. However, difficult to implement in existing houses that have wall-mounted radiators
			Wall-mounted	?	Above 50 degrees, implementation in old houses is easier by replacing the wall radiators with larger ones
DH connection strategies to end user	Direct connection or indirect connection with heat interface unit (HIU)	Direct connection or indirect connection with heat interface unit (HIU)?	Direct	~	Although direct connections have reduced distribution losses and costs there is an increased risk for contamination and leakage
			Indirect	+	Safer option than direct systems. A heat interface unit (HIU) separates the primary flow of the street level with the secondary flow of the building level. However, this option has increased costs
	Individual or shared connection	Individual or shared connection?	Shared	+	Reduced costs, road excavation, pipework length, and number of connections
			Individual	−	Expensive and labour intensive to apply on a large scale because of the high excavation costs for each house
	Ground level/roofs	If shared, then connection to multiple buildings from the ground	Ground level	~	Reduced costs because there is only one branch on the street level. There might be cross-boundary and coordination problems when connecting adjacent dwellings and gardens

		level or through roofs?	Roofs	~	Road excavation, pipework length, and the number of connections is reduced. Problems may arise concerning legal rights and coordination of multiple property owners
Domestic retrofit strategies	Floor heating/wall-mounted radiators	Install new radiant floor heating or replace or retain current radiator and pipework?	New	~	For new houses, install radiant floor heating and provide low/medium temperature heat
			Replace	~	For old houses and for LTDH supplying heat at a temperature that is higher than 50 degrees Celsius, replace radiators with larger ones
			Retain current	~	For old houses heated with gas, retain current radiators if the temperature of the geothermal source is higher than 90 degrees Celsius
	HIU or DWH cylinder	Install new HIU or retain DWH cylinder?	New	+	For old houses heated with gas, install a new HIU and replace the DHW cylinder together with new mains pipework to provide both heating and DHW
			Retain current	+	Retain current only if it is heated with solar energy
Phase 5. Heat Demand/End user					
Gas consumption (PC6)		Are the gas consumption levels high in the area?	Yes	–	Gives an indication of the average gas consumption in the area. Not very precise but useful for a comparison with the modelled energy demand and energy labels to have an overview of the energy performance of buildings in the area
			No	+	
Building energy simulation		Is there a high enough heat demand in the modelled area?	Yes	+	
			No	–	3D models that yield realistic diurnal heat demand curves at the building scale. Very useful for future predictions and balancing supply with demand
		Is there a strong correlation with energy labels for the same dwellings?	Yes	+	Validates the outcomes of the heat demand analysis. Buildings that have a low heat demand and high energy labels are more energy efficient with reduced heat losses. Best candidates for DH connection
			No	–	If the energy label is high enough, select these houses
		Is there a strong correlation with gas consumption PC6 levels of consumption on the scale of the urban fabric?	Yes	+	Validates the outcomes of the heat demand analysis. These buildings have a low heat demand and high energy labels, thus more energy efficient with reduced heat losses. Best candidates for DH connection
			No	–	Give priority to the other indicators for the assessment
		Select dwellings that have a low heat demand (kWh/m^2)	Yes	+	Low heat demand per m^2 is associated with high building energy efficiency
			No	–	High heat demand per m^2 is associated with poor energy efficiency
Housing ownership		Are the houses rentals or owner-occupied?	Rental	+	Social housing
			Purchased	–	Private homeowners
		Do the houses belong to a housing corporation?	Yes	+	Easier to make an agreement on the end user side for multiple dwellings at the same time
			No	–	Difficult to coordinate DH connection in the neighbourhood
Building construction year		Are the dwellings relatively new or old?	New	+	Best candidates for LTDH networks
			Old	–	Old buildings should be avoided for LTDH networks because they are incompatible and have a poor energy performance leading to high heat losses
Dwelling type		What is the composition of dwelling types for this scenario?	MFH	+	Apartment and gallery complexes are more likely to have a higher heat demand density that improves the overall economics of the system. Also, usually the owners are housing corporations and it is easier to implement a connection
			TH	+	Terraced houses are also beneficial in the sense that a shared connection on the street can take place. If most of the landlords are private owners there is a difficulty in coming to an agreement for all the houses on the street

			SFH	−	Single family houses, especially the detached ones, are usually located in less dense areas and most often owned by individual homeowners
Building height		Are most of the buildings high-rise or low-rise in the area?	High-rise	+	High-rise residential buildings are MFH houses, thus same recommendations apply as described above
			Low-rise	~	Depends on whether the type is a TH or SFH
Population density		Is the concentration of humans relatively high or low in the urban fabric?	High	+	More people will be serviced with clean energy in relation to the area
			Low	−	Less people will be serviced with clean energy in relation to the area

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