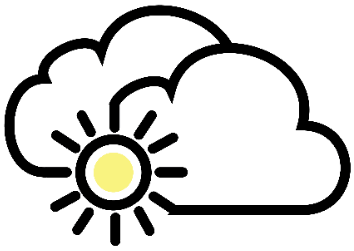
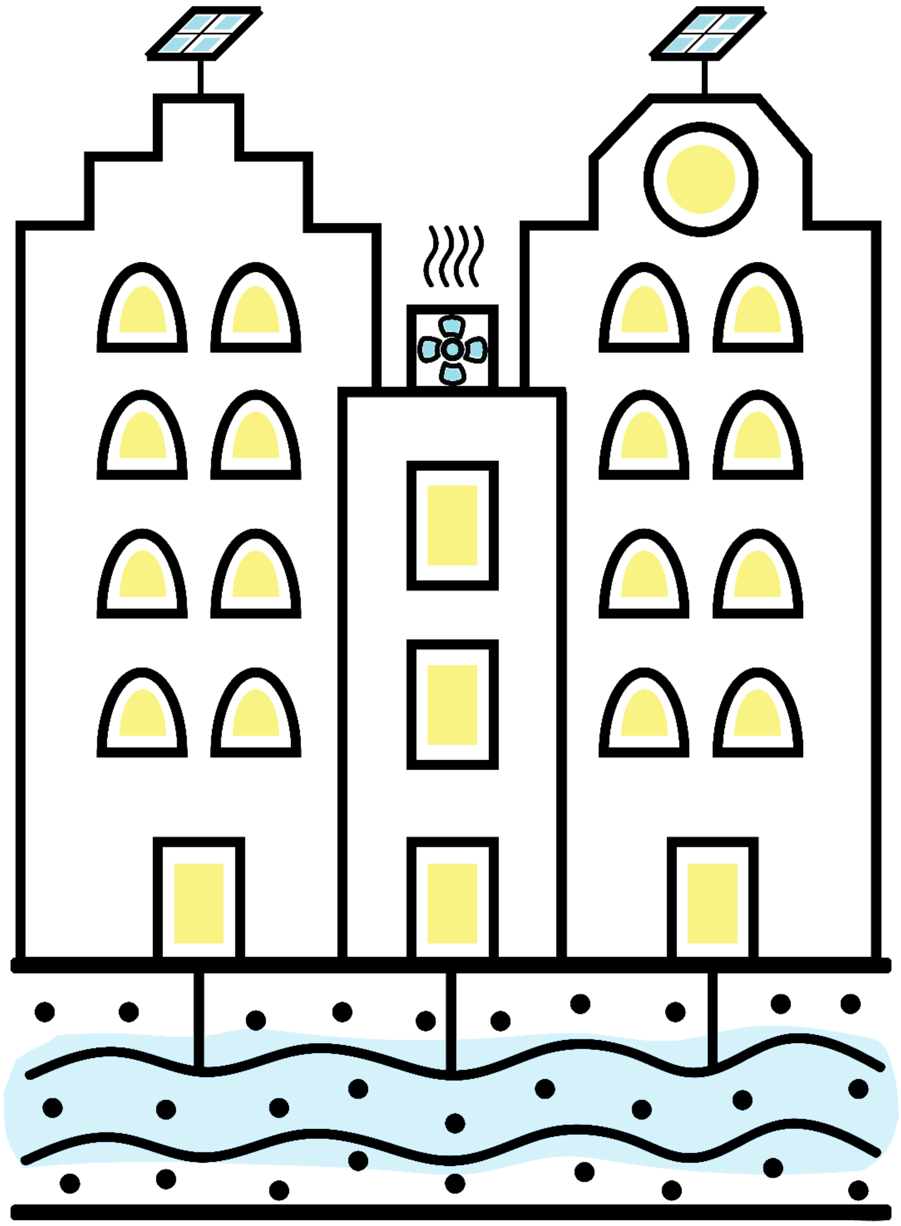


NO GAS ALL LOCAL

developing a renewable-based and decentralised energy system for the historic centre of amsterdam

master's thesis by melih fırat ayaz



COLOPHON

Title No gas all local: Developing a renewable-based and decentralised energy system for the historic centre of Amsterdam

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PREFACE

Working on such a complex societal issue as the climate crisis that leaves nowhere untouched in our daily life is always the greatest professional motivation for me as an urbanist, and this thesis study provided me with the opportunity to test and expand my understanding of human-nature interaction through urban energy systems. Even though the scope of this research was highly limited when considering the scale and complexity of the energy transition phenomenon, I have gained great insights into how to respond to such metropolitan challenges in a different way that involves radical strategies and creative tactics. As I expected, it was not an easy job for me to do since the research was mainly structured around the technical aspects of urban energy infrastructures that require engineering skills and knowledge. Yet, I have managed to get the job done thanks to the great help of my supervisors, family, and friends. First of all, I would like to thank my supervisors Regina Bokel and Hung-Chu Chen who patiently helped me get through the demanding research process. Likewise, I appreciate the help and advice from Maéva Dang and Paul Voskulien as part of the urban energy team at AMS Institute. I would like to send special thanks to all my friends in Amsterdam for the great experience and joy we had together in the city during my studies, and I am so grateful to my mother, father, and all my family for their remote but warm support. Finally, I am grateful for the financial sponsorship of the government of the Republic of Turkey that enabled me to pursue my studies in the Metropolitan Analysis, Design and Engineering master's program at AMS Institute.

ABSTRACT

Urban energy systems are the key elements of combating the climate crisis as the energy transition is crucial to curb greenhouse gas emissions in urban areas, one of the main drivers of climate change. As such, there is a great effort in Amsterdam to phase out natural gas use by 2040, and to become carbon neutral by 2050. It is a great challenge since the existing centralised energy systems are specifically built on the transportation and use of large amounts of fossil fuels while renewable energy has many limitations due to the volatility of its sources, lack of capacity for energy load and storage. Yet, since renewable energy sources are locally available everywhere, the establishment of decentralised renewable energy infrastructures based on local sources can help overcome these limitations. On this basis, this research explores the possibility of developing such systems through a case study in the historic centre of Amsterdam where many local challenges like urban monumentality pose risks for the energy transition. The research is structured around the use of Smart Urban Isle approach as a methodological tool to reveal local potentials for energy reduction, reuse and production, and to design energy concepts based on these potentials to reduce the reliance on external energy input. The results of the case study show that it is possible to cover the heat and cold demand with local sources and to cut almost half of the external energy input into the site without bringing any significant pressure onto the power grid. This outcome is highly promising as it proves that such local interventions can make great contributions to the energy transition process by significantly reducing the tension on the regional and national energy systems for the replacement of fossil fuels. As for the field of architecture and urban planning, the results implicate that the bioclimatic design principles, mixed-use of buildings and urban spaces, and small-scale and decentralised urban infrastructures based on the circular economy and self-sufficiency principles are crucial to achieve higher energy efficiencies and more local energy inputs.

ABBREVIATIONS

ATES	Aquifer thermal energy storage
BTES	Borehole thermal energy storage
BZK	Ministerie van Binnenlandse Zaken en Koninkrijksrelaties
CBS	Centraal Bureau voor de Statistiek
COP	Coefficient of performance
DHW	Domestic hot water
GIS	Geographic information systems
ICT	Information and communications technologies
KNMI	Koninklijk Nederlands Meteorologisch Instituut
KPIs	Key performance indicators
MVHR	Mechanical ventilation with heat recovery
NA	Not applicable/available
NEN	Nederlandse Norm
NHER	Noord Hollandse Energie Regio
PDOK	Publieke Dienstverlening Op de Kaart
PVT	Photovoltaic thermal
RVO	Rijksdienst voor Ondernemend Nederland
SUI	Smart Urban Isle
UNESCO	United Nations Educational, Scientific and Cultural Organisation
WCED	World Commission on Environment and Development

UNITS

CO_2	Carbon dioxide
°C	Degrees celsius
GJ	Gigajoule
h	Hour
ha	Hectare
K	Kelvin
kJ	Kilo joule
kWh	Kilowatt hour
l	Litre
MWh	Megawatt hour
m	Metre
m^2	Square metre
m^3	Cubic metre
mm	Millimetre
n	Number
%	Percentage point
s	Seconds
TWh	Terawatt hour

CONTENTS

1. INTRODUCTION

A. Background Information

The rapid urbanisation of human societies on a global scale during the modern era provided humanity with the opportunity to satisfy their basic needs and to live at ease in many regions of the world. Yet, this whole progress has been enabled by the manipulation of nature, depletion of limited resources and release of an excessive amount of waste and emissions into all spheres of the planet. As climate change is escalating into an existential crisis for life on Earth, the reorganisation of the modern city in line with sustainability is key to curbing human impact on nature. In doing so, the transformation of urban energy systems plays a major role as energy production and consumption activities based on fossil fuels are the biggest contributors to the trends that paved the way for the climate crisis.

Urban energy systems consisting of power and gas grids, and district heating networks to deliver final energy to end-users are traditionally connected to larger scale and centralised infrastructure systems transporting energy carriers on regional, national and global bases. Thanks to the highly optimised and advanced technological and infrastructural systems for extraction, transportation, storage and use of fossil fuels, primary energy sources for these systems are still mainly fossil-based all around the world. Since these centralised energy systems require a large amount of energy, it is a great challenge to replace fossil fuels with renewable energy sources due to the fact that renewable energy has many limitations because of the volatility of renewable energy sources, limited capacity for energy load, and lack of advanced storage systems [1].

Yet, renewable energy sources such as solar, wind, hydro, and geothermal are locally available almost everywhere in the world, offering a great potential for the development of decentralised and fragmented energy systems based on these local sources in cities and regions [1, 2]. Bringing primary energy sources and final energy supply closer, these local energy systems can help eliminate the need for large scale energy infrastructure systems relying on fossil fuels. Therefore, while the replacement of fossil fuels in the large scale and centralised energy systems is challenging, shifting the focus towards local level can open up many opportunities to tap into renewable energy solutions, and to reduce the dependency on external energy inputs.

B. Problem Statement

Since all efforts mainly focus on eliminating the use of fossil fuels with the advent of the Paris Agreement, the Dutch government has adopted plans to transition towards renewable-based energy systems and to make the country carbon neutral by 2050 [3]. As such, the Municipality of Amsterdam followed the same pathway by setting a target to reduce greenhouse gas emissions by 55 % by 2030, and 95 % by 2050 from the 1990 levels and to become completely gas-free by 2040 [4]. This plan includes the establishment of renewable-based energy systems in the city by retrofitting the existing infrastructure as well as complying with the requirements for the new urban development projects. Moreover, the Municipality also plans to become fully circular by 2050, which means external primary energy inputs need to be reduced to zero while transitioning to renewable energy [5]. The realisation of these two ambitious plans is a demanding task for the city as achieving carbon neutrality and circularity poses many technical, financial and societal challenges.

Figure 1. Historic canal houses of Amsterdam on Singel Street (own photo)

In Amsterdam, 60 % of the total CO_2 emission comes from natural gas use in buildings, and the production of electricity and heat for buildings [4]. Therefore, retrofitting the building energy systems is a major part of the energy transition process in the city. Yet, the historic centre has many local challenges in this regard due to its monumentality and density. There are three conservation areas including the Canal Ring Area which is one of the World's Heritage Sites [6] and more than 9.000 national and municipal monumental buildings in the historic centre [7]. This cultural status of the city blocks many forms of alterations in buildings for energy retrofitting including insulating building envelopes or installing solar panels on roofs [4, 8]. Besides, the historic centre is a densely populated area built on a highly sensitive canal structure, which limits the use of underground space for new infrastructural additions such as new pipelines for the expansion of district heating networks [4, 8, 9]. As such, the establishment of a local and renewable-based energy system in the historic centre requires a careful examination of the existing buildings and infrastructure, and the local capacity for renewable energy generation and storage systems.

C. Research Aim & Scope

As briefly discussed above, the shift towards renewable energy and the localisation of urban energy systems are the core elements of the energy transition process. In this regard, Amsterdam offers a great opportunity to study energy transition thanks to the municipality's ambition to achieve carbon neutrality as well as the local challenges that need to be overcome. As such, this research explores the possibility of developing a renewable-based and decentralised energy system through a case study in the historic centre of Amsterdam. In doing so, the research uses the Smart Urban Isle approach as a methodological tool to understand the local energy potentials, and develop energy concepts for the case study. The scope of this research covers the technical challenges regarding the retrofitting of the energy systems of buildings, and this technical exploration is structured around the city's unique urban characteristics and challenges.

D. Reading Guide

This report provides information on the key elements of this thesis study in the following sections. Literature Study presents the theoretical basis of the research through analysis of the key concepts regarding the energy transition from a historical perspective, and the local context of Amsterdam. Afterwards, Case Study lays out the basic information and data from the case study site, pointing out its urban and energetic characteristics. The fourth section is Research Design in which the methodological structure of the research is explained. The detailed information on the research questions, approach and methods is provided in this section. Afterwards, Results presents the main outcomes of the research including the energy potentials for reduction, reuse and production, energy concept development and the quantified evaluation of the concepts. While, the academic and societal relevance of the main findings, shortcomings of the research and recommendations for further research are presented in Discussion, the last section, Conclusion, summarises the key findings of the research.

2. LITERATURE STUDY

A. Key Concepts

The historical background of the energy transition phenomenon traces to the 1970s when the oil crisis triggered by the political and economic turmoil sparked new discussions around the global energy regime. As Berman [10] describes, this period marked the end of the "expressway world" based on cheap and abundant fossil fuels, once the limitation of natural resources was realised. New concepts were developed on this basis such as "global equilibrium" from the Club of Rome's Limits to Growth [11] questioning the status quo of the global economic system, and "sustainable development" from the United Nations' Our Common Future report [12] focusing on the efficient use of the limited resources. These concepts paved the way for the development of new energy strategies and design principles for the built environment.

While the early research focused on the efficient use of limited energy sources, the focus shifted towards more comprehensive approaches including renewable energy systems when the impacts of the global warming fueled by the greenhouse gas emissions caught global attention in the 1990s [13, 14]. One of the most influential energy strategies, "the Trias Energetica", was developed by Lysen [15] during this period on the basis of an integrated energy strategy based on energy reduction, renewable energy supply, and clean use of remaining energy. This trend brought more attention to energy design principles at building level. While energy labels for buildings and green building certifications increasingly became popular in the property sector, "zero energy building design" [16] was developed on the basis of reducing energy demand to a highly low level and covering the remaining demand with renewable energy sources.

In the 2000s, the concept of circularity started dominating the sustainability field, popularised by various works such as "Cradle to cradle" [17], "The circular economy" [18], "Doughnut economics" [19]. Based on the acknowledgement of the tension between humanity and nature, this concept aims at reducing this tension by minimising human dependence on natural resources via circular design principles. This led to the establishment of a new research focus on the use of local renewable energy potential at the highest level to minimise the external energy input in cities [20]. Afterwards, thanks to the incorporation of the exergy concept with the energy transition strategies, the idea of energy reuse was developed [21, 22]. According to this, the heat generated for urban energy systems generally has a higher quality than needed [23]. By means of an energy reuse system, the excess heat can be recirculated between different functional units of an urban energy system or can be stored in storage systems (e. g. ATES), enabling reducing external energy inputs [20, 23]. On this basis, "the New Stepped Strategy" was developed with the reformulation of "the Trias Energica" in a three-step approach as follows: Reduce the energy demand through bioclimatic design, reuse waste heat streams, solve the remaining energy demand with renewable energy [20, 23].

With the addition of energy reuse, the previous focus on energy design at building level has been expanded towards larger scales such as neighbourhood and district levels to benefit from local energy potentials at the highest level [2, 23, 24]. As such, decentralised/distributed local energy systems started gaining a great attention since renewable energy enables the development of such systems completely based on local potentials. In contrast to the rigidity of the traditional energy systems which are centralised and based on one type of energy carrier, these decentralised energy systems can be highly resilience and flexible thanks to the use of various local sources that enables bringing energy production and use closer and developing a multi-energy systems combining multiple energy carriers with different technologies and solutions [1, 2, 25].

As summarised above, the literature shows that the strategies and design concepts for the energy transition in urban areas have been gradually advanced through the incorporation of new insights. In this regard, while the common strategy is structured around the three pillars (reduce, reuse and produce), the design concepts aim to develop smart local multi-energy systems at neighbourhood/district level. Based on this structure, "the Smart Urban Isle approach" was developed by an international research team for a JPI Urban Europe project as a comprehensive and step-by-step approach [26]. As such, the SUI approach aims to develop 'urban isles', a cluster of units centred around a public building, with a smart local energy system to minimise the external energy input [26, 27]. In doing so, the approach has three complementary design blocks; bioclimatic design, management design, and energy design [26]. The first block focuses on the reveal of maximum comfort level in buildings with a minimum energy input, while the second block aims at the development of a management platform that actively measures the reliability of the energy system in a chosen area [26]. The third block is the energy design block that focuses on the three pillars of the energy transition strategy (reduce, reuse, produce), the development of energy concepts with different solutions on this basis, and finally the evaluation of the concepts through the sustainability indicators to select the best alternative [26]. Therefore, this research uses the SUI approach as the conceptual and methodological basis on which to build a case study.

B. Local Context

Amsterdam is one of the most iconic cities in the world thanks to its cultural, historical, political and economic prominence established through the centuries of global trade activities. The historic centre of the city is characterised by the dynamic commercial and cultural functions and a dense urban fabric consisting of the archetypal canal rings and monumental buildings. As indicated in Introduction, the monumentality of the historic centre poses risks for energy transition due to the limits to physical alteration of the buildings for energy retrofitting measures [4, 9]. Yet, the mixed use of buildings for different functions has many advantages for the development of energy exchange systems between commercial and residential units [28]. The energy network of Amsterdam consists of a natural gas grid, district heating and cooling networks, combined power and heat plants using fossil fuels and waste, renewable energy systems such as wind farms, solar panels, and underground thermal sources [4, 8, 29]. The historic centre has a fossil-based energy system as heat is supplied through the natural gas grid, and electricity is mainly supplied by the power plants using fossil fuels and waste [8]. While there are many district heating and cooling networks around the city that supply approximately 13 % of the total heat demand, they are located outside the historic core [8, 30]. Increased annually by 50 % between 2012 and 2019, the installed capacity for wind and solar power is 127 megawatt which can cover around one-fifth of the total consumption of electricity in the city [29, 31].

The Municipality of Amsterdam has ambitious plans to radically change the energy outlook of the city by shifting from fossil-based energy systems to renewable-based ones [4]. As such, the municipality aims to increase the installed capacity for wind and solar power from 127 megawatt to 527 megawatt by 2030, which can supply 80 % of the total electricity consumption of households [29, 31]. While half of the total roof space of buildings is aimed to be used for solar panel installations, there are 7 search areas for the placement of around 40 wind turbines with 2 or 3 megawatt capacity [29, 31]. As for the heat transition, the municipality's plan [4] is structured around phasing out natural gas by 2040. According to this plan, 72 % of the buildings will be connected to district heating networks with different temperature levels (low, medium, high) that use different kinds of sources (e. g. underground thermal, aquathermal, residual) and technologies (e. g. heat pumps). While 13 % of the buildings will be renovated for an 'all electric' solution, the municipality envisions the use of biogas and green hydrogen as an alternative to natural gas for the rest of the buildings located mainly in the historic centre.

The literature points out specific challenges in the historic centre that pose risks for energy transition. Described as "energy gobbler", the historic centre has a great energy demand due to the low efficiency of the buildings, and a high population density that causes difficulties for infrastructural retrofits [32]. As the urban monumentality of the historic centre limits energy renovation options and solar panel installations, it is highly difficult to reduce the heat demand or switch to different energy systems like solar power [4, 8]. Moreover, since the underground space in the historic centre is crowded with different infrastructural elements, the expansion of district heating networks into the area is considered impossible [4, 8]. Based on these challenges, the municipality suggests that the establishment of renewable-based energy systems to achieve carbon neutrality in the historic centre is not realistic with the current status of technology [4, 32]. Therefore, the energy transition strategy for this part of the city focuses on keeping the existing natural gas network while implementing energy efficiency measures to reduce gas consumption around 70 % by 2040 [4]. By providing financial incentives and technical expertise for the property owners and housing associations, the municipality aims to boost the energy renovations, especially focusing on the post-war buildings in the area that constitute 15 % of the building stock and can help reduce the consumption by one-fifth [4, 33]. As for the remaining energy demand, the municipality proposes the use of green gas and green hydrogen which will be imported outside the city as there is highly low potential for these sources in Amsterdam [4].

Focusing on the challenges and plans summarised above, the Amsterdam Energy Transition Roadmap [8] was developed by a group of researchers discussing three pathways for energy transition in the historic centre. These pathways are structured around three options for energy renovation of the buildings as deep, limited, and no renovation in combination with three energy systems as solar power, heat network and green gas. According to this, the combination of the deep renovation option with solar panels on surfaces and the combination of no renovation option with green gas are the most ecological or economic options, respectively. Yet, the former challenges the urban monumentality of the historic centre, while the latter is not compatible with the circular economy goals as it requires importing green gas from outside the city. The last option is the combination of the limited renovation option with the expansion of the district heating network into the historical centre through the canals. According to this idea, the pipelines for heat networks can be laid out in the canals and supply medium or high temperature heat to the buildings, which require highly limited renovations of the buildings. Similarly, the Green Light District project initiated by a local collaboration between public institutions and community organisations to transform the iconic Red Light District of Amsterdam into a future-proof area also focuses on developing strategies to understand how to realise an energy transition in the historic centre [34]. Based on a bottom-up approach, the project aims to guide and support the community to take initiative to develop individual or collective retrofit projects such as greening the roofs and energetically renovating the buildings [34]. Within this project, a group of researchers from Delft University of Technology developed an energy transition project based on the three steps of the New Stepped Strategy [20] to reveal the general energy reduction, reuse and production potentials of the area [35, 36, 37].

As for the energy reduction potentials of the Green Light District [35], the researchers analysed the energetic and architectural characteristics of the buildings located in the area. As seen in Figure 2 and 3, the area is mainly occupied by the buildings that were built before the Second World War and have poor energy labels, which indicates a low level of energy efficiency. Therefore, heating constitutes a large part of energy consumption and heat loss is the biggest problem in terms of energy efficiency. As such, the researchers used three renovation options (advanced, standard, and non-renovated) with custom adjustments for different protection levels of buildings (i.e Orde 1, 2 & 3). By means of two case study buildings, the results show that there is 35 % energy reduction potential in heat demand and it can be raised up to 60 % with advanced renovation options. They also revealed that 60 % and 25 % energy reduction potential can be achieved through the measures taken for domestic hot water and electricity use.

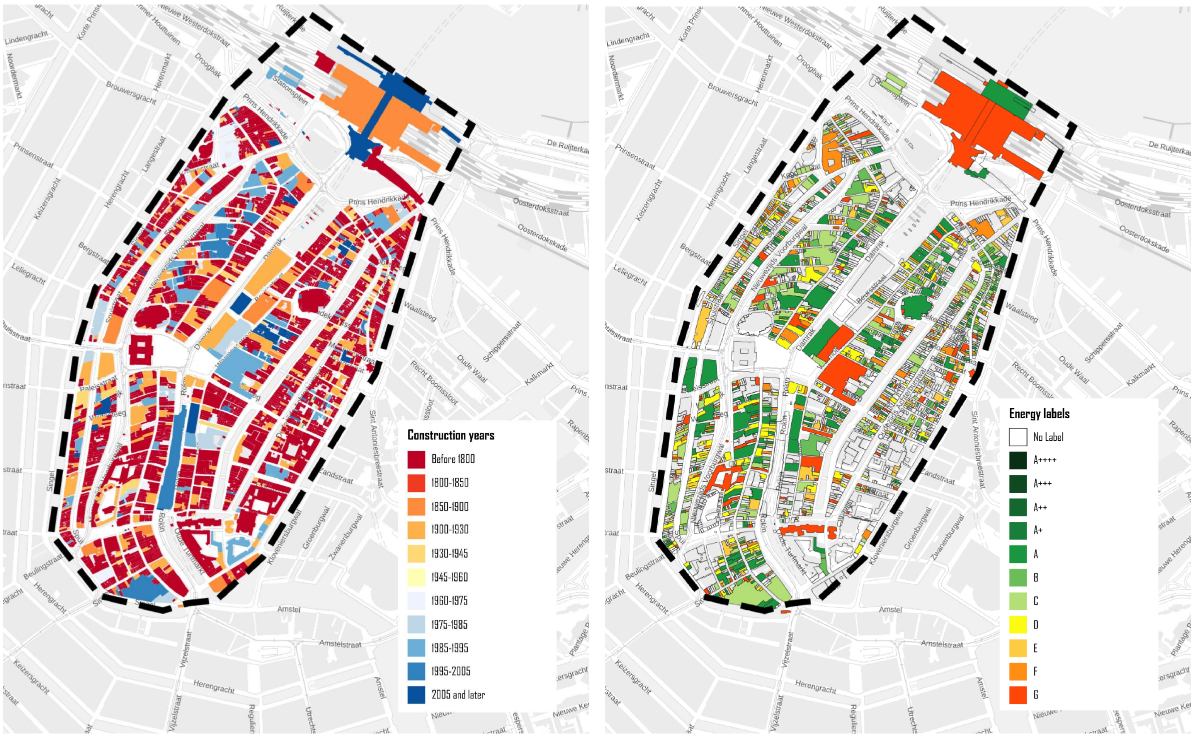

Figure 2 & 3. Construction years and energy labels in the Green Light District area [38]

In addition to the energy reduction potential, the researchers also analysed the general energy reuse potential in the area [36], specially focusing on energy exchange systems between residential and commercial units. They point out that there is a great potential for an energy exchange and reuse system, especially around the Dam Square, based on the combination of a low temperature heat network with thermal storage systems and heat pumps. Yet, they also stress the challenges regarding spatial restrictions for the development of such systems and express the need for further location-based research. As a last step, the energy production potential of the area [37] was explored to identify the ways to match the demand and supply in the area. The results of this part of the research show that there is a great potential for solar and aquathermal energy, yet the need for heat pumps to use the aquathermal potential may cause electricity import from outside areas as the monumentality of the buildings may hinder the installations of solar power systems. That is why the researchers point out the need for a focus on larger scale to make use of different types of energy systems such as large wind turbines and deep geothermal sources.

As the Green Light District project shows the great potential of a local energy network in the historic centre, a realised energy exchange project, called Tussen Kunst en Kas, proves the viability of this idea. As seen in Figure 4, the energy systems of the Hermitage Amsterdam and Hortus Botanicus Amsterdam are connected through the underground pipelines to exchange surplus heat and cold [39]. As part of the project, Hermitage Amsterdam implemented several measures such as better insulation and more efficient air conditioning systems to reduce energy consumption [40]. Afterwards, an ATES system and the pipelines connecting the buildings were placed to transfer the surplus heat from the museum to the botanical garden and cold water in return [39]. As a result, the botanical garden saves 77.215 cubic metres of gas, the museum saves 200.000 kWh energy, and therefore 259.000 kilos of CO_2 are saved each year [39].

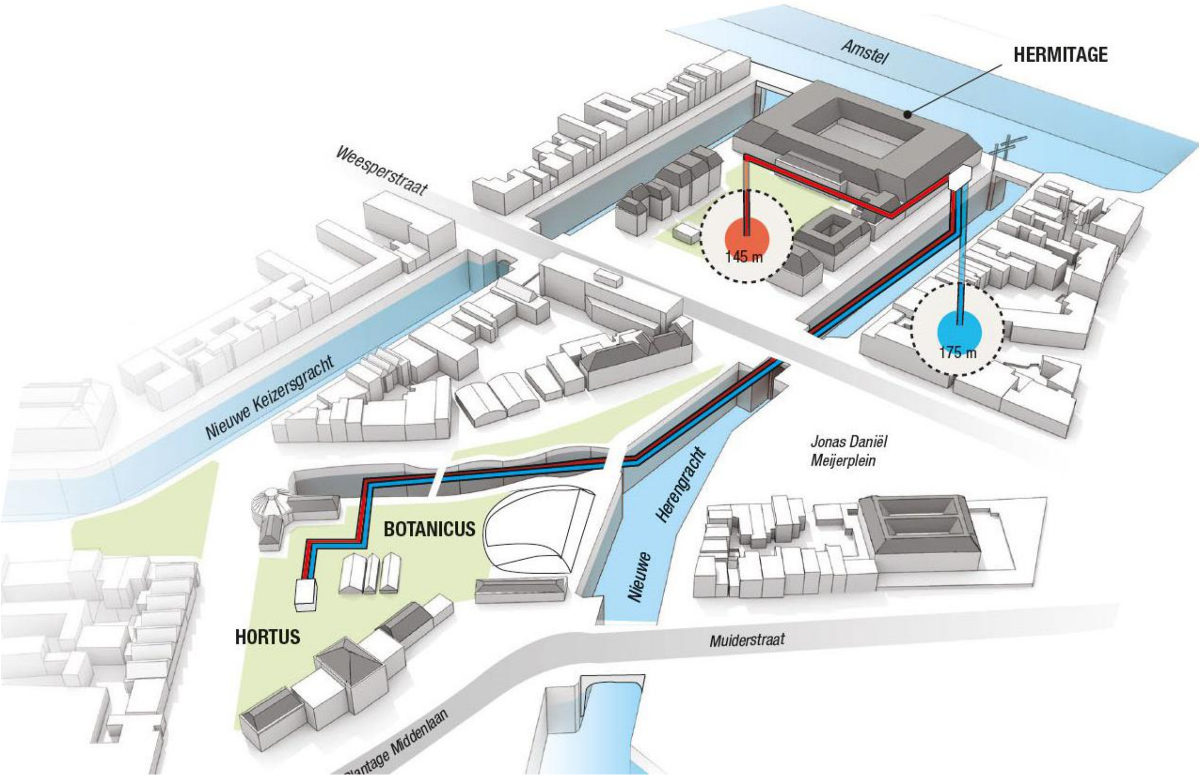

Figure 4. Tussen Kunst en Kas project visual [40]

3. CASE STUDY

A. Site Characteristics

In accordance with the 'urban isle' concept of the SUI approach, the western part of the Oude Kerk neighbourhood in the Centrum district, called Damrak for the rest of the report, was chosen for the case study. Located between Amsterdam Centraal, Dam Square and Nieuwmarkt, this site is centred by Beursplein and Beursstraat and bordered by Dam Square, Damrak and Warmoesstraat (Figure 5 & 6). Some of the most iconic buildings of the city are located on the site such as Beurs van Berlage, De Bijenkorf Amsterdam, and Euronext Amsterdam (Amsterdam Stock Exchange). These special historic buildings constitute three of the four blocks on the site, and another block is home to typical canal houses of Amsterdam that function as hotels, restaurants, and residences (Figure 5 & 6). As for the climatic conditions, the average annual outdoor temperature is 10 °C in the city, 6 °C for the winter season and 17 °C for the summer season [41, 42]. The annual average precipitation is 589.7 mm/year in Amsterdam, and the annual solar irradiation is 1047 kWh/m² [41, 42].

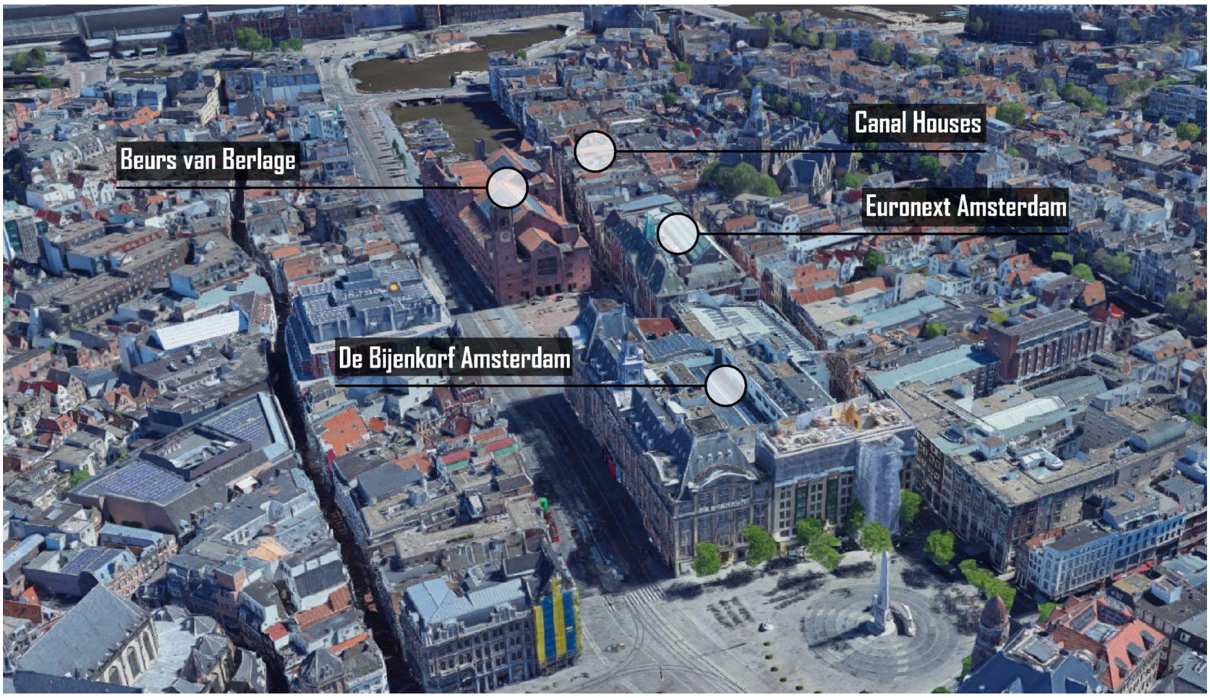

Figure 5. A satellite image of the case study site [43]

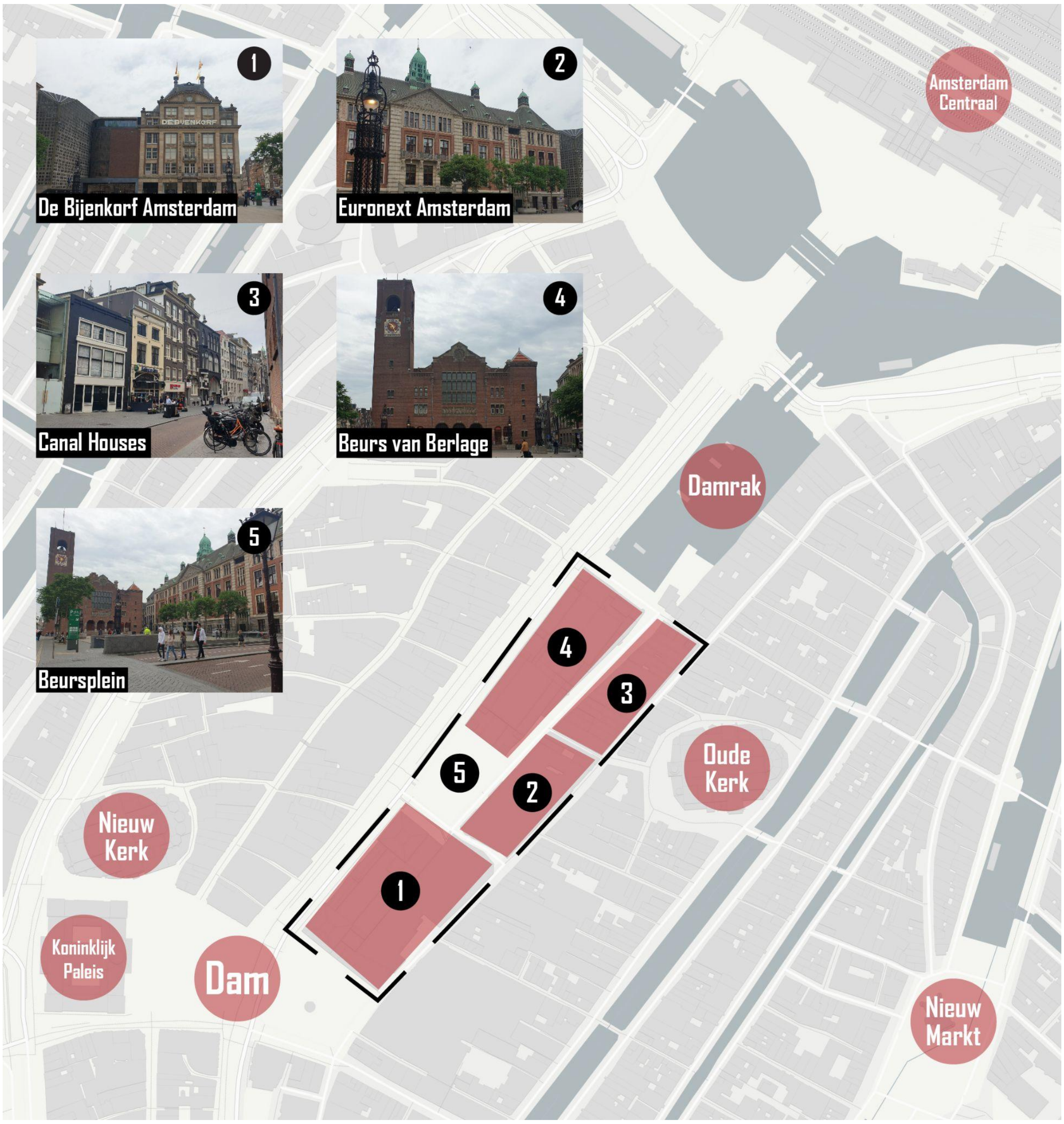

Figure 6. The case study site (own photos)

In total, there are 30 buildings in Damrak, constituting a good combination of residential, non-residential and mixed use (Figure 7 & Table 1). While there are three large buildings that host different functions in the area (De Bijenkorf Amsterdam, Euronext Amsterdam, Beurs van Berlage), the small buildings (i. e. canal houses) are mainly home to residences, hotels, restaurants and bars (Figure 7 & 8). The building typology and floor areas of the buildings and functions were calculated according to the information and map service provided by the Municipality of Amsterdam [44, 45]. As Table 2 shows, residences and hotels occupy the largest floor areas in the canal houses, followed by restaurants as the third largest function. There are 84 residential units on the site, and it is assumed the total population is between 150-200 due to the fact that the average number of residents per household is 2.14 as of 2021 in Amsterdam [46]. There is also a bicycle parking under Beursplein that provides more than 1000 parking spaces.

Table 1. Building typology

Function	Number of buildings	Number of addresses	Average number of floors	Average height (m)	Roof type
Residential (Apartment)	5	15	4*	14**	Flat/Gable
Mixed	13	124	5*	16**	Flat/Gable/ Mansard/Hip
Non-residential	12	14	5*	17**	Flat/Gable/ Mansard/Hip
Total	30	153	NA	NA	NA

* Excluding basements
** Rounded and approximate

Table 2. The floor areas and functions of the buildings in Damrak

<table>
<tr><th>Building</th><th>Function</th><th>Units</th><th colspan="2">Floor area (m²)</th></tr>
<tr><td>De Bijenkorf Amsterdam</td><td>Retail store, Restaurant/cafe/bar</td><td>1</td><td colspan="2">28762</td></tr>
<tr><td>Euronext Amsterdam</td><td>Office, Restaurant/cafe/bar</td><td>1</td><td colspan="2">14703</td></tr>
<tr><td>Beurs van Berlage</td><td>Office, Retail store, Restaurant/cafe/bar, Meeting rooms</td><td>1</td><td colspan="2">16000*</td></tr>
<tr><td rowspan="7">Others (27)</td><td>Residence</td><td>84</td><td>8033</td><td rowspan="7">25668</td></tr>
<tr><td>Hotel</td><td>6</td><td>7089</td></tr>
<tr><td>Restaurant/cafe/bar</td><td>12</td><td>3548</td></tr>
<tr><td>Retail store</td><td>6</td><td>594</td></tr>
<tr><td>Supermarket</td><td>1</td><td>159</td></tr>
<tr><td>Office</td><td>1</td><td>265</td></tr>
<tr><td>Parking garage</td><td>1</td><td>6000*</td></tr>
</table>

* Rounded and approximate

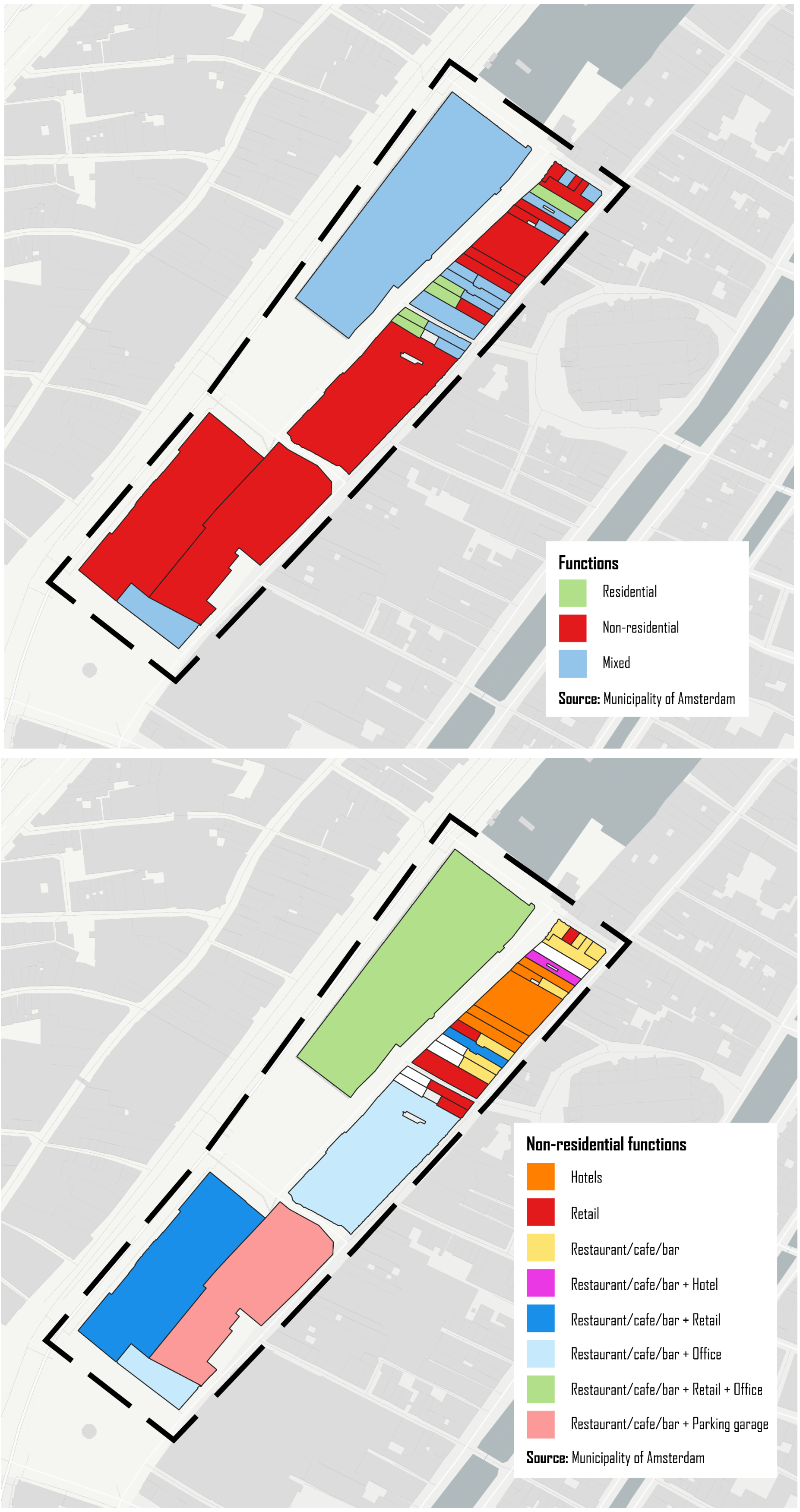

Figure 7 & 8. Functions of the buildings [44]

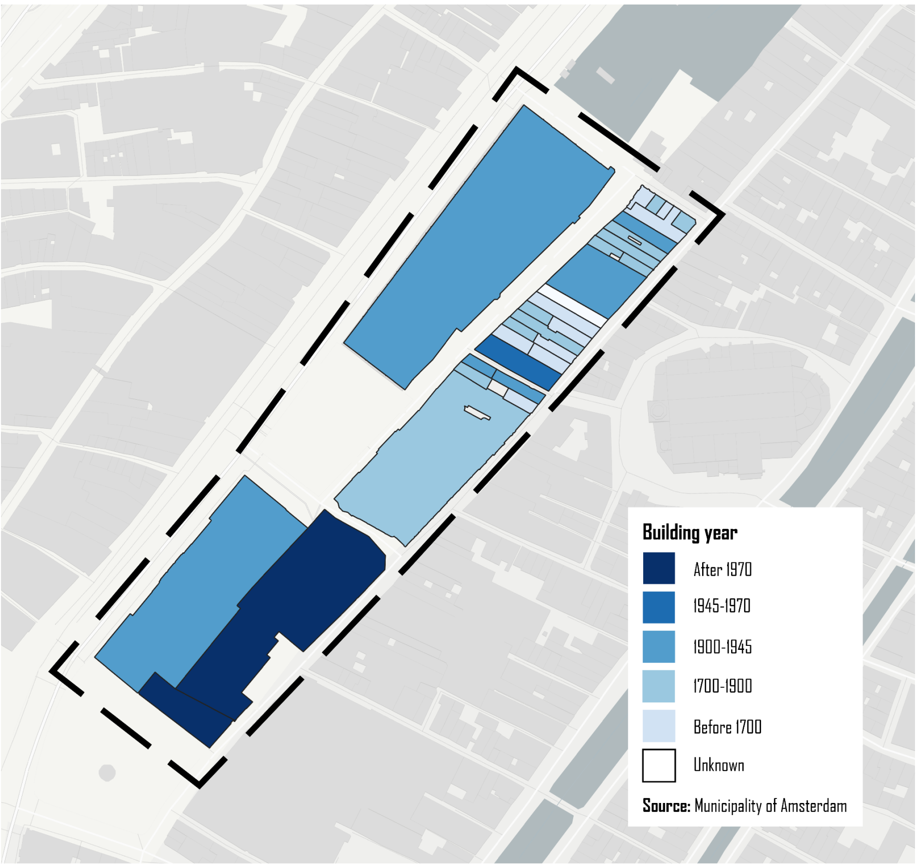

Figure 9. Construction years of the buildings [47]

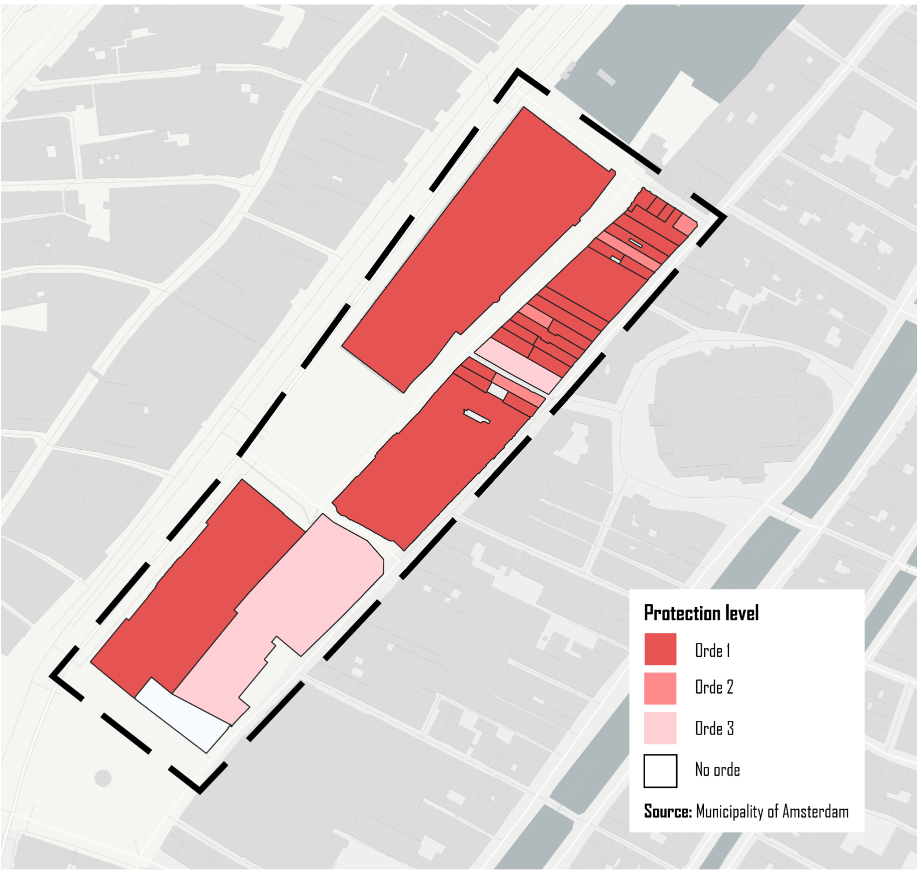

Figure 10. Protection levels (orde) of the buildings [44]

Damrak represents the urban monumentality of Amsterdam as the majority of the buildings in the area were built before the Second World War (Figure 9). Therefore, these buildings are either national or municipal monuments. There are three level of architectural heritage protection in the Netherlands: "Orde 1" contains the monumental buildings to which the highest level of restrictions are applied, "Orde 2" is for the historic buildings in which limited alterations are allowed, and "Orde 3" includes the buildings that are not monumental/historic but still suit the architectural characteristics of the area [35]. The majority of the buildings in the area have the highest level of protection (Orde 1), and there are a couple of buildings on lower protection levels (Orde 2 and Orde 3), as seen in Figure 10. The architectural and historic importance of the buildings has a great influence on the energy system since there are many restrictions regarding the renovation of buildings according to their protection levels.

B. Energy Status Quo

As in the whole historic core of Amsterdam, the energy system of Damrak is fossil fuel-based, relying on the natural gas and power grids. As discussed before, the monumentality of the buildings poses challenges in many ways for energy transition in the area, causing low levels of energy efficiency and limiting solar power potentials. The suitability of solar panel installations on roofs is low on the site, yet there are a few buildings with solar panels. In total, there are 80 solar panels on the roofs of three buildings with 22650 watt capacity (Figure 12). There is no other type of renewable energy system or thermal underground storage systems within the case study site. As for the energy labels, there is no energy label registration for many buildings in the area, which causes difficulties for understanding the energy efficiency level of the site. It is assumed this situation is associated with the difficulties for energy renovation since obtaining a poor energy label may not be desirable for the property owners. As seen in Figure 11, the buildings with energy labels have low energy efficiency since they mainly have Label C and lower labels as the dominant energy label. Yet, the calibration of the energy labels was carried out in 2021 in the Netherlands, simplifying energy label calculations by fixing the labels on primary energy use per square metre [48]. Due to the change in the method for the calculations, a shift in approximately 45 % of the energy labels is expected [49].

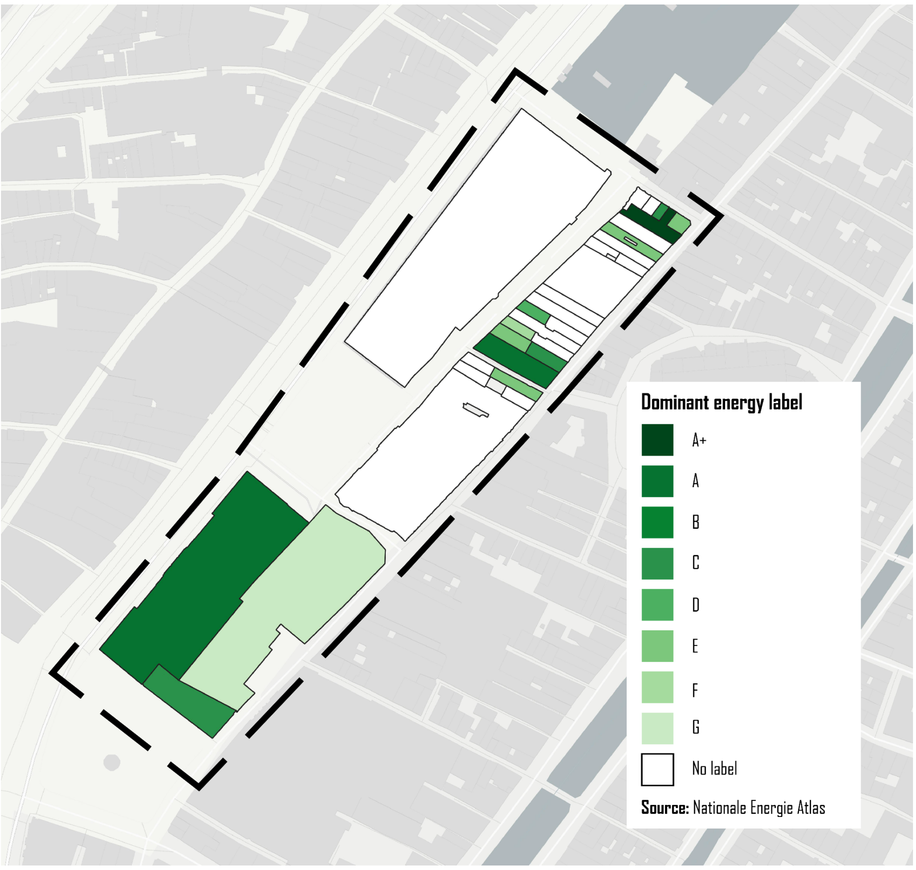

Figure 11. Dominant energy labels in the buildings [50]

Figure 12. Possibility of installing solar panels on roofs [51]

When it comes to the final energy consumption (on the meter), various data and information platforms were used. Since there are many different functions in the buildings, the energy consumption information is presented in Table 4 according to different functions as residences, small businesses (i. e. hotels, restaurants, retail stores), and large buildings (De Bijenkorf Amsterdam, Euronext Amsterdam, Beurs van Berlage). The final energy consumption information for the large buildings and the supermarket was obtained through personal communication. Nevertheless, due to the privacy issues, the energy consumption of the large buildings is combined to protect their anonymity. The reference year for energy consumption for these buildings is 2019. It is worth noting that the supermarket and parking garage consumes no natural gas but a high amount of electricity. As for the small businesses, the data from the energy network operator [52] as well as the national statistics [53], as presented in Table 3, were used for the calculation of energy consumptions. Likewise, the Green Light District Research Report [54] was used for the calculation of energy consumption of the residences in the area.

According to research done for the Green Light District project [54] based on the data from the energy provider (Liander) for 2017, the residential units in the Oude Kerk neighbourhood of Amsterdam where the case area is located consume about 33 kWh/m² electricity and 134 kWh/m² gas in a year. This is approximately 20 % higher than what an average household consumes in Amsterdam, which is 27 kWh/m² electricity and 106 kWh/m² gas [54]. The reason behind this difference is the fact that this neighbourhood hosts monumental buildings with low energy efficiency. As such, when calculating the energy consumption of the businesses (hotels, restaurants, retail stores) in the area according to the average consumption data from CBS [53], 20 % higher amounts were taken into consideration to achieve more realistic results for the case study site. Besides, the national data for the greenhouse gas emission factors [55] was used for the calculation of CO_2 emissions from the energy use in buildings. According to the data for the reference year of 2019, the use of one unit (megawatt/hour) of electricity and gas emits 369 kilograms and 183 kilograms of CO_2, respectively.

Table 3. Average energy consumption of commercial functions [53]

Commercial functions	Gas (m³/m²)					Electricity (kWh/m²)				
	0-250 m²	250-500 m²	500-1000 m²	1000-2500 m²	2500-5000 m²	0-250 m²	250-500 m²	500-1000 m²	1000-2500 m²	2500-5000 m²
Retail with refrigeration	18,7	17,2	13,7	11,1	7,3	231,8	174,8	243,6	279,7	201,8
Retail without refrigeration	17,0	11,9	8,8	6,9	6,2	105,2	84,8	70,6	76,1	70,0
Catering: Restaurant	37,4	33,1	26,5	21,3	NA	227,8	184,2	149,5	127,3	NA
Catering: Cafe	38,1	28,7	24,3	NA	NA	265,3	172,5	201,5	179,4	NA
Hospitality: Hotels	22,8	22,6	21,9	21,3	21,1	64,9	71,5	85,1	97,6	107,7
Office: Other	17,3	15,0	12,8	10,9	10,7	57,2	50,8	54,9	66,3	76,1

Table 4. Final energy consumption and CO_2 emissions in Damrak in 2019

Function	Number of objects	Gas (MWh/ year)	Electricity (MWh/ year)	Total (MWh/ year)	CO_2 Emission (tons/ year)
Residence**	84	1073	266	1339	294
Hotel**	6	1765	834	2599	630
Restaurant/cafe/bar**	12	1336	792	2128	536
Retail store**	6	117	75	192	48
Supermarket*	1	NA	180	180	66
Office**	1	46	16	62	14
Parking garage**	1	NA	373	373	137
Large building*	3	5849	13117	18966	5910
Total	114	10186	15653	25839	7635

* Based on actual data
** Based on generic data

Another important step for understanding the energy status quo in Damrak is to identify the proportion of energy consumption for different uses such as gas use for space heating, domestic hot water, cooking, and electricity use for ventilation, cooling, lighting, refrigeration. The data from the national statistics [56] was used to determine the share of energy consumption for different uses in residential units, as seen in Table 5. According to this, an average household in the Netherlands uses 78 % of natural gas for space heating, 20 % for domestic hot water, and finally 2 % for cooking [56]. Likewise, the literature was used for understanding energy uses in commercial units such as retail shops, restaurants, and offices in Damrak. Based on case studies, Meijer and Verweij [57] lay out the proportions of different uses of gas and electricity for each sector and/or function including education, retail, office and so on (Table 5). As for the large buildings, the documents obtained through personal communication were used for the determination of the proportion of different energy uses (Table 6).

Table 5. Proportion of energy uses in residential and commercial units [56, 57]

Function	Gas (%)			Electricity (%)				
	Space heating	DHW	Cooking	Venti-lation	Cooling	Light-ing	Commercial refri-generation	ICT, Appliances & Other
Residence	78	20	2	NA	7	14	NA	79
Office	98	2	NA	5	11	37	NA	47
Supermarket	98	2	NA	1	2	27	62	8
Hospitality/ Catering	80	10	10	10	20	38	8	24
Retail store	100	NA	NA	3	11	67	NA	19
Car companies	100	NA	NA	5	7	60	NA	28

Table 6. Gas and electricity use per function for different uses in Damrak

Function	Gas (MWh/year)			Electricity (MWh/year)				
	Space heating	DHW	Cooking	Venti-lation	Cooling	Light-ing	Commercial refri-generation	ICT, Appliances & Other
Residences	840	210	22	NA	18	37	NA	211
Hotels	1411	186	168	83	166	317	66	200
Restaurants/ cafes/bars	1068	145	123	80	158	301	63	190
Retail stores	117	NA	NA	2	8	50	NA	15
Supermarket	NA	NA	NA	2	4	48	112	14
Office	44	2	NA	1	2	6	NA	7
Parking garage	NA	NA	NA	18	26	223	NA	104
Large buildings	5627	178	44	1531	1366	5338	21	5098
Total	9108	721	357	1717	1748	6320	262	5839

The crucial part of this step is to determine the actual heat and cold demand of the buildings to form a basis for energy reduction measures in Damrak. When calculating the heat and cold demand, the efficiency rates of heating technologies such as gas boilers for space heating and DHW, and gas stoves for cooking, and the COPs of cooling installations (i. e. air conditioners and heat pumps) were taken into account. The efficiency of the gas boilers in the residential units in the Netherlands is considered 85 % [26]. It must be noted that the standstill losses in hot water storage units were disregarded for this research when calculating the heat demand for DHW. As for the small businesses and large buildings, it is identified that high efficiency gas boilers (condenser boilers) with efficiency rates ranging from 98 % to 104 % are used [58], while average gas boiler efficiency is considered 89 % for small businesses in the historic centre of Amsterdam [54]. As for the gas stoves, the efficiency rate is considered around 32 % for the calculation of heat demand for cooking [59]. Finally, the average COP of the cooling installations (air conditioners, heat pumps) was taken as 3 to calculate the cold demand according to the electricity used for these installations [60]. Table 7 shows the results of this calculation per function in Damrak.

Table 7. Heat and cold demand in Damrak in 2019

Function	Heat demand (MWh/year)			Cold demand (MWh/year)
	Space heating	DHW	Cooking	
Residences	714	178	7	54
Hotels	1256	165	53	498
Restaurants/cafes/bars	950	129	39	474
Retail stores	104	NA	NA	24
Supermarket	NA	NA	NA	12
Office	39	2	NA	6
Parking garage	NA	NA	NA	78
Large buildings	5627	178	14	4098
Total	8690	652	113	5244

4. RESEARCH DESIGN

A. Research Objectives & Questions

The results of Literature Study show that the general concepts and strategies regarding energy transition have gradually been advanced through the incorporation of new insights, and the SUI approach provides a powerful tool for the development of local energy systems by combining the concept of distributed/decentralised energy systems with the three-step strategy based on energy reduction, reuse and production. Moreover, although local challenges have a great negative impact on the plans for the energy transition, the Green Light District and the Tussen Kunst en Kas projects show the way to overcome the challenges by revealing the potential for renewable-based systems in the historic core of the city. As a result, it is identified that there is a great need for further research to advance the existing knowledge and experience on the energy transition in the historic centre of Amsterdam by revealing the local energy potentials of a specific location and developing energy concepts on this basis. As such, the objective of this research is to use the case study of Damrak for the application of the SUI approach to achieve comprehensive results that can provide generic insights into how an energy transition project can be carried out in the historic centre of Amsterdam. In this regard, the research questions are formulated in accordance with the step-by-step structure of the SUI approach to reveal the local energy potentials, and to develop different scenarios for energy transition in Damrak. On this basis, the main research question and subquestions are developed as presented in Table 8.

Table 8. The main research question and subquestions

Main	How can a renewable-based and decentralised energy system be developed in Damrak under the unique urban challenges of the historic centre of Amsterdam?
I	What is the local potential for energy reduction in Damrak?
II	What is the local potential for energy reuse in Damrak?
III	What is the local potential for energy production in Damrak?
IV	What kind of energy concepts can be developed on the basis of the local potentials for Damrak?
V	Which energy concept is the best option for Damrak according to the quantified KPIs?

B. Research Approach & Structure

The methodological structure of the research is built on the SUI approach to answer the research questions. Although the SUI approach has three complementary design blocks as bioclimatic design, energy design, and management design [26], as explained in Key Concepts, the energy design block is used in this research to work on different aspects of urban energy systems to design complete energy concepts at neighbourhood level. Therefore, the research follows the step-by-step structure of this block in three phases as the local energy potentials, energy concept development, and evaluation and selection as seen in Table 9. The first step is based on revealing the local potentials for energy reduction, reuse, and production on the case study site to form a basis for the energy concept development. As such, the combination of the results from the local potentials are used to determine how to match energy demand and supply in different energy concepts. The last step is the assessment of these different concepts by means of the quantification of their performances according to the KPIs.

Table 9. Structure of the research in three phases

Phase I	Local energy potentials: Reduction, reuse, production
Activity	Understanding the energy efficiency status of the case study site and developing an energy renovation scenario, and quantifying the residual heat and renewable energy generation potential of the case study site
Method	Algorithms, geographic information services, literature sources
Result	Amount of the total reduction, reuse and production potential
Phase II	Energy concept development
Activity	Conceptual design of the final energy supply scenarios based on the local energy potentials
Method	Technology inventory, algorithms
Result	Different energy concepts showing the balance of the energy system based on local and renewable energy supply options
Phase III	Evaluation and selection
Activity	Quantifying the performance of each energy concept
Method	Key performance indicators
Result	Best option for the case study

C. Research Methods

As indicated in the previous section, this research consists of three phases corresponding to different research subquestions, and different research methods were designed to answer these questions in each phase. As for the first phase based on revealing the local potentials for energy reduction, reuse, and production, different algorithms for calculations and geographic information services were used to understand how to increase energy efficiency and to meet the remaining demand with local renewable energy supply. On the basis of the results of this phase, Technology Inventory developed for the SUI approach was used to generate different energy concepts that show the energy balance in the area. Finally, the KPIs were used to assess the concepts, and to select the best option for the case study site.

I. Heat algorithms

The major step towards renewable-based energy systems in cities is to increase the energy efficiency of buildings to overcome the possible shortcomings of renewable energy supply. This entails upgrading energy technologies in buildings, improving building envelope insulation, and developing heat recovery and energy reuse systems. Increasing energy efficiency can help use local low temperature heat sources, and therefore reduce the reliance on external energy inputs. Fortunately, it is now a legal obligation to increase the energy efficiency of the buildings in the Netherlands. For instance, starting from 2023, the office buildings must have at least Label C level energy efficiency otherwise they cannot be used as offices [61]. Plus, starting from 2030, it will be prohibited to rent a building with low level of energy efficiency (Label G, F, E) irrespective of its function [62]. Although upgrading electric appliances is an important part of energy efficiency measures, this research only focuses on the thermal efficiency of the buildings on the case study site by analysing the energy reduction and reuse potentials. This is particularly due to the fact that the energetic renovation of buildings and the use of low-medium temperature heat sources are the biggest challenges to energy transition in the historic centre of Amsterdam, as discussed in Literature Study.

As such, a stepped method consisting of various algorithms was used to calculate energy reduction and reuse potential for the case study of Damrak. The steps consist of Technology upgrade to understand energy loss reduction potential, Thermal insulation and Heat recovery to determine heat loss reduction potential, Residual heat for energy exchange potential, Thermal storage for energy storage potential, and finally Heat pump comes for the theoretical efficiency level of the most crucial element of the heat transition process. As for the determination of the values for the variables such as the measurements of the different parts of the buildings, flow rates of ventilation, and operation period of the energy systems, various sources were used, including specification sheets provided for the large buildings, the data and map services and literature for other buildings. While the indoor temperature level is considered 21 °C, the outdoor temperature level was identified through the weather services [41, 42] and the weather seasons were categorised as the heating season between October and May, and the cooling season between June and September according to the average temperature level in these months.

a. Technology upgrade

The heating system in Damrak consists of a natural gas grid connected to the gas boilers and stoves in the buildings for space heating, domestic hot water and cooking. Due to the low efficiency of gas boilers and stoves, there is a great amount of energy losses occurring during this process. Since the Municipality of Amsterdam aims to phase out natural gas use in the city, the buildings are required to switch to renewable energy-based technologies such as heat pumps and electric or induction stoves. As these new technologies are more efficient than the current ones, this technology upgrade reduces energy losses caused by lower efficiency of gas boilers and stoves. For instance, the efficiency rates of typical heat pumps with average temperature lifts between 25-40 K ranges between 300-500 % [63], therefore it is possible to achieve a 100 % energy loss reduction with heat pumps since they cause no energy losses. Likewise, an induction stove has an average efficiency rate of 85 %, causing only 15 % energy loss [59]. Table 10 provides an overview of the technologies and their efficiency rates. It must be noted that the energy efficiency rates of gas boilers presented in the table are for the residential and small commercial units since the large buildings were excluded from the calculations due to the fact that they use high-efficiency (98-104 %) condenser boilers.

Table 10. Efficiency rates of technologies for heating and cooking [26, 54, 59, 63]

Energy use category	Technology	Efficiency (%)
Space heating & DHW	Gas boiler	85 - 89
	Heat pump	300+
Cooking	Gas stove	32
	Electric stove	75
	Induction stove	85

Energy loss reduction through technology upgrade can be calculated according to Equation 1 below that is based on the efficiency rates of the technologies presented in Table 10 as well as the current energy use via these technologies. The result of this calculation for space heating and DHW provides the actual heat demand on the case study site since heat pumps cause no energy losses. Therefore, heat loss reduction potential that is calculated in the next step directly corresponds to energy use reduction in the area. This is the main reason why the energy efficiency potential is calculated step-by-step.

Equation 1 $ELR = (EC_{current} \times ELR_{current}) - (HD \times ELR_{new})$

ELR	Energy loss reduction (MWh)
$EC_{current}$	Energy consumption via the current technology (MWh)
HD	Heat demand (MWh)
ELR_{new}	Energy loss rate of the new technology (n)
$ELR_{current}$	Energy loss rate of the current technology (n)

b. Thermal insulation

In addition to energy losses stemming from the low efficiencies of heat technologies, transmission heat losses occur through the different parts of the building envelope. This is because of the second law of thermodynamics, known as entropy, that is based on the transfer of heat to colder areas to reach an equilibrium between two different environments. As such, the transmission of the warm indoor air to the cold outdoor environment through roof, facade, windows and ground floor of a building occur during the cold seasons. Therefore, better building insulation can help prevent transmission heat losses, reducing energy use for heating. The general insulation measures that can be taken in the monumental buildings from all protection levels (Orde 1, 2 & 3) are presented in Table 11. Since almost all buildings on the case study site are in the high protection category (i. e. Orde 1), the measures that suit this level are taken into consideration for this research. One major aspect of the general measures is that the materials used for the insulation of the building envelope must suit the architectural authenticity of the building, and therefore they must have the same details including colour, design, and shape with the original materials [35]. Therefore, the renovation project for a monumental building must be approved by a municipal committee that checks the suitability of the measures to the cultural and architectural characteristics of the building.

Table 11. General measures for Orde 1 protection category [35, 64]

Part of building envelope	Insulation measures
Roof	- Interior and exterior insulation is possible for pitched roofs if there is no historic wooden structure
Facade	- Exterior Insulation is not allowed - Interior Insulation is possible in case of no historical wall elements - Cavity wall insulation can be applied for the ones built after 1920 if possible - Crack sealing is only possible if the materials are removable, and modern materials (e.g. PUR) are not allowed
Window	- In case of a historic glazing and wooden frame, the replacement is not allowed but window pane and window foil are possible - If there is no historic glazing, a thin double glazing is possible
Ground floor	- Insulation from the crawl space is possible

Each insulation material used for the implementation of the measures described above has a unique insulation capacity value (U-value), as presented in Table 12. Transmission heat losses through the building envelope can be calculated according to these values and the surface area of each part of the building envelope [35]. Yet, it must be noted that this calculation provides theoretical potential for energy reduction while the actual reduction potential may be lower for the monumental buildings due to the cold bridges that occur during post-insulation in old buildings and that cause higher transmission losses [35]. The calculation is carried out according to Equation 2 below.

Equation 2 $HLR = (U_{uninsulated} - U_{insulated}) \times A \times \Delta T \times t / 10^6$

HLR	Heat loss reduction (MWh)
$U_{uninsulated}$	U-value of the uninsulated building material (W/m². K)
$U_{insulated}$	U-value of the insulation material (W/m². K)
A	Surface area of the building envelope part (m²)
ΔT	Temperature difference between the indoor and outdoor air during the time period considered (K)
t	Operation period of the heating system (h)

Table 12. The U-value for different insulation materials [35, 65]

Part of building envelope	Material		U-value
Roof	Uninsulated	Wood (pitched roof)	2.60
		Concrete (flat roof)	2.00
	Insulated (inside)	Glass/Rock wool	0.32
	Insulated (outside)	PIR	0.23
Facade	Uninsulated	Brick/stone wall	2.78
	Insulated (solid wall)	Glass/Rock wool	0.30
	Insulated (cavity wall)	Glass wool	0.32
Window	Uninsulated	Single glazing	5.37
	Insulated	Thin double glazing	2.80
		Window pane	2.70
		Window foil	3.80
Ground floor	Uninsulated	Wood	3.13
		Concrete	2.00
	Insulated (wood)	Glass wool	0.22
		Rock wool	0.54
	Insulated (concrete)	EPS	0.36
		PIR	0.31

c. Heat recovery

Heat losses also occur through the infiltration and ventilation processes in buildings. While sealing cracks on walls can help reduce the infiltration heat losses, heat recovery systems needed to reduce the ventilation heat losses. Ventilation can occur naturally through windows and doors or mechanically through air handling units. In the Netherlands, the Building Decree 2012 [66] indicates that mechanical air ventilation systems are mandatory for new buildings and all commercial units. The capacity of mechanical air ventilation is 2 l/s/m² per person for office, school, healthcare units, 3.8 l/s/m² for catering businesses, and 3 l/s/m² for parking garages [66, 67]. As such, mechanical ventilation with heat recovery (MVHR) is a great option as it helps recover the residual heat in the exhaust air from a building to preheat the outdoor supply air entering the building. There are already some MVHR systems with the efficiency rates ranging from 50 to 80 % in use in the large buildings on the case study site.

The efficiency rates of the MVHR systems is an important factor in the calculation of reduction in the ventilation heat losses, and they differ according to the type of heat exchanger used in these systems. The most common and efficient heat exchangers are the cross plate exchangers transferring sensible heat and the heat recovery wheels transferring both sensible and latent (moisture) heat from the exhaust air [68]. The transfer of latent heat where the humidity level is high like the Netherlands is not a desirable option due to the indoor air quality issues, therefore it is identified that the cross plate exchangers that only transfer sensible heat from the exhaust air is a suitable option for the case study of Damrak. The efficiency rate of the cross plate heat exchangers is around 80 % on average, which means that the 80 % of the lost heat in the ventilation system can be recoverable [68]. To understand the maximum reduction potential for the ventilation heat losses, it is assumed that crack sealing is also implemented to reduce the infiltration heat losses. According to PLANHEAT [69], the heat potential in the exhaust air from a building can be calculated if the floor area of the building and the flow rate of the ventilation system are known. Based on the algorithm provided by PLANHEAT [69], Equation 3 is developed to calculate ventilation heat loss reduction.

Equation 3 $HLR = ER \times A \times Q \times c_p \times \Delta T \times t / (3.6 * 10^6)$

HLR	Heat loss reduction (MWh)
ER	Efficiency rate of heat recovery in the MVHR system (n)
A	Floor area of the building (m^2)
Q	Flow rate of the ventilation system (m^3/h)
c_p	Specific heat capacity of air, which is 1.2 ($kJ/m^3 \cdot K$)
ΔT	Temperature difference between the indoor and outdoor air during the time period considered (K)
t	Operation period of the heating system (h)

d. Residual heat

Densely populated areas like the historic centre of Amsterdam host many commercial units such as supermarkets, shopping malls, offices, hospitals that use different types of energy technologies and appliances producing an excessive amount of heat. While the buildings with the MVHR systems internally reuse a certain portion of this residual heat, there is still a great amount of residual heat that is not internally recoverable and therefore available for external uses. The common residual heat sources in urban areas are the air handling units, cooling installations, as well as drain/return water systems of buildings. The residual heat potential from buildings can either be directly used or stored in thermal storage units for later uses. The calculation of residual heat potential differs according to the source system. As seen in Equation 4 used for residual heat potential from the air handling units, the method is similar to the one for heat recovery in the MVHR systems. The only difference is that the efficiency rate of heat recovery is reversed to determine the remaining residual heat potential in the exhaust air after the heat exchanger in the heat recovery unit. Yet, the efficiency rate of heat recovery is disregarded when calculating residual heat potential in summer since heat recovery is not in use during this season. A special attention must be paid to the temperature level of residual heat from the air handling units due to the fact that while the exhaust air from buildings normally has an average room temperature level (21 °C), heat recovery systems cause a significant drop in this temperature level which is determined by the ratio of the efficiency rate of the heat exchanger to the temperature difference (ΔT) used in Equation 4. As such, the temperature level of residual heat from the air handling units differs between the seasons.

Equation 4 $RHP = (1 - ER) \times A \times Q \times c_p \times \Delta T \times t / (3.6 * 10^6)$

RHP	Residual heat potential (MWh)
ER	Efficiency rate of heat recovery in the MVHR system (n)
A	Floor area of the building (m^2)
Q	Flow rate of the ventilation system (m^3/h)
c_p	Specific heat capacity of air, which is 1.2 ($kJ/m^3 \cdot K$)
ΔT	Temperature difference between the exhaust and outdoor air during the time period considered (K)
t	Operation period of the ventilation system (h)

In addition to exhaust air from air handling units, return warm water from the heating systems of buildings can also be used as a residual heat source through an underground thermal storage system since its temperature level is still higher than the natural temperature level of surface water or groundwater. The calculation method is similar to the one used for the air handling units, as seen in Equation 5. The only difference is that the flow rate of the injection wells for the preferred underground storage system is taken into account for the calculation. Besides, residual heat from cooling installations is also an important local heat source for dense urban areas due to the fact that the heat released from these installations is around 40 °C and available all year round [69]. Therefore, in addition to the energy storage option, it can directly be used as a low temperature heat for neighbouring units. As such, the supermarket located in Damrak is used as a local heat source for this research. The calculation method for residual heat from cooling installations is based on the COP of cooling installations and electricity use, as seen in Equation 6 [60, 69]. The average COP of cooling installations in supermarkets is considered 3 for this research [60].

Equation 5 RHP = Q x c_p x ΔT x t / (3.6 * 10^6)

RHP Residual heat potential (MWh)
Q Flow rate of the injection wells (m^3/h)
c_p Specific heat capacity of water, which is 4200 (kJ/m^3. K)
ΔT Temperature difference between the injected and groundwater (K)
t Operation period of the heating system (h)

Equation 6 RHP = EC x (COP + 1)

RHP Residual heat potential (MWh)
EC Electricity use of the cooling installation (MWh)
COP Coefficient of performance of the cooling installation (n)

e. Thermal storage

Since the immediate use of residual heat is not always possible due to the temporal differences between the energy released and needed, there is a great need for thermal storage systems to store residual heat for later use. Underground thermal storage systems are the most common and efficient ones in the Netherlands thanks to the suitable conditions for these storage systems [70]. Their types can be open (ATES) and closed (BTES), depending on energy need, local capacity, and geological suitability. These systems basically provide an opportunity to inject surplus heat and cold through water to the underground layers, and to recover it when needed. In the ATES systems (Figure 13), the aquifer layer is used to store water containing residual heat and cold. However, in the BTES systems, residual heat and cold is injected into or recovered from the solid subsurface layers (i.e. rocks) through the heat exchange between water pipes and solid layers. Compared to the BTES system, the ATES system is the most popular underground thermal storage option in the Netherlands, with more than 3000 licensed projects [70]. This is particularly because of the fact that the ATES systems provide higher amount of heat storage and peak power capacity with less construction costs, which is highly feasible for large scale use, and the presence of a large natural aquifer layer makes the use of the ATES system greatly possible [70, 71, 72]. As such, the literature indicates that the BTES systems are generally used when there is no suitable aquifer for the ATES systems [70]. Therefore, this research focuses on the ATES system as the underground thermal storage option.

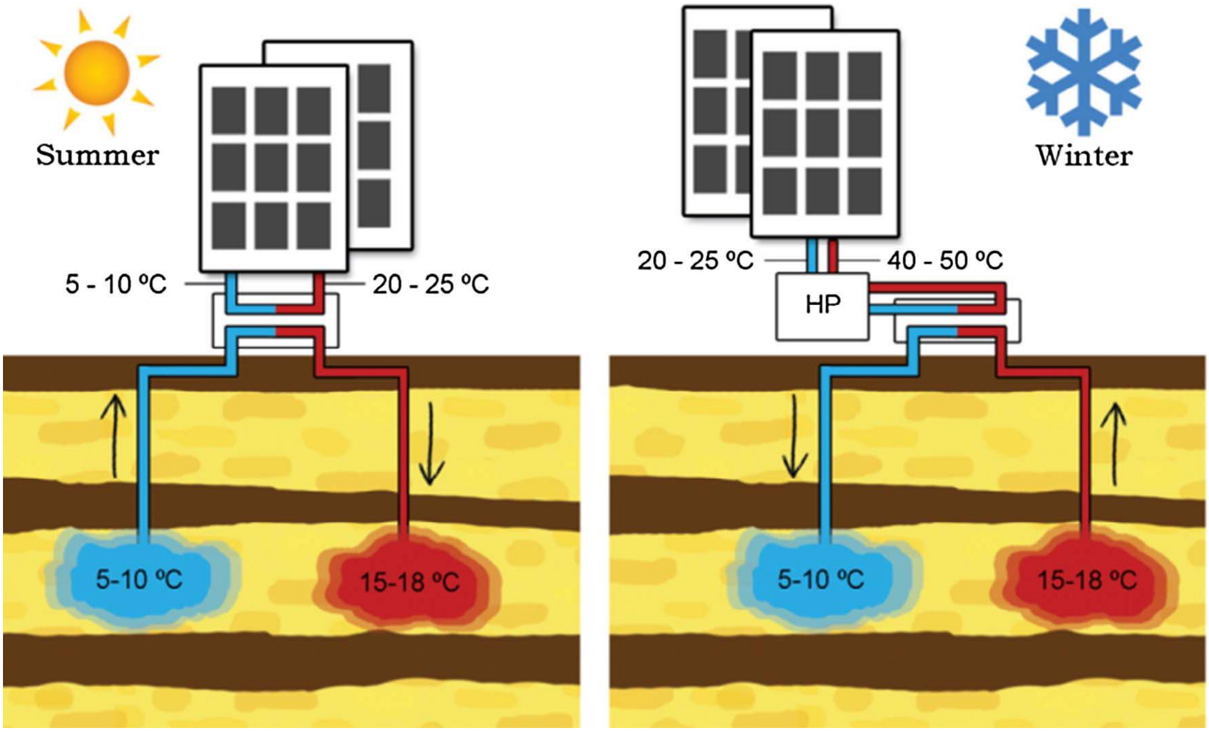

Figure 13. Schematic visual of an ATES system with doublet [73]

While the ATES systems can be installed at a depth of 20–200 metres, according to Noome [71], the combination of the second and third aquifer layers at a depth of 70–200 metres is the most suitable level for the ATES systems in Amsterdam. The natural temperature of groundwater is around 10–12 °C at this level, increasing 3 °C per 100 metres [72]. While this naturally present groundwater can already be an energy source when coupled with heat pumps as explained in Production Potential, the use of residual heat and other heat sources makes it possible to store and recover heat at higher or lower temperatures in the ATES systems. According to this, the temperature level in the cold units of an ATES system can be between 5–10 °C, while the heat units have a temperature level of 15–18 °C on average [73]. The energy potential of an ATES system depends on the flow rates of the ATES wells and the volumetric capacity of the heat and cold units that are adjusted to meet the heat and cold demand of buildings. Equation 7 is used to understand and quantify the relationship between the energy potential and volumetric capacity of the ATES storage units.

Equation 7

$$ED = Q \times c_p \times \Delta T \times t \,/\, (3.6 * 10^6)$$
$$VC = Q \times t$$

EP	Energy potential of the ATES unit (MWh)
VC	Volumetric capacity of the ATES unit (m^3)
Q	Flow rate of the wells (m^3/h)
c_p	Specific heat capacity of water, which is 4200 (kJ/m^3. K)
ΔT_1	Temperature difference between the extracted and injected water (K)
t	Operation period of the ATES for heating or cooling (h)

It must be noted that there are certain regulations for designing ATES systems in the Netherlands to protect the underground ecosystem while keeping the storage system as efficient as possible. The major aspect of these regulations is to keep the underground temperature level same over the year by balancing the volumetric capacity and temperature level of the heat and cold storage units [71, 74]. Therefore, for instance, it is not possible to design an ATES system with a heat storage unit which has an extremely higher temperature than the natural ground water temperature and larger amount of energy than the cold storage unit. Residual heat sources can be used for ATES regeneration to balance the heat and cold storage units. Plus, the heat and cold storage units must be kept at least 100 metres away from each other to prevent negative influence between them which reduces the efficiency of the ATES system [71]. Therefore, these regulations also affect the energy potential and volumetric capacity of the ATES systems, which is explained in Concept Development.

f. Heat pump

Heat pumps are the most crucial element of the heat transition process thanks to their high efficiency level that helps use of low temperature heat sources such as groundwater and ambient air. The COP of heat pumps differs according to the source temperature and temperature lift (K). The COP of heat pumps is higher when temperature lift between the source and sink unit is lower, and the COP of the air source and water source heat pumps ranges between 3 and 5 on average [63]. As the ATES systems that store residual heat and locally available heat at higher temperatures in the storage units, the COP of heat pumps connected to the ATES are higher. As for the calculations, Equation 8 is used, which is based on the temperature level of the heat source and sink, temperature lift between them, and finally the Carnot efficiency rate which sets the limits for the efficiency of heat pumps and engines [63]. The Carnot rate generally ranges between 0.4 and 0.6 for heat pumps [63], therefore an average rate of 0.5 is used for the calculations in this research. The COP of heat pumps for cooling is considered 1 lower than the heating mode [73].

Equation 8 $COP_{heating} = T_{hot} / (T_{hot} - T_{cold}) \times CR$

COP	Coefficient of performance of heat pump (n)
T_{hot}	Temperature of heat source or sink (K)
T_{cold}	Temperature of cold source or sink (K)
CR	Carnot rate (n)

II. Geographic information services

As for the quantification of the local potential for renewable energy production, open source geometric data services providing information on different renewable energy sources can be used. These sources include PDOK, a web service providing open source geographic datasets, Warmte Atlas and Waternet Omgevingswarmte, online map tools providing information on local energy potentials, and Maps Amsterdam, providing data sets and maps about different aspects of urban characteristics of the city, as seen in Figure 14. In addition to the production potential, the maps showing architectural and archeological spatial restrictions are also used for the determination of potential areas for the placement of the ATES system.

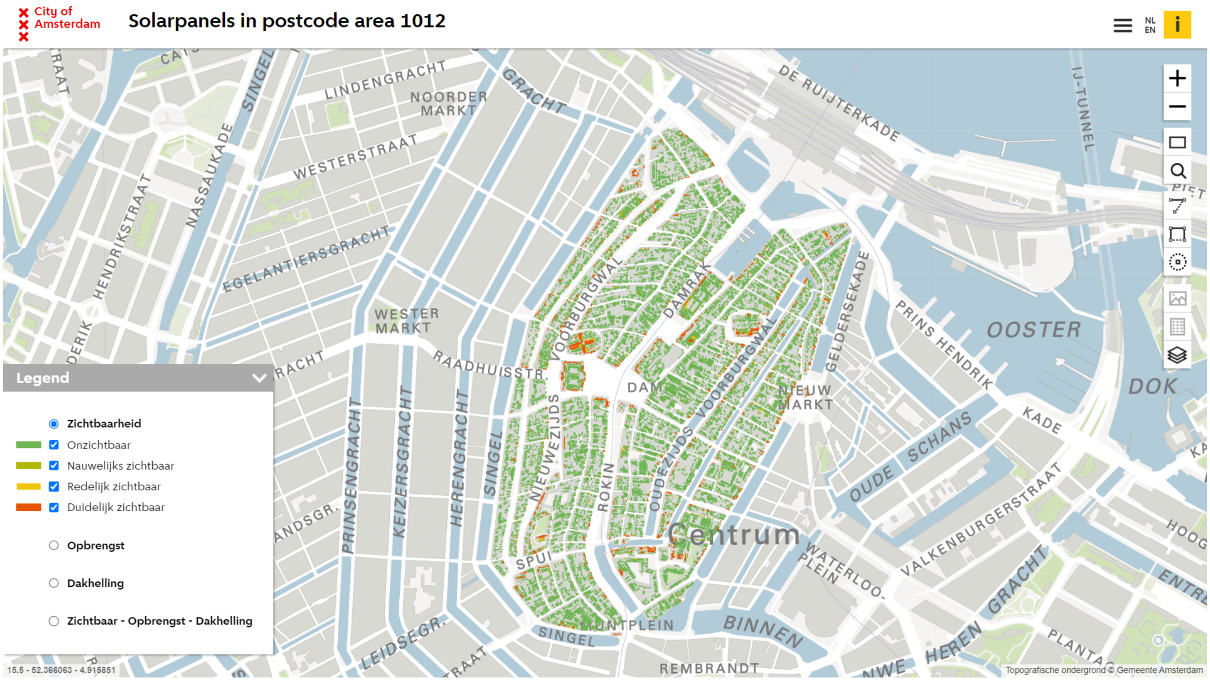

Figure 14. An example map of solar panel installation possibility in the centre of Amsterdam [75]

III. Technology inventory

Following the completion of the first phase, the next step is the energy concept development that is based on the translation of the local potentials into energy concepts for the desired energy balance solutions. This step was carried out by means of Technology Inventory [76] developed for the SUI approach to provide an overview of the available technologies, products, and services. Based on this, different energy concepts are developed by combining renovation and final energy options. The categorisation of the energy concepts can be based on the energy network type which is either individual or collective. In the individual energy systems, although the buildings can still be connected to a power and gas grid, final energy options for renewable energy supply based on local sources are customised for each building according to their potential for energy reduction, reuse and production. In most cases, heat pumps are utilised to meet the heat demand in the buildings [26]. As for the collective systems, a heat grid based on the collective use of local heat sources is developed and all components of the local energy system such as solar panels on roofs, underground thermal storage units, and air handling units of buildings to exchange residual heat between different units are connected to this grid. The collective systems can be based on different heat supply options with different temperature levels such as high (>65 °C), medium (45-65 °C), low (25-45 °C) or ultra-low (<25 °C) temperature [26].

IV. Key performance indicators

The final step of the research is the quantified evaluation of each energy concept according to the performance indicators defined by the SUI approach. These indicators are based on assessing the self-sufficiency and sustainability of the concepts designed for a case study area [27]. The indicators selected among the KPIs for this research are local renewable fraction (%), annual external energy input (MWh), and annual CO_2 emissions (tons) from the use of external energy. Each indicator is quantified for each energy type (electricity and heat) for each concept, and the best option is chosen according to the results of this assessment. The indicators and their quantification methods and explanations are presented in Table 13.

Table 13. KPIs and the explanation of their quantification method

Key performance indicators	Method
Local renewable fraction (%)	The ratio of local (renewable) energy supply to the total energy input
Annual external energy input (MWh)	Remaining energy demand that is supplied by external energy sources
Annual CO_2 emissions (tons)	Calculated according to the CO_2 emission factors

5. RESULTS

A. Reduction Potential

The quantification of the energy reduction potential in Damrak was carried out according to the methods explained in Heat Algorithms, including the equations for technology upgrade, thermal insulation and heat recovery. The first step is based on energy loss reduction through technology upgrade, while heat loss reduction by means of thermal insulation and heat recovery was calculated as the second and third steps. Based on this structure, a renovation scenario was developed in which different interventions for each step were designed to reduce energy use. The technology upgrade part of the renovation scenario is based on the replacement of gas boilers with heat pumps, and gas stoves with induction stoves in all buildings in Damrak. As for the thermal insulation part, glass wool as one of the most common and efficient insulation materials is considered for the insulation of roofs, facades and ground floors of the buildings, while thin double glazing is chosen for windows. In order to identify the buildings that need to be insulated, a categorisation was carried out through the energy labels. According to this categorisation, 23 buildings with either poor energy labels (E, F, G) or no energy label registration were focused for the implementation of the insulation measures. A special attention was paid to the large buildings due to the fact that they have historic elements on the building envelope such as reliefs on the wall and wooden window frames that block the interventions for those parts. Last but not least, the MVHR systems with cross plate heat exchangers for the commercial units (except for the large buildings which already have these systems) were considered for the heat recovery part.

Table 14. Energy reduction potential in Damrak

Renovation scenario in three steps	Energy use (MWh/year)				Energy reduction (MWh/year)
	Space heating	DHW	Cooking	Total	
Current status	9108	721	357	10186	NA
Technology upgrade	8690	652	130	9472	714
Thermal insulation	6968	652	130	7750	1722
Heat recovery	5980	652	130	6762	988
Total					3424

Table 14 presents the results of the renovation scenario in three steps for the case study of Damrak. As such, each step helps reduce a certain amount of energy use, and the total reduction is around 3424 MWh/year which constitutes 34 % reduction in total energy use for space heating, DHW and cooking in Damrak. It must be noted that this reduction can be achieved for the energy use for space heating, DHW, and cooking, which is based on the replacement of natural gas use in the area. Yet, the use of high efficient technologies such as heat pumps and induction stoves to achieve this result increases the electricity consumption on the case study site. The increase in the electricity use was disregarded for this part of the research. This is due to the fact that the amount of electricity needed for these technologies depends on the energy reuse and production potential in Damrak. Therefore, the overall energy balance that includes the increase in electricity use due to the technology input are presented in the energy balance tables of the energy concepts in Concept Development.

B. Reuse Potential

The energy reuse potential in Damrak was revealed through the analysis of residual heat potential from the buildings. The equations in Residual heat were used for the quantification of these potentials, and Table 15 provides the results of the calculations. As seen in the table, the exhaust air from the air handling units and the return warm water from the heating systems are the most promising residual heat sources in Damrak. It must be noted that the results provide the theoretical potential of the available residual heat, while the usable amount is determined by the design of the energy concepts. This is because a certain portion of residual heat can be directly used via an energy exchange system between the different units or buildings. For instance, the residual heat from the cooling installations in the supermarket is available all year round at around 40 °C, and it can be directly used as a low temperature heat source in winter. Nevertheless, the residual heat from the exhaust air is only usable via the ATES system due to the mismatch between the availability period and temperature level of residual heat and the amount and temperature level of heat demand. In that case, the amount of residual heat potential is reduced due to the heat losses during the heat transfer between the source, storage and use units.. The residual heat from the air handling units and heating systems are mainly used for the regeneration of the ATES potential and for adjusting the temperature level of the groundwater in the ATES storage units.

Table 15. Energy reuse potential in Damrak

Source category	Output temperature level (°C)	Energy potential (MWh/year)
Air handling units	9-21	7296
Cooling installations (supermarket)	40	448
Heating systems (return warm water)	20-25	4800

As mentioned before, there are certain regulations to take into account when designing an ATES system. Especially dense urban areas pose risks for negative influence of heat and cold units on each other. To prevent this in Amsterdam, there is an interference area designed by the municipality [71, 77], as seen in Figure 15. The case study site is also part of this interference area, and therefore installing a thermal storage system is restricted and subject to permission. The first issue is to keep the heat and cold storage units in balance. Since the heat demand is higher than the cold demand in Damrak, local low temperature cold sources can be used for ATES regeneration to keep the heat and cold units in balance. Another important challenge is to keep the storage units at least 100 metre away from each other. As the total area is approximately 4 ha on the case study site, it is assumed that there is enough space to install two separate storage units without any interference. In addition, there are spatial restrictions in the area such as the Noord-Zuid metro line going under Damrak street, the wooden pile foundations and the shaft under the buildings [71]. Based on the regulations and spatial restrictions, Noome [71] provides a map showing the potential areas for drilling to install the ATES wells in Damrak, as seen in Figure 16. Due to the fact that there is an underground bicycle parking under Beursplein and this area is defined as limited possibility for drilling, the locations in Dam and Damrak are more suitable for an ATES system with a doublet as each of these locations can be used for either heat or cold storage. It must be noted that this ATES system will collectively be used by all buildings in the area since there is a highly limited possibility to install individual ATES systems per building without interference.

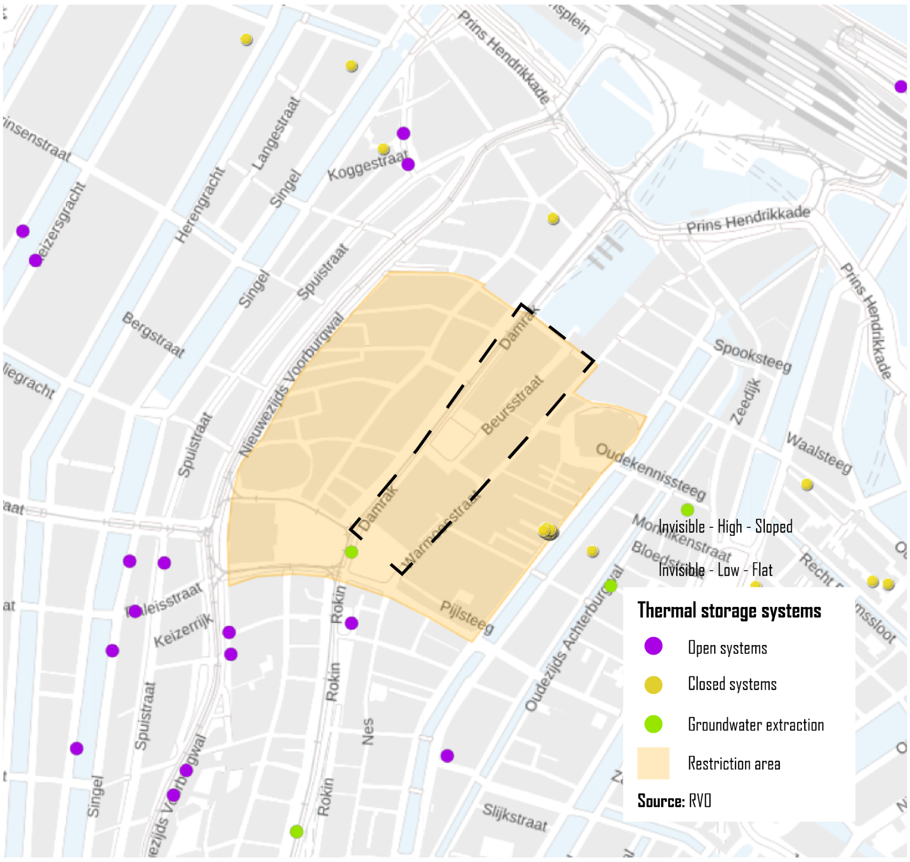

Figure 15. The restriction area and present thermal storage systems [77]

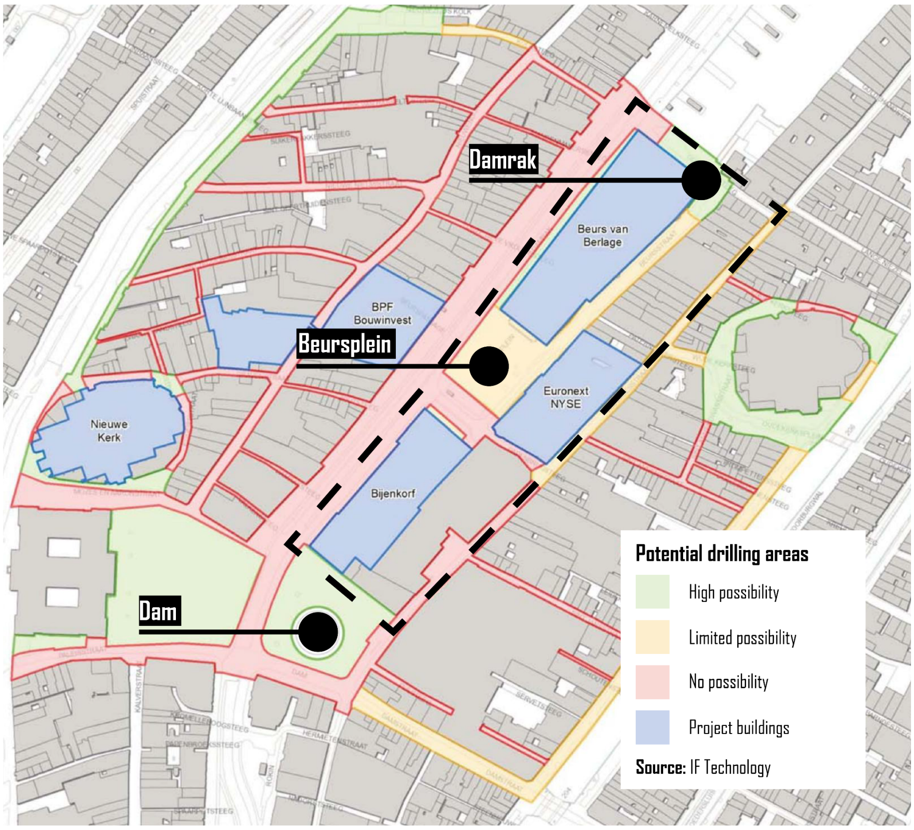

Figure 16. Potential drilling areas for thermal storage systems [71]

C. Production Potential

As a densely populated urban area at the heart of the city, Damrak has many limitations when it comes to the local potential for renewable energy production. Wind energy options are not suitable for the area due to the fact that there is no available space for large wind turbines, and urban monumentality and technical issues block the use of small wind turbines [37]. Likewise, biomass energy potential is extremely limited since there is no green space or agricultural land in the area that can provide organic materials as biomass [37]. The utilisation of organic household waste is also problematic due to the difficulties for waste separation in the historic centre of Amsterdam [78]. Similarly, there are certain challenges regarding geothermal energy, as the literature points out that the geothermal energy potential of Amsterdam remains unknown since there is no geothermal well in the city [37, 79]. Geographical data show that the chance of benefiting from deep (2-4 km) and ultra-deep (>4 km) geothermal energy at high temperatures in Amsterdam is very limited due to the thickness of the aquifer below 10 metres at these depths [80]. Nevertheless, the case study area has potential for other local renewable sources, as presented in Table 16.

Table 16. Energy production potential in Damrak

Energy source	Energy use category	Temperature level (°C)	Energy potential (MWh/year)
Solar	Power	NA	607
	Heat	40	1250
Aqua thermal (surface water)	Heat & cold	8-17	605
Groundwater	Heat & cold	10-12	NA
Ambient air	Heat & cold	5-17 (average)	NA

Solar energy is one of the most promising local renewable energy sources in the area, and thanks to the recent technological advancements, solar energy installations called PVT panels can generate electricity and heat at the same time. Yet, as previously discussed in this report, the urban monumentality of Amsterdam limits the ability to use solar energy potential. While the solar panel installations on the roofs of monumental buildings are subject to the permission of the municipal committee, the city view protection directly blocks the installations on visible spots of roofs [36]. Nevertheless, the Municipality of Amsterdam has an online tool [75] to help identify which spots on roofs in the historic centre of the city are available for solar panel installations. In the form an interactive map, this tool provides information on the visibility of the available spots on roofs (after excluding unusable spaces on roofs), the roof types (flat or pitched) and the potential power yield (high or low) per solar energy installation according to solar radiation potential of that spot (Figure 17). By means of this online tool, the solar energy potential of Damrak was calculated through the selection of certain features of the map. Due to the monumentality and city view protection as well as feasibility issues, only invisible spots with high energy yield were chosen. As such, it is identified that the total available space for solar panel installations is 3712 m², which makes enough room for the installation of 2250 solar panels [75]. The average solar power and heat (40 °C) yield per panel is 270 kWh/year and 555 kWh/year, respectively [75, 79, 81]. It must be noted that since the heat yield from the PVT panels mainly occurs in the warm seasons, thermal storage systems should be utilised to make use of this energy potential.

Figure 17. Solar panel installation possibilities in Damrak [75]

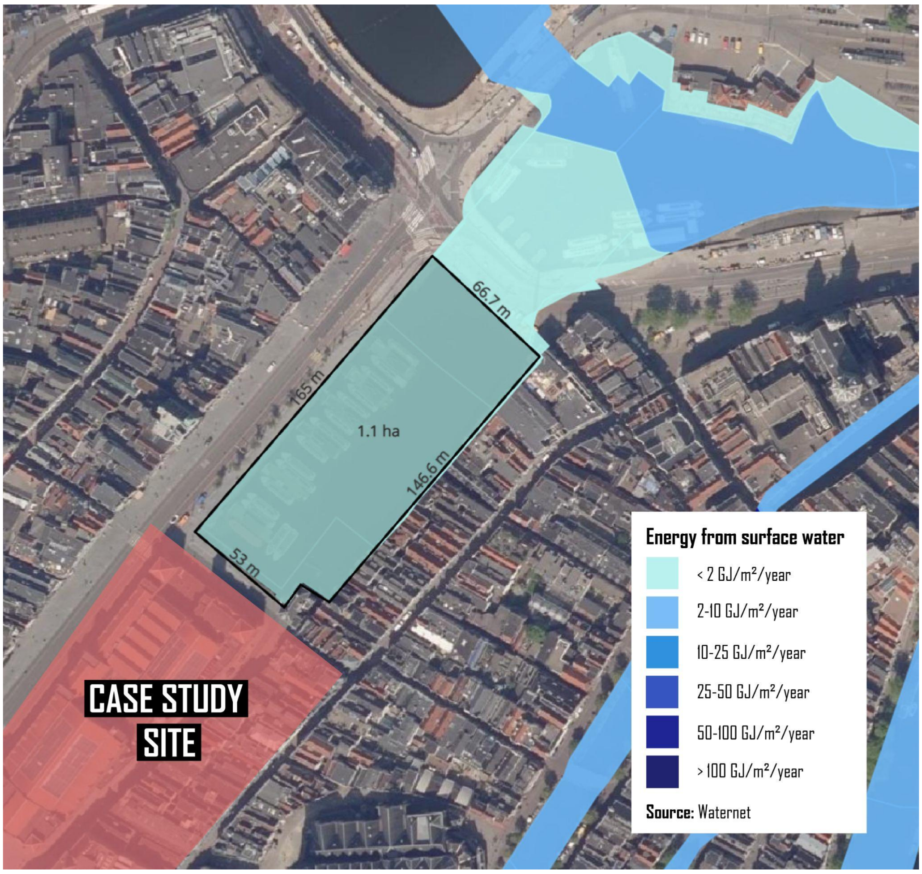

Figure 18. Energy potential from surface water [82]

In addition to solar energy, another local renewable energy source in Damrak is surface water as it provides heat (17 °C) during summer and cold (8 °C) during winter [82]. Called aqua thermal energy, this energy source can be a reliable choice to meet the certain portion of heat and cold demand through the ATES storage units. Waternet [82] shows that surface water can provide heat and cold up to 2 GJ/m²/year (0.55 MWh/m²/year) in Damrak. As such, a maximum amount of 605 MWh heat can be generated from the canal extension (1.1 ha) in Damrak, as presented in Figure 18. Last but not least, the groundwater and ambient air can also be used as energy sources with the help of heat pumps. The temperature level of the groundwater in the aquifer layers (the second and third aquifer at the depth of 70-200 m) is around 10-12 °C year-round. As such, while cold supply can be carried out through free cooling systems in buildings, heat supply is carried out through water source heat pumps to increase the temperature level of groundwater to the desired level. Likewise, air source heat pumps can be used to increase or decrease the temperature level of the ambient air to heat and cool the buildings. The average temperature level of the ambient air is around 5 °C in winter, and 17 °C in summer in Amsterdam [41, 42]. The most important parameters for the calculation of energy potential from the groundwater and ambient air are the COPs of the heat pumps, which is explained in Concept Development.

D. Concept Development

As indicated before, the development of energy concepts was carried out on the basis of local potentials for energy reduction, reuse, and production. According to this, three different concepts were developed for heat generation and distribution as two individual options and a collective one. While the individual options are structured around heat generation within each building, a heat grid that connects the ATES units to each building was designed for the collective system. The main differences between the concepts are the type of the heat pump, as air source and water source, and the use of the ATES system. The calculations for the COPs of the heat pumps were separately carried out for each concept. In all systems, the buildings are still connected to the city's power grid since local electricity production capacity is extremely low to meet the demand.

The individual options (Option A and B) are fully decentralised heat systems in which each building generates its own heat and cold by means of solar panels and heat pumps, as seen in Figure 19 and 20. Option A is based on the use of air source heat pumps, while water source heat pumps using the groundwater are considered for Option B. In contrast to the individual options, there is a ultra low temperature heat grid that helps use the ATES system in the collective option (Option C). As seen in Figure 21 and 22, the heat grid connects each building to an ATES system with a collective heat pump to supply heat and cold. All energy efficiency steps (technology upgrade, thermal insulation, heat recovery) are considered to be taken for all options to increase the ability of the system to use low temperature sources. As such, while the PVT panels on roof supply renewable heat (40 °C) and power, the ambient air (5-17 °C on average), the groundwater (10-12 °C), and the ATES storage units (8-16 °C on average) are the main heat and cold sources in Damrak. Plus, there is an energy exchange system designed between the supermarket and its neighbouring units within the same building to directly use the residual heat from the cooling installations which is available year-round at 40 °C.

In Option A, the heat and cold supply is carried out through heat pump, while in Option B and C, the cold supply is carried out through a free cooling system based on groundwater, and heat pumps are utilised to increase the temperature level of the groundwater to 40 °C and 60 °C for space heating and DHW, respectively. The size of the ATES heat and cold units in Option C is considered around a million cubic metre for each unit to meet the heat and cold demand, calculated according to the equation in Thermal storage. Likewise, based on the method explained in Heat pump, the COP of heat pumps was calculated. According to this, The COP of the heat pumps in Option A is 4 for space heating, 2.8 for DHW, and 3 for cooling; in Option B, it is 4,5 for space heating and 3.3 for DHW; and in Option C, it is 5.2 for space heating and 3.7 for DHW. As seen in Table 17, the total heat and cold demand can be supplied with the combination of heat pumps and local heat sources in all options, which constitutes considerable reduction in the total external energy input, 35 %, 42 %, and 43 % for Option A, B, and C respectively. It must be noted that the amount of reuse and production potential presented in the table is for direct use, while the rest is considered to be used in the ATES system.

Table 17. Energy balance table of the all concepts

Steps		Heat (MWh/year)	Cold (MWh/year)	Power (MWh/year)
Current energy consumption		10186 (G)	1748 (E)	13905
Reduction potential	Technology upgrade	– 714 (G/T)	NA	NA
	Thermal insulation	– 1722 (T)	NA	NA
	Heat recovery	– 988 (T)	NA	NA
Reuse potential	Cooling installations (direct use)	– 230 (T)	NA	NA
Production potential	Solar thermal & power (direct use)	– 480 (T)	NA	– 607
Technology input	Induction stove	NA	NA	+ 130
	Option A – Individual Air source heat pump	– 5922 (T)	– 5244 (T)	+ 3297
	Option B – Individual Water source heat pump	– 5922 (T)	– 5244 (T)	+ 1368
	Option C – Collective Water source heat pump with ATES system	– 5922 (T)	– 5244 (T)	+ 1189
Remaining energy demand	Option A	NA	NA	16725
	Option B	NA	NA	14796
	Option C	NA	NA	14617

G = Gas, E = Electricity, T = Thermal energy whose medium is water or air

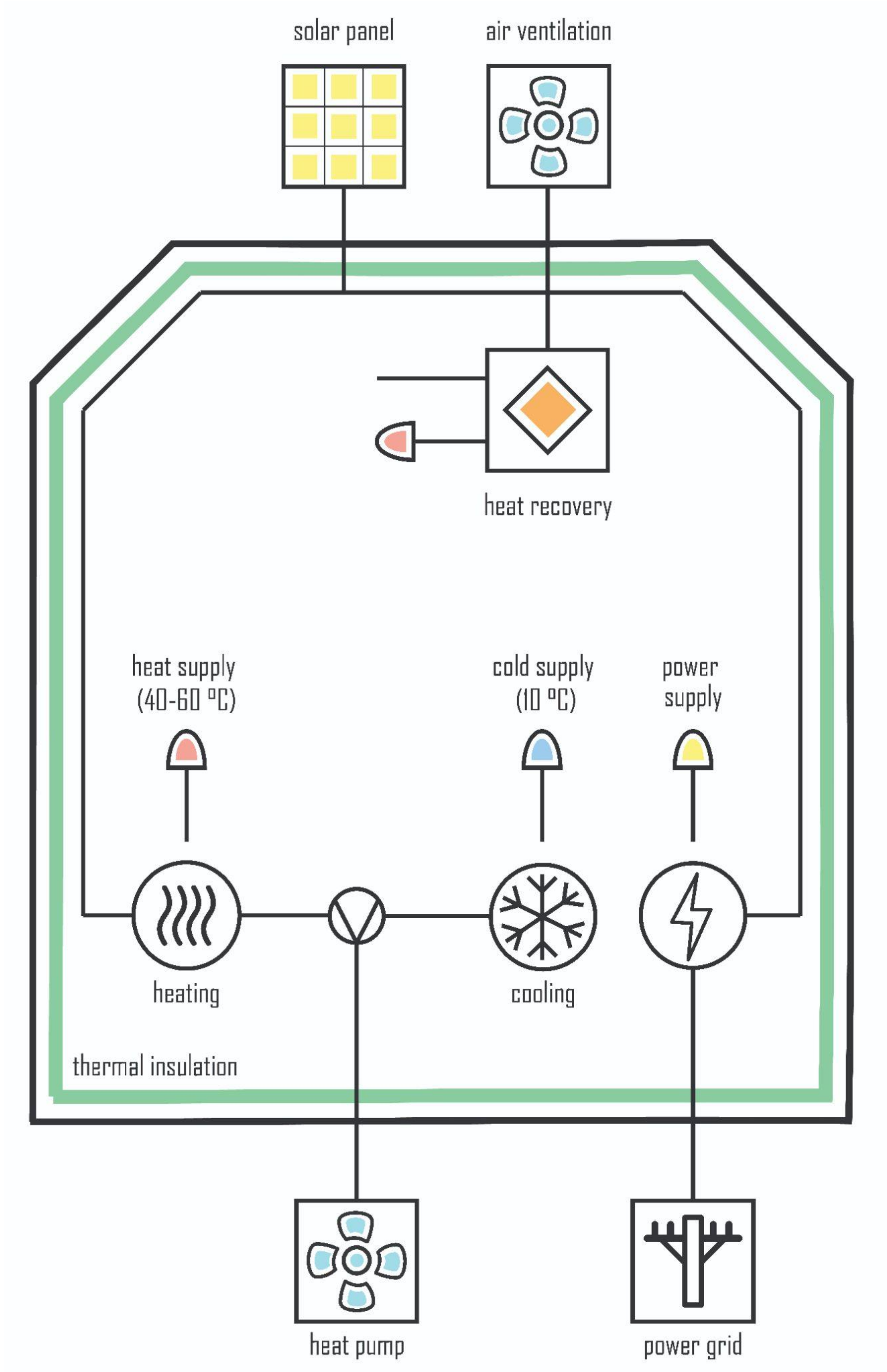

Figure 19. Schematic diagram of Option A

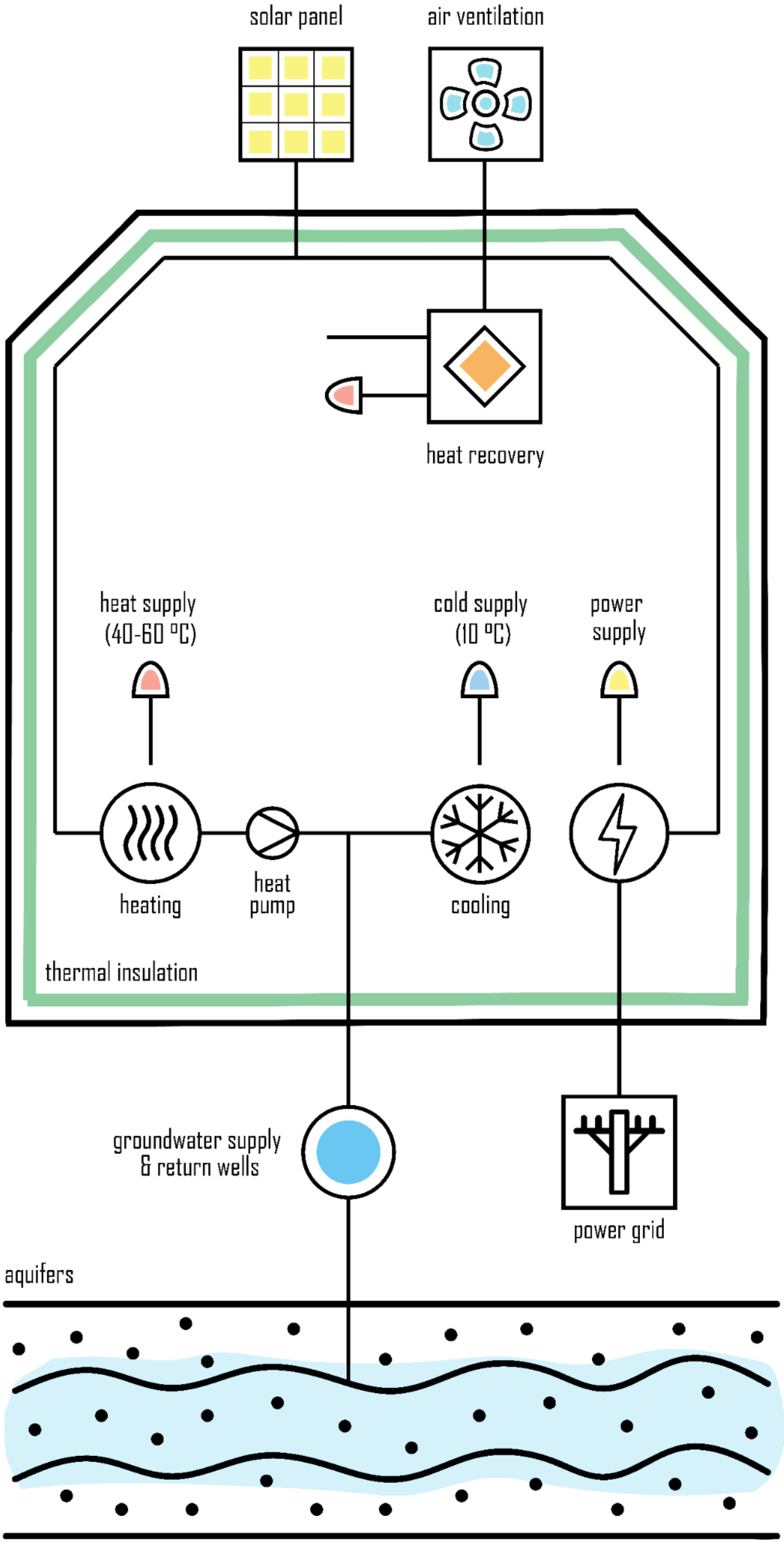

Figure 20. Schematic diagram of Option B

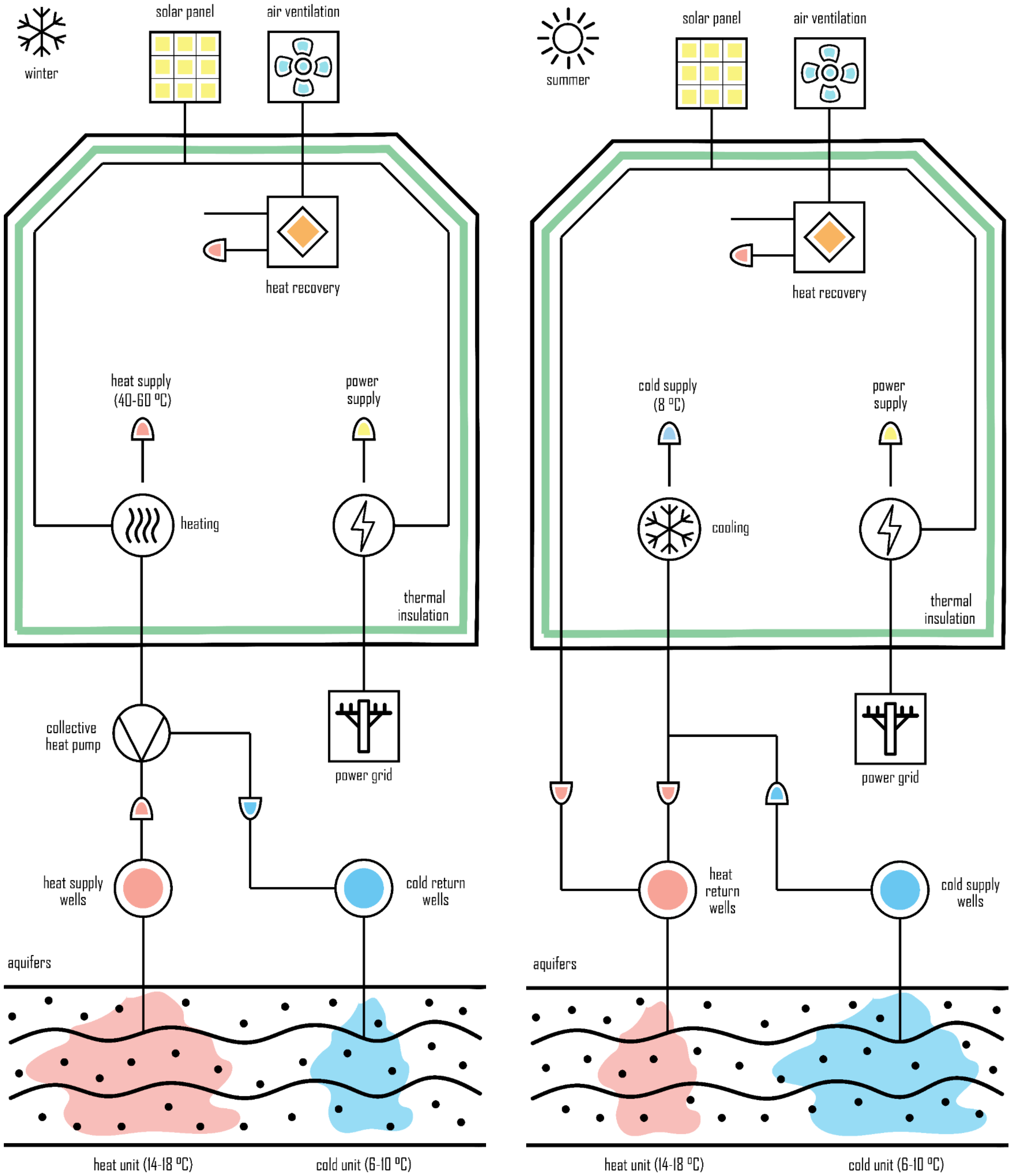

Figure 21 & 22. Schematic diagrams of Option C for heating and cooling

E. Evaluation

The evaluation of the energy concepts described in the previous section was carried out according to the KPIs explained in Research Methods. As such, three KPIs were quantified per concept and the result is presented in Table 19. It must be noted that the local renewable fraction is the ratio of total local renewable heat and electricity production to the total energy demand on the case study site. The annual external energy input which is fully electricity is as presented in the energy balance tables of each concept, and CO_2 emissions are associated with the external electricity input, 369 kilograms of CO_2 per MWh energy [55]. As seen in the table, the options with water source heat pumps (Option B and C) show better performance in each category than the option with air source heat pumps (Option A). This is particularly thanks to the free cooling system with groundwater and heat sources with higher temperatures. Overall, the collective option (Option C) performs the best among the concepts, being the best option for the case study of Damrak. This is enabled by the ATES system that helps use heat sources with higher temperatures than groundwater and therefore increases the COP of the heat pumps. Nevertheless, the ATES systems entail many financial and environmental issues that are disregarded for this research but must be taken into account when designing technical projects.

Table 19. The performances of the concepts according to the KPIs

KPIs	Option A	Option B	Option C
Local renewable fraction (%)	% 42	% 45	% 46
Annual external energy input (MWh)	16725	14796	14617
Annual CO_2 emissions (tons)	6171	5459	5393

6. DISCUSSION

A. Findings & Implications

As discussed in Literature Study, the heat transition is considered the most problematic part of the fight against the climate crisis in Amsterdam due to the local challenges for energy renovation of buildings in the historic centre of the city. Focusing on increasing the energy efficiency level of the buildings, and tapping into the local energy sources, this research shows that heat and cold demand can easily be covered without bringing any significant pressure onto the power grid on the case study site, as seen in the energy balance table of the energy concepts in Concept Development. This helps reduce the external energy input into the case study site by almost half in some options, which constitutes a major step towards carbon neutrality in urban areas as there will be less pressure on the regional and national energy infrastructure systems for the replacement of fossil fuels with renewable energy sources. Energy reduction through the energy efficiency measures is one of the most promising steps of the research, as it helps achieve more than one-third reduction in the total energy use for heating, and almost 15 % reduction in the total energy use on the case study site. Likewise, the use of heat pumps for heating and cooling is another key part of the research, providing the opportunity to supply heat and cold demand with local sources and therefore to cut the external energy input by around one-fourth alone. Nevertheless, as the research shows that renewable power generation is actually the most challenging part of the energy transition process in Amsterdam. This is particularly because of the fact that the high urban density and architectural characteristics of the buildings extremely limits the possibility to install renewable power generation systems such as solar panels and small wind turbines. As such, there is a great need for the establishment of large scale renewable power generation units such as wind and solar energy farms in the hinterland of Amsterdam to supply electricity to the urban areas. Yet, this requires the allocation of a large portion of agricultural land and industrial sites for renewable energy systems, which is highly likely to cause new tensions and conflicts between different stakeholders and business sectors of the city.

Based on these main findings of the research, some implications can be made for the field of architecture and urban planning as the new strategies and design principles needed to facilitate the energy transition process in urban areas. First of all, it must be acknowledged that the modern architecture and urbanism practices in the past century are the biggest contributors to the climate crisis by creating a great tension between humanity and nature. This is particularly because of the large scale and centralised energy systems channelling large amounts of fossil fuels into the cities, which triggered the emergence of metropolitan areas on the basis of excessive urban sprawl and depletion of natural resources. This paved the way for the large urban development projects that disregard local bioclimatic conditions and cause high levels of energy intensities. Therefore, there is a great need for a radical shift in modern architecture and urban planning to develop energy conscious and sustainable design and planning principles at building and urban level. For instance, the zoning system that has been dominating modern urban planning for a long time divides urban areas into different functional units as residential, commercial, recreational zones, and creates automobile-centric busy transportation networks between them. Instead, developing new planning approaches and strategies based on the mixed-use of buildings and urban spaces can help benefit from the energy exchange system between the commercial and residential units while reducing transportation-related energy consumption thanks to enabling micro-mobility options for commuting. Moreover, focusing on the development of small-scale urban communities instead of large urban development projects can boost urban resilience and energy security through the establishment of local energy initiatives based on decentralised renewable energy systems at neighbourhood/district level. This particularly helps use more local energy potentials to reduce the reliance on external energy input, and therefore develop circular and self-sufficient urban energy systems.

B. Limitations & Recommendations

Although the outcomes of the research are promising in terms of how high energy efficiencies and local energy inputs can help transition to renewable energy systems in urban areas, it must be noted the results only provide the theoretical local energy potentials whereas the actual amounts may differ due to the technical issues disregarded for this research. This is particularly because of the difficulties for data acquisition, uncertainties regarding certain energy efficiency measures and renewable energy systems, and time limitations for this thesis study. First of all, as indicated in <u>Case Study</u>, some generic data sources were used to understand the energy status quo in Damrak due to the hardships to access the actual data for some buildings on the case study site. Nevertheless, since the historic centre of Amsterdam has highly unique characteristics, using generic data may not provide the full picture of the energy status quo of the site. Likewise, the unique architectural characteristics and monumental status of the buildings also cause difficulties to develop a generic approach for energy efficiency measures like thermal insulation for the case study site. Therefore, the actual energy reduction potential can only be understood through the development of more detailed renovation options for each building. Another important issue is the uncertainties regarding the actual energy potential of the aquifers in the area as two energy concepts are based on this potential. The groundwater level and subsoil substances that are present in the aquifers are important parameters for the energy potential of the groundwater and thermal recovery potential of the ATES units. There should be a careful examination of these aspects as the use of underground energy systems entails many environmental impacts and technical challenges.

Since the energy transition is a complex societal issue, the social aspects of this phenomenon must be taken into account when designing such energy systems for a specific location. This is one of the main limitations of this research as it is only based on the technical aspects of the urban energy systems. Phasing out natural gas and shifting to low temperature heat sources certainly have social implications as it is highly likely to cause changes in the usual indoor thermal comfort level in modern buildings. This has to be communicated with stakeholders and users to adjust the comfort level when designing such energy systems to reduce the potential social tension and prevent user dissatisfaction. Besides, the energy transition entails certain financial challenges since it requires a considerable amount of investment for the energy renovation of buildings and installations of new energy systems. How to share this financial burden is already the subject of heated debate among public and private stakeholders, and there are many financial mechanisms created through subsidies, grants and loans to boost the investments. As such, it is crucial to carry out feasibility analysis alongside the development of energy concepts to communicate with stakeholders about the payback periods which are also important performance indicators for evaluation of the concepts. Therefore, the stakeholder engagement designed for the social and financial aspects of the energy transition should be included in the future research and studies for the development of such concepts for local and decentralised energy systems.

7. CONCLUSION

Since the planetary impacts of the climate crisis are exacerbating every year, there needs to be an urgent action in reversing the trends that caused this crisis, and the energy transition in urban areas is the key to achieving these climate goals. As such, this research aims at providing generic insights into how an energy transition scenario can be developed in Amsterdam. In doing so, the research bases on the general and local challenges for the transition to renewable energy systems, and uses the Smart Urban Isle approach as a methodological tool to understand how to overcome these challenges. As identified in Literature Study, while the large scale and centralised energy systems are problematic for the transition to renewable energy, local and decentralised energy systems can help benefit more from renewable energy. On this basis, the research focuses on understanding the local energy potential for energy reduction, reuse, and production, and designing energy concepts based on this potential for the case study of Damrak located in the historic centre of Amsterdam. The research questions were formulated according to this research aim and structure, and the methods used to answer the questions are mainly structured around the quantification of the local energy potential, including heat algorithms for energy reduction and reuse potential, and geographic information services for production potential.

One of the main outcomes of the research is that the localisation and decentralisation of urban energy systems can make significant contributions to the energy transition process as the results of the research show that high energy efficiency levels and more local energy inputs can easily be achieved by means of such systems. Therefore, shifting the focus to the utilisation of local energy sources through the development of decentralised, small-scale energy systems can help drastically reduce the reliance on external energy inputs that require larger scale energy networks and transportation of fossil fuels. While this facilitates the heat transition thanks to the abundant local heat sources, power supply stays short of the demand, remaining dependent on the power grid for external input. Overall, this research provides a strong basis for the viability of local and decentralised heating and cooling systems in urban areas, while pointing out that new strategies and tactics are required for the local power supply systems. Plus, further research that takes the social and financial challenges into account when developing such energy transition scenarios is needed to achieve more comprehensive results.

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