Transforming urban heating systems

Integrating perspectives on water use, committed emissions and energy justice in the city of Amsterdam

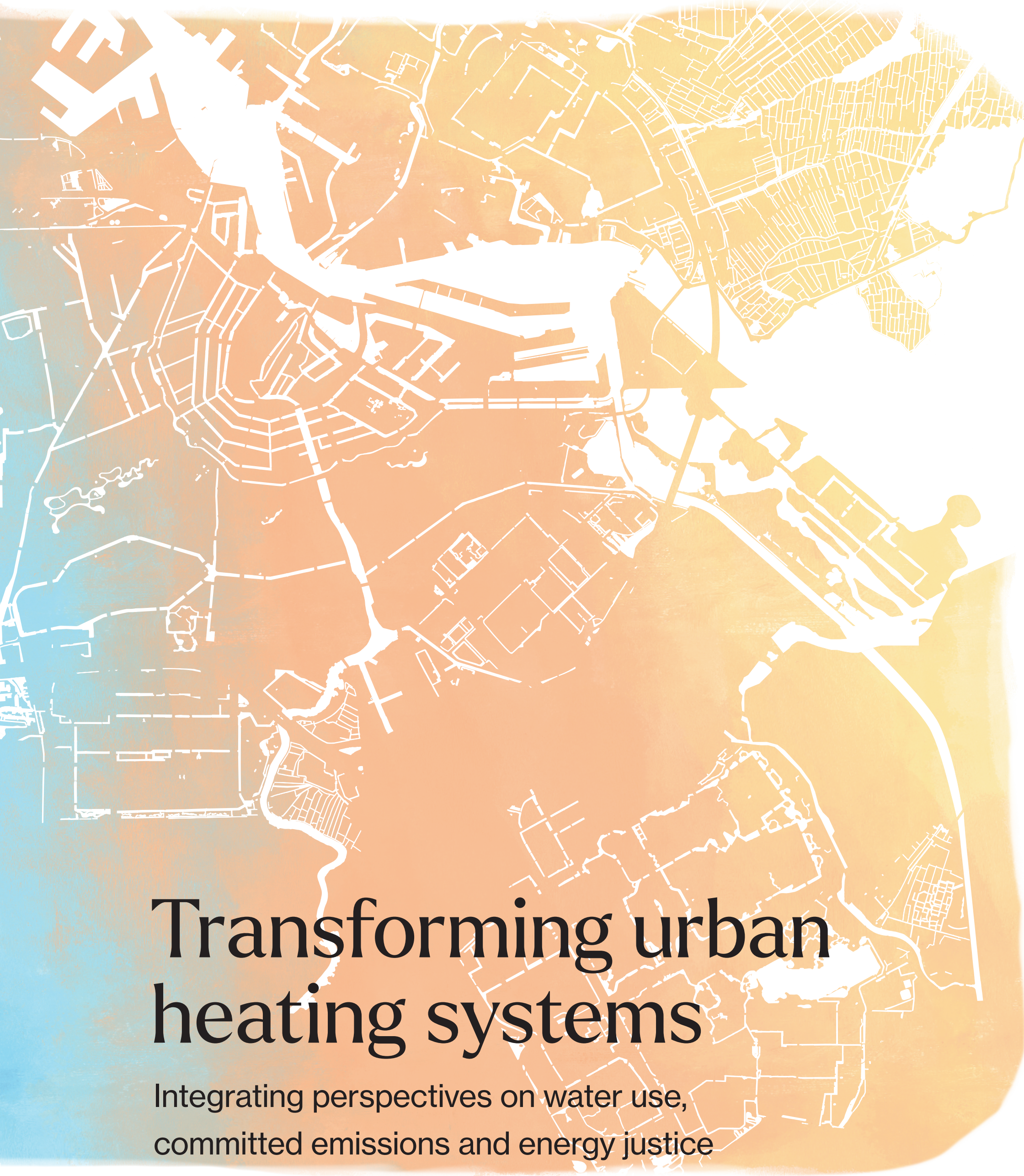
Kaandorp, C.

DOI
10.4233/uuid:2c4855b0-96f8-4a0f-bbca-22e1dad25874

Publication date
2023

Document Version
Final published version

Citation (APA)
Kaandorp, C. (2023). *Transforming urban heating systems: Integrating perspectives on water use, committed emissions and energy justice in the city of Amsterdam*. [Dissertation (TU Delft), Delft University of Technology]. https://doi.org/10.4233/uuid:2c4855b0-96f8-4a0f-bbca-22e1dad25874



Transforming urban heating systems

Integrating perspectives on water use, committed emissions and energy justice in the city of Amsterdam

Chelsea Kaandorp

Transforming urban heating systems

Integrating perspectives on water use, committed emissions and energy justice in the city of Amsterdam

Transforming urban heating systems

Integrating perspectives on water use, committed emissions and energy justice in the city of Amsterdam

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof. dr. ir. T.H.J.J. van der Hagen,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen op donderdag 29 juni 2023 om 15:00

door

Chelsea KAANDORP

Master of Science in Cultural Anthropology: Sustainable Citizenship,
Utrecht Universiteit, Utrecht, Nederland,
Master of Advanced Study in Applied Mathematics,
Universiteit van Cambridge, Cambridge, Verenigd Koninkrijk,
geboren te Amsterdam, Nederland.

Dit proefschrift is goedgekeurd door de promotoren.

Samenstelling promotiecommissie bestaat uit:

Rector Magnificus,	voorzitter
Prof. dr. ir. N. van de Giesen,	Technische Universiteit Delft, promotor
Dr. ir. E. Abraham,	Technische Universiteit Delft, copromotor
Onafhankelijke leden:	
Dr. E.H. Krueger	Universiteit van Amsterdam
Dr. W.P.M.F. Ivens	Open Universiteit
Dr. C. Johnson	University College London
Prof. dr. M.E. Warnier	Technische Universiteit Delft
Prof. dr. ir. A.A.J.F. van den Dobbelsteen	Technische Universiteit Delft

This work was funded by the Netherlands Organisation for Scientific Research (NWO) (Project ID: 438-17- 407), under the Sustainable Urbanisation Global Initiative (SUGI) / Food-Water-Energy Nexus, The Netherlands (Project ID: 11057366).

Water Resources Section
Department of Water Management
Faculty of Civil Engineering and Geosciences
Delft University of Technology
The Netherlands

Keywords: urban heating systems, water-energy Nexus, climate change mitigation, urban sustainability transitions

Printed by: Proefschrift All In One

Front & Back: Francesca Mazzucchi

ISBN 978-94-93315-82-2

An electronic version of this dissertation is available at
http://repository.tudelft.nl/.

To my father David

CONTENTS

SUMMARY

The transition towards low-carbon and renewable urban heating systems is crucial for the reduction of greenhouse gas emissions needed to mitigate global warming. In most buildings in the Netherlands, space heating still relies on natural gas, contributing to 13% of the national greenhouse gas emissions. In the city of Amsterdam, various technological interventions are being implemented to facilitate a 'Heat Transition', including the retrofitting of buildings, electrification of heating, and the implementation of heat networks.

The Heat Transition does however not only involve material measures but shapes and is shaped by different social, environmental and technological developments at multiple scales. The aim of this thesis is therefore to provide research on the social-environmental-technological transformations occurring at multiple scales due to the transition towards low-carbon and renewable heating in Amsterdam. To do so, urban heating infrastructures are taken as the unit of analysis to trace these changes across different scales. The scope of the studies presented in this thesis includes three themes: water use, committed emissions, and energy justice.

The first theme, i.e. water use, is studied through a multi-scale energy and water use model. The model is applied to multiple scenarios for electricity and thermal energy production in 2050 in the Netherlands and the city of Amsterdam. Based on the modelling results, it is concluded that, due to water withdrawal by Aquifer Thermal Energy Storage (ATES) systems, national water withdrawal associated with heat production may increase up to the same order of magnitude as the current national water withdrawals for cooling processes in electricity production. The main type of water usage for energy production may therefore shift from cooling practices to energy storage. Water use for heating is hence a relevant topic to consider to avoid future water stress.

Studies on the water use for heat production should moreover encompass an area beyond the local site of energy production to inform how water stress elsewhere can be limited. The results show for example that the virtual water flows embedded in fuels, such as biomass and hydrogen, are higher than the local water consumption for thermal energy generation. A multi-scale assessment of water use for heat production may especially become more relevant, considering an increase in the electricity use for thermal energy production. This increase is anticipated in all scenarios due to the electrification of heating.

The second study highlights committed emissions as a key environmental indicator for designing infrastructures under transition. The notion of committed emissions is defined in this thesis as the cumulative carbon emissions over a specified future planning period. This concept is important for designing heating systems which emit as little as possible carbon emissions for the upcoming decades and thus optimally mitigate global climate change. In this study, a bottom-up heat demand model, which estimates the heat demand at building and neighbourhood levels, is integrated with a mixed-integer nonlinear optimisation problem, targeted at minimising committed emissions between 2030 and 2050. It is shown that the modelled scenarios with the most ambitious measures for insulation of buildings and decarbonisation of electricity production can increase the uptake of low temperature (LT) heating systems, significantly reducing committed emissions and the need for high temperature (HT) heating systems with natural gas, biogas, or hydrogen. Moreover, the results show that the minimum heat density for LT heat networks is not always achieved, creating risks for carbon lock-ins when applying these heat networks, i.e. locking out the potential for alternatives with lower carbon intensities.

The third theme is energy justice. Through ethnographic research methods, the connections between collective heating initiatives and concerns regarding energy justice were studied. It is shown that energy justice concerns related to the transformation of urban heating systems in Amsterdam are present. Moreover, it is described how collective heating initiatives contest the current logic of transitioning towards renewable heating infrastructures, while simultaneously opening up and closing down spaces for different actors to come together. It is argued in this thesis that conceptualising the activities of these initiatives with the notion of 'commoning practices' supports the development of a dynamic understanding of how energy justice is shaped in practice. This notion refers to activities aimed at enhancing decision-making liberties, ownership, or responsibilities over resources for a community of users.

The combination of the presented studies on these three themes provides a contribution to multidisciplinary research on urban sustainability transitions. Methodologically, this thesis advances current nexus research through multi-scale assessment approaches and complements it with social science research methods. It is shown that providing these different perspectives together gives new insights into how a transition towards low-carbon and renewable heating systems is interlinked with multiscalar social-environmental-technological transformations. As such, this thesis provides an example of multidisciplinary research on transformations, which can be applied in future transformation research.

SAMENVATTING

Een transitie naar hernieuwbare stedelijke verwarmingssystemen met een lage CO_2-uitstoot is cruciaal voor het verminderen van broeikasgasemissies en dus voor het tegengaan van klimaatverandering. In de meeste gebouwen in Nederland wordt aardgas nog steeds gebruikt voor het verwarmen van ruimtes en kraanwater. Hierdoor draagt energieopwekking voor warmte in de gebouwde omgeving bij aan 13% van de nationale broeikasgasemissies.

In de stad Amsterdam worden verschillende technologische maatregelen genomen voor een 'Warmtetransitie' naar aardgasvrije, hernieuwbare warmtesystemen met een lage CO_2-uitstoot. Voorbeelden van deze maatregelen zijn: de renovatie van gebouwen, de implementatie van warmtenetten en de installatie van elektrische apparaten die warmte kunnen opwekken. Deze Warmtetransitie bestaat echter niet alleen uit technologische veranderingen in de stad. Stedelijke transities gaan gepaard met maatschappelijke, ecologische en technologische ontwikkelingen op lokale, landelijke en mondiale schaal. Voor dit proefschrift is daarom onderzocht welke ontwikkelingen optreden bij een transitie naar hernieuwbare stedelijke warmtesystemen met een lage CO_2-uitstoot in Amsterdam. Stedelijke infrastructuren voor het verwarmen van gebouwen zijn hiervoor als analyse-eenheid genomen. Het onderzoek is hiervoor opgedeeld in drie thema's, namelijk watergebruik, *committed emissions* en energierechtvaardigheid.

Het eerste thema, watergebruik, is onderzocht met een model dat het energie- en watergebruik op lokale, nationale en mondiale schaal berekent. Het model is toegepast op verschillende scenario's voor de opwekking van elektriciteit en warmte in Amsterdam en Nederland in 2015 en in 2050. Uit de resultaten blijkt dat de nationale wateronttrekking voor open warmte-koude-opslag systemen kan toenemen tot dezelfde orde van grootte als de huidige nationale waterwinning voor koelprocessen bij elektriciteitsproductie. De wateronttrekking voor energieopslag kan daarom een relevante vorm van watergebruik door de energiesector worden, naast de gangbare waterwinning van koelwater bij elektriciteitscentrales. Watergebruik voor warmte kan daarom een belangrijk onderwerp worden om waterschaarste te voorkomen.

Daarnaast zou onderzoek naar het watergebruik voor warmteproductie niet alleen over lokaal watergebruik moeten gaan, om waterschaarste elders te voorkomen. Uit de resultaten blijkt bijvoorbeeld dat de waterconsumptie voor de productie van brandstoffen zoals biomassa en waterstof groter is dan de lokale waterconsumptie bij warmte-opwekking. Studies naar watergebruik voor warmteproductie op nationale en mondiale schaal worden ook relevanter vanwege de verwachte toename van het elektriciteitsgebruik voor warmte-opwekking. Deze toename wordt in alle scenario's verwacht door de elektrificatie van warmtesystemen.

De tweede studie belicht *committed emissions* als een relevante criterium voor het ontwerpen van duurzame infrastructuren tijdens transities. Het begrip '*committed emissions*' wordt in dit proefschrift gedefinieerd als de cumulatieve CO_2-uitstoot over een afgebakende tijdsperiode. Dit concept is belangrijk voor het ontwerpen van verwarmingssystemen die voor de komende decenia zo weinig mogelijk CO_2 uitstoten en dus klimaatverandering zo goed mogelijk tegengaan. In deze studie werd een *bottom-up* model, dat de warmtevraag op gebouw- en buurtniveau berekent, geïntegreerd met een *mixed-integer nonlinear optimisation problem.* Het model is gebruikt om voor drie wijken te berekenen welke mix van warmtetechnologieën een zo laag mogelijk hoeveelheid *committed emissions* zal geven tussen 2030 en 2050. Zodoende werd in deze studie aangetoond dat 'lage temperatuur' (LT) verwarmingssystemen het meest geschikt zijn voor het minimaliseren van *committed emissions* wanneer er ambitieuze maatregelen voor de isolatie van gebouwen en voor de vermindering van de CO_2-uitstoot voor elektriciteitsproductie toegepast worden. Voor het scenario met de meest ambitieuze doorvoering van deze maatregelen was er een vermindering van de *committed emissions* met een tienvoud. Daarbij is er bij ambitieuzere scenarios minder afhankelijkheid op 'hoge temperatuur' (HT) verwarmingssystemen die gebruikmaken van aardgas, biogas of waterstof. Ook werd er aangetoond dat een ambitieus isolatieniveau ervoor kan zorgen dat de warmtevraag in een wijk onder de minimale warmtedichtheid voor het effectief inzetten van LT warmtenetten kan komen. Bij deze systemen kan dus een *carbon lock-in* ontstaan. Dit wil zeggen dat warmte-alternatieven met een lagere CO_2-uitstoot gehinderd worden door al gedane investeringen in infrastructuur met een lange levensduur en al bestaande sociaal-technische verhoudingen.

Het derde thema is *energy justice*, oftewel 'energierechtvaardigheid'. Met etnografische onderzoeksmethoden werden verbanden tussen collectieve warmte-initiatieven en zorgen over energierechtvaardigheid bestudeerd. Met de resultaten van deze studie wordt beschreven dat er zorgen zijn over de Warmtetransitie in Amsterdam en energierechtvaardigheid. Daarnaast wordt beschreven hoe collectieve warmte-initiatieven dominante redeneringen in de Warmtetransitie betwisten. Tegelijkertijd creëren ze ruimtes voor verschillende partijen om samen te komen, maar verminderen ze potentiëel ook de mogelijkheden tot inspraak voor anderen af. In deze studie worden de initiatieven geanalyseerd met het concept *'commoning practices'*. Met dit concept wordt verwezen naar activiteiten die gericht zijn op het versterken van de invloed, het eigendom en de verantwoordelijkheid van een gemeenschap van gebruikers over een gegeven infrastructuur, grondstof of hulpbron. In deze derde studie wordt beargumenteerd dat door het gebruik van het concept *commoning practices* een beter begrip kan ontstaan over hoe energierechtvaardigheid in de praktijk gevormd wordt.

De combinatie van de deze drie studies over deze thema's draagt bij aan multidisciplinair onderzoek naar stedelijke duurzaamheidstransities. Methodologisch gezien vult dit proefschrift het huidige nexus-onderzoek aan met kwantitatieve modellen over interacties op lokale, nationale en mondiale schaal en met onderzoeksmethoden uit de sociale wetenschappen. De combinatie van deze drie studies biedt meerdere perspectieven op hoe een transitie naar hernieuwbare verwarmingssystemen met een lage CO_2-uitstoot samenhangt met maatschappelijke, ecologische en technologische transformaties op zowel lokale als mondiale schaal. Dit proefschrift dient daarom als een voorbeeld van multidisciplinair onderzoek naar transformaties.

Policy and practice recommendations

The transition towards low-carbon and renewable heating systems, i.e. the 'Heat Transition', is crucial for achieving climate change mitigation targets and reducing fossil fuel consumption. As stated in the Dutch Energy Agreement, the government of the Netherlands targets to become 'carbon neutral' by 2050 (Ministry of Economic Affairs, 2016). The changes in energy infrastructures that are needed to achieve this will not only affect carbon emissions, but also the ways in which energy carriers are distributed and spaces are heated. In this thesis, the effects of the Heat Transition beyond the reduction of carbon emissions are therefore analysed. More specifically, the effects of the Heat Transition on water management, committed emissions and energy justice are discussed. It is proposed that studies on these kinds of indicators are needed to design sustainable heating systems in the built environment, which contribute to supporting human well-being while remaining within planetary boundaries (Raworth, 2017).

Water use

Water is needed for the supply of energy carriers, energy generation and energy storage. Water is for example used for the production of biofuels, cooling processes at power plants, and underground thermal energy storage. If not properly managed, the transition to low-carbon heating systems could exacerbate water stress. The transition can also be limited by water scarcity. Sustainable energy policies should therefore be based on integrated assessments of future water use by energy systems. From our study on water use for low-carbon and renewable heating systems we recommend that:

- The ecological impact of heat generation through water use should be incorporated into the sustainable design of energy systems and regulations. Water withdrawal for electricity production decreases in scenarios in which thermal power plants are replaced by wind and solar energy. More water withdrawal is however expected for the supply of heat due to an increase in Aquifer Thermal Energy Storage (ATES) systems and thermal energy extraction from surface water.

- It is important to consider the impact of urban heating systems on water use elsewhere. The concept of virtual water flows stands for the indirect water use embedded in fuels, such as biomass and hydrogen. We found that virtual water flows are higher than the local operational water consumption for heating. This implies

The recommendations presented are an adaptation to the previously published full policy briefs Kaandorp et al. (2021b) (in English) and Kaandorp et al. (2020) (in Dutch).

that areas other than the local site of energy production are relevant for assessments of water use for heat production. Considering the increased use of electricity for heating, the virtual water use embedded in electricity may especially become more prominent.

COMMITTED EMISSIONS

Achieving net-zero carbon emissions by 2050 is not enough. To mitigate global climate change, it is important to reduce the total sum of carbon emissions during the upcoming years. The carbon emissions per heat technology may however change over the upcoming years due to changes in heat demand and electricity production. We therefore looked into the carbon emissions of different technologies over time, i.e. 'committed emissions'. From our study on committed emissions, we recommend that:

- The insulation of buildings is important for reducing thermal energy demand and facilitating the implementation of low thermal heating technologies.
- Pathways for the retrofitting of buildings and the decarbonisation of electricity generation need to be taken into account simultaneously when minimising committed emissions.
- A carbon lock-in can be created when investments are made in technologies that will have a higher carbon intensity in the future than other technologies. A combination of different low-carbon and renewable heating systems such as low temperature (LT) heat networks, hydrothermal energy, Power-to-Heat (P2H) applications, and hybrid solutions can create adaptable heating systems and support avoiding carbon lock-ins.

ENERGY JUSTICE

The transition towards renewable heating systems in the built environment can be seen as an opportunity to address energy justice concerns. Collective heating initiatives are envisioned to make positive contributions to neighbourhoods, because they can raise attention for local issues and reshape current relations between citizen-led, public and private parties. From our study on energy justice and collective heating initiatives, we recommend that:

- Looking beyond the conventional roles of stakeholders can stimulate new valuable partnerships, and promote citizen participation and supervision of private-public governance arrangements.
- The sharing of success stories about collaboration, participation and co-creation projects can help to support bottom-up initiatives.
- It should be considered how collective heating initiatives open up spaces for some while closing down spaces for others to contest and reshape current energy justice issues.

1

Introduction

This is a thesis about research on local solutions to global challenges. Current global challenges include climate change, biodiversity loss, resource depletion, land and ecosystem degradation, and increasing inequality of wealth. Since more than half of the people on this planet live in urban areas, solutions for (parts of) these problems are continuously created, proposed and incorporated in the urban context. However, as problems are often connected, solving one almost inevitably gives rise to another. To minimise negative effects, it is proposed in this thesis to analyse the potential impacts of urban transitions at multiple scales. This thesis is therefore a call for integrating multiscalar perspectives on the social, environmental and technological impacts of urban transitions for sustainability. The urban transition discussed in this thesis is the transition towards low-carbon and renewable urban heating systems in the capital of the Netherlands, the city of Amsterdam.

1.1. THE NEED FOR A HEAT TRANSITION

1.1.1. MITIGATING GLOBAL CLIMATE CHANGE

Climate change gives rise to different weather patterns, increasing weather-related risks, including floods, droughts and wildfires, sea level rise, ecosystem changes, threats to various species from all kingdoms of life, and harming livelihoods (IPCC, 2022). An important way to mitigate global climate change is to reduce the emission of greenhouse gases (IPCC, 2014a). These emissions are produced in multiple ways, such as during the incineration of fuels in engines, methane emissions from livestock, subsiding wetlands in the Netherlands (from lowering the water levels), or melting permafrost in Greenland (Burke et al., 2012). These emissions accumulate in the atmosphere and 'trap' thermal energy from the sun, in a similar fashion to glass construction of a greenhouse. Therefore, the reduction of greenhouse gas emissions can effectively decrease the 'greenhouse effect' and impede the rising average global temperature.

Globally, agreements and policies have been made to abate greenhouse gas emissions and avoid global average temperature rise. One example is the Paris Agreement which was adopted at the 2015 United Nations Climate Change Conference (UNFCCC, 2015). In this agreement, signing parties state an intention that "aims to strengthen the global response to the threat of climate change, in the context of sustainable development and efforts to eradicate poverty [...] Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognising that this would significantly reduce the risks and impacts of climate change". In these agreements and policies, phrases such as 'reduction of carbon emissions', 'low-carbon', 'net-zero', or 'decarbonisation' are often used to refer to the reduction of greenhouse gas emissions. Carbon Dioxide (CO_2) is one of the major anthropogenic greenhouse gases. In addition to CO_2, ambitions to abate climate change also include the reduction of other greenhouse gases such as methane and NO_2. Based on their global warming potential, greenhouse gases can be expressed in carbon dioxide equivalent (CO_2-eq). As such, the notion of 'carbon emissions' is used in this thesis to refer to greenhouse gas emissions expressed in CO_2-eq if not stated otherwise.

1.1.2. OPPORTUNITIES FOR CARBON EMISSION ABATEMENT FROM URBAN HEATING SYSTEMS

A transition towards low-carbon urban heating systems provides relevant opportunities for reducing global carbon emissions associated with human activities. In this thesis, 'urban heating systems' refer to an assemblage of physical elements, such as building insulation, thermal energy generation and distribution technologies, but also the rules, entities and practices which shape and operate these systems (see Section 2.2 for a definition of notion of assemblages). Globally, direct emissions for space and tap water heating in buildings accounted for 2486 Megaton CO_2, i.e. 7% of global carbon emissions, in 2019 (IEA, 2022c,b). The total carbon emissions are even higher given that indirect emissions occur at a global scale by the production and transportation of energy carriers such as biomass, natural gas, and electricity. The carbon emissions associated with this sector can however still be further reduced. In 2021, 64% of the global thermal energy demand

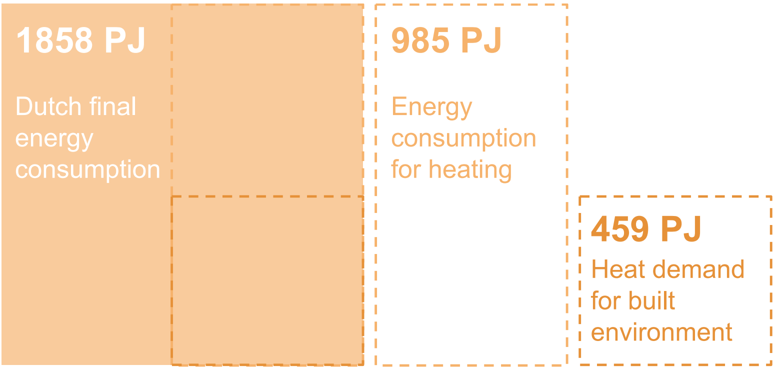


Figure 1.1: The energy consumption in petajoules (PJ) for heating in the built environment in 2019 is about a quarter of the final energy consumption in the Netherlands Segers et al. (2019).

for the built environment was still met with fossil fuels (IEA, 2022c), and 80% of the sold space and tapwater heating appliances still operate on fossil fuels (IEA, 2021).

In the Netherlands, space and tap water heating for the built environment accounts for almost a quarter of the national final energy consumption (Segers et al., 2020) (see Figure 1.1). To compare, it is known that space heating for households, so not the total built environment, accounted for 17% of the final energy consumption of the European Union in 2020 (Eurostat, 2022). In the Netherlands, urban heating systems generate 13% of the national greenhouse gas emissions (see Figure 1.2 for a comparison of greenhouse gas emissions per sector) (Statistics Netherlands, 2023). There are opportunities to reduce the carbon intensity of urban heating, considering that most of the energy for space and tap water heating for the built environment of the Netherlands, i.e. 85%, is generated from natural gas (Segers et al., 2020; Statistics Netherlands, 2023). Consequently, the national government aims to eliminate the use of natural gas and simultaneously achieve net zero emissions by 2050 (Ministry of Economic Affairs, 2016). Even more ambitious is the city of Amsterdam, the capital of the Netherlands. The target of the city is to have eliminated natural gas use for heating by 2040 and reduce carbon emissions by 95% with respect to the emissions in 1990 by 2050 (Municipality of Amsterdam, 2019b). These efforts for the implementation of low-carbon and renewable urban heating systems are in this thesis referred to as the 'Heat Transition'.

These ambitions to phase out the use of natural gas are not only based on the wish to abate carbon emissions, but are also informed by the decision made by the Dutch Minister of Economic Affairs and Climate in 2018 to cease withdrawing natural gas from the reserves in the province of Groningen, due to local earthquakes that instigated protests within that region (Wiebes, 2018). As such, a shift towards renewable heating can potentially decrease international fuel dependency, air pollution, and depletion of fossil fuels. In this way, multiple objectives are connected with political ambitions to phase out the use of fossil fuels and reduce carbon emissions.

The decarbonisation of urban heating systems are challenging, considering that it requires changes in natural-gas based heating systems, retrofits in existing building stock, and consumer behaviour. Because space heating in the Netherlands is predominantly

1

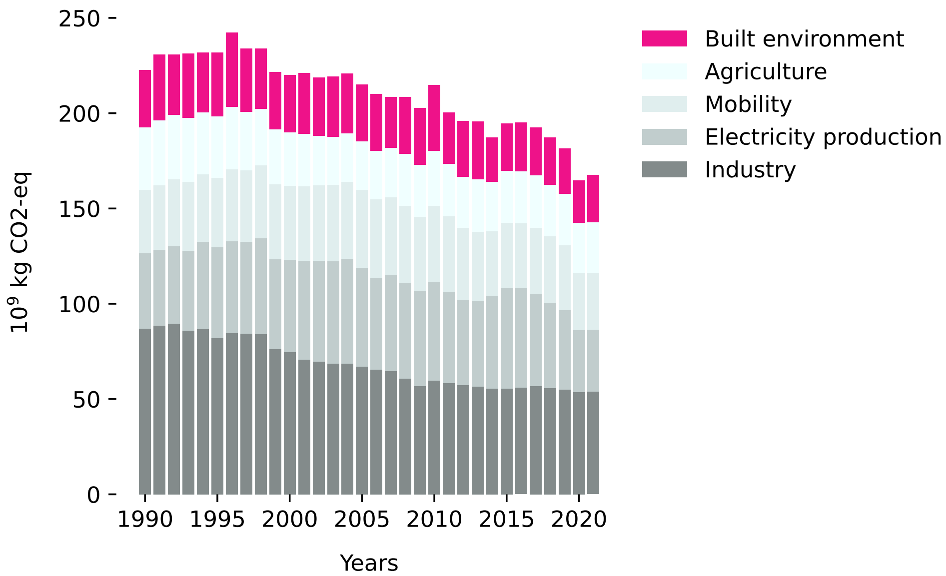


Figure 1.2: Emissions per sector in the Netherlands, expressed in terms of 10^9 CO_2 equivalents. Data retrieved from Statistics Netherlands (2023).

still produced with natural gas, efforts to shift towards renewable and low-carbon heating systems will cause technological, institutional and societal change 'from one societal regime or dynamic equilibrium to another' (Hölscher et al., 2018, p.1). While transitioning towards renewable and low-carbon heating systems, it is paramount to consider potential causes for future carbon-intensive infrastructure to persist over time. Such a 'carbon lock-in' can occur due to the difficulties in changing energy infrastructures with long life spans, building shells, institutional structures and behavioural patterns, creating a 'carbon lock-in', which 'locks out' lower-carbon alternatives (Seto et al., 2016; Fisch-Romito et al., 2021; Erickson et al., 2015).

1.2. MULTISCALAR SOCIAL, ENVIRONMENTAL, AND TECHNICAL TRANSFORMATIONS

A transition towards low-carbon and renewable urban heating systems requires a myriad of technological changes in urban heating infrastructure. In short, carbon emissions and fossil fuel use can be lowered by reducing energy demand through the insulation of buildings, heat recovery, heat storage, and adaptations of heat delivery systems, such as radiators and floor heating. Thermal energy is generated without fossil fuels when energy carriers, such as electricity, biomass and hydrogen, are made with renewable energy sources. Alternatively, already available thermal energy sources, such as geothermal wells, surface water, and residual heat from industry can be used to reduce carbon emissions and fossil-fuel use (see Chapter 3 for an explanation of heating systems).

To support a transition with 'desirable' outcomes, it is important to not only perform

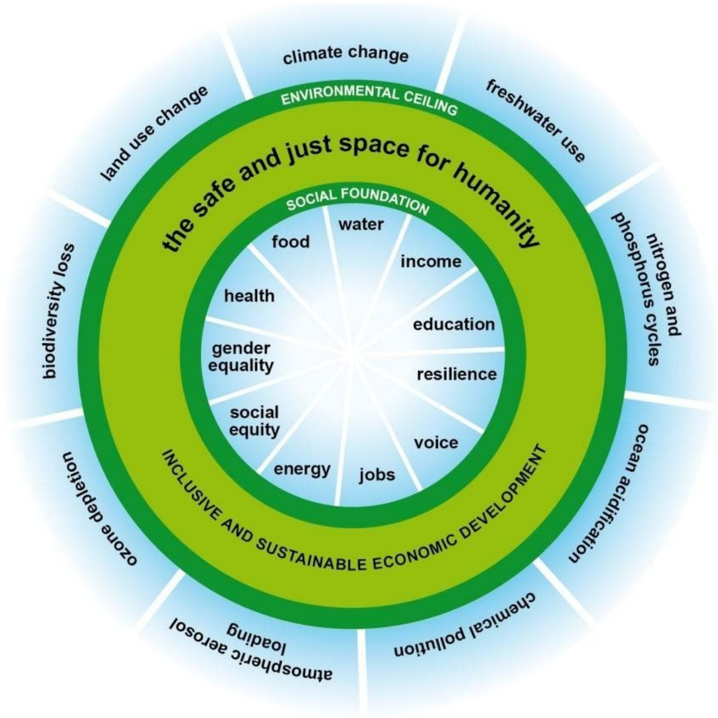


Figure 1.3: Visualisation of a 'safe and just' operating space for humanity in the framework of the Doughnut Economy made by Raworth (2017)

technical studies which enable the transition, but also to study how the transition impacts the environment and human well-being at multiple spatial scales (Raworth, 2017). Desirable outcomes are based on different values and intentions, such as reducing resource depletion, biodiversity loss, inequality and poverty. To structure and visualise a set of possible intentions, a framework of a 'safe and just' operating space for humanity developed by Raworth (2017) is presented in Figure 1.3. It is argued in Raworth (2017) that a 'safe and just' operating space for humanity is one in which anthropogenic impacts do not overshoot planetary boundaries, i.e. the environmental ceiling, and where humans can live above the minimum of a social foundation (Raworth, 2017). Similarly, Krueger et al. (2022, p.8) appraise viewing urban areas as interdependent social-ecological-technological (SET) systems, i.e. coupled systems of the natural and built environment, governance systems, and urban communities, and propose an integrated, cross-scale perspective on the governance of SET systems to better understand "what it takes to overcome the SET system challenges associated with urban sustainability transformations". The notion of transformation refers to changes "in the fundamental attributes of natural and human systems at multiple scales" (IPCC, 2022, p.7). The notion of transformation therefore involves interacting human and biophysical elements (Hölscher et al., 2018).

1.2.1. IMPACTS ON PLANETARY BOUNDARIES

One indicator from the planetary boundaries model which is especially linked with energy production is water. In 2020, more than 90% of the electricity was generated by either hydropower or thermal power plants (IEA, 2022a). Hydroelectric dams are notorious for changing river flows and water quality, negatively affecting people and ecosystems (Mekonnen and Hoekstra, 2012). It also happens that droughts cause hydropower plants to curtail output (IEA and OECD, 2016). Moreover, thermoelectric plants with open-loop cooling use surface water, influencing surface water temperature and therefore concentrations of oxygen, algae growth and life underwater (CBS et al., 2020). Cooling water standards limit thermal pollution and harm to aquatic ecosystems, but limit electricity production in hot and dry periods and therefore decrease energy security (King et al., 2008). Van Vliet et al. (2016) estimated that both hydroelectric dams and thermoelectric plants globally will have capacities limited due to reduced water availability and increased water temperatures.

In the Netherlands specifically, more than 60% of the water withdrawal was done by the energy sector in 2020 (CBS et al., 2022). This water was mainly used to cool (heat and) power plants which operate on fossil fuels. Low-carbon energy technologies, such as biofuels, concentrating solar power, carbon capture, and electrolysis for hydrogen production require water to operate (IEA and OECD, 2016). For thermal energy generation specifically, water is needed for energy storage, production of renewable energy carriers, and, indirectly, generation of electricity for Power-to-Heat (P2H) applications. To secure future energy production, reduce water stress, and limit environmental degradation, it is therefore important to assess the impact of a transition towards low-carbon and renewable energy systems on water use.

Another environmental indicator is climate change, which, as discussed earlier, is related to greenhouse gas emissions. Although multiple agreements are made to strive towards net zero carbon emissions by 2050, it is important to design heating systems that will not only emit net zero carbon emissions by 2050, but also base decisions on the carbon emission reduction potential for the upcoming years. According to the Intergovernmental Panel on Climate Change (IPCC), the maximum amount of carbon emissions that can be emitted while remaining below 1.5°C or 2°C global warming above pre-industrial levels is reached in the upcoming 10 or 25 years, respectively, if the current yearly quantities of carbon emissions are not reduced (IPCC, 2018). It is therefore important to aim for immediate and structured carbon abatement during the upcoming years. Moreover, it is important to not only have solutions which reduce local carbon emissions, but to find solutions which contribute towards the lowest carbon emissions at a global scale. This means that it is important to analyse the carbon emissions associated with different decarbonisation strategies. In this thesis, the notion of 'committed emissions' is used to refer to the cumulative carbon emissions, including embedded emissions, emitted during a given future planning period (Fisch-Romito et al., 2021; Davis et al., 2010).

1.2.2. IMPACTS ON HUMAN WELL-BEING

Energy systems "manifestly mould trans-local power geometries, forms of uneven development, and structures of feeling more broadly" (Bouzarovski, 2022, p.755). The way thermal energy is organised impacts energy poverty, building types, living comfort and distribution of resources. In other words, the ways in which thermal energy systems are (re)organised influence human interactions and lived environments. Heating provides shelter for outdoor cold, which is especially important in temperate and frigid climates. Moreover, it is of great socio-cultural and physiological importance considering its role in social life and cultural practices, such as entertaining guests, wintertime cosiness and providing comfort (Itten et al., 2021). Heating can thus be seen as an element of the most intimate places of human life.

Beyond the realm of the urban dwelling, energy can be viewed as a commodity or a basic need, which influences what is being perceived as legitimate ways of organising and supplying thermal energy. Moreover, the generation, distribution and consumption of energy are based on different rules, norms and principles, including "wider racial and post-colonial inequalities that underpin energy flows" (Bouzarovski, 2022, p.762). The Heat Transition thus shapes and is shaped by diverse forms of unpaid and informal labour (Bouzarovski, 2022). It does not only changes employment practices and urban interactions between urban professionals, dwellers and governmental officials, but also those of communities globally. At last, trade on energy carriers or materials for energy production influences prices for natural resources globally.

One concept which has been used by researchers and activists to support human well-being in relation to energy systems is energy justice. The concept of energy justice has been used in literature to discern how injustices can be materialised and institutionalised into social organisation. The notion of energy justice is related to the notion of environmental justice that came up in the 1970s to raise awareness about socially deprived and ethnic minorities (McCauley et al., 2019). Energy justice is often discerned into the three tenets of 'distributional', 'recognition' and 'procedural' justice (Heffron and Mccauley, 2014). These tenets allow scholars to describe the unequal distribution of the ills and benefits of energy systems, the missing recognition for certain groups and the use of inequitable or discriminatory procedures. Energy justice can however also be discussed in the context of 'the rules of the game' that are embedded institutions. These rules structure the actor's behaviour and assessments of decisions and procedures considered 'fair', but also may give rise to contestation if societal actors come to dispute the moral legitimacy of these rules (Pesch, 2021).

Another concept which has been used to describe these 'rules of the game', is the (urban) commons. Traditionally the commons are used to describe (the management of natural resources (Carrozza and Fantini, 2016). However, the understanding of what a commons can refer to has broadened. Based on Feinberg et al. (2021), a commons can be defined as a system consisting of shared material and symbolic resources with the characteristic that their users have input in the management of resources, the institutions binding them, and the associated processes. The 'urban commons' are characterised by (parts of) its governance, production, and distribution of resources or infrastructure being performed by a group of users in an urban context. The urban commons in relation to space heating can therefore not only refer to thermal energy sources, but also spaces and tools to transform heating systems. Because the notion of the commons relates to the role of users, research uses "the concept to analyse alternative forms of collective (re-)production" (Becker et al., 2017, p.64). Especially in the case of urban energy systems, the notion of the commons can enhance the analysis of "new grassroots energy initiatives and the politics that unfold in remunicipalisation conflicts, offering a new avenue for enriching research on the co-production of energy" (Becker et al., 2017, p.63).

1.2.3. MULTISCALAR IMPACTS

In order to contribute to 'safe and just' urban heating systems, it is important to note that on the one hand side local heating systems shapes SET transformations at multiple spatial scales, and on the other side is shaped by those transformations (Raworth, 2017). A Heat Transition shifts resource flows, land use, and chemical pollution globally. Synergies, tensions and trade-offs between different resource flows happen at multiple spatial scales, varying from the local to the global. Moreover, decision-making on energy systems takes place at different scales. Global views on resource management, for example, integrated water management, influence how resources are managed locally. Multi-level collaboration is needed to ensure a positive contribution to the environment and human well-being from local, regional, and global supply chains for space heating. Research targeted at supporting this positive contribution should thus be carried out with methods for analysis suitable to generate information about the effects of urban heating policies on multiple spatio-temporal scales. Additionally, to make sure that the knowledge produced by models is actionable, it is important that information is generated at a decision-relevant scale.

1.3. THIS THESIS

The title of this thesis is 'Transforming urban heating systems'. The title can be interpreted in three ways. First, it is argued in this thesis that urban heating systems in Amsterdam are *transforming* through multilevel and cross-scale processes, and can therefore be considered to constitute a sustainability transformation (Olsson et al., 2014). Second, it is explored how the Heat Transition is *transforming* SET systems at multiple scales. Third, in Chapter 2 it is proposed to contextualise and politicise nexus studies by complementing them with social science research methods to generate knowledge which better contributes to *transforming* urban heating systems in a direction that supports humanity to stay within a 'safe and just' operating space (Raworth, 2017). In other words, the central question in this thesis is:

"What are social-environmental-technological transformations caused at multiple scales by a transition towards low-carbon and renewable heating in Amsterdam?"

To narrow down this question, the main body of this thesis is divided into three separate studies. These studies analyse the impacts of a transition towards low-carbon and renewable heating systems in Amsterdam on (i) water use, (ii) committed emissions, and (iii) energy justice (see Chapters 4, 5, and 6 respectively). Subsequently, the research methods and insights from these chapters are synthesised in Chapter 7. This synthesis chapter is followed by an afterword reflecting on the context of the PhD project on which this thesis is based. Before starting with the main body, more information is provided in Chapters 2 and 3 on the methodology applied in this thesis together with its topic, i.e. the Heat Transition in Amsterdam.

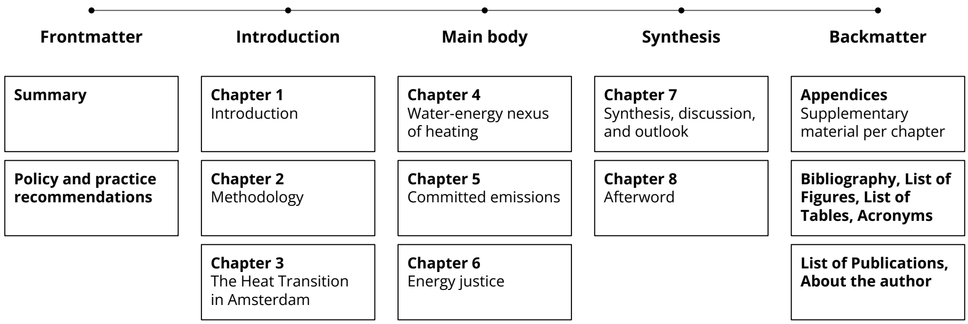


Figure 1.4: Chapter outline of this thesis

2

Methodology: a multidisciplinary approach to study social-environmental-technological transformations

In the previous chapter, it is argued that a Heat Transition in Amsterdam has and will have social-environmental-technological impacts at multiple scales. But how to study these changes? Methods applied in 'nexus' research have been brought forward in recent years to study the flow of resources. However, nexus research is being criticised for depicting a too 'apolitical' image of these flows, leading to knowledge that is not suitable for decision-making processes and questioning current rationales and power structures, which maintain unsustainable practices. The aim of this thesis is therefore to apply nexus modelling approaches together with social science research methods to study social-environmental-technological transformations linked with the Heat Transition in Amsterdam.

2

2.1. Nexus thinking for environmental impact assessment

One research approach which is specifically aimed at the integrated analysis of biophysical systems is 'nexus' research (Khan et al., 2022). The idea of the Water-Energy-Food (WEF) Nexus has been developed during the last 15 years. It especially gained in popularity with the World Economic Forums in 2008 and 2011, and the Bonn conference in 2011 where notions of growing risks for resource insecurity were prevailing (Hoff, 2011; Al-Saidi and Elagib, 2017). The 'nexus', which can be translated from Latin to 'that what is bound together', refers to interconnected resource systems (Khan et al., 2022). The idea behind nexus research is to analyse interdependencies and interconnections between the management of different resources to help solve issues of resource scarcity and environmental pollution. The emergence of the use of the nexus can be understood with the increasing global science-policy trends on "integration as an ideal; an emphasis on technical solutions to environmental problems; achievement of efficiency gains and 'win-wins'; and a preference for technocratic forms of environmental managerialism" (Cairns and Krzywoszynska, 2016, p.164).

One of the main ideas behind nexus thinking is thus to have an integrated perspective on resource use and flows critiquing traditional institutional distinctions between such flows, and proposing alternative forms of how resources should be connected (Hoff, 2011; Williams et al., 2018). In other words, nexus research contests 'siloed approaches' (Hoff, 2011). The 'silos' or sectors, studied in nexus research include water, energy and food, i.e. the WEF Nexus. Studies also exist adding waste, i.e. the FEW2 Nexus, including the environment, i.e. the WEFE Nexus, or focusing on the interactions between climate, land, energy, and water systems (CLEWs). Figure 2.1 shows themes occurring in WEF Nexus research from a review on the Global Food-Energy-Water Nexus by D'Odorico et al. (2018).

Being a young field, it does not yet have a wide consensus on an established common set of concepts and methodologies applied (McGrane et al., 2018). Nevertheless, based on a collaboration between 75 scientists, Khan et al. (2022, p.4) state that "the essence of nexus studies is to try and capture the relevant trade-offs and feedbacks that may influence their outcomes". Methods that are often applied in nexus research are those that enable tracking and managing the changes in resource availability, such as life cycle assessment (LCA), footprint analysis, and material flow analysis (MFA) (Al-Saidi and Elagib, 2017). Systems thinking, which is also applied in the systems dynamic model in the 'The Limits to Growth' report, is part of the heritage of nexus studies (Al-Saidi and Elagib, 2017). Al-Saidi and Elagib (2017) found that nexus studies, aimed at analysing the three WEF sectors as one system, most often apply problem-focused, reductionist approaches such as macro-level assessment with indicators and indices, integrated modelling, and metabolism studies. Resource connections are most often conceptualised under the categories of tensions, trade-offs, maladaptations and synergies (Williams et al., 2018).

The knowledge paradigms behind these approaches share characteristics of logical positivism or post-positivism. The prefix 'logical' refers to the aim to state scientific knowledge in analytic statements. Analytic statements have a logical structure and the meaning of individual concepts is clearly defined (Tijmstra and Boeije, 2011). The word

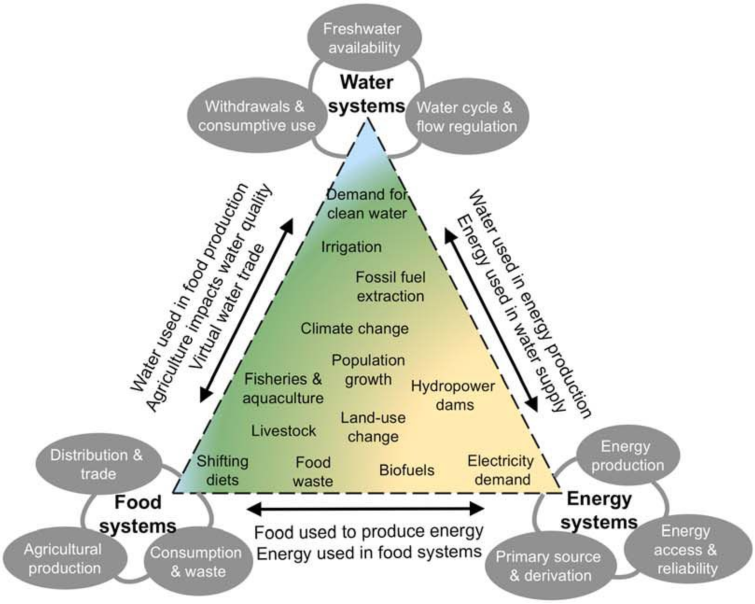


Figure 2.1: Themes discussed in the Water-Energy-Food Nexus literature as visualised in a review on the Water-Energy-Food Nexus made by D'Odorico et al. (2018)

positivism is etymologically related to the Latin verb *ponere*, i.e. "to put down". Positive knowledge is in this sense *a posterior* knowledge derived from sensory experience through reason and logic. Whereas in positivism the belief is that the objective truth can be reached through rigorous inquiry; post-positivists acknowledge that researchers are biased by their background and prior experiences and thus more open to the possibility that the conclusions reached might be wrong (Floden, 2009). It is discussed in the following Section how (post-)positive, problem-focused, reductionist research approaches can fall short in solving real-world problems related to resource management.

2.2. POLITICISING NEXUS STUDIES

Infrastructures, such as heating systems, are connected, inherently interdependent, co-produced and co-producing, and politically and materially contingent (Williams et al., 2018). They mediate flows of resources, people and ideologies (Williams et al., 2018). When infrastructures are not sufficient to fulfil human needs, new ways of collaboration, sharing and solidarity are explored (Dalakoglou, 2016). Especially at times of disruptions, changes in infrastructures can be a source to learn about social structures and political paradigms (Dalakoglou, 2016). In the next Chapter, in Section 3.2, it will, for example, be discussed how the expansion for district heating has been hindered in the 20th century by existing rules on resource use for energy, interests in gas-revenues from municipalities, and connotations between collective heating systems and communism. Also, current efforts to abate natural gas use for heating can be seen as expressions of concerns about climate change, geopolitical developments, and the destruction of habitats by resource extraction. Both in the past and the present moment, infrastructures are thus important sites for political and social change (Monstadt and Coutard, 2019).

Recently, scholars such as Allouche et al. (2019); Williams et al. (2018); Scott et al. (2011), have argued that the political nature of how resources are managed is not well reflected in current nexus research. They argue that the ways of "knowing, representing, and intervening" in nexus studies are too reductionist and 'techno-managerial', and therefore not appropriate to solve challenges concerning flows of resources (Allouche et al., 2019; Williams et al., 2018; Wesselink et al., 2017, p.5). Dai et al. (2018, p.405) for example state that "identification of stakeholders and their roles in governing the Water-Energy nexus is often missing [...] making the potential use of the research results difficult to assess". The term is also not always associated with ministerial priorities or legal requirements which can lead to issues on problem ownership. There may therefore often be barriers to translate nexus research into practice (Cairns and Krzywoszynska, 2016).

Additionally, Scott et al. (2011) argue that the focus on the 'pumps and turbines' creates a lack of insight into the political nature behind the systems interacting at different scales. Methods such as LCA and footprint analysis decontextualise resource flows from the sociopolitical context. In this way, problems such as resource scarcity seem to be solvable by optimising efficiencies, improving technological systems, or changing policies. Challenges for sustainable resource management are however not merely shaped by physical technologies, but also by economic feasibility, social organisation, and individual worldviews. So although the ideal of integration for sustainable resource management seems logical, it does not, according to Williams et al. (2018), provide direct solutions for resource scarcity and sustainability, and is not sufficient to support decision-making processes and the implementation of technical solutions (Allouche et al., 2019; Dai et al., 2018; Williams et al., 2018).

But maybe more stringent, Williams et al. (2018, p.1) argue that "by conceptualising resource connections under the simple categories of tensions, trade-offs, maladaptations and synergies [...] nexus thinking reduces socio-material heterogeneity to a set of manageable and depoliticising relationships". In other words, studies formulated as searches for technical solutions to natural resource scarcity can give the impression that flows or resources and the study on these flows are 'apolitical' (Allouche et al., 2019). Similar processes of quantification in socio-hydrology are described by Wesselink et al. (2017, p.5) to "'screen out' pluralistic perspectives" and "obscure how power plays a role in the status quo". Narratives on resource management are however socially constructed and the perception of problem boundaries, change processes, uncertainties, and incommensurable value sets may differ (Patterson et al., 2017). Depicting a depoliticised picture of resource flows can thus distract from questioning current rationales and power structures which support unsustainable practices. Williams et al. (2018, p.10) for example argue that the language of "efficiency-through-integration" suggests a support of market-environmentalist ideology, potentially promoting "expansionist consumption by delivering cheap and abundant water and power". Moreover, the term 'nexus' has been criticised to be a buzzword, which is ambiguous in definition and carrying a normative resonance. This makes it "particularly susceptible to processes of 'semantic appropriation' to suit particular agendas", for example, of those of a managerial elite who are capable of adapting to a fast-changing and exclusive vocabulary (Cairns and Krzywoszynska, 2016, p.165).

A more political approach to resource flows can therefore be beneficial to understand how the production of socio-biophysical landscapes takes shape and which alternative ways of social innovation might be available for managing interventions (Wittmayer et al., 2022). In other words, there is a need "for a more political understanding of urban infrastructural connectivities, one that emphasises the complex material and social hybrid relationality and contingency that characterises the contested development of the resource nexus" (Williams et al., 2018, p.9). That is to say, Williams et al. (2018) are arguing for a research approach considering hybrid relationalities, similar to 'political ecology'.

To foster the analysis of this 'social hybrid relationality', 'assemblage thinking' can be employed. The use of the interpretation of assemblage forwarded by Deleuze and Guattari (1987) fosters a representation of ways in which humans and objects can be "understood in terms of the intensive environment in which they emerge" (McLean, 2017; Dewsbury, 2011, p. 148). An assemblage consists of heterogeneous elements constantly composted and entangled with other elements (McLean, 2017). These elements coexist and shape each other continuously. Additionally. the notion of an assemblage therefore refers to a historically contingent entity (Delanda, 2006), consists of subassemblages, and is part of bigger assemblages. This thesis employs a lens informed by the notion of assemblages to investigate the social-environmental-technological entanglements.

Moreover, this thesis, and especially Chapter 6, is influenced by a political ecology approach. The research field of political ecology is diverse and the commonality between different studies is more the concern with environmental inequalities than through a common analytical framework or theory (Wesselink et al., 2017, p.6). At the heart of political ecology studies lie questions about power, situatedness and mutual interaction between society and nature. Furthermore, political ecology scholars recognise that nature and society do not exist separately. A variety of academic disciplines influence or show similarities with political ecology research such as geography, anthropology, sociology, political science, and (political) economy (Bryant and Bailey, 1997).

To motivate the methodological benefits of complementing or juxtaposing nexus thinking with research approaches that include the political dimension, the discussion on socio-hydrology and hydrosocial research from Wesselink et al. (2017) can be useful. In both of these research disciplines the link between the social and the natural realms are studied with a focus on water resources. Hydrosocial research is the study of human-water systems as hydrosocial systems, and can be typified as falling into the categories of human geography and political ecology. Within this field of research, the social and the natural are seen as a hybrid and existing together. Taking such an approach opens up space to not only study the impacts and relations between things, i.e. external relations, but also how the properties constituting things emerge from the relations with other things and phenomena, i.e. the internal relations (Wesselink et al., 2017). Cultural, economic and political processes can for example be studied to describe how these processes constitute social and cultural meanings of water, and how they result in different relationships with water and choices for water management (Wesselink et al., 2017). Notions of resources, such as water, infrastructures or societal challenges are in this sense not reduced to one definition, but seen as fluid and entangled with different processes.

Matter of concerns are also not stable and the political aims of nexus research are also fluid (Cairns and Krzywoszynska, 2016). Cairns and Krzywoszynska (2016, p.165) therefore highlights “the importance of social science-led productive critique in developing nexus debates”. Just like nexus studies, hydrosocial research often has “an explicit societal and therefore political goal (usually along the lines of improving sustainability)” (Wesselink et al., 2017, p.8). This is a reason for hydrosocial researchers to often provide a reflection on how and who the knowledge may serve (Wesselink et al., 2017). Knowledge is not created in a vacuum but is situated in a political landscape while at the same time shaping it. The position of different perspectives in hegemonic structures influences what type of knowledge is deemed relevant and which type of knowledge is not (Allouche et al., 2019). Scholars have for example argued that the visualisation of the hydrological cycle is dominated with ideas fitting the historical and geographical circumstances of a dominant group of scholars situated in a northern temperate society (Linton, 2008; Wesselink et al., 2017). Similarly, the notion of energy justice has been critiqued to be too much relying on western theories (Sovacool et al., 2017).

In general, there are many elements that guide and drive research in different directions. Who, for example, gets to do the research and who does not? How are the researcher and research institute positioned in social structures? Which groups are being brought together? What is being problematised? What is being identified as a case study? Which (popular) methods are being chosen? Who has access to new technologies? How much (monetary) resources are allocated for the project? Which scenarios are being studied? Which research data can be accessed? Which results are being spread? Which actors receive these results? How will the knowledge be used? What are the impacts of proposed interventions? And who will benefit from the proposed changes? This understanding of the contested nature of research is important because (academic) knowledge does impact governance, resource management, and appraisal or marginalisation of ideas and resource use.

The need for reflection on the position of the researcher is however more common in disciplines, such as political ecology and cultural anthropology, following a different research paradigm than positivism. Following a textbook definition, the goal of researchers in the tradition of interpretivism is to try to understand how experienced social realities drive human actions (Tijmstra and Boeije, 2011). In other words, researchers following this philosophical strand are “concerned with how the social world is interpreted, understood, experienced, produced or constituted” (Mason, 2002, p.3). They therefore collect empirical evidence on lived experiences and intend to incorporate the concepts and language of participants in the research (Tijmstra and Boeije, 2011). Clarification of concepts and values from the researcher themselves is key in this type of research because these shape the researcher’s perceptions of the social world that is being investigated (Tijmstra and Boeije, 2011). Moreover, some (social science) research approaches do not only intend to describe social realities but also to contest the status quo and empower certain communities; for example through action research (Tijmstra and Boeije, 2011). The community or intention of the researchers is therefore often reflected upon in the studies.

2.3. A MULTIDISCIPLINARY APPROACH TO INFRASTRUCTURES

In this thesis, it interrogated how social-environmental-technological changes are related to a Heat Transition in Amsterdam. In the previous subsections, it was discussed how social science research approaches, such as political ecology, can enrich nexus research by describing the socio-political context of resource use and flows (and the research about them). However, it can additionally be argued that nexus studies are complementary to these approaches. For example, one of the criticisms on hydrosocial research has been that it provides too much attention to the theoretical positioning of the research, resulting in a use of abstract concepts which may hinder people from outside the field to engage with the research (Wesselink et al., 2017). Additionally, according to Wesselink et al. (2017, p.7), "the natural system and the technical interventions are often under-emphasized [in hydrosocial research]". These two factors can lead to limited uptake of the gained knowledge and therefore its translation into action. The focus on the bio-physical elements of nexus studies can thus supplement research on socio-political dimensions with information on natural systems and technical interventions. This thesis therefore presents a more 'politicised' approach to nexus studies by complementing two studies on resource and environmental assessment indicators with a study using ethnographic research methods.

The first study, presented in Chapter 4, employs a Water-Energy Nexus approach. It presents an exploration of the interdependencies between water use and thermal energy generation on the national and urban scales. As stated in the Introduction, water is an indispensable resource for the generation and distribution of energy. Locally generated energy does not only account for water use in the region of production, but generates virtual water flows through trade in energy carriers and material use. For this study, a multi-scale water and energy use model was hence built to analyse the changing water use of the energy sector under different scenarios integrating more renewable energy sources in 2050. According to Williams et al. (2018) little attention has been paid to nexus interactions across national or administrative boundaries. With this multi-scale model, the urban, national and global scales are considered and the study therefore goes beyond administrative boundaries.

National and urban level assessments provide broad environmental, resource and economic impacts of energy transition pathways. However, actual feasibility of specific pathways requires a higher spatial resolution model - at neighbourhood to buildings levels - to assess localised constraints and opportunities for incorporation of different technologies. In the case of Amsterdam, Voskamp et al. (2018) performed a space-time information analysis for identifying data gaps in urban metabolism studies for urban planning practices. More specifically, they looked into information about water and energy flows. They found that current urban metabolism studies provide data on the city level and at yearly time steps. However, most of the urban planners and decision-makers interviewed needed information on higher spatio-temporal scales. The level of resolution needed, whether daily, weekly, household or district level, varied a lot and depended on the intervention that was to be planned. A methodology supporting urban decision-making on heating systems should therefore enable studies to provide information on higher spatio-temporal resolutions than the urban scale and yearly time steps.

For the second study (see Chapter 5), advanced modelling techniques were hence developed for environmental impact assessments of urban heating systems, by increasing the resolution from an urban to the neighbourhood and building scale. As discussed in the Introduction, committed emissions are an important indicator to consider when assessing the environmental impacts of the Heat Transition. A spatio-temporal optimisation model is therefore built to find the technology mixes for space heating with the lowest committed emissions under different scenarios. This model accounts for yearly changes made in the decarbonisation of electricity production, head demand from the building stock, and technological heat demand constraints at both the building and neighbourhood levels. It therefore explores the link between the energy sector and environment by considering carbon emissions.

The first two studies assess the different urban heating pathways and the technologies being considered for integration under different policy scenarios. To 'politicise' these studies, and place them in a socio-political context, a third study depicts a perspective on socio-political narratives linked to the Heat Transition in Amsterdam (see Chapter 6). For this study, data was collected through ethnographic research methods focusing on collective heating initiatives. Overall, this study depicts how the material reality of urban heating infrastructure is intrinsically related to different ideas on energy justice and the urban commons.

As such, the different approaches presented in this thesis are based on different knowledge paradigms. These approaches hence differ in views on what can be known about the world (epistemology), and what/how the collected knowledge should serve (axiology) (Wesselink et al., 2017). The modelling approaches presented applied in Chapters 4 and 5 can be categorised as falling more in the tradition of post-positivism. This is because these studies present knowledge of modelled dependencies. This knowledge can serve to be used as descriptive, quantitative data for people who want to perform 'data-based decision making'. The approach applied in the study in Chapter 6 shows similarities with interpretivism. This study provides empirically obtained descriptive histories that can be used as qualitative knowledge. Furthermore, this last study extends the application of the concepts of 'energy justice', the 'urban commons' and 'commoning practices', which can serve to generate new views on ways of thinking, doing and organising of space heating (Wittmayer et al., 2022).

By presenting these three studies together, the aim is to recognise the strengths of different approaches to contribute to one goal, i.e. generating knowledge that supports action towards satisfying human needs within planetary boundaries (Raworth, 2017). The units of analysis in each study are urban heating infrastructures in Amsterdam. Following Bouzarovski (2022) and Williams et al. (2018), infrastructures are taken as unit of analysis to conceptually connect socio-technical networks and natural resource flows to political dynamics. This thesis is therefore a call for more multidisciplinary work that combine quantitative modelling approaches with qualitative narratives on resource management with infrastructures as unit of analysis.

3

The heat transition in Amsterdam

The topic of study in this thesis is infrastructures for space and tap water heating in the built environment in Amsterdam. Within this city, a diversity of adaptations are made to decarbonise heating in the built environment. In order to understand the social-environmental-technological transformations linked with these adaptations, in this chapter a short introduction is given to (i) the geography of the city, (ii) the history of heating infrastructures in the Netherlands, and (iii) technological measures for the decarbonisation of the built environment.

3.1. GEOGRAPHIC CONTEXT

Amsterdam is the capital of the Netherlands and located in Northwestern Europe. Nevertheless, the Heat Transition in Amsterdam is interesting for cities all over the globe because a range of changes are made to the organisation of urban energy infrastructures and the implementation of heating and cooling technologies (Eggimann et al., 2020; Honoré, 2018; Werner, 2017; Olsthoorn et al., 2016; N.V. Nederlandse Gasunie, 2018; Hoogervorst, 2017). Dutch scenarios include a variety of low-carbon heating pathways that are also applicable across Europe, such as electrification of heating, the application of district heat networks supplied with the incineration of renewable energy carriers, and thermal energy storage (Honoré, 2018; Eggimann et al., 2020; Werner, 2017; Olsthoorn et al., 2016; N.V. Nederlandse Gasunie, 2018; Hoogervorst, 2017). By considering a diverse variety of heating technologies, this approach enables a quantitative analysis of the social-environmental impacts of different heating technologies. Moreover, the future heating scenarios for the Netherlands are starkly different from the current, natural gas dominated, energy mix. The national plan to provide 'natural gas-free' (Dutch: *aardgasvrij*) heating by 2050 Ministry of Economic Affairs (2016) motivates an integrated analysis of transitional, socio-environmental, impacts of CO_2 mitigating infrastructure choices.

In the first two studies presented in this thesis, the assessed impacts of a Heat Transition on water use and committed emissions are presented. With current climatic and demographic developments, both studies are relevant. First, when the national freshwater shortages caused by increasing droughts and desalinisation of coastal regions are considered, it becomes clear that research on the water withdrawal by the energy sector is very relevant for the Netherlands and other nations that need to address the potential compounding impacts of new infrastructures on climate-driven water scarcity (KNMI, 2018). The Netherlands has a temperate maritime climate, characterised by mild summers and cool winters. The average yearly temperature between 1981 and 2010 was 10.2°C (KNMI, 2018). This is 0.8°C warmer than the average yearly temperature measured between 1951 and 1980 (KNMI, 2018). Overall, an increase in the average yearly temperature of 1.6°C has been measured between 1950 and 2015 (KNMI, 2018). The Netherlands experienced milder winters due to a higher occurrence of wind blowing from the sea towards the land, and warmer summers due to the increase in sunshine. An increase in average temperature does not only increase the likelihood of days without frosts or days with the temperature reaching above 25°C. It also contributes to droughts, sea level rise and increased salt intrusion. These changes contribute to shifts in surface water temperature and nutrient concentration (PBL, 2012). The average yearly rainfall increased from 769 millimetres in 1901 to 933 millimetres in 2010. During summers, the number of rainy days is expected to decrease, which may lead to further precipitation deficits (ibid). Higher rainfall, additionally, seems to occur in urban regions of the Netherlands. Possible explanations are the warmer air temperatures in these regions are their location close to the sea.

Second, the number of inhabitants in the city of Amsterdam is growing, leading to an increased need for a rapid implementation of low-carbon and renewable urban heating systems. The number of inhabitants in the city was 882 633 on 1 January 2022 (CBS, 2022b). This increased to approximately 903 thousand inhabitants with the addition of the 'Weesp' region to the municipality on 24 March 2022. With this addition, the surface of the municipality is almost 19 thousand hectares (CBS, 2022a). The prognosis is that in 2050 the population of the city of Amsterdam will have grown to 1 070 000 inhabitants (Smits, 2022). To accommodate these inhabitants, 114 000 extra houses are expected to be built between 2022 and 2050 (Smits, 2022). Besides residential areas, the Amsterdam Metropolitan Area also houses a financial district, two airports, a seaport and clusters of companies in the creative industries, which also influence the heat demand of the city.

3.2. HISTORY OF URBAN HEATING SYSTEMS IN THE NETHERLANDS

In order to better the understanding the current ways in which space and tap water heating is organised in the city of Amsterdam and the energy justice perspectives raised in Chapter 6, it can serve to understand the history of urban heating systems in the Netherlands. As stated in the Introduction most of the thermal energy for space and tap water heating in the built environment of the Netherlands is generated with natural gas (Segers et al., 2020). In order to understand how this became the most dominantly used energy carrier for heating, a summary of the history of natural gas use in the Netherlands based on Raven and Verbong (2007) is given in this paragraph. In 1959, large reserves of natural gas were found in the Netherlands by the Dutch oil company the NAM (short for *Nederlandse Aardolie Maatschappij*) after which there was a nationwide expansion of the natural gas transport and the distribution grid. This grid was partially built upon existing infrastructure for coal gas. A private-public partnership was established between Esso, Shell and DSM (Dutch State Mines), called the *Gasunie* (translation: gas union). The NAM would produce the gas after which it was transported by the *Gasunie* to existing gas distribution companies, large industries and to large consumers abroad. From the 1960s central heating with gas replaced traditional stoves which mostly incinerated solid energy carriers such as coal (and to a lesser extent peat and wood). Later on, with the oil crisis and the rise of environmental concerns in the 1970s, natural gas became considered a strategic fuel for the future and was therefore only allowed to be used for 'high-grade applications' which were mainly domestic heating and cooking.

A history of heat networks in the Netherlands is also discussed in Raven and Verbong (2007) and summarised in the following. Heat networks, sometimes called district heating, are systems of pipelines that transport hot liquids (or steam). Two district heating systems were already established in Utrecht and Rotterdam in the years 1923 and 1949 respectively. Between 1920 and 1940 collective heating systems on building blocks appeared. The city of Amsterdam was the only city in the country with the application of district heating at this scale. No new systems in the Netherlands were however constructed in the 1950s and 1960s. In 1974, the Dutch government created a committee to investigate the prospects of district heating. Sixteen district heating plants were built and no district heating plants were constructed after 1983 till the mid-1990s, when heat networks were built in large house expansion projects, also known as Vinex locations.

The uptake of district heating has been different in multiple regions in Europe. Countries as Denmark, Sweden and Poland have high implementation rates of district heating in buildings around and above 50% (Werner, 2017). In the Netherlands, less than 5%

of the heating in the built environment in 2019 was delivered by heat networks (Segers et al., 2020). Raven and Verbong (2007) mention four reasons for this limited uptake of district heating in the 20th century.

First, municipalities often owned local gas distribution companies. The profits of these companies were used to finance municipal facilities such as swimming pools and sports centres, leaving fewer financial means to invest in district heating infrastructure. District heating infrastructures were therefore more often established by regional electricity companies, which were mostly owned by the provinces. The result of this was that district heating infrastructures became an alternative for space heating and therefore provided competition for municipal gas companies, which led to resistance from the municipality.

The second reason mentioned is that there was a dislike for district heating. This dislike can be explained by a general aversion to collective services because these services were connected to communism (Van Overbeeke, 2001).

Third, households connected to district heating often needed electric cooking to avoid being dependable on more than two energy sources, i.e. district heating for heat, electricity for light and gas for cooking. In 1920, already a major part of the inhabitants of Amsterdam people cooked on gas and used electricity for lighting. This was in line with the policy of the Minister of Agriculture, Industry and Commerce in May 2017 which was aimed at the most efficient energy use (so electricity for lighting, gas for cooking, and solid energy carriers for space heating) (Schippers et al., 2020). There was resistance against electric cooking because users were not familiar with this. Dutch consumers, therefore, showed a preference for individual heating systems on gas.

Fourth, district heating companies had multiple financial challenges. They took over the tariff structure of natural gas supply which did not reflect the actual cost structure of heat supply, i.e. high capital costs and low energy costs instead of low fixed costs and large variable costs. Moreover, the heat demand turned out to be lower than expected due to the construction of smaller houses, delays in house-building programmes, and a successful national programme for house insulation. This led to more than 130 million euros of cumulative losses for district heating projects in 1989. The Dutch government did decide to financially support the district heating companies with 45 million euros which prevented bankruptcy for some companies.

Nevertheless, in 2020 more than 15% of the heat demand in the built environment in Amsterdam was delivered by one of the two major high temperature heat networks (Municipality of Amsterdam, 2020b). These two networks were both connected in 2020 (Vattenfall, 2022). One network is owned by the Swedish multinational energy company Vattenfall, and delivers thermal energy which is mostly generated at a gas-fired CHP (Segers et al., 2020). The other heat network is used by the heat company called 'Westpoort Warmte' (Dutch for 'Westpoort Heat') to deliver thermal energy. This company is a joint venture between the waste-to-energy company 'AEB' (Dutch abbreviation for *Afval Energie Bedrijf*), which is owned by the municipality of Amsterdam, and the company Vattenfall (Segers et al., 2020). These systems also include natural gas-fuelled heat boilers to ensure heat supply at peak demand.

Next to bigger energy companies, many other smaller companies are involved to the heat transition in Amsterdam, such consultancies, contractors, and technological, communication, or installation companies. Moreover, there are non-profit organisations, such as seven energy cooperatives in the city. At last, owner, tenant and neighbourhood associations organise themselves to decide on how to reduce natural gas use for heating.

3.3. TECHNOLOGICAL MEASURES FOR THE DECARBONISATION OF SPACE HEATING

The technological changes for the decarbonisation of urban heating systems can be made on both the heat demand and supply side. The heat demand of a building can be reduced technically by the insulation of the building envelope, including the floor, roof, walls and windows. Other measures that can be taken to keep more thermal energy inside the building, are energy recovery, energy recovery ventilation, draft strips, radiator reflector, and window coverings. At last, the heat distribution systems in buildings can be adapted by changing the temperature of the distributed water in central heating systems, updating radiators or installing floor heating systems.

On the supply side, a plurality of alternatives to the natural gas heat boilers for "hastening, retarding, redirecting, collecting, converting, or producing thermal energy " exist (Oppermann and Walker, 2019, p.129). No system is yet to be considered as a one-size-fits-all solution in Amsterdam because of the great diversity in housing types, building infrastructures and spatial availability of heat sources. Multiple studies have been performed to determine the heat options that are most preferable to achieve low-carbon and renewable heating systems on the neighbourhood level (e.g. Van den Dobbelsteen et al. (2020), PBL (2021), Schepers and Meyer (2017), and Municipality of Amsterdam (2020b)). Due to the application of different models and design criteria, varying technological interventions have been recommended by these studies.

In one study, the municipality of Amsterdam has screened which heat sources are affordable and can be available per neighbourhood (Municipality of Amsterdam, 2020b). They have presented the outcomes of this study in Transition Vision Heating (Dutch: *Transitievisie Warmte*) employing a map. A translated version of this map is presented in Figure 3.1. The city of Amsterdam expects that the urban heating infrastructure in the city in 2040 will consist of 50-60% of mid temperature (MT) and high temperature (HT) heat networks, 35-40% of all-electric solutions in combination with low temperature (LT) and very low temperature heat networks, and 15% on hybrid solutions Municipality of Amsterdam (2020b).

Following the thermal regimes defined by the Municipality of Amsterdam in (Municipality of Amsterdam, 2019a), HT heat networks are district heating systems supplying thermal energy above 90°C. MT heat networks transport water at 70°C. Examples of thermal energy sources for HT and MT heat networks are Combined Heat and Power (CHP) plants, industrial-sized heaters, electric boilers, residual waste from industry, and geothermal energy. The latter refers to sources that tap into the Earth's sub-surface geothermal heat sources. The multiple advantages of current HT strategies are: supply can always be ramped up to match demand with the combustion of fuels, control of the system is centralised, existing business models can be applied and costs can be limited for building owners because no insulation measures are required at the building level. The disadvantages of HT district heating are that in the long run, drawbacks may

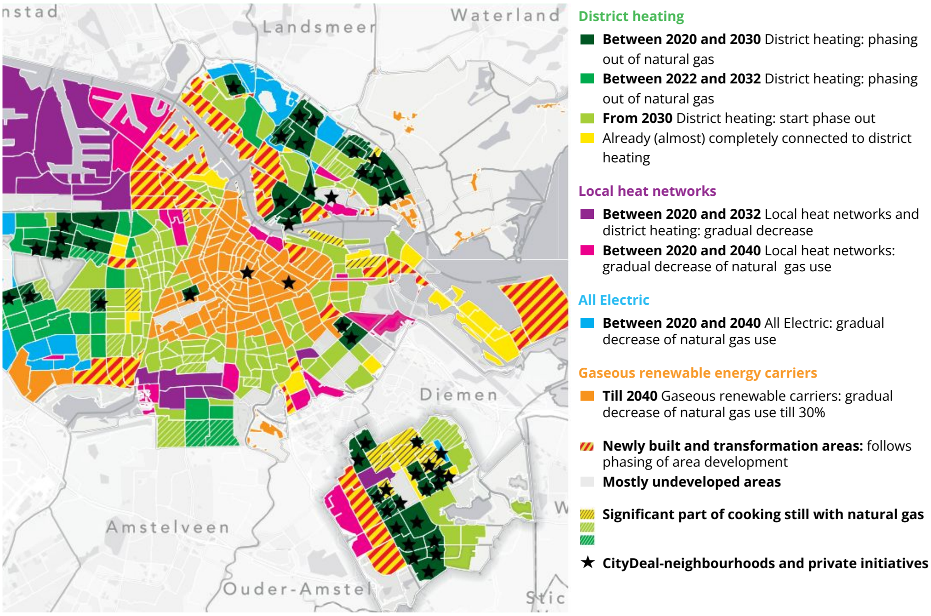


Figure 3.1: Map of envisioned distribution of heating systems in the city of Amsterdam. Edited and translated from the 'Transition vision for Heat' (Municipality of Amsterdam, 2020b).

occur. The costs for heating in non-retrofitted buildings can be higher than after insulation. This is because the demand for heat is and remains higher. In addition, there is no certainty about the future availability of high-temperature heat sources in Amsterdam that do not depend on the combustion of energy carriers. In Amsterdam, there are plans to feed the heat networks with the combustion of biomass and the heat from geothermal energy (Municipality of Amsterdam, 2020b). It is however not yet known whether geothermal energy sources are suited for development in Amsterdam (Municipality of Amsterdam, 2020b). The HT heating infrastructure that is now being laid out may therefore still cause CO_2 emissions related to the combustion of energy carriers in the coming decades (Maselis and Hisschemöller, 2018). Alternatively, LT heat networks distribute water at 40°C. 'Very low temperature' heat networks also exist, transporting water at temperatures below 20°C. The advantage of heating systems operating at lower thermal regimes is that more local, low-carbon, thermal energy sources can be used. Examples of such sources are ambient heat from surface water or air, solar energy collected with solar boilers, and residual heat from data centres or wastewater. In this thesis, thermal energy from surface water is referred to as hydrothermal energy. These heat networks operating at very low temperatures can be designed for both heating and cooling purposes (Buffa et al., 2019).

To facilitate the use of these thermal energy sources, ensure reliability, and increase efficiency, heat networks can be integrated with thermal energy storage. One form of thermal energy storage is Underground Thermal Energy Storage (UTES). Most UTES systems are designed with a 'heat' and 'cold' well. In this way, both heat and cold can

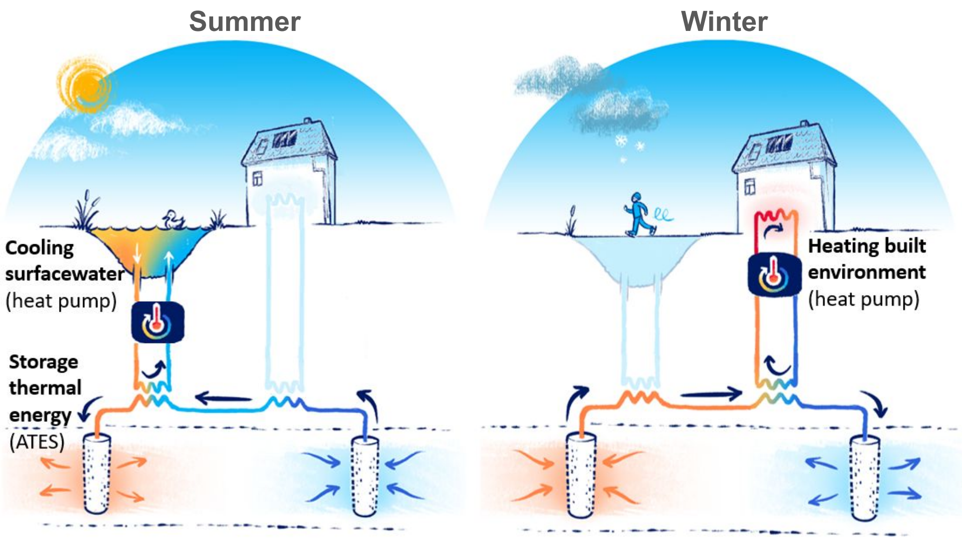


Figure 3.2: Seasonal thermal energy storage for heating and cooling. Edited picture from Waternet (2020); Ramaker (2020)

be provided in different seasons (see Figure 3.2). UTES systems can be open systems, called Aquifer Thermal Energy Storage (ATES), and closed systems, referred to as Borehole Thermal Energy Storage (BTES) (Pellegrini et al., 2019). The use of cooling is important in the future when temperatures rise due to global climate change and urban heat islands. UTES systems are often used for small heat networks at the building or neighbourhood scale. Heat pumps play an important role in the transfer of thermal energy, within and between heat networks (operating at different thermal regimes), the operation of UTES systems, or direct heating of indoor spaces by extracting thermal energy from the ground, air or water bodies.

The integration of heat pumps in heating systems is an example of the electrification of heating. Scholars argue that electrification of heating is an important part of the decarbonisation of heating (Thomaßen et al., 2021; Eggimann et al., 2020; Eyre and Baruah, 2015). Electrification of heating includes the (partial) replacement of gas boilers with electric heat generation technologies. These 'all-electric' or P2H solutions are technologies that generate heat using electricity. More examples of such electric heat generation technologies include infrared panels and electric boilers. A consequence of the electrification of heating is the need to reinforce the electricity grid (Andersen et al., 2017; Eggimann et al., 2020). In the future, the electricity network is expected to be more heavily burdened by electric heating technologies. This means that (peak) electricity consumption will increase and the electricity network may need to be reinforced. The use of hybrid solutions can be applied to limit the burden on the electricity grid. In the Dutch context, hybrid solutions often refer to the use of low-carbon heating alternatives, such as heat pumps, to supply base load heat and the incineration of gas to cover the peak demand.

4

The water use of heating pathways to 2050: analysis of national and urban energy scenarios

As the first study in this thesis on the social-environmental-technological changes linked with the Heat Transition, the potential changes in water use are analysed. Water is used for the distribution and storage of thermal energy, and the production of (renewable) energy carriers such as biomass, hydrogen and electricity. Assessment of the potential change in water use by transforming energy systems is thus important for avoiding increased environmental degradation, water shortages, and energy insecurity. In this chapter, an integrated approach for assessing how future heating pathways can change the water use of future energy systems is presented.

ABSTRACT CHAPTER 4: 'THE WATER USE OF HEATING PATHWAYS TO 2050: ANALYSIS OF NATIONAL AND URBAN ENERGY SCENARIOS'

Sustainable energy systems can only be achieved when reducing both carbon emissions and water use for energy generation. Although the water use for electricity generation has been well studied, integrated assessments of the water use by low-carbon heating systems are lacking. In this chapter, a Water-Energy Nexus approach is therefore employed to interrogate the interdependencies between water use and thermal energy generation. An analysis of the water use scenarios for heat and electricity production for the year 2050 for the Netherlands and its capital, Amsterdam, is presented. The analysis shows that (i) the water withdrawal for heating can increase up to the same order of magnitude as the current water withdrawal of thermoelectric plants due to the use of Aquifer Thermal Energy Storage (ATES), (ii) the virtual water use for heating can become higher than the operational water consumption for heating, and (iii) the water use for electricity production becomes a relevant indicator for the virtual water use for heat generation due to the increase of Power-to-Heat applications.

Keywords: low-carbon heating pathways, water-energy nexus, water withdrawal, water consumption, water footprint, Power-to-Heat, and multi-scale energy and water use model.

4

This chapter is based on the text in Kaandorp et al. (2021a). The workbook used for this study can be found at the 4TU data repository (Kaandorp et al., 2023a).

4.1. INTRODUCTION

The current body of scientific literature on water use by the energy sector mostly covers the topics of water use for electricity generation and fuel production (Hoff, 2011; Endo et al., 2016; D'Odorico et al., 2018). Studies have aimed to collect data on the water footprint of electricity production (e.g. Macknick et al. (2012) and Meldrum et al. (2013), and Spang et al. (2014)) or energy crop production (e.g. Gerbens-Leenes et al. (2009)). These data have been used to assess the current and future water use of electricity production (Byers et al., 2014; Rio Carrillo and Frei, 2009). The consumptive water use of heat production has been assessed for the years 2000 and 2012 on a global scale, showing a growth in water use for heating mainly driven by increases in the use of firewood (Mekonnen et al., 2015). No study, to the author's knowledge, has however analysed how a mix of decarbonisation strategies would affect different types of water use for heating. Consequently, these studies offer a too narrow depiction of water use for future heat generation.

In this chapter, this knowledge gap is filled by presenting a integrative assessment of the water use of future heating pathways, including the impact of electrification of heating. To do so, a multi-scale energy and water use model was developed and used to comparatively assess the energy scenarios for the Netherlands and its capital, Amsterdam for the years 2015 and 2050.

4.2. METHODS

4.2.1. MULTI-SCALE ENERGY AND WATER USE MODELLING FRAMEWORK

In order to model the water use of heating in an integrated way, (see Figure 4.1). The operational water use is the water used at the location of energy generation whereas virtual water flows can come from elsewhere. A model which accounts for water uses at global, national and urban scales is therefore developed .

The operational water use includes both water withdrawal and water consumption. Water withdrawal refers to the abstraction of water from ground and surface water sources (IEA and OECD, 2016). The amount of water which is not discharged back into a water body is called water consumption. The water withdrawal and consumption rates for power plants were collected from literature (see supplementary material, Tables A.1 and A.2). The water use values mentioned in literature for thermoelectric power plants can vary significantly, but a mean value is often given. Research shows that using the median values for modelling the water withdrawal and consumption for thermoelectric plants in European countries gives results that correspond reasonably well to water withdrawal and consumption reported in national statistics (Larsen and Drews, 2019).

The water withdrawal rates for heating systems, excluding combined heat and power CHP plants, are based on the calculations given in Table A.3 of the supplementary material. For these heating systems, heat is extracted from geothermal and hydrothermal energy sources, or UTES systems (see Section 3.3 for an explanation of these heating systems). The water withdrawal needed to extract heat from these sources depends on the temperature difference between the water that is extracted and discharged back into the

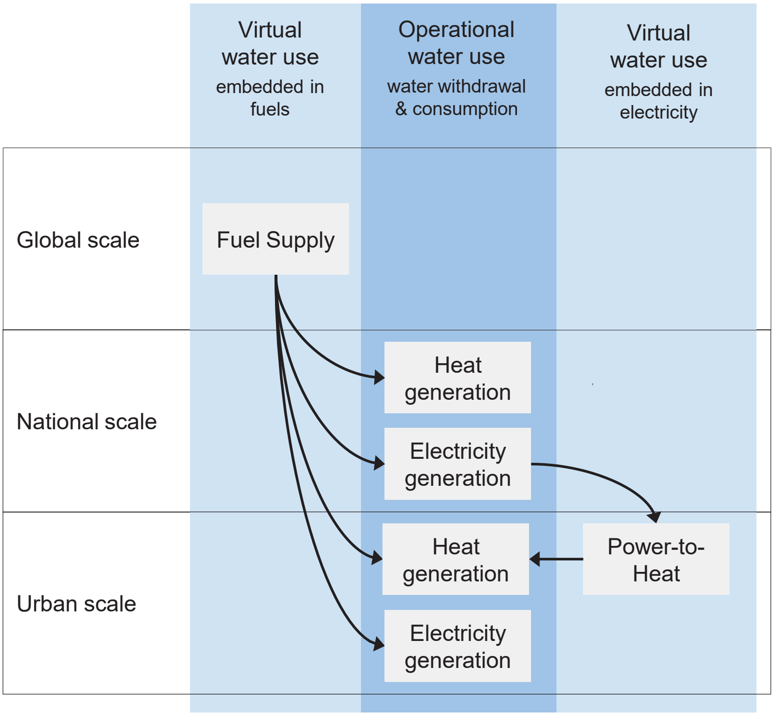


Figure 4.1: Conceptual visualisation of multi-scale water and energy use model that allows the delineation of localised operational water use and virtual water use through energy carriers. In the model, it assumed that the electricity needed for P2H applications on an urban scale is withdrawn from the national power grid.

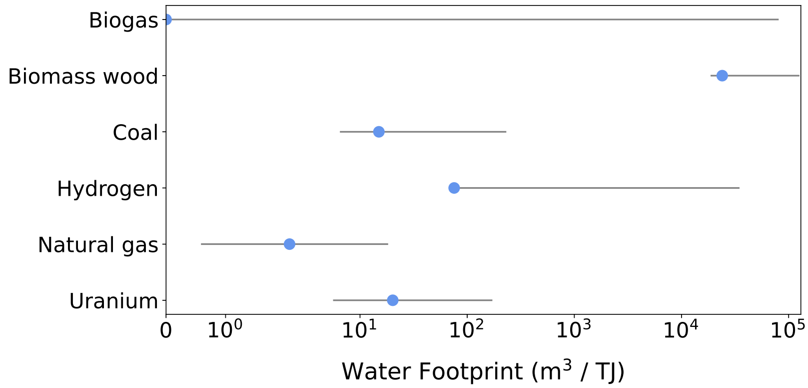
heat source. This withdrawal volume is expressed by the equation:

$$V = \frac{J_{\text{ext}}}{\Delta T \cdot C_{\text{water}}}, \tag{4.1}$$

where V is the volume of water extracted, J_{ext} denotes the energy extracted from the volume of water, ΔT denotes the difference in temperature of the volume of water before and after heat extraction, and C_{water} is the volumetric heat capacity of the water (RVO and CBS, 2015). The volumetric heat capacity in the model is set equal to the volumetric heat capacity of freshwater (C_{water} = 4.182 MJ / Km^3). In the case of hydrothermal energy, also brackish or salt water could be used. Salt water has a lower heat capacity, which would result in a higher volume of water withdrawal. For heat extraction from UTES systems and surface water, a ΔT of 4°C was chosen, based on the average ΔT given by national statistics (RVO and CBS, 2015). For geothermal energy, ΔT was set equal to 40°C (Ree and Kelfkens, 2019). The water consumption for these heat technologies is set equal to zero, since water is not consumed per se but is returned to the source at a different temperature.

The virtual water use of energy carriers in this work refers to the volume of water required to produce fuels and electricity (Allan, 2003). The virtual water use of fuels (VW_{fuel}), i.e. combustibles and nuclear materials, was determined from water footprint (WF) data in the literature. The WF of a product, such as an energy carrier, is the "volume of freshwater used to produce the product", measured over its full supply chain (Hoekstra et al., 2011). The values used for different carriers can be found in Figure 4.2 and Table A.5 of the supplementary material. The WF values of fuels chosen in the main analysis and discussion are on the lower end of the WF values from the literature. As such, these values serve to analyse how the substitution of fossil fuels by renewable energy carriers may affect the water use of the energy sector, starting from the least impact. The VW_{fuel} per scenario was modelled by multiplying the amount of energy produced by the given technologies, the Energy Required for Energy (ERE) values, and the WF per unit energy of the used energy carrier (see supplementary material, Tables A.4 and A.5). The ERE value stands for the amount of energy from an energy carrier needed to produce one unit of energy (Mekonnen et al., 2015). It therefore corresponds to the heat value and heat rate of an energy carrier for heat and electricity production respectively. For the case of technologies that use 'gas', it is assumed that gas is supplied through the national gas grid. The grid is assumed to supply a mix of natural gas and biogas and the mix is different per scenario. The ratios between natural gas and biogas in the mix are given in Table A.6 of the supplementary material.

Only for the energy carrier electricity, the virtual water use was determined in a different manner. With electrification of heating, the water used for electricity production is concurrently used for heating purposes through P2H. It can therefore be argued that the virtual water use of electricity (VW_{P2H}) should not be overlooked in an integrated assessment of the water use for future heating pathways. The VW_{P2H} of heating appliances on an urban scale was determined by scaling down the water use for generating electricity on a national scale (see Figure 4.1). This is because it was assumed that electricity needed for heat generation on an urban scale is extracted from the national grid and therefore depends on the national electricity mix. The water use for electricity produc-



4

Figure 4.2: Water footprint of fuels. Range of values found in literature for the water footprint of fuels. The dot depicts the value chosen.

tion on the national scale is modelled in terms of water withdrawal, water consumption and VW_{fuel}. In this chapter, the VW_{P2H} is expressed in these three types of water use.

In order to calculate the electricity demand for P2H applications it was assumed that all heat pumps in the technology mixes would be electrified. This assumption is can be argued to be reasonable for the 2050 scenarios, where heat pumps are not expected to be fuelled by gas because of Dutch political ambitions to reduce the use of natural gas (Ministry of Economic Affairs, 2016).

4.2.2. FUTURE HEATING PATHWAYS FOR THE NETHERLANDS AND THE CITY OF AMSTERDAM

In order to study the potential change in the water use of the national energy sector, four major energy scenarios for 2050 are compared with the technology mixes for heat and electricity production in 2015 (see Figure 4.3). The year 2015 is chosen as reference year because, at the time of this study, this year was the most recent year for which national statistics existed on water withdrawal from the electricity sector and Underground Thermal Energy Storage (UTES) systems. The year 2050 is chosen because the Netherlands has committed to phasing out fossil fuels and achieving a 95% emissions reduction by this year (compared to emission levels in 1990) (Ministry of Economic Affairs, 2016).

The 2050 scenarios are based on the four major scenarios laid out by the main Dutch network operators in an integrated infrastructure exploration of possible low-carbon energy systems adhering to the Dutch Climate Agreement (Den Ouden et al., 2020; Government of the Netherlands, 2019). The interpretation of these qualitative scenarios to specific technology mixes is inspired by the technology mixes given by the Energy Transition Model (ETM, 2020). As the report states (Den Ouden et al., 2020), the scenarios are not representative of the future energy system of the Netherlands, but rather typify extremities of different transition pathways and associated the possible technology mixes. The scenarios are therefore suitable for accessing the different potential impacts of a heat transition on the water use of the energy sector.

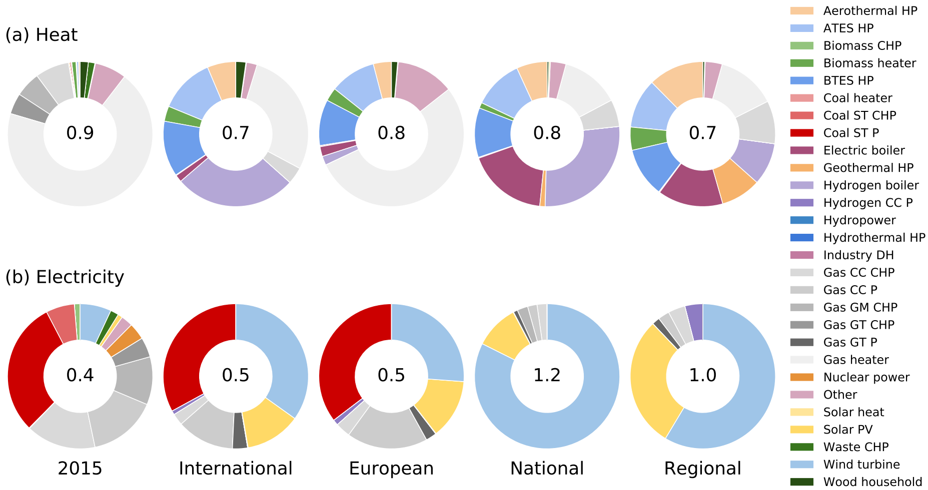


Figure 4.3: Technology mixes for (a) heat and (b) electricity generation in the Netherlands in 2015 and in four major scenarios for 2050. The amount of energy generated per scenario is presented in units of exajoules in the middle of the doughnut diagrams. Abbreviations: ATES = Aquifer Thermal Energy Storage, BTES = Borehole Thermal Energy Storage, CC = Combined Cycle, CHP = Combined Heat and Power, DH = District Heating, GM = Gas Motor, GT = Gas Turbine, PV = Photo-voltaic, ST = Steam Turbine.

The labels of the scenarios refer to the conceptual 'governance structures', i.e. socio-economic drivers for shaping low-carbon energy systems defined in the report on climate-neutral energy scenarios (Den Ouden et al., 2020). The 'International' scenario is mostly driven by an international energy market leading to more import of hydrogen compared to the other scenarios. The 'European' scenario is driven by European taxes on CO_2 emissions on all sectors, import duties at the European border and subsidies for relevant sectors. This scenario may be more effective than the current EU Emission Trading System because it covers all sectors (Zhu et al., 2019). The tax rates increase towards the year 2050 and will lead to more import of energy in the Netherlands. The strategies characterising this scenario are carbon capture and storage and hybrid electrification. With hybrid electrification, conventional combustion technologies are partially replaced by electric solutions. The main driver in the 'National' and 'Regional' scenarios is self-sufficiency on the national and regional levels; the term 'Regional' here refers to a scenario where the Dutch government gives control of the energy transition largely to sub-national regional government bodies. Given the climate and geography of the country, this leads to higher capacities in wind and solar energy combined with electrification of heating in the National scenario. Similarly, the Regional scenario is characterised by more electrification of heating, and the use of geothermal energy for heat networks. The report describes that citizens have a more active role in the Regional scenario leading to higher citizen awareness of low-carbon heating systems and increased involvement in sustainable initiatives of citizens. This is an important driver given that social acceptability is expected to be a great challenge for decarbonising heating systems (Sovacool

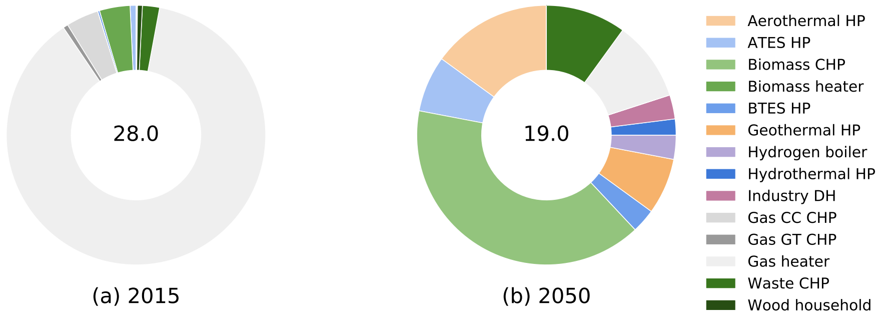


Figure 4.4: Heat technology mixes for 2015 and 2050 scenarios for the city of Amsterdam. The urban technologies mix for the year 2015 was derived from several sources (AEB Amsterdam, 2016; CBS, 2020; Directorate-General for Public Works and Water Management, 2020; Menkveld et al., 2017; Van Der Hoek et al., 2017; Vattenfall, 2019). The 2050 technology mix was based on the road map presented in the report 'New Amsterdam Climate' (Municipality of Amsterdam, 2020a). The amount of energy generated per scenario is presented in units of petajoules (PJ) in the middle of the doughnut diagrams. Abbreviations: ATES = Aquifer Thermal Energy Storage, BTES = Borehole Thermal Energy Storage, CC = Combined Cycle, CHP = Combined Heat and Power, GT = Gas Turbine

4

et al., 2021b). A more active role of citizens in decarbonising heating systems can increase literacy on low-carbon heating technologies and desirability of change, which is now often low across countries in Europe (Sovacool et al., 2021b,a). Given the complexity of the mentioned socio-economic drivers in practice, in this Chapter, the water use of the given scenarios is studied quantitatively without further elaboration on the potential implications of socio-economic drivers on energy and water use.

In addition to the four national scenarios, urban heating scenarios for Amsterdam are also considered (see Figure 4.4). This is done in order to show how the change in technology mix for electricity production on a national scale can affect VW_{P2H} on an urban scale. The 2050 scenario is based on the road map outlined in the report 'New Amsterdam Climate' (Municipality of Amsterdam, 2020a). This report sketches that 50-60% of the heat demand in the built environment could be met with collective heating systems. Such systems can be fuelled with thermal energy from CHP plants or residual heat from industry. Another 35-40% of the heat demand may be generated through all-electric heating systems. These systems can be connected to low-thermal heat sources, such as UTES and datacenters, in order to increase the efficiency. Around 15% of the heat demand could also be met with hybrid systems.

4.3. RESULTS

The modelled water use of the national technology mixes are presented in Figure 4.5. The figures in the middle column show the aggregated (1) water withdrawal, (2) consumption, and (3) VW_{fuel} of both electricity and heat production. Figure 4.5.1b shows that, compared to the 2015 scenario, the calculated water withdrawal for heat production increases significantly in all four scenarios, for three scenarios even exceeding the water withdrawal for electricity production. Moreover, Figures 4.5.2b and 4.5.3b suggest that the VW_{fuel} for heating is more than four orders of magnitude higher than the water consumption for heating in all four scenarios. This means that virtual water use becomes higher than local operational water consumption.

In the left and right columns, the water use per technology for electricity and heat production are depicted. Figure 4.5.1c suggests that the water withdrawal for heat production increases primarily because of the use of ATES systems and secondarily due to geothermal systems. The water withdrawal for electricity production (see Figure 4.5.1a and Figure 4.5.1b) is highest in the scenarios where coal powered generation is employed, i.e. the International and European scenarios. The water consumption for heat production, mostly consisting of the water consumption by gas fired CHP plants, is significantly smaller than that for electricity production (see Figures 4.5.2a-c). The VW_{fuel} of both electricity and heat production depends on the employment of energy carriers such as biomass, coal gas, hydrogen, and wood (see Figures 4.5.3a-c). In some cases the relative contribution per technology might seem similar (e.g. the VW_{fuels} for the International and European scenarios in Figure 4.5.3a). This is because these columns prominently show only the relative water use contributions of the technologies that have higher water use indicators. Looking at the actual technology mixes in Figure 4.3, the differences in the technology mixes of the International and European scenarios are significant in the technologies but for ones that use less water; for example, there is relatively more wind energy in the international scenario for electricity production, but still around the same ratio of coal and gas fired power plants as in the European scenario.

In order to assess how different WF values per fuel would affect the results, a first order sensitivity analysis was performed varying the WF value per fuel between the minimum and maximum values found in literature. The results of this analysis are shown in the heat maps in Figure 4.6. The Figure shows that the VW_{fuel} for heating scales almost linearly with the VW_{fuel} of biomass. The VW_{fuel} for electricity generation in the future scenarios does not increase when substituting higher values for biomass. Moreover, if the VW_{fuel} value for coal is changed, only the values for electricity generation in the International and European scenarios show a near linear change, both of which have a large mix of coal based power generation (see Figure 4.3).

One strategy for decarbonising heating pathways is the electrification of heating. The yearly national consumption of electricity for P2H applications was estimated to be 2.08 exajoules (EJ) in the 2015 scenario and projected to be between 65.0-450 EJ in the 2050 scenarios (the values per scenario are included in the supplementary material, Table A.7). In other words, the calculated fraction of electricity needed for heating compared to the total electricity production, given in Figure 4.3, is 0.5% for the 2015 technology mix and between 14-37% for the four 2050 scenarios. For the case of Amsterdam, an increase in electricity demand for P2H applications from 68 TJ in the 2015 technology mix to 1 309 TJ in the 2050 scenario was observed.

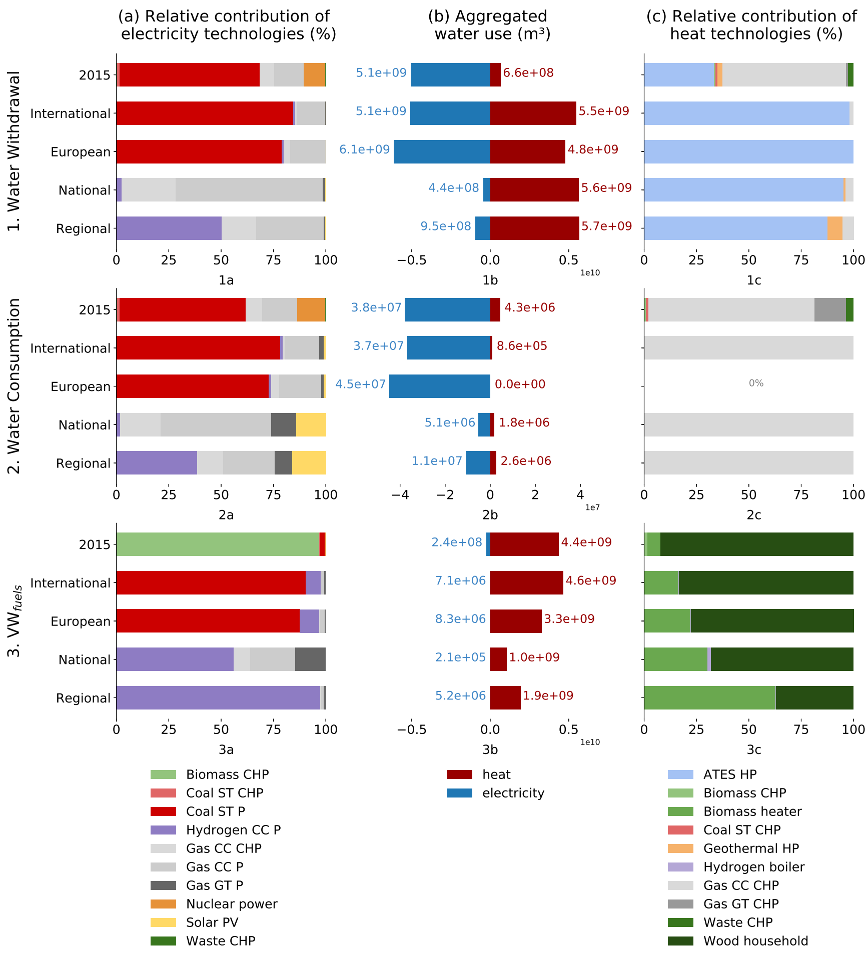


Figure 4.5: Modelled water use for heat and electricity production in the Netherlands in 2015 and four 2050 scenarios called International, European, National and Regional. Water use is expressed using the indicators (1) water withdrawal, (2) water consumption, and (3) virtual water use for fuels. Column (b) depicts the water use for the production of electricity (in blue) and heat (in red). The left and right columns show the relative contribution of heat and electricity technologies, respectively, towards the corresponding aggregate water use indicators in column (b). Abbreviations: CC = Combined Cycle, CHP = Combined Heat and Power, GT = Gas Turbine, ST = Steam Turbine

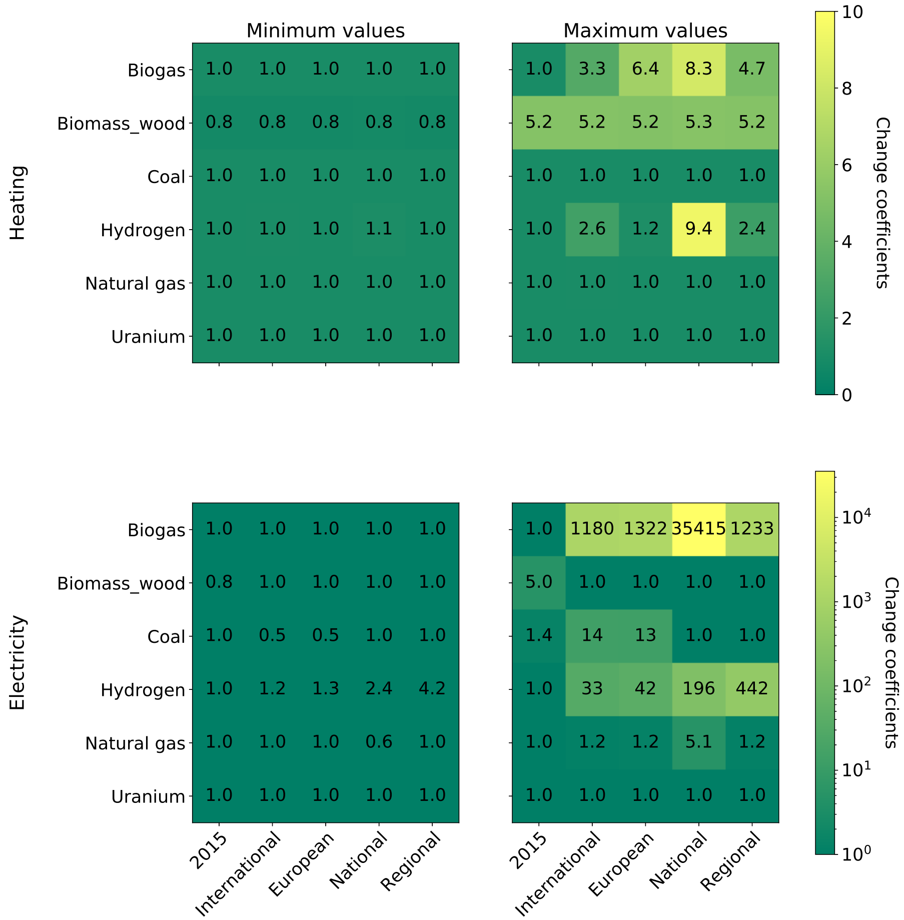
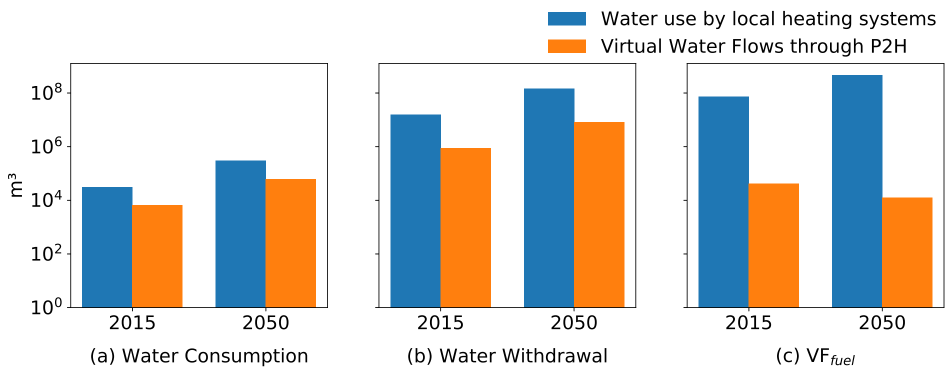


Figure 4.6: Sensitivity analysis VW_{fuel}: minimum (left column) and maximum (right column) values given for VW_{fuel} when changing the Water Footprint of fuels according to the range of values found in literature. The change coefficient shows the relative change of the VW_{fuel} with respect to analysis for the VW_{fuel} of heating (upper row) and electricity (bottom row) generation.



4

Figure 4.7: Water use for local heat production for the city of Amsterdam and VW_{P2H}. Diagrams (a), (b) and (c) depict the model output for water withdrawal, water consumption and the virtual water use for fuels respectively. The values are plotted on a logarithmic scale and are in units of cubic meters.

This increase in P2H applications affects the virtual water use of heat production. In Figure 4.7 the operational water use and VW_{fuel} for urban heating systems are compared with the VW_{P2H} in the scenarios for 2015 and 2050. In the case for 2050, the average for the four national scenarios was taken (see supplementary material, Table A.8, for the results per scenario). The data in Figure 4.7 suggest that the virtual water abstraction and water consumption for P2H applications is not negligible compared to the local water withdrawal and consumption of urban heating systems. The VW_{fuel} for P2H applications, on the other hand, is negligible compared to VW_{fuel} of the fuels used by local heating systems. In Table 4.1 the ratio between VW_{P2H} and 'direct' water use of local heating technologies are given per scenario. The ratios between direct water use and VW_{P2H} for 2015 and the average of the 2050 scenarios remain similar for the operational water use and WF_{fuel} (i.e. 5.6% for water withdrawal, 21% for water consumption and around 0% for the VW_{fuel}). Nevertheless, the ratios for water withdrawal and consumption do differ among the four major 2050 scenarios between 0.3%–11% and 1.8%-41% respectively. This variation is to be explained with the significant variation in the water withdrawal and consumption for electricity generation per scenario as presented in Figures 4.5.1b and 4.5.2b.

Table 4.1: Comparison of VW_{P2H} with water use requirements for urban heating in Amsterdam. In this table a comparison is shown of indirect water requirements for electricity production for P2H applications under different national scenarios for electricity production with the water withdrawal, consumption and VW_{fuel} associated with the heat mixes in Amsterdam. The VW_{P2H} is divided into the water withdrawal, consumption and VW_{fuel} needed to generate the electricity needed for P2H applications.

Scenarios	$\frac{VW_{P2H,\ water\ withdrawal}}{water\ withdrawal}$ (%)	$\frac{VW_{P2H,\ water\ consumption}}{water\ consumption}$ (%)	$\frac{VW_{P2H,\ VW_{fuel}}}{VW_{fuel}}$ (%)
2015	**5.6**	**21**	**0.1**
International	10	35	0.0
European	11	41	0.0
National	0.3	1.8	0.0
Regional	0.8	4.7	0.0
2050 average	**5.6**	**21**	**0.0**

4.4. DISCUSSION

From the results, three main insights are derived on how heat transitions can impact the water use of the energy sector. First, the national water withdrawal for heating for the 2050 scenarios is an order of magnitude higher that the water withdrawal in 2015. This means that the national water withdrawal for heating in the 2050 scenarios is of the same order of magnitude as that of the current water withdrawal for electricity generation. The increase in water withdrawal for heating between the 2015 and 2050 technology mixes is due to an increased use of ATES systems in the technology mix from 0% to 10-12%. This means that the water withdrawal for heating can increase to the same order of magnitude as the water withdrawal of thermoelectric power plants in 2015 if only around a tenth of the heating is supplied through ATES. To validate the modelled water withdrawal for ATES systems, the output for the 2015 scenario was compared to national statistics. This value, $278 \cdot 10^6$ m^3, is based on energy sales data, data on energy storage and provincial data on groundwater flow, and include water withdrawal for both heating and cooling (Meurink and Segers, 2016). It is comparable with the modelled water withdrawal for ATES systems being $220 \cdot 10^6$ m^3 for the 2015 scenario (i.e. almost a third of the national water withdrawal for heating given in Figure 4.5.1b).

Second, the VW_{fuel} of heating remains higher than the water consumption for heating. To model the VW_{fuel} of gas, it is important to note that a mix of natural gas and biogas was used, varying in composition per scenario. The VW_{fuel} of biogas was set equal to zero because of two assumptions. The first assumption was that biogas would in future scenarios be produced through anaerobic digestion with mainly manure as mixing liquid instead of water. In comparison, the Water Footprint for the anaerobic digestion phase with water as mixing liquid is approximately 437, 450, 474 m^3 / TJ when digesting the energy crops Maize, Wheat and Sorghum respectively (Pacetti et al., 2015). The second assumption is that the biogas made from residual materials, such as sewage sludge, has no virtual water use associated with it since the availability of these materials does not depend on the demand for biogas (Meurink and Segers, 2016). Resources for biogas can however be assigned a VW_{fuel}. The sum of the blue and green water footprint of biogas production from wheat, for example, is 79 340 m^3 / TJ (Pacetti et al., 2015). Changing the VW_{fuel} of biogas to 79340 m^3 / TJ in the model, increases the VW_{fuel} of heat generation by a factor of 3.3 to 8.3 depending on the considered scenario; for electricity generation the increase factors range from 1 180 to 35 415 (see Figure 4.6). The relatively high increase for VW_{fuel} for electricity production in the national scenario in comparison to the other scenarios is not to be explained by a higher share of gas fired power plants in the technology mix (see Figure 4.3). Instead, this is due to the fact that the mix of gas in the national gas grid consists of relatively more biogas than natural gas in comparison to the other scenarios (see supplementary material Figure A6). A higher value for biogas thus mostly affects the VW_{fuel} of electricity production. The replacement of natural gas with biogas in gas fired power plants can therefore significantly increase the VW_{fuel} of heat and electricity generation.

The sensitivity analysis also showed that the VW_{fuel} of electricity production would increase significantly when higher values for the WF of hydrogen are used (see Figure 4.6). In the main analysis of this study, the VW_{fuel} for hydrogen was set equal to 75.6 m^3 / TJ, which is the direct water use for producing hydrogen through proton exchange membrane electrolysis, assuming no water losses and not accounting for the WF of electricity (Webber, 2007). Hydrogen can however be made in other ways. Research has shown that the water use for hydrogen production in nine potential production pathways can range between 326 and 34 216 m^3 / TJ (Mehmeti et al., 2018).

4

Lastly, the third insight of this study is that the water withdrawal and consumption for electricity production for P2H applications is comparable to the local water withdrawal and consumption for heating in the case of Amsterdam. Assessments of water use for future urban heat generation should therefore include the virtual water flows embedded in electricity used for P2H applications.

The amount of electricity needed for heating is determined by the coefficient of performance (COP) of electric heating applications. In this research a COP of 1 for electric heaters, and 4 for heat pumps were used (RVO and CBS, 2015). In practice the COP of heat pumps varies, depending on factors such as temperature differences between heat source and the space that is to be heated, and technology specifics. A range in COPs between 2.9 and 4.5 can be found in literature (Joint Research Centre of the European Commission, 2014). The amount of electricity needed for P2H applications - and therefore the VW_{P2H} - scales inversely proportionally with COP. The model output for VW_{P2H} will therefore be almost proportionally higher than the values presented in Figure 4.5 if the COP value is set lower than 4.

The water use calculations for electricity generation depend on the parameters used for the different technologies in the mix. The modelled water withdrawal for electricity production was $5.1 \cdot 10^9$ m^3 for the technology mix in 2015. This number is less than half of the total water withdrawal for the cooling of power plants, which was reported to be about $11 \cdot 10^9$ m^3 in national statistics (Statistics Netherlands, 2020). In a study using similar approaches an underestimation between 30%-35% was shown (Larsen and Drews, 2019). It can therefore be argued that the results presented in this chapter are comparable with the results presented in Larsen and Drews (2019), given that for the study presented in this chapter, the water withdrawal of CHP plants was divided into electricity and heat production instead of only electricity production. A more accurate value for the water use for power generation could be obtained by using power plant-specific water use data instead of water withdrawal rates from the literature.

Since such specific data on power plants are often not openly available, an alternative method to model the water withdrawal and consumption of CHP plants could be developed. CHP plants produced 18% and 40% of the delivered heat and electricity respectively in the 2015 technology mixes for the Netherlands. The modelled water use of power plants was attributed to the water use of electricity or heat production proportionally to the total energy produced. In this work, it was assumed that the water withdrawal and consumption rates of CHP plants were 10% of the water withdrawal and consumption for power plants which only produce electricity (Mekonnen et al., 2015). To the best of my knowledge, there is no other method given in literature to estimate the water withdrawal and consumption of CHP plants. In order to better estimate the water needed for heat networks, a method should account for the water use not only for the production of electricity, but also for thermal energy production. This approach addresses the water use attribution problem similarly faced by multipurpose hydropower reservoirs, where there are no agreed methods on how to attribute use and evaporation losses between different user sectors such as agriculture and hydropower Bakken et al. (2017).

Hydrogen fuelled combined cycle (CC) power plants are currently not applied at a large scale and therefore knowledge on water use is limited, and lacking in current literature. In this study, the specifications, and therefore water use, of these plants were set equal to those of natural gas CC plants (ETM, 2020). Although this technology accounts for only about 4% of the total electricity produced in the Regional scenario for 2050, it does have a significant share of the water withdrawal and consumption in this scenario.

4.5. CONCLUSION

Three main insights can be drawn from the results: (i) the water withdrawal for heat production increases significantly in scenarios in which heat is stored with ATES systems, (ii) the future VW_{fuel} for heating is significantly higher than the operational water consumption for heating, and (iii) the virtual water consumption and withdrawal to generate the electricity needed for P2H applications can be relevant for assessing the water use of heating. Based on these three insights, it can be argued that the water use of future heating systems needs to be assessed in an integrated manner to support sustainable policy. Water use should be added as an extra dimension in policy-making besides reducing costs and CO_2 emissions to create sustainable energy systems. This means that water use for heating, including water use for storage and production of energy carriers needs to be accounted for.

If not properly managed, the transition to low-carbon heating systems could exacerbate water stress or be limited by it. In this chapter, it is shown that studies on the water use for heating systems, besides the well-studied interdependencies between water and electricity production, can support to indicate how future water stress may be avoided. To make these data useful for preventing future water stress, environmental degradation, and reduced energy production capacity, projected water use for heating should be connected with spatially explicit models with time-varying indicators such as water temperature, water availability and environmental water demand.

5

Reducing committed emissions of heating towards 2050: analysis of scenarios for the insulation of buildings and the decarbonisation of electricity generation

As stated in the Introduction, not only water use, but also carbon emissions from urban heating systems have major environmental impacts. It is therefore important to design heating systems that will not only emit net zero carbon emissions by 2050, but also minimise carbon emissions during the coming years. This chapter presents an analysis of the cumulative carbon emissions of different scenarios for transitioning towards low-carbon heating systems in the built environment based on an integration of a heat demand model with a optimisation approach.

Abstract chapter 5: 'Reducing committed emissions of heating towards 2050: analysis of scenarios for the insulation of buildings and the decarbonisation of electricity generation'

Infrastructure for heat provision in the built environment needs to change remarkably to support lowering carbon emissions and achieving climate mitigation targets before 2050. In this Chapter, a computational approach is proposed for finding a mix of heat options per neighbourhood that minimises cumulative carbon emissions between 2030 and 2050, referred to as 'committed emissions', while at the same time adhering to technological constraints at both the household and neighbourhood scales. To establish this approach, bottom-up heat demand modelling at the neighbourhood scale was integrated with a mixed-integer nonlinear optimisation problem. Nine scenarios with different pathways for the insulation of buildings and the decarbonisation in electricity generation were considered and applied to three neighbourhoods in the city of Amsterdam, the Netherlands. The results show that (i) the committed emissions can be ten times lower between 2030 and 2050 if ambitious measures are taken for the insulation of buildings and the decarbonisation of electricity generation, (ii) high temperature heat options can be part of the heat mix with lowest committed emissions, (iii) low temperature heat systems are optimal solutions in scenarios with ambitious insulation and decarbonisation measures for lowering committed emissions, and (iv) the minimum heat density for low temperature heat networks is not always achieved, which may lead to carbon lock-ins. The results indicate that pathways for the retrofitting of buildings and the decarbonisation in electricity generation need to be taken into account jointly when designing renewable and low-carbon heating systems to optimally reduce carbon emissions towards 2050 and reduce future carbon lock-ins.

Keywords: urban heating systems, committed carbon emissions, retro-fitting of the building stock, electrification of heating, carbon lock-in, mixed-integer nonlinear programming

5

This chapter is based on the text in Kaandorp et al. (2022). The data and code used for the study presented in this chapter is made publicly available in Kaandorp et al. (2023b).

5.1. INTRODUCTION

Heat demand models enable policymakers to track whether current goals are realised, to define realistic future goals, and to avoid policies that lead to weaker results (Vásquez et al., 2016). High-level, spatio-temporal data and modelling results are useful for designing future heating systems because recommendations can then be formulated on decision-relevant scales (Voskamp et al., 2018; Eggimann et al., 2020). Additionally, information about the heat demand on both the building and neighbourhood scale can inform whether heat systems can be applied or not (Cornelisse et al., 2021). Decentralised heating systems such as heat pumps may, for example, require a certain insulation level on the building scale, whereas centralised heating systems, on the other hand, do require a minimum heat density in the neighbourhood to be economically preferable and technically feasible (Municipality of Amsterdam, 2020b).

Estimating the heat demand in urban areas is however challenging, given that these areas develop over time and are hence often made up of a heterogeneous building stock. Buildings within cities differ in building age, construction methods, and temporal heat demand patterns associated with current use (e.g. domestic, business, and hospitality) (Voulis, 2019). Bottom-up heat demand models calculate the energy consumption of representative samples and extrapolate this energy demand to represent a larger building stock (Aksoezen et al., 2015; Swan and Ugursal, 2009). The work in Hietaharju et al. (2021), for example, included modelling each building separately and then applying a Monte-Carlo simulation for estimating future heat load profiles and peak demand under different renovation interventions of buildings. Bottom-up heat demand models can therefore be used to address the challenges of spatially explicit modelling accounting for the diversity in building types, and therefore heat demand, in urban areas (De Oliveira Fernandes et al., 2021).

Optimisation studies are used in combination with heat demand models to inform how to minimise the impacts of heating systems on indicators such as costs, carbon emissions and resource use. Some studies focus on optimising one type of heat supply, e.g. on district heating (Vesterlund et al., 2017), or hydrogen, e.g. (Sunny et al., 2020). Other studies include modelling multi-energy systems to estimate which technology would be most suitable according to chosen indicators. In Jennings et al. (2014), for example, a mixed-integer linear program (MILP) tool is offered for modelling both supply side and demand side technologies of residential energy systems in order to minimise costs under different scenarios. Another example is given by Gabrielli et al. (2018) who present a MILP tool to minimise costs and carbon emissions by integrating hourly and yearly demand and supply profiles to include seasonal energy storage.

Up to the author's knowledge, no optimisation studies for urban energy planning however exist to determine the configuration of heat systems with the lowest cumulative carbon emissions over time. This is in line with an extensive literature review on carbon lock-in induced by long-lived capital in which it was identified that the carbon lock-in in the built environment is insufficiently addressed in the current body of literature (Fisch-Romito et al., 2021). This is however needed given the large capital costs and long infrastructure lifetimes often associated with urban heating systems (Fisch-Romito et al., 2021). Doing so is however not straightforward, given that urban energy systems comprise large distributed systems, creating many degrees of freedom (Jennings et al.,

5

2014). Carbon emissions of heating additionally depend on both the spatially heterogeneous heat demand and the infrastructure for thermal energy generation. The heat demand can decrease with the retrofitting of buildings, which would lead not only to a decrease in carbon emissions for heating but also makes it possible to implement different low-carbon heating alternatives. Additionally, the emission factor of heat generation can change when energy carriers or heat sources are replaced. Heat pumps are, for example, considered to be a technology suited for well-insulated buildings, but the emission factor of heat pumps is lower if the used electricity is generated from renewable energy sources instead of fossil fuels.

To determine the configuration of heat systems with the lowest cumulative carbon emissions, I propose to use the notion of 'committed emissions'. Different from the main literature body, where the notion of committed emissions is defined as cumulative emissions that occur over the remaining operational lifetime of an asset, the notion is used in this study to indicate the cumulative carbon emissions emitted during a given future planning period (Fisch-Romito et al., 2021; Davis et al., 2010). This is because the infrastructure for heating, such as heat networks, electric heat pumps, and piped networks with fuel gas, have different operational lifetimes, creating difficulties in meaningfully comparing the emissions over the operational lifetime, and assessing the emissions towards 2050. To find the mix of heating technologies in urban areas for which the committed emissions are minimised under different scenarios for the insulation of buildings and the decarbonisation in electricity generation, a computational framework is proposed combining bottom-up heat demand models with optimisation methods.

The proposed computational framework is applied to three neighbourhoods in the city of Amsterdam, the capital of the Netherlands. The names of the neighbourhoods analysed, are 'Felix Meritis', 'Molenwijk', and 'Prinses Irenebuurt' (see Appendix B.1, Figure 5.3 for the location of the neighbourhoods on a map of Amsterdam). The neighbourhoods are chosen for their diversity in building types. Felix Meritis is a historic neighbourhood, consisting mostly of terraced houses and apartment buildings built before 1945. Molenwijk is a neighbourhood consisting only of apartment buildings built between 1946 and 1975, whereas the Prinses Irenebuurt is a neighbourhood with a mix of (semi-)detached houses, terraced houses, and apartment buildings mostly built between 1946 and 1975.

The computational framework with which the neighbourhoods are analysed is presented in Section 5.2. The results of this analysis are shown in Section 5.3. Section 5.4 includes a discussion of the results and is followed by concluding remarks on policy implications in Section 5.5.

5.2. METHODS

The proposed computational framework, shown in Figure 5.1, consists of a bottom-up heat demand model and mathematical optimisation for finding a mix of heat options with the lowest committed emissions. In this section, I will discuss the case study neighbourhoods, the bottom-up heat demand model, the heating systems considered, the studied scenarios, and the formulated optimisation problem.

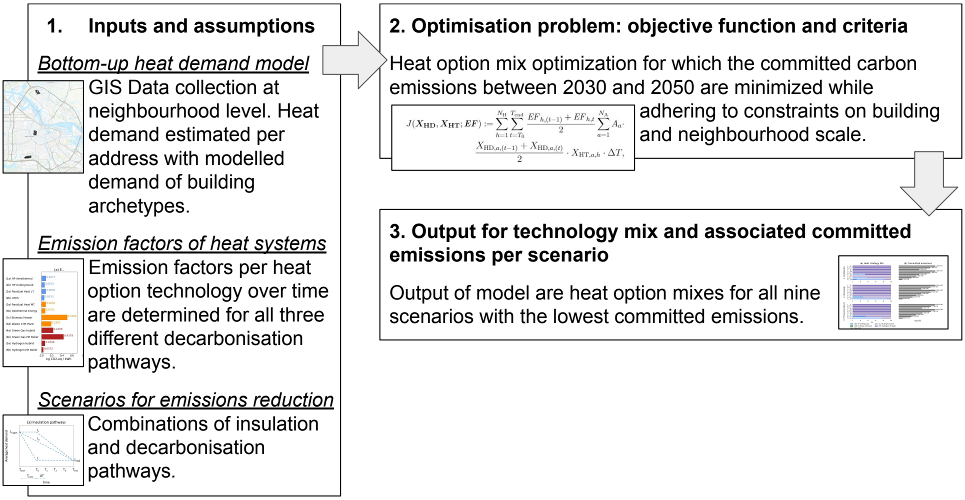
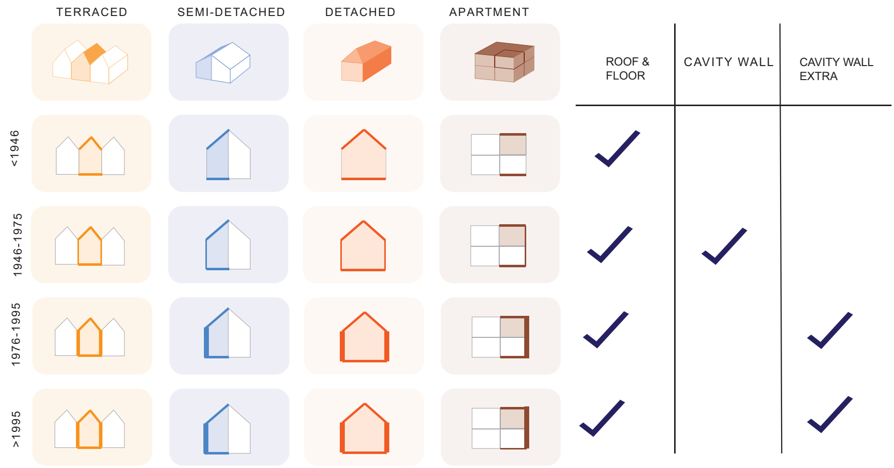


Figure 5.1: Modelling framework for minimising committed emissions. The input data needed for the optimisation model are obtained from a bottom-up heat demand model, emission factors per heat option and scenarios for emissions reduction.

5.2.1. BOTTOM-UP HEAT DEMAND MODEL

Bottom-up heat demand modelling means that the heat demand is modelled for representative samples and extrapolated to represent a larger building stock (Aksoezen et al., 2015; Swan and Ugursal, 2009). In this study sixteen building archetypes were used. The used building archetypes are a combination of four building types and four construction periods (see Figure 5.2), and are derived from the report ‘Standard and Target values for existing housing’ (in Dutch: *standaard en streefwaardes bestaande woningbouw*) (Cornelisse et al., 2021). This report is used by the National Government to provide standard insulation references to building owners (Cornelisse et al., 2021; Ollongren, 2021). The four building types represent buildings with a similar number of exterior walls or walls connected to other buildings. The four building types used are ‘mid-terrace’, ‘semi-detached’, ‘detached’, and ‘apartments’. The building types cover all building types included in the registration of buildings and addresses by the Netherlands’ Cadastre, Land Registry and Mapping Agency (ESRI NL, 2021). The only difference is that the building types ‘end of terrace’ and ‘semi-detached’ were considered as one category in this study because the heat demand of these building types are similar due to a similar amount of exterior walls.



5

Figure 5.2: Overview of the sixteen building archetypes together with possible insulation measures per construction period

The construction period was also used to define the building archetypes because it can be used as an indicator of the building characteristics related to common insulation measures over time shown in Figure 5.2 (Cornelisse et al., 2021). Buildings built before 1946 do not often have cavity walls, which means that roof and floor insulation are the main insulation measures that can be applied (a more detailed description of insulation measures used from (Cornelisse et al., 2021) can be found in Appendix B.1, Figures B.1 and B.2). Buildings built between 1946 and 1975 generically have a cavity wall, so cavity wall insulation is applied additionally to roof and floor insulation. After 1980, building insulation became mandatory, so in these cases the already existing insulation in the cavity can be improved. The four construction periods used in this research are (i) before 1946, (ii) between 1946 and 1975, (iii) between 1976 and 1995, and (iv) after 1995.

For each building archetype, the yearly heat demand per unit of floor area is modelled for standard insulation levels defined in (Cornelisse et al., 2021). As input for the optimisation the ‘current’ and ‘advanced’ insulation levels were used (see Table 5.1, and Figure B.3 in Appendix B.1 for the modelled heat demand for ‘basic’ and ‘intermediate’ insulation level). The ‘current’ insulation level stands for a state in which some regular insulation measures are already undertaken with respect to the original state at construction. The advanced insulation level represents technologically complex improvements that happen less often in practice, but are technologically feasible.

The modelled values for the ‘current’ and ‘advanced’ heat demand are static and do not change over time (Vásquez et al., 2016). The optimisation model itself can however be characterised as a dynamic model as it analyses the heat demand over multiple years (Vásquez et al., 2016). In the optimisation model, the ‘current’ heat demand of each address in the neighbourhood is first estimated and the insulation of addresses is simulated by lowering the heat demand, keeping the heat demand associated with the ‘advanced’

Table 5.1: Modelled heat demand per building archetype for the 'current' and 'advanced' insulation levels expressed in kWh per square metre of floor area per year

		Heat demand [kWh m^{-2} $year^{-1}$]	
Building type	Construction period	Current insulation level	Advanced insulation level
Apartment	<1946	193	24.2
	1946 - 1975	159	24.2
	1976 - 1995	113	24.2
	>1995	79.5	24.2
Detached	<1946	177	30.9
	1946 - 1975	133	30.9
	1976 - 1995	107	30.9
	>1995	67.7	30.9
Semi-detached	<1946	143	26.1
	1946 - 1975	109	26.1
	1976 - 1995	84.8	26.1
	>1995	58.0	26.1
Terraced	<1946	177	21.3
	1946 - 1975	156	21.3
	1976 - 1995	124	21.3
	>1995	79.3	21.3

5

insulation level as a minimum heat demand. The 'current' or 'advanced' heat demand per address is determined by associating each address with a building archetype and multiplying the modelled heat demand per square metre floor area of the 'current' or 'advanced' insulation level with the floor area of the associated address. The floor area per address and the information needed to cluster all addresses into building archetypes, i.e. the information on the building type and the construction year, is collected with Geographic Information System (GIS) data through ArcGIS pro software. Feature layers are collected from the ArcGIS Living Atlas collection of Esri Nederland Content on the 5th of May 2021 (ESRI NL, 2021) (see Figure 5.3). The names of the feature layers are: *'BAG - pand', 'Woningtypering', 'BAG - adres', 'BAG - Verblijfsobject'*.

The heat demand for the building archetypes is estimated with Passive House Planning Package (PHPP) software (see Table 5.1). The input data for the PHPP model are the thermal resistance of materials, the area size of the surfaces of the building envelope, the orientation, the infiltration rates and the ventilation mechanism. The thermal resistances, also known as the R-values, of the different materials of the shell of the houses were taken from Cornelisse et al. (2021) and presented in Figures B.3 and B.4 in Appendix B.1. Additionally, the infiltration rates and the insulation measures were used from Cornelisse et al. (2021) (see Table B.2 in Appendix B.1, and Figures B.1 and B.2 in Appendix B.1). The sizes of the building envelope areas are extracted from a study by Agentschap NL, presently known as RVO The Netherlands Enterprise Agency, and presented in Table B.1 in Appendix B.1 (Agentschap NL, 2011). For this study, the height of ceilings are set at a standard of three metres for all building types. It is also assumed that all terraced housing, semi-detached and detached buildings have two floors while all apartments only have one floor and are in three-storey apartment buildings. The cho-

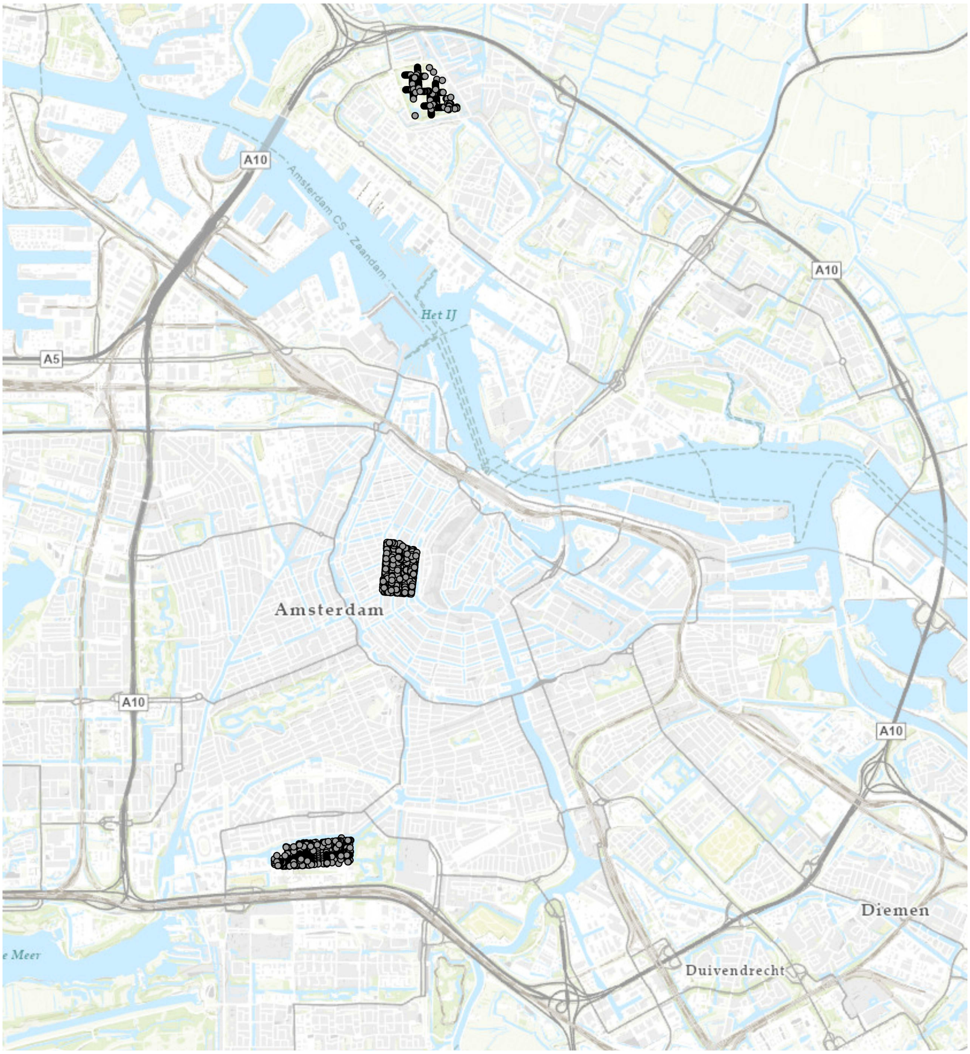


Figure 5.3: Map of Amsterdam with addresses used in ArcGIS Pro. The neighbourhoods analysed are Molenwijk, Felix Meritis and Prinses Irenebuurt (appearing on the map from top to bottom).

sen cardinal directions for the building types are 'North' for terraced housing, 'East' for semi-detached houses, 'South' for detached houses and 'West' for apartments to generate a distribution of orientations in the neighbourhoods. Nevertheless, the influence of cardinal direction on the modelled heat demand can be minimal (Cornelisse et al., 2021).

5.2.2. EMISSION FACTORS OF HEATING SYSTEMS

A rich mix of supply systems and energy sources that are currently being considered in national policy and in practice is included in this study. I refer to heating systems as the collection of technologies that generate and distribute heat. Five major heating systems were considered, which are the same as the 'heating strategies' included in the PBL Netherlands Environmental Assessment Agency's decision tool for Dutch municipalities to transition to renewable heating (Hoogervorst et al., 2020). For each of these five major heating systems listed in Table 5.2, several 'heat options' were analysed. The heat options within one heating strategy share similarities in how thermal energy is supplied, but differ in the thermal energy sources.

Table 5.2: Constraints per heating system defined by (Municipality of Amsterdam, 2020b). Abbreviations: HT = high temperature, MT = mid temperature, and LT = low temperature.

Heating System	Thermal regime	Maximum heat capacity [kWh m^{-2} $year^{-1}$]	Minimum heat density [MWh hec^{-1} $year^{-1}$]
1. Individual Heat Pump	LT	50	-
2. LT Heat Network	LT	50	165.75
3. MT Heat Network	MT	80	165.75
4. Green gas	HT	-	-
5. Green hydrogen	HT	-	-

The first system, i.e. '1. Individual Heat Pump', stands for a heating system in which electric heat pumps are used. The two heat options analysed for this heating system are '(1a) Heat Pump (HP) Aerothermal' and '(1b) HP Underground'. The second heating system is called '2. LT Heat Network'. The definition given by the Municipality of Amsterdam (Municipality of Amsterdam, 2020b) for a LT heat network is used, i.e. a heat network that delivers heat at 40 °C. The heat options for such a heat network considered in this study are residual heat from industry, such as from datacenters, and thermal energy withdrawn from UTES systems. The thermal energy stored in UTES systems can originate from multiple sources, e.g. ambient heat from surface water or air, solar energy collected with solar boilers, or residual heat from wastewater. The names of the two heat options are: '(2a) Residual Heat LT' and '(2b) UTES'. The third heating system is a 'mid-temperature' (MT) heat network delivering heat at 70 °C (Municipality of Amsterdam, 2020b). The heat options considered are: '(3a) Residual Heat MT', '(3b) Geothermal energy', '(3c) Biomass Heater', and '(3d) Waste CHP plant'. The latter heat option stands for a combined heat and power (CHP) plant where waste is incinerated. Both heating systems 4 and 5 are decentralised systems at the address level that incinerate green gas and green hydrogen respectively. Green gas refers to biogas which is processed to have the same heat capacity as natural gas and so can be distributed through the existing natural gas grid. Green hydrogen refers to hydrogen produced with water electrolysis with electricity generated by renewable energy carriers. For both systems, two heat options are considered: (a) a hybrid option, being a combination of a heat pump with a gas-fired heat condensing boiler and (b) a gas-fired heat condensing boiler. In the hybrid option, the heat pumps are used most of the time, and the boiler is activated when more heating is required. By using gas-fired heat condensing boilers, heating systems 4 and 5 can deliver heat at 'high temperature' (HT), i.e. 90 °C (Municipality of Amsterdam, 2020b).

Table 5.2 also contains minimum and maximum heat demand constraints posed in the optimisation problem. The first constraint restricts the heat demand of an address from being higher than the maximal 'heat capacity' of the chosen heating option. The maximum heat capacity is defined in this chapter as the maximum thermal energy demand per square metre of floor area for which a heat option can 'comfortably' heat up a space. In practice, whether a heating system can 'comfortably' heat up a space depends on a variety of factors, such as the indoor heating system and the type of heat pump installed. However, according to the municipality of Amsterdam, the temperature of the heat source can be used as an indicator for the heat capacity (Municipality of Amsterdam, 2020b). A heating system which delivers heat at mid temperature has a maximum heat capacity of 80 kWh m^{-2} $year^{-1}$, where m^2 stands for the amount of floor area in square metres. The maximum heat capacity for LT heat strategies is equal to 50 kWh m^{-2} $year^{-1}$. No maximum heat capacity is assigned for HT strategies. The second constraint in the table, defined at the neighbourhood level by the Municipality of Amsterdam (Municipality of Amsterdam, 2020b), applies to heat networks, i.e. heating systems 2 and 3. Heat networks are more profitable and efficient in areas with higher heat density. Following Municipality of Amsterdam (2020b), the yearly minimum heat density per hectare of land for heat networks is set equal to 165750 kWh.

In order to model the mix of heat options with the lowest committed emissions between 2030 and 2050, the emission factor per heat option is determined and presented in Figure 5.4. The emission factors are expressed in units of mass of carbon equivalents per unit of thermal energy supplied (kg CO_2-eq / kWh) and are only based on the emissions during the operational phase of heat generation. This scope is chosen because the operational phase is currently responsible for the higher share of carbon emissions with respect to the other phases. In the case study on Tuscany, for example, the contributions to greenhouse gas emissions of the operational phase are 96.6%, 95.4%, 97.6%, and 96.9% for the considered strategies: natural gas heaters at the household level and heat networks distributing thermal energy from geothermal energy, a biomass heater, or a natural gas heater (Bartolozzi et al., 2017). In order to determine the emission factors during the operational phase the emission factor per energy carrier and the ERE factor were used. The emission factor per energy carriers include the emissions associated with supplying and using, often by combustion, the energy carrier. The ERE factors are based on the efficiencies or COP of technologies. The used emission factors per energy carrier and the ERE factors can be found in Tables B.5 and B.6 in B.2.

Three stages in the supply chain of heat were considered: direct emissions, indirect emissions for fuel supply and indirect emissions for electricity supply. Direct emissions take place locally where heat is generated. Indirect emissions, on the other hand, can be emitted elsewhere during different processes in the supply chain of heat. By making a

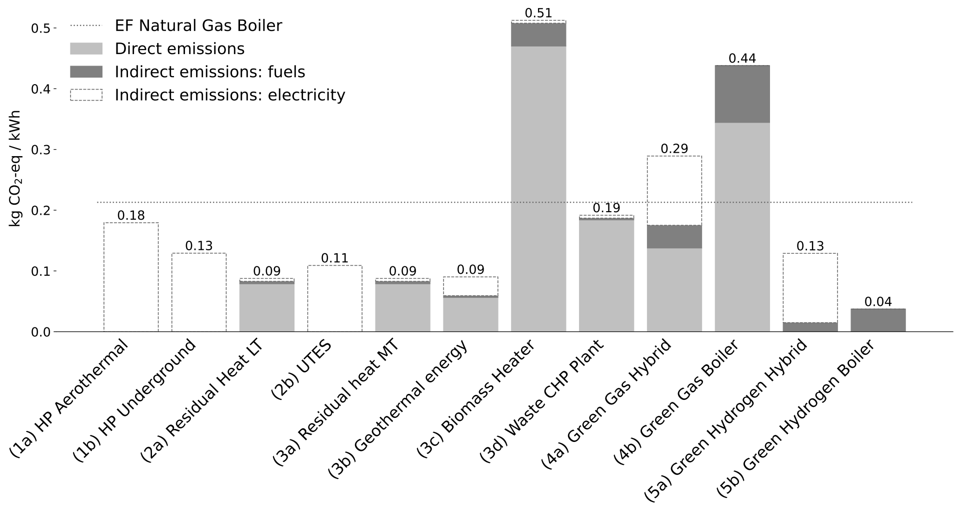


Figure 5.4: Emission factor (EF) per heat option in terms of kg CO_2 equivalents per kWh of thermal energy supplied. These heat options are considered to replace heating with a natural gas boiler at the household level, which has an emission factor of 0.213 kg CO_2 kWh^{-1} (see Appendix B.2).

distinction between direct and indirect emissions the multi-scale effects of energy generation is highlighted. The emission factors for direct emissions and indirect emissions for fuel supply are based on data found in literature (see B.2, Tables B.5 and B.6 for input data and references). The magnitude of indirect emissions for electricity consumption, defined as the emission per unit of electricity supply, depends on the power mix of the electricity grid at the time of electricity use and hence the decarbonisation pathway for electricity. Different pathways for the decarbonisation of electricity production are therefore considered in the scenarios used in this study.

5.2.3. SCENARIOS FOR EMISSION REDUCTION

To analyse which heat options should be implemented in the neighbourhoods to minimise committed emissions between 2030 and 2050, nine scenarios that span different combinations of decarbonisation pathways are considered: three pathways for the insulation of buildings and three pathways for decarbonisation of electricity generation (see Figure 5.5). Using scenarios composed of varying pathways for electricity grid decarbonisation and neighbourhood insulation capabilities, uncertainty in future drivers are thus explicitly considered. The three insulation pathways, I_+, I_0 and I_-, are input for the maximum rate of insulation which can take place per year (Figure 5.5a). The pathways have a common startpoint, i.e. I_{start}, and endpoint, i.e. I_{end}, expressed as the average areal heat demand in the neighbourhood. The difference between the three pathways is the timing at which the insulation measures start and end. The average areal heat demand in pathway I_0 decreases immediately in 2020 and drops linearly at a low rate, reaching I_{end} in 2050. For I_-, the average areal heat demand starts with a delay, dropping with a higher insulation rate beginning in 2030, to reach I_{end} in 2050. The I_+ pathway begins immediately with a high reduction rate, reaching I_{end} already in 2030. In other words, the three pathways represent future situations wherein addresses are insulated relatively early, relatively late or during the whole period with the same insulation rate.

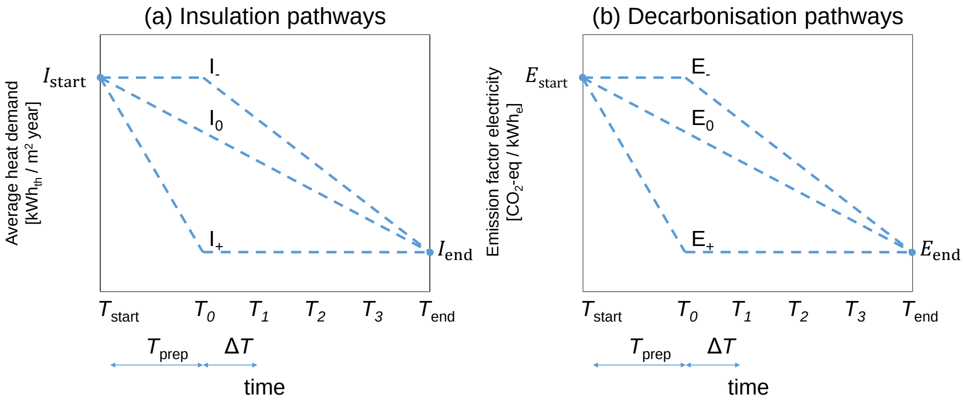


Figure 5.5: Pathways for (a) the insulation of buildings and (b) the decarbonisation of electricity generation. The average heat demand is expressed in kWh of thermal energy per square metre of floor area per year and the emission factor of electricity in kg of CO_2 equivalents per kWh of electricity. T_{start} is the year 2020, T_0 the year 2030 and T_{end} the year 2050. The pathways are annotated with a +, 0 or – representing different ambition levels on when to start and attain the goal posed at T_{end}.

The value of the average heat demand in 2020, i.e. I_{start}, is modelled by multiplying the modelled 'current' heat demand per building archetype with the surface area of that building archetype present in the neighbourhood (as collected previously with the GIS analysis). I_{end} is set equal to 60 kWh m^{-2} year^{-1} based on policy of the municipality to insulate 70% of all addresses to 70 kWh m^{-2} year^{-1} and 30% to 50 kWh m^{-2} year^{-1}. At 70 kWh m^{-2} year^{-1} buildings can be comfortably heated with central heat systems pumping around water at 70°C (Municipality of Amsterdam, 2020b). Heating at this temperature is an economic optimum for most existing buildings in Amsterdam according to an economic analysis by (Municipality of Amsterdam, 2020b, pp. 59).

The three pathways for the decarbonisation in electricity generation are defined similarly to the insulation pathways. In pathway E_0, the emission factor for electricity between 2020 and 2050 decreases with a constant rate during that time period. In pathways E_+ and E_- a linear decrease in the emission factor of electricity production takes place between 2020 and 2030 and 2030 and 2050, respectively. The emission factor of electricity in 2020 is based on the technology mix for electricity production in the Netherlands (Wielders and Nusselder, 2020). The endpoint in 2050 is set equal to 14.7 g CO_2-eq/kWh, which is the emissions factor of offshore wind energy (Wielders and Nusselder, 2020). This renewable electricity source is expected to be one of the most important renewable electricity sources in the Netherlands by 2050 (Den Ouden et al., 2020; Wielders and Nusselder, 2020).

5.2.4. OPTIMISATION OF HEAT OPTIONS

To find a mix of heat options per neighbourhood that has the minimal committed emissions between 2030 and 2050, while adhering to the two formulated technological constraints, mixed-integer nonlinear program (MINLP) optimisation problem with the following objective function is posed:

$$J(\boldsymbol{X}_{\mathbf{HD}}, \boldsymbol{X}_{\mathbf{HT}}; EF) := \sum_{h=1}^{N_{\mathrm{H}}} \sum_{t=T_0}^{T_{\mathrm{end}}} \frac{EF_{h,(t-1)} + EF_{h,t}}{2} \sum_{a=1}^{N_{\mathrm{A}}} A_a \cdot \frac{X_{\mathrm{HD},a,(t-1)} + X_{\mathrm{HD},a,(t)}}{2} \cdot X_{\mathrm{HT},a,h} \cdot \Delta T, \tag{5.1}$$

where the parameters N_{A}, N_{H}, and A_a stand for the number of addresses in the neighbourhood, the number of heat options considered, and the floor area (in m^2) per address a respectively. For each heat option indexed h, the parameter $EF_{h,t}$ represents the emission factor in year t in terms of kg CO_2 equivalents per kWh of thermal energy supplied. The optimisation problem has three sets of indexed variables: $\boldsymbol{X}_{\mathbf{HD}}$, $\boldsymbol{X}_{\mathbf{HT}}$ and $\boldsymbol{x}_{\mathbf{HF}}$. The indexed variables are defined as follows:

$$\begin{aligned} &X_{\mathrm{HD},a,t} \in [HD_{\min,a}, HD_{\max,a}], && \forall a \in [1, N_{\mathrm{A}}]; \forall t \in [T_{\mathrm{start}}, T_{\mathrm{end}}], \\ &X_{\mathrm{HT},a,h} \in \mathbb{Z}_{[0,1]}, && \forall a \in [1, N_{\mathrm{A}}]; \forall h \in [1, N_{\mathrm{H}}], \\ &x_{\mathrm{HF},h} \in \mathbb{Z}_{[0,1]}, && \forall h \in [1, N_{\mathrm{H}}], \end{aligned}$$

where, $X_{\mathrm{HD},a,t}$ stands for the yearly heat demand per m^2 of floor area for address a in year t. The binary variable $X_{\mathrm{HT},a,h}$ represents the heat option at address level - it is equal to 1 if a heat option h is applied at address a and equal to 0 if not. The variable $x_{\mathrm{HF},h}$ stands for whether or not the minimum heat density for heat option h is attained in the neighbourhood. $HD_{\min,a}$ and $HD_{\max,a}$ are the minimal and maximal yearly heat demand of address a in terms of kWh m^{-2} $year^{-1}$. They correspond to the modelled heat demand per floor area of the building archetype associated with address a at the advanced and current insulation levels, respectively. The three decision variables are subject to the following constraints:

$$X_{\mathrm{HD},a,t} \le X_{\mathrm{HD},a,(t-1)}, \; \forall a \in [1, N_{\mathrm{A}}], \forall t \in [T_{\mathrm{start}}, T_{\mathrm{end}}], \tag{5.2}$$

$$X_{\mathrm{HT},a,h} \cdot X_{\mathrm{HD},a,t} \le HS_{\max,h}, \; \forall a \in [1, N_{\mathrm{A}}], \forall h \in [1, N_{\mathrm{H}}], \; \forall t \in [T_0, T_{\mathrm{end}}], \tag{5.3}$$

$$\sum_{h=1}^{N_{\mathrm{H}}} X_{\mathrm{HT},a,h} = 1, \; \forall a \in [1, N_{\mathrm{A}}], \tag{5.4}$$

$$\sum_{a=1}^{N_A} A_a \cdot (X_{\mathrm{HD},a,(t-1)} - X_{\mathrm{HD},a,t}) \leq \sum_{a=1}^{N_A} A_a \cdot (HD_{\mathrm{avg},(t-1)} - HD_{\mathrm{avg},t}), \quad \forall t \in [T_0, T_{\mathrm{end}}], \tag{5.5}$$

$$\sum_{a=1}^{N_A} A_a \cdot X_{\mathrm{HD},a,t} \cdot X_{\mathrm{HT},a,h} \geq A_n \cdot x_{\mathrm{HF},h} \cdot HS_{\mathrm{min},h}, \; \forall h \in [1, N_H], \quad \forall t \in [T_0, T_{\mathrm{end}}], \tag{5.6}$$

$$x_{\mathrm{HF},h} \cdot N_A \geq \sum_{a=1}^{N_A} X_{\mathrm{HT},a,h}, \; \forall h \in [1, N_H]. \tag{5.7}$$

Equations (5.2)-(5.4) describe constraints at the address scale. Equation 5.2 imposes the heat demand of address a to decrease in time. As described in Section 5.2.2, the implementation of a heat option at the address level is constrained by the maximum heat capacity of that heat option (see the bilinear constraint Equation (5.3)). The maximum heat capacity is expressed with the parameter $HS_{\mathrm{max},h}$ and has the unit kWh m^{-2} year^{-1}. The integral constraint in Equation 5.4 enforces that only one heat option is chosen per address. Equations (5.5)-(5.7) enforce the link between the situation at the address scale and the neighbourhood scale. The heat demand reduction through insulation per time step for an address is constrained by the insulation pathways described in Section 5.2.3. This is translated into Equation (5.5), which states that the decrease in heat demand in the neighbourhood due to insulation at address level can not be higher than the decrease in the average heat demand, $HD_{\mathrm{avg},t}$, given by the insulation pathway. Equation (5.6), which is also bilinear in the decision variables, imposes that the total heat supplied by heat option h in the neighbourhood should be larger than the minimal heat density, $HS_{\mathrm{min,h}}$, in terms of kWh ha^{-1} year^{-1} times the area of the neighbourhood in hectares, A_n. At last, the constraints in Equations (5.6)-(5.7) together enforce the complementary condition that heat option h is not chosen at neighbourhood and address levels (i.e. $x_{\mathrm{HF},h}$ and $X_{\mathrm{HT},a,h}$, for all addresses a are equal to zero) unless the minimum density requirements for heat option h are strictly met.

All computational experiments were performed using a MacBook Pro computer with a 2.4 GHz QuadCore Intel IntelCore i5 CPU and 16 GB RAM. The optimisation problem is implemented within the python based Pyomo Algebraic Modelling Language and solved using Gurobi. The resulting optimisation problem is a MINLP due to the two sets of indexed nonlinear (i.e. bilinear) constraints and objective, which was solved efficiently with GUROBI 9.1 and an allowable MINLP gap of 1% (Gurobi Optimization, LLC, 2021). The computations took seconds to minutes to converge to the MINLP gap set per scenario. The results of the MINLP problem are reported in the following section.

5.3. RESULTS

In Figure 5.6 the heat option mixes with the lowest committed emissions between 2030 and 2050 for the different neighbourhoods under different scenarios, are depicted together with the corresponding committed emissions. The results suggest that in almost all scenarios the majority of all the addresses should be connected to the heat option (5a) Green Hydrogen Hybrid or (5b) Green Hydrogen Boiler to minimise the committed emissions. Only in the most 'ambitious' scenario, i.e. scenario (I_+, E_+), the heat option (2b) UTES is applied to a majority of the addresses. The committed emissions in the most ambitious scenario is for each neighbourhood almost ten times smaller than the committed emissions in the least 'ambitious' scenario, i.e. scenario (I_-, E_-) (see Figure 5.6b).

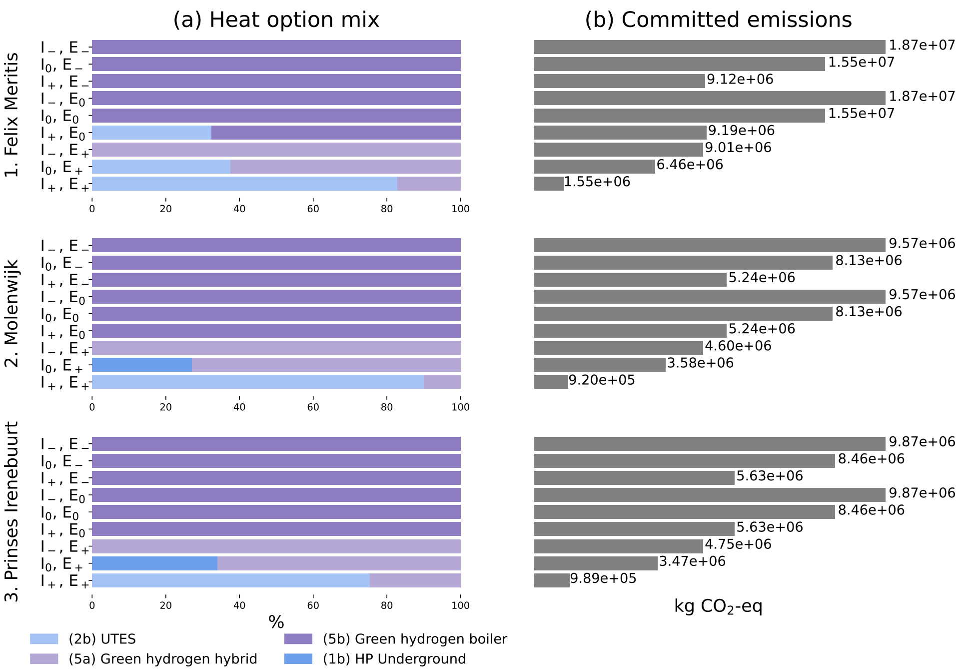


Figure 5.6: Mix of heating options in the three case study neighbourhoods. On the left is the heat option mix shown in terms of percentages of addresses connected to a certain heat option. On the right is the total committed emissions between 2030 and 2050.

Whether or not heat options are included in the mix is a result of the optimisation problem in which cumulative emissions over time are minimised while satisfying the two posed technological constraints. The emission factors over time depend on the different rates of decarbonisation in electricity generation (see Figure 5.5). The bar charts in Figure 5.7 depict the average carbon emission factors ($EF_{average}$) per heat option between 2030 and 2050 for the three decarbonisation pathways as used in the optimisation to generate the results as presented in Figure 5.6. For pathway E_{-} (see Figure 5.7a), the heat option with the lowest $EF_{average}$ is heat option (5b) Green Hydrogen Boiler, a HT, decentralised heating system applied at address level and therefore not subject to any constraints in the model (see Tabel 5.2). As such, the optimisation chooses this technology for all addresses in the scenarios with decarbonisation pathway E_{-} (see Figure 5.6). The vertical black bars in Figure 5.7 indicate the $EF_{average}$ for a situation in which the direct emissions associated with the incineration of organic energy carriers are set equal to zero, and will be discussed in Section 5.4.1.

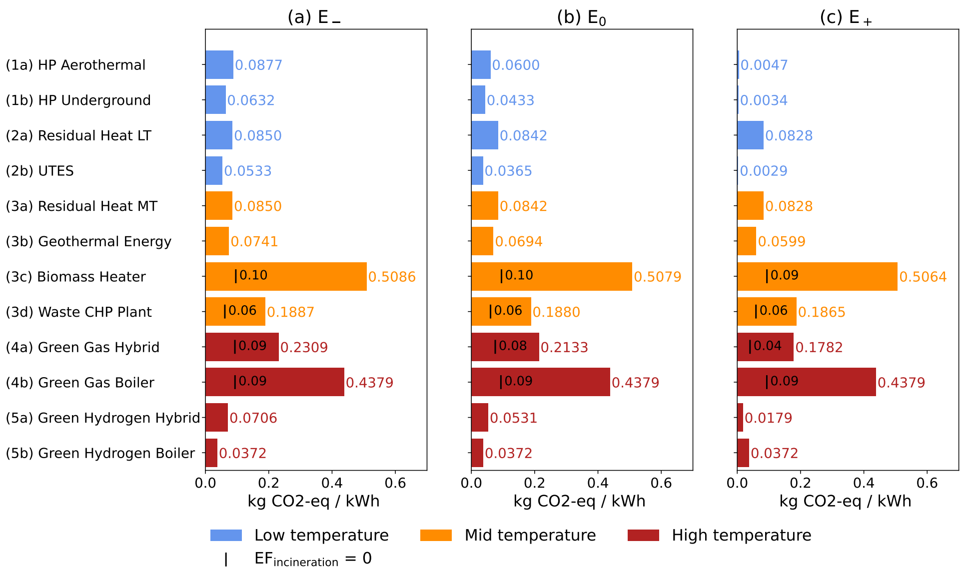


Figure 5.7: Average carbon emission factors between 2030 and 2050 expressed in terms of kg CO_2 equivalents per kWh of thermal energy supplied for all heat options. The average is taken for the three decarbonisation pathways. The colours of the bars in the figure indicate the thermal regimes of the heat options. The heat option (3c), (3d), (4a) and (4b) incinerate biomass or biogas. A vertical bar indicates the average emission factors for these four heat options if the carbon emissions associated with the incineration or organic energy carriers are set equal to zero.

For pathways E_{+} and E_0, the heat option (2b) UTES has the lowest $EF_{average}$ (see Figure 5.7b and 5.7c). This heat option is a heating system with a LT heat network and can therefore only be applied to addresses with a heat demand lower than 50 kWh m^{-2} $year^{-1}$ (see Tabel 5.2). Addresses with a heat demand above 50 kWh m^{-2} $year^{-1}$ can not be heated by LT heating systems and the model will therefore choose a MT or HT heat option. The heat options with the lowest $EF_{average}$ for pathways E_0 and E_{+}, which do operate at MT and HT level, are the heat option (5a) Green Hydrogen Boiler and (5b) Green Hydrogen Hybrid respectively. This is why the options (2b) UTES, (5a) Green Hydrogen Boiler, and (5b) Green Hydrogen Hybrid are visible in the heat option mix for the Felix Meritis neighbourhood.

The heat option (2b) UTES is however not applied in the neighbourhoods Molenwijk and Prinses Irenebuurt. Instead, the heat option (1b) HP Underground is applied in scenario (I_0, E_+) even though it has a higher EF_{average} than the heat option (2b) UTES. This is because the heat option (2b) UTES is subject to the heat density constraint (see Table 5.2). As a consequence, the sum of the heat demand of all addresses that can be connected to this heat option divided by the total area of the neighbourhood needs to be higher than the posed minimal heat density. If the heat density is too low, then this heat option can not be applied in the neighbourhood. In that case, two different decisions can be made by the optimisation model: either addresses are less insulated so that the heat density is higher, or the heat option with the second lowest carbon emissions, i.e. (1b) Underground HP or (5b) Green Hydrogen Boiler in pathways E_+ and E_0 respectively, are chosen. This is why heat option (2b) UTES is applied in scenario (I_+. E_0) in the Felix Meritis neighbourhood, but not in the Molenwijk and Prinses Irenebuurt neighbourhoods in Figure 5.6.

5

In order to assess how uncertainties in the heat demand model for the existing building stock would affect the heat density for LT Heating, a first-order sensitivity analysis is performed on the two main insulation parameters: I_{start} and I_{end} (see Figure 5.5a). Figure 5.8 shows the heat density based on summing over the heat demand of all addresses with a LT heat supply suggested by the optimisation when considering different values for I_{start} and I_{end}. The first row in Figure 5.8 shows the heat density for the results, called the ‘Reference’ case. The scenarios plotted are the scenarios in which (2b) UTES could be applied, i.e. scenarios (I_0, E_+) and (I_+, E_0) and (I_+, E_+).

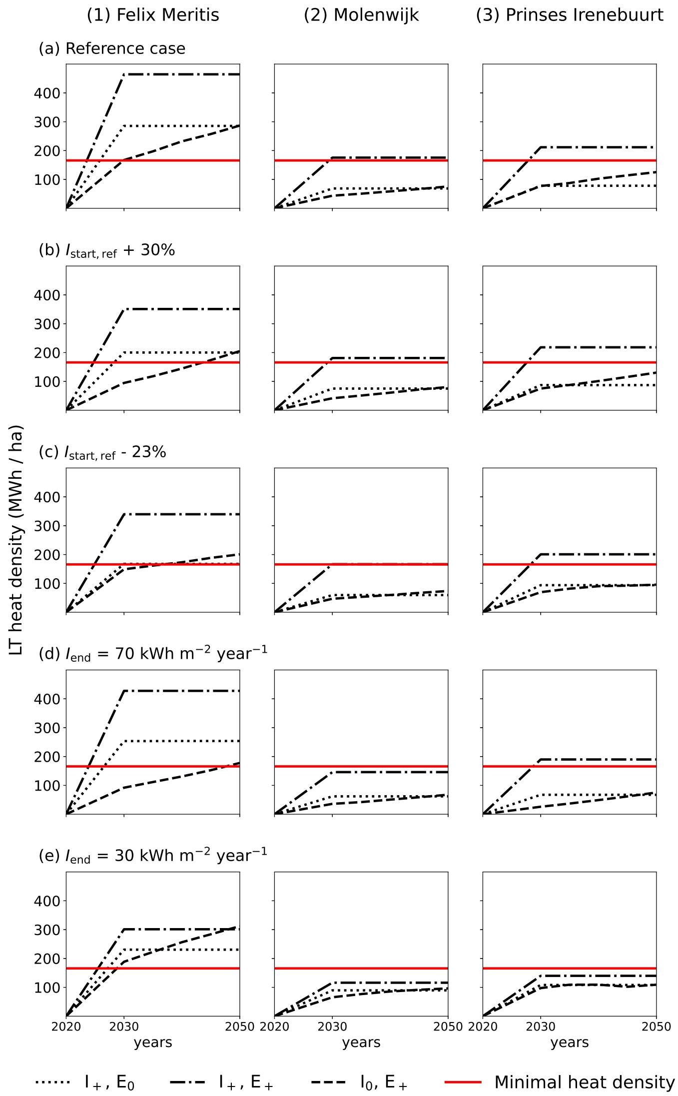


Figure 5.8: LT heat density per neighbourhood. With insulation, the number of addresses with a heat demand below the maximum heat capacity for LT heating increases for the different pathways. This figure shows the LT heat density based on summing over the heat demand of all addresses ready for LT heating for the three neighbourhoods 'Felix Meritis', 'Molenwijk', and the 'Prinses Irenebuurt' for the scenarios (I_+,E_0), (I_+, E_+), and (I_0, E_+). Each row shows the result of a first-order sensitivity analysis: row (b) and (c) I_{start} show the results for varying I_{start} with respect to I_{start} as modelled in the reference case with +30% and -23%. The rows (d) and (e) show the results for choosing the parameter I_{end} to be equal to 70 kWh m^{-2} year^{-1} and 30 kWh m^{-2} year^{-1} respectively.

As a first step in the sensitivity analysis, I_{start} was varied with +30% or -23% with respect to the I_{start} used for the results in Figure 5.6. The results (see Figure 5.8, rows (b) and (c)) show that varying I_{start} in the Felix Meritis neighbourhood (see Figures 5.8.1b and 5.8.1c) cause the heat density in 2030 for scenario (I_0, E_+) to fall below the minimal heat density required for district heating (i.e. below the red line). In these cases, heat option (2b) UTES can therefore not be in the mix and heat option (1b) HP underground is chosen as heat option for addresses with a LT heat demand. The results of the sensitivity analysis for the neighbourhoods Molenwijk and Prinses Irenebuurt show that it is only in scenario (I_+, E_+) where the heat density for LT heating was above the minimum required heat density as stated by (Municipality of Amsterdam, 2020b) (see Figures 5.8.2a-5.8.2c and 5.8.3a-5.8.3c). For the reference case, this is reflected in the results in Figure 5.6, where heat option (2b) UTES was only applied in that scenario. The results of the sensitivity analysis show that the heat density in this scenario remains above the minimum heat density for increasing and decreasing I_{start}.

As a second step in the sensitivity analysis, I_{end} was varied. The results of the reference case were based on target end demand levels of I_{end} = 60 kWh m^{-2} year^{-1}. The model was also run for I_{end} = 70 kWh m^{-2} year^{-1} and I_{end} = 30 kWh m^{-2} year^{-1}. The first value was chosen because the city of Amsterdam aims to insulate 70% of all addresses to 70 kWh m^{-2} year^{-1} and 30% to 50 kWh m^{-2} year^{-1} (Municipality of Amsterdam, 2020b). There therefore may be neighbourhoods in which all buildings will be insulated till a heat demand of 70 kWh m^{-2} year^{-1}. The second value was chosen based on the heat demand modelling performed in this study, that showed that all addresses could in principle be sufficiently insulated to reduce heat demand to 30.9 kWh m^{-2} year^{-1} (see Table 5.1).

The results of the sensitivity analysis for varying I_{end} are given in Figure 5.8, rows (d) and (e). For I_{end} = 70 kWh m^{-2} year^{-1}, the heat density in the Felix Meritis neighbourhood for scenario (I_0, E_+) is lower than the minimum required heat density in 2030. The heat density for a LT heat network can therefore not be high enough for insulation pathway I_0, i.e. when insulation is performed at a constant rate from 2020 till 2050. For I_{end} = 30 kWh m^{-2} year^{-1}, there are no scenarios for which the heat density is high enough for a LT heat network in the Molenwijk and Prinses Irene neighbourhoods. In these neighbourhoods for scenario (I_+, E_+) the optimisation even assigned 100% of the addresses to (1b) HP Underground, meaning that the heat demand for all addresses fell below the maximum heat capacity posed for LT heating.

Ambitious insulation targets can thus create 'LT-ready' buildings, leading the heat density in a neighbourhood to decrease below the minimum heat density required for heat networks, possibly creating inefficiencies for in the heat supply by heat networks. If heat networks are therefore applied, an incentive may therefore arise for not applying ambitious insulation, restricting the further reduction of carbon emissions. Additionally, an incentive may be to increase the heat network to a larger area which may however not always be the solution with the lowest carbon emissions and costs. Due to the infrastructural inertia of heat infrastructure, implementing heat networks in neighbourhoods where the heat density can decrease below the minimum heat density required by the heat network can therefore lead to more committed emissions in the future than if other heat options were chosen (Davis et al., 2010).

5.4. DISCUSSION

From the results four major insights can be drawn: (i) the committed emissions between the years 2030 and 2050 can be ten times lower if ambitious measures for both the insulation of buildings and the decarbonisation in electricity generation are taken together, (ii) HT heat options can be part of the heat mix with lowest committed emissions, (iii) LT heat options are optimal solutions in the more ambitious scenarios, and (iv) the minimum heat density for heat networks is not always reached. In short, the results show that the composition of future heat supply with the lowest committed emissions between 2030 and 2050 depends jointly on the rates of the insulation of buildings and the decarbonisation of electricity generation. In the following, it is discussed how the choice for heat options in the mix depends on the input parameters and modelling objectives.

5.4.1. SCENARIOS WITH HIGH-TEMPERATURE HEAT OPTIONS IN THE MIX

The results in Figure 5.6 show that HT heat options are part of the mix in all scenarios, and more dominantly in the scenarios with less ambitious measures for insulation. In most scenarios considered in this study, heating with green hydrogen is the optimal choice for minimising committed emissions between 2030 and 2050 (see Figure 5.6). Currently, hydrogen is not produced at large scale in the Netherlands. It is, however, uncertain whether substantial green hydrogen will be available at market-competitive rates in the future; this is because of its dependency on the availability of renewable electricity (IEA, 2021; Hoogervorst et al., 2020; Sunny et al., 2020) and the investments needed for production and storage. The technology for producing green hydrogen, i.e. water electrolysis, can respond rapidly to load variations, but has high operating expenses, making it favourable to apply the technology when renewable electricity is abundant and costs are low (Sunny et al., 2020). Producing green hydrogen with demand response techniques can therefore support balancing the grid, but may however lead to extra costs for hydrogen storage.

Heating with green gas may be an alternative to HT heating with green hydrogen. The use of green gas could, when available from existing production facilities, be used as a renewable transition fuel from heating with natural gas to heating with green hydrogen, while minimising committed emissions. This is because both heat options using hydrogen or green gas can provide HT heating using parts of existing distribution infrastructure for natural gas (Sunny et al., 2020). The ranking of heat options with the lowest EF_{average}, if hydrogen-based heat options would not be included in the heat mix, would be the same for all three decarbonisation pathways, i.e. (2b) UTES, (3b) Geothermal Energy, and (4a) Green Gas Hybrid for the LT, MT, and HT thermal regimes, respectively. It is however important to note that the only pathway in which the EF_{average} of (4a) Green Gas Hybrid is lower than the emission factor for heating with a natural gas boiler, i.e. 0.213 kg CO_2-eq kWh^{-1}, is E_+. The application of the heat option (4a) Green Gas Hybrid therefore only emits fewer emissions than heating with natural gas if ambitious measures for the decarbonisation in electricity generation are taken.

Green gas may also be an alternative for HT heating with other types of hydrogen. An example of an alternative way to produce hydrogen is 'grey hydrogen', i.e. hydrogen produced through steam reforming with the use of natural gas. The EF_{average} for heat option (5a) Hydrogen Hybrid using grey hydrogen is 0.173, 0.209 and 0.226 kg CO_2-eq kWh^{-1} for pathways E_+, E_0 and E_- respectively. Additionally the $EF_{average}$ for heat option (5b) Hydrogen Boiler using grey hydrogen is about 0.427 kg CO_2-eq kWh^{-1} for all pathways. If grey hydrogen is applied in the optimisation instead of green hydrogen, the heat options with the lowest emission factors for LT, MT and HT heating would be (2b) UTES, (3b) Geothermal Energy and (5a) Hydrogen Hybrid relatively for all pathways (see Figure 5.7). The emission factor of (5a) Hydrogen Hybrid using grey hydrogen are however between the 2% and 3% lower than the $EF_{average}$ of heat option (4a) Green Gas Hybrid as shown in Figure 5.7 (i.e. 0.178, 0.213 and 0.231 kg CO_2-eq kWh^{-1} respectively). The $EF_{average}$ of heat option (5b) Hydrogen Boilers is also only 3% smaller than the $EF_{average}$ of heat option (4b) Green gas Boiler. Green gas could therefore be used as a renewable energy source for HT heating instead of hydrogen while emitting around the same amount of emissions.

The $EF_{average}$ for the heat options incinerating organic energy carriers, i.e. (3c) Biomass Heater, (3d) Waste CHP Plant, (4a) Green Gas Hybrid, (4b) Green Gas boiler are the highest of all heat options in Figure 5.7. Some authors however argue these emissions can be set lower because carbon emissions have already been sequestered from the atmosphere and will be sequestered again as plants grow (Booth, 2018). Since the operational emissions of heat production is assessed in this study, the direct emissions associated with the incineration of organic materials is explicitly accounted for. The black vertical bar in Figure 5.7 shows the $EF_{average}$ for the case in which the emissions associated with the incineration of organic materials are not included in the analysis. The Figure shows that the heat option (3d) Waste CHP Plant becomes the MT heat option with the lowest $EF_{average}$, instead of (3b) Geothermal Energy. This is also the case in pathway E_+ where the $EF_{average}$ of heat option (3d) Waste CHP Plant is equal to 0.0592 kg CO_2-eq kWh^{-1} and therefore smaller than the $EF_{average}$ of heat option (3b) Geothermal energy. Nevertheless, the $EF_{average}$ of (3d) Waste CHP plant is still higher than the values for the $EF_{average}$ of (5b) Green Hydrogen Boiler in pathways E_- and E_0 and (5a) Green Hydrogen Hybrid in pathway E_+ leaving heating with green hydrogen the preferred heat system for addresses well enough insulated for MT heating in the optimisation and therefore not changing the results as presented in Figure 5.6.

5.4.2. SCENARIOS WITH LOW TEMPERATURE HEAT OPTIONS AS DOMINANT SOLUTIONS

The results show that LT heat options can become optimal solutions for minimising the committed emissions between 2030 and 2050 in scenarios with more ambitious measures for the insulation of buildings and the decarbonisation in electricity generation. All LT heat options use electricity and their emission factor therefore depends on the final emission factor for electricity in 2050, E_{end} (see Figure 5.5b). In this study, emission factors for electricity production are taken from Wielders and Nusselder (2020): E_{start} is set to be equal to the emission factor of the electricity grid mix in 2018 and E_{end} the emission factor of offshore wind energy, i.e. 14.7 g CO_2-eq kWh^{-1}. According to Dutch policy, electricity is expected to be generated from only renewable energy sources by 2050 (Ministry of Economic Affairs, 2016). The value of wind energy is used for E_{end}, because it likely to become the dominant form of renewable energy in the Netherlands (Den Ouden et al., 2020). The renewable energy source with the highest emission factor for electricity generation is however biomass, with an emission factor of 75 g CO_2-eq kWh^{-1} (Wielders and Nusselder, 2020). This number does only account for the supply chain of biomass, and not for the emissions generated during the incineration of biomass. Increasing E_{end} to 75 g CO_2-eq kWh^{-1} only changes the results discussed for pathway E_0, i.e. heat option (2b) UTES does not have the lowest $EF_{average}$, but heat option (5b) Green Hydrogen Boiler. Electrification of heating may therefore only be an effective way to lower carbon emissions if electricity production is associated with a low emission factor.

The emission factors for most LT heat options, except heat option (2a) Residual heat LT, depend on the amount of electricity needed to generate and deliver heat, i.e. the COP values (see Table B.6 in B.2 for the values chosen). A COP of 5.1 was chosen for the heat option (2b) UTES, only accounting for the energy needed to deliver thermal energy and not to charge the storage with thermal energy. This is because heat option (2b) UTES are often used for both heating and cooling. In this chapter, the energy needed for heating is only accounted for, leaving out the energy needed for cooling. However, during the cooling process thermal energy is stored which can be used for winter. The recharging efficiencies given in Nuiten et al. (2019) vary between the 0.018 - 0.045 $GJ_{electricity}$ / $GJ_{thermal\ energy}$, which would lead to an increase of 9 - 23 % of the emission factor of heat option (2b) UTES. By including recharging of the UTES system, heat option (1b) HP underground could thus be the heat option with the lowest emission factor for pathway E_+ and heat option (5b) Green Hydrogen Boiler for pathways E_0 and E_-. LT heating alternatives are thus better suited as low-carbon heating alternatives in pathways with ambitious measures for the decarbonisation of electricity production.

In this study, a constant emission factor for electricity per year is used. The use of heat pumps is however not constant during the year, but fluctuates per season and hour of the day. Additionally, the temporal electricity demand for heat pumps changes when demand response or energy storage is applied. In Neirotti et al. (2020) hourly profiles of heat pumps and generation mix data for the year 2018 of 10 European countries including the Netherlands were analysed, taking into account the weighted emission factor of electricity by analysing the heat demand and the electricity grid on higher-resolution temporal scale (Neirotti et al., 2020). The study concluded that annual weighted emission factors for electricity in the considered European countries is between the -3% and +9.6% different from the unweighted yearly emission factors. A similar analysis to compute the expected weighted emission factor for 2050 is performed for the study presented in this chapter. To do so, hourly heat demand profiles of mid-rise apartments from Voulis (2019) was used, and the weighted emission factor of electricity was modelled by weighing it with hourly generation mix data of four major energy mix scenarios presented in Den Ouden et al. (2020); ETM (2020). The range of difference in the emission factor of electricity for the use of heat pumps was between 3.0% and 10.3%. For these heat demand profiles and scenarios for 2050, the emission factor of heat option (2b) UTES may therefore not be lower than the emission factor of heat option (5b) Green Hydrogen Boiler in the E_0 pathway depending on the mix of renewable electricity sources used (see Figure 5.7).

The scenarios in which LT heat options are dominant, are the scenarios with more ambitious insulation pathways, i.e. I_0 and I_+. One reason for this is the maximum heat capacity imposed for LT heating which is defined based on a report by the municipality of Amsterdam (Municipality of Amsterdam, 2020b). Up to the author's knowledge there are no more sophisticated ways in current state-of-the-art literature for assessing the constraints on when a heat technology can comfortably heat up spaces including the height of the peak demand, the heat delivery systems, and the yearly heat demand of those spaces. Additionally heat pumps and heat delivery systems at building scale and heat pumps are continuously being improved to provide more heating at higher temperatures. To assess the sensitivity of assumptions made, the model was run with a maximum heat capacity of 65 kWh m^{-2} $year^{-1}$ instead of 50 kWh m^{-2} $year^{-1}$, showing more addresses could be applied to the heat option (2b) UTES in scenario (I_+, E_+) with respect to the results in Figure 5.6 if the heat capacity was increased (see B.3, Figure B.5). Increasing the maximum heat capacity of heat pumps can therefore increase the number of addresses heat pumps can be installed in. I therefore argue for adaptive planning strategies for future urban heating systems, evaluating advances in technologies.

5.4.3. Uncertainties in heat demand modelling and the minimum heat density

Currently, it is still challenging to model the energy demand of existing buildings (Majcen et al., 2013; Van den Brom, 2020). There are for example often differences in existing models (see Appendix B.1, Figure B.4 for a comparison between heat demand per building archetype according to Netherlands Enterprise Agency, PBL Netherlands Environmental Assessment Agency and the results presented in this study (Agentschap NL, 2011; Folkert and Van den Wijngaart, 2012)). This is because heat demand is influenced by factors such as input data, occupancy time, indoor temperature, and family size. At the neighbourhood level this is even more challenging considering that neighbourhoods do not only contain residential buildings but also offices, school, restaurants, etc. (Hietaharju et al., 2021; Voulis, 2019). Additionally the building energy use can be influenced by inter-building effects (Nutkiewicz et al., 2021).

Due to privacy reasons, data needed for calibration, e.g. gas demand data, is often aggregated. This is also true for the city of Amsterdam for which data on gas demand for households (weather corrected data) and businesses is publicly available on postcode level for the year 2019 (Statistics Netherlands, 2021). Because publicly available gas and electricity demand data is aggregated on postcode level, it is challenging to determine the energy consumption for heating accurately for validation. Although it can be assumed that a fraction of the energy use is for space heating based on national averages for households, this would assumption would not be a reliable one at neighbourhood level. Moreover, differences in modelled heat demand and estimates from measured gas demand are likely to arise because buildings in a neighbourhood can be significantly different from the building archetypes, for example in size or in insulation level, or due to different user profiles per building, including consumption patterns and family size, affecting what fraction of household energy use is for space heating (Bogin et al., 2021). Future research could therefore validate and improve the accuracy of the heat demand model used for this study through measurement campaigns of heat demand specifically. Additionally, the heat demand was modelled by using the heat demand of the 'current' insulation level for the building archetypes per unit of floor area, simulating a situation where all addresses are insulated to the same state. To validate the heat demand model itself, more high level data is needed including the insulation measures taken per address. Nevertheless, based on the sensitivity analysis presented in Figure 5.8, it can be argued that the analysis does serve to assess the order of magnitude of the future heat density and therefore to indicate whether or not the future heat density may fall below the minimum required heat density for heat networks, which is needed to check whether there is a change on future carbon lock-ins.

5.4.4. SYNERGIES AND TRADE-OFFS WITH OTHER OBJECTIVES

In order to legitimise and realise the implementation of low-carbon urban heating systems, it is important to analyse the synergies and trade-offs of the decarbonisation strategies for heating with other objectives. One relevant objective is costs. It is important that the implementation of new heating systems leads to affordable energy supply (Municipality of Amsterdam, 2020b). Costs related to investments and operations can be location specific and also vary over time depending on learning curves and material prices. In Appendix B.4, the distribution of the costs for the implementation of renewable heating systems and the expected height of the costs in the neighbourhoods specifically studied in this chapter are discussed. These expected costs are based on a tool developed by PBL Netherlands Environmental Assessment Agency in B.4. In general, early installation of low-carbon heating systems can avoid future costs associated with carbon taxes or stranded assets (Fisch-Romito et al., 2021; Erickson et al., 2015). Retrofits of buildings can be economically attractive, sometimes even at net negative costs due to large improvements in performance and costs (IPCC, 2014b). Additionally, retrofits can also be beneficial given changes in prices for heating due to future developments in electricity and gas pricing and potentially CO_2-eq taxing. However, advanced retrofitting of buildings or the installation of LT heating systems can also be more expensive than implementing MT or HT renewable heating options. To support the implementation of heat systems which are at lowest costs now and in the future, while avoiding a carbon lock-in or stranded assets, projections of the costs of heating systems should be combined with assessments of committed emissions as presented in this chapter.

Besides costs, it is important that the implementation of low-carbon heating systems does not have an adverse influence on other environmental indicators. Increased use of UTES and hydrogen can, for example, increase the withdrawal of ground and surface water, making collaboration between the energy and water sectors vital (Kaandorp et al., 2021a). In (De Oliveira Fernandes et al., 2021) material versus energy-related impacts of building retrofit were analysed through a process-based Life Cycle Assessment on twenty retrofit scenarios for the Netherlands. They show that improving the retrofitting of existing buildings can contribute to a significant reduction of environmental impacts under the current Dutch energy mix. If more renewable energy will be used, then the energy-related impacts will lower and material impacts will become more important in the assessment of environmental impacts of the retrofitting of buildings. For example, about 10-12% of the total energy use is currently embodied energy use in standard homes for building materials versus 36-46% in energy efficient homes, which use less energy (Koezjakov et al., 2018). Material-related impacts for retrofitting may therefore become of a bigger importance in future environmental impacts assessments and policy. Additionally, the materials chosen for heating systems, e.g. for the pipes of heat networks, can change whether most environmental impact is made during the operational phase or other phases in the life-cycle of heat networks (Andrić et al., 2017).

5.5. CONCLUSION

To support a transition towards low-carbon heating, a computational model is proposed in this study to find a mix of heat options with the lowest committed emissions between 2030 and 2050 under different pathways for the insulation of buildings and the decarbonisation in electricity generation. The computational model consists of a bottom-up heat demand model together with a MINLP optimisation problem for finding an optimal heat supply mix on the neighbourhood scale. From the results four main insights can be drawn. Firstly, the committed emissions can be ten times lower between 2030 and 2050 if ambitious measures for the insulation of buildings and the decarbonisation in electricity generation are taken together. Secondly, heating systems with green hydrogen are the optimal choice in most scenarios that minimise committed emissions. If hydrogen is not considered as an option, then UTES, geothermal energy and green gas can provide renewable heat sources with relatively low-carbon emissions. Thirdly, LT heating dominates the optimal technology mix in the scenarios with the ambitious targets for both insulation and electricity grid decarbonisation. Finally, LT heat networks may not always be feasible because the minimum heat density is not always reached, creating a risk for not attaining maximal reduction in carbon emissions.

To exploit all four insights, I argue for adaptive planning strategies for future urban heat systems. Given the path dependence and the long life spans of energy infrastructure and building shells, carbon-intensive infrastructure may persist over time, creating a 'carbon lock-in', which 'locks out' lower-carbon alternatives (Fisch-Romito et al., 2021; Erickson et al., 2015). Adaptive planning that implements heat options in stages can help avoid a carbon lock-in and, consequently, support a transition towards renewable and low-carbon heating systems. An example of an adaptive pathway from HT heating to LT heating is to create hybrid systems with condensing boilers and the installation of heat pumps at the building level. With further insulation of buildings and decarbonisation in electricity generation, the use of fuels can be phased out and replaced with all-electric heating. Another example is designing heat networks in such a way that they can be adapted for LT heating in the future. It is then important to consider the future heat density in a neighbourhood under different insulation pathways to evaluate business cases for heat networks.

To improve realistic estimations of current and future heat densities on a high spatial level, heat demand models need to be improved. In the model used for this study, the heat demand was assessed with a bottom-up heat demand model extrapolating the modelled heat demand of building archetypes of households. This method can be further developed by adding heat demand profiles of other types of users such as shops, restaurants and offices (Voulis, 2019). These heat demand models addressing all types of users can then be calibrated and validated with gas use data at neighbourhood scale (Statistics Netherlands, 2021). To assess which heat systems can be applied for these users, studies need to be done to indicate the maximum heat capacity and minimum heat density of the heat systems.

To conclude, the presented four insights on the influence of different pathways for the insulation of buildings and electricity grid decarbonisation on the committed emissions of heating systems are key for supporting policies on sustainable heating systems. They imply that the currently technically feasible heat options with the lowest carbon emissions may not be the solution with the least carbon emissions during the upcoming years. This can lead to less reduction in greenhouse gases or increased costs of heating infrastructure due to stranded assets (Fisch-Romito et al., 2021; Gross and Hanna, 2019). It is therefore important to take into account pathways for insulation and electricity decarbonisation when designing renewable and low-carbon heating systems to minimise carbon emissions and achieve climate mitigation targets.

6

‘Commoning practices’ for energy justice? A perspective on collective heating initiatives in the city of Amsterdam

In the last two chapters, it has been described how urban heating systems are linked to both water use and carbon emissions at multiple scales. Urban transitions however take place in their socio-political contexts in “which actors strive to defend and create their own environments in a context of class, ethnic, racial, and/or gender conflicts and power struggles."(Kaika, 2004, p.25). Technological systems are shaping and shaped by the local context, including local values, historical developments and hegemonic relations. In order to describe the social implications of the Heat Transition in Amsterdam, the link between bottom-up heating initiatives in the city of Amsterdam with energy justice is explored in this Chapter by using the concept of commoning practices.

Abstract chapter 6:''Commoning practices' for energy justice? A perspective on collective heating initiatives in the city of Amsterdam'
Decarbonisation of the built environment is needed to minimise the use of fossil fuels and abate greenhouse gas emissions. The city of Amsterdam, the Netherlands, aims to generate all space- and tap water heating with renewable resources by 2040 and achieve 'carbon neutral' heating by 2050. In the city, collective heating initiatives have been developed in which urban dwellers collaborate to achieve low-carbon heating systems. These initiatives are important to achieve decarbonisation goals, because the retrofitting of buildings takes place in the existing built environment where people live, work and gather. In order to support a heat transition that fosters human well-being, the aim of this study is to investigate the link between these collective heating initiatives and energy justice. It is argued that the integration of concepts of energy justice and commoning practices can enhance a dynamic understanding of how energy justice concerns are expressed and reshaped in practice. Based on this integration of concepts and ethnographic fieldwork performed between 2019 and 2022 in the city of Amsterdam, it is shown that collective heating initiatives can contest current logic for transitioning towards renewable heating infrastructure, while at the same time opening up and closing down spaces for different actors to come together.

6

Keywords: urban heating systems, energy transition, energy justice, urban commons, commoning practices, urban anthropology

This chapter is based on the text in Kaandorp et al. (N.D.)

6.1. INTRODUCTION

This chapter presents a study on the relation between energy justice and collective heating initiatives in the city of Amsterdam. To support this transition towards low-carbon energy systems, the ambition is stated in the Dutch Climate Agreement (Dutch: *Klimaatakkoord*) that half of all renewable energy production on land will be owned by local entities, i.e. citizens and companies (Klimaatakoord, 2019, Chapter Electricity). Citizen-driven, collective forms of organisation are therefore required to reach decarbonisation goals. Examples of 'collective heating initiatives' are knowledge-sharing events, networking activities, decision-making processes by owner associations (Dutch: *vereniging van eigenaren (VvE)*), organising collective buy-in schemes of solar or infra-red panels, or setting up energy cooperatives (Ebrahimigharehbaghi et al., 2022). Although energy communities for electricity projects have been well studied, community-based initiatives for heating have received less attention in academic literature, leading to an inadequate understanding of general motivations and concerns, such as financial benefits and environmental concerns, driving the individuals constituting these initiatives (Fouladvand et al., 2022). To fill this knowledge gap, this chapter presents a study on the relation between collective heating initiatives and energy justice.

With the notion of energy justice, scholars evaluate "(a) where injustices emerge, (b) which affected sections of society are ignored, (c) which processes exist for their remediation in order to (i) reveal, and (ii) reduce such injustices" (Jenkins et al., 2016, p.175). Collective heating initiatives can be driven by energy justice concerns and can be aimed at reshaping prevailing energy justice arrangements. On the one hand, these initiatives are formed through the collective action of individuals, and therefore reproduce existing norms and values (Fouladvand et al., 2022). They can also change power and institutional relations, reshaping the institutional bricolage and redistributing risks, rights and responsibilities (Pesch et al., 2017). The concept of energy justice enables scholars to identify how the generation, distribution and decision-making processes of urban heating systems can be seen as unjust. However, the notion of energy justice does not provide the analytical power to describe how energy systems are contested and actively reshaped by collective heating initiatives (Astola et al., 2022; Van Uffelen, 2022). In order to describe how collective heating initiatives contest and actively reshape the way in which energy systems are organised in relation to energy justice, it is proposed in this chapter to link the concept of energy justice with the notion of 'commoning practices', which will be featured as a form of protest against existing justice arrangements as well as the development of alternative arrangements (Pesch, 2021).

The verb 'commoning' refers to practices aimed at increasing ownership and responsibilities of a community of users over resources (Feinberg et al., 2021; Foster and Iaione, 2019). 'Commoning practices' can therefore be understood as those ways of thinking, doing and organising related to increasing users' decision-making liberties, ownership, or responsibilities over urban heating systems (Wittmayer et al., 2022). Local claims of urban resources and city space as a 'commons' can consist not only of assertions of a 'right' to a particular resource, but can also be the expression of a "*common stake or common interest in resources shared with other urban inhabitants as a way of resisting the privatisation and/or commodification of those resources*" (Foster and Iaione, 2015, p.284). In this sense, the notion of commoning practices can be linked with the question of how urban resources and spaces are organised in a 'just way' (see Section 6.2 for a further discussion on 'commoning practices'). The linkages between the concepts of urban commons or commoning practices and energy justice are, to the author's knowledge, not widely discussed in literature. The contribution of this chapter is therefore that it offers a heuristic approach for advancing conceptual understanding of energy justice and commoning practices in the context of urban energy transitions.

To generate these insights, it was in this study (i) how drivers for collective heating initiatives relate to energy justice, (ii) how collective heating initiatives can be conceptualised with commoning practices, and (iii) which new insights on energy justice arise from these commoning practices. In order to answer these questions, ethnographic fieldwork was performed in the city of Amsterdam spread over a period between 2019 and 2022 (see Section 6.3). In the first four months of 2022, a collective energy initiative called '*02025*' was researched as a case study (see Section 6.4). Based on the fieldwork, it can be concluded that commoning practices can open up and potentially close down spaces for addressing energy justice concerns and provide alternative ways of organising urban heating (see Sections 6.5 and 6.6).

6.2. CONCEPTUAL FRAMEWORK: INTEGRATING COMMONING PRACTICES WITH ENERGY JUSTICE

6

In this chapter, it is proposed to integrate the concept of commoning practices with the concept of energy justice in order to enhance a dynamic understanding of how energy justice arrangements are expressed and reshaped in practice. The notion of commoning practices stems originally from the concept of the commons, which is explained in the Introduction. The concept of 'commoning' is popularised by the historian Peter Linebaugh to "describe the social practices used by commoners in the course of managing shared resources and reclaiming the commons" (Linebaugh, 2008; Foster and Iaione, 2015, p.302). The notion of commoning practices can refer to practices intended to increase the influence and ownership of a community of users over resources, without much relating it to a power struggle or against commodification (Feinberg et al., 2021; Foster and Iaione, 2019). However, commoning practices can also challenge existing power relations and ownership structures and can purposefully be directed against logics of commodification, marketisation and privatisation (Becker et al., 2017; Von Winterfeld et al., 2012). This is aligned with Harvey's idea of commoning practices, movements as "*counterattack the commoditization of the urban fabric by collectively creating urban commons* (Harvey, 2012)" (Zapata Campos et al., 2020, p.1151).

Because of this contestation of existing power relations and ownership structures, it is proposed in this chapter to use the notions of commoning practices and energy justice in concert in order to understand current and potential controversies within energy systems. In other words, it is proposed to link the concepts of energy justice and commoning practices to enable analysis on how energy justice issues drive commoning practices on the one hand, and how commoning practices can reshape energy justice concerns on the other hand. It is conceptualised that, the notion of commoning practices can enhance the analysis of existing energy justice concerns and how they are expressed in practice (see Figure 6.1). Additionally, it is suggested in this chapter the concept of energy justice can be a useful tool to analyse the (ethical) implications of commoning practices. Although these implications can be sketched out in terms of distributional, procedural and recognition justice, categorisations closer aligned with the perspectives found in this research will be used.

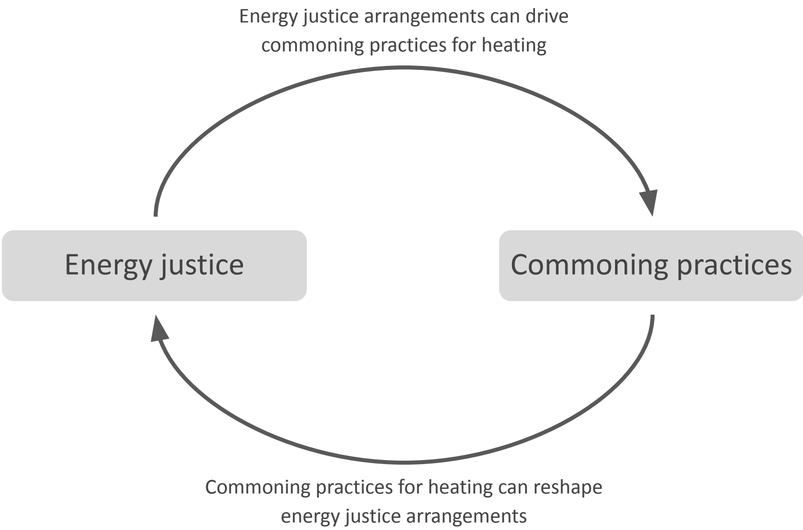


Figure 6.1: Conceptual framework for integrating the concepts of energy justice and commoning practices for urban heating systems.

6.3. METHODS

In this study, ethnographic research methods have been applied in an urban setting. The research is based on semi-structured interviews and participant observation. In total 19 interviews were collected and 13 participant observation events took place, of which 10 were connected with *02025*. In this chapter, the individuals who participated in the interviews are referred to as 'participants'. All participants have given consent for the data collected during the interviews being processed for this chapter. Moreover, historical accounts of heating in Amsterdam, *02025* newsletters, municipal policy documents, and newspaper articles about the heat transition in Amsterdam were analysed (Van Overbeeke, 2001). As I grew up in Amsterdam and started researching the heat transition in Amsterdam in 2018, I was already familiar with existing norms and ideas of urban professionals working on the energy transition in Amsterdam. I aimed to mitigate this limitation by collaborating with other researchers of different nationalities and research backgrounds.

The fieldwork for this paper took place from autumn 2019 till summer 2022. In order to understand the narratives on energy presented in this paper, it is important to note that the interviews and fieldwork of this research took place after the decision made in 2018 to reduce natural gas withdrawal from the gas reserves in the province of Groningen, during the COVID-19 pandemic, and before actions such as the 'REPowerEU' strategy of May 2022, which are targeted at reducing the reliance of European Union nations on Russian fossil fuels (Wiebes, 2018; European Commission, 2022).

Due to the COVID-19 pandemic, the research was split into two phases. The first part of the research was intended as an orientation phase and took place between October 2019 and December 2021. During this phase, interviews were held with ten different participants: a teacher in a neighbourhood, two homeowners, an employee at the water utility company, two employees from the municipality, an environmental policy researcher, a research coordinator on the topic of energy in Amsterdam, and two employees at the municipality. These people were approached because of their diversity in professional roles and living situations in Amsterdam. Seven of these interviews were held online, due to distancing measures related to the pandemic. In order to be able to do more in-person fieldwork, the second part of the research took place from January 2022 to April 2022. So, although spread over three years, most participant observation was performed in a time span of four months. This research did therefore not take place in the prolonged time span that characterises most ethnographic research. Nevertheless, narratives shared among multiple participants were collected, and relevant information on the drives and practices of citizens in transforming heating systems was therefore gathered.

6

The research question at the start of the first phase was on how people experience a (potential future with) diversity in heating systems in the city. From the interviews in the first phase, it was found that energy justice concerns were mostly on how the heat transition was organised, focusing less on the technological outcomes. A tension could be noted between the perceptions of space heating as a commodity, e.g. supply of natural gas or thermal energy from a heat network is a paid service, and at the same time something that should be accessible for all. Moreover, the interviews displayed energy justice concerns on the major district heating systems in the city, and ideas on the benefits of bottom-up initiatives (as described in Section 6.5.1). This is how the aim of the study was shifted towards the notion of urban commons and, more specifically, its relationship with energy justice in the context of collective heating initiatives in the city of Amsterdam.

In order to study collective heating initiatives, the platform *02025* was chosen as a case study. The platform is a bottom-up initiative, started by citizens. Currently, it is financially supported by the municipality and collaborates with multiple partners. It can therefore also be conceptualised as an intermediary organisation connecting local innovation projects (Hargreaves et al., 2013). By connecting with a platform, I was able to interview individuals who are involved with the heat transition in the city and perform participant observation at networking events organised by the platform. Because intermediaries "*are able to identify common issues and problems encountered across multiple local projects*", the platform enabled me to connect to a large network of actors involved with the heat transition in Amsterdam, including citizen-driven initiatives, which shaped my understanding of the dynamics between commoning practices and energy justice on the municipal scale and not only at the neighbourhood level (Hargreaves et al., 2013, p.869). I got access to the platform by first interviewing one of the consortium members twice and attending an online energy breakfast. After that, an interview was held with the founder of the platform and who gave me permission to visit the office a couple of times for participant observation.

In total, I did participant observation for three days at the office of the *02025* consortium and two other events to which consortium members were invited. I also attended one online and three in-person energy breakfasts. At the start of the energy breakfasts, I introduced myself to everybody in the room stating that I was there as part of my research. In this second phase of the research, nine interviews were taken: the founder of the consortium, a consultant on the energy transition, a municipal worker on participation for natural gas-free heating, a member of an energy committee in a neighbourhood, a resident who took part in a participation programme for the heat transition in her neighbourhood, a consultant working as a consortium member, and an employee of a tenant support agency. Two interviews were held with the latter two to get more information about their viewpoints. These people were approached because of their role within the platform or because they solicited to be interviewed based on my call during one knowledge session or my advert on the platform's website.

The field notes and transcriptions of the interviews were analysed with a heuristic approach. The interviews were transcribed with transcription software and uploaded in Atlas.ti. Quotes were analysed with extracted from the transcription following an iterative process of analysis. At the start, quotes were clustered asking how the current heat transition is problematised by the participants, and how collective heating initiatives were legitimised and operationalised. In order to study the link between commoning practices and energy justice, the transcriptions and field notes were analysed by focussing on (i) how collective heating initiatives can be seen as to 'common' the urban heating infrastructure, and (ii) how do commoning practices relate to claims and activities for energy justice.

In order to answer the first question, activities which were aimed at increasing users' ownership or input over urban heating systems and the heat transition itself were considered. It was not the aim of this study to provide a general representation of all activities and narratives existing concerning the energy transition in Amsterdam. Nevertheless, the aim was to reflect on how these initiatives take place and shape the transition towards renewable urban heating in the city of Amsterdam. In Section 6.5.2 an account is given on activities of the platform which were recurring in multiple events and interviews. In order to answer the second question, parts of the interviews in which the participants explicitly used the terminology of energy justice or when the concerns raised could be linked to distributional, procedural or recognition justice were used. The participants were made aware before the interviews that energy justice was a theme in this research.

6.4. Case Study: collective heating initiatives in Amsterdam

As stated in Section 6.1, the fieldwork of this study is centred on a network called *02025*. The name *02025* stands for zero emissions (first 0) in region 020 by 2025. There are different ideas on what *02025* is, being for example a brand, movement, website, platform, or learning circuit. The platform started in January 2018 and came forth from another citizen-led initiative that had started in 2011. Since 2018, *02025* is not only the name of an initiative, but also of a consortium. The consortium consists of six to seven individuals affiliated with consultancies, non-governmental organisations, and engineering companies. The consortium is partially funded by the municipality, because, according to a consortium member, "*the city of Amsterdam thought that well, it's a great platform, but there is nothing that makes it grow, makes it stronger, makes it better* [...] *[it] needed to be scaled up*". The consortium aims to help neighbourhood initiatives and urban dwellers by answering technical questions, supporting communication with entities such as the municipality, helping to get projects funded, and connecting people with others in their social network of around 8000 people. Knowledge is spread individually, i.e. people can contact people from the consortium itself, but also through the platform of the website, and through knowledge sessions.

Regular events that are organised by *02025* are the monthly 'energy breakfasts' (Dutch: *energieontbijt*). Energy breakfasts were described by a consortium member as one of the stable pillars of the organisation. Energy breakfasts are visited by 20 to 150 people. The scale of the networking events changed over the years. Before it was on a city level, but now, because of the growth of the platform, the scale became larger. During times of lock-time due to the COVID-19 pandemic, online meetings were held. At the energy breakfasts, multiple stakeholders for the decarbonisation of heating attend. The founder of *02025* described that *02025* collaborates with eight 'spheres' (Dutch: *kringen*), presented in Table 6.1.

6

Table 6.1: Eight 'spheres' around the *02025* initiative.

Spheres	Description
Front-runners (Dutch: *koplopers*)	Front-runners can be typified as people who strive to create more clean energy use in the neighbourhood. According to the homepage of *02025*: "*02025 connects a community of front-runners in the Amsterdam Energy Transition who help each other to make their city sustainable in a more effective way*".
Energy collectives (Dutch: *Energie coöperaties*)	Based on the information from *02025* there are around 50 energy collectives in the city including collectives focused on electricity production.
Local hubs	Places where people work and come together. During the energy breakfasts, these hubs are discussed and promoted. Events of *02025* are organised at these hubs, which are also being promoted through the *02025* website.
Energy commissioners (Dutch: *energiecommissarissen*)	These are volunteers who act as a contact point per neighbourhood (often divided by postcode level).
OranjeEnergie	A cooperative of entrepreneurs, owner of the brand *02025*.
Partners	Organisations who support the goal of clean energy.
Young02025 (Dutch: *Jong02025*)	Students, young professionals who collaborate for clean energy.
Supporters	Individuals who support the goal of clean energy but are not yet actively engaging with the transition.

6.5. COMMONING PRACTICES AND ENERGY JUSTICE CONCERNS IN AMSTERDAM

In this chapter, it is interrogated how the concept of 'commoning practices' can deepen an understanding of collective heating initiatives in the context of energy justice. Firstly, Section 6.5.1 describes how collective heating initiatives in Amsterdam are driven by energy justice concerns and propose alternatives to 'the rules of the game' (arrow to the right in Figure 6.1). Secondly, it is discussed in Section 6.5.2, how activities organised by members of *02025* can be seen as commoning practices and how new energy justice questions arise from these activities (arrow to the left in Figure 6.1). Overall, the results shows that commoning practices can open up and potentially close down spaces for collaboration between urban dwellers, urban professionals, and government officials for addressing energy justice concerns. It is therefore argued in this chapter that using the notions of commoning practices and energy justice in tandem can bring a more dynamic understanding of how energy justice concerns and wishes are continuously shaped in practice.

6.5.1. FROM ENERGY JUSTICE TO COMMONING PRACTICES: CONTESTING HOW THE HEAT TRANSITION SHOULD BE ORGANISED

We went upstairs. I got a tour of the house to see all the adaptations that were made to lower the gas demand for heating. The view from the attic was partially blocked by a heat pump and a solar boiler which were standing next to the sedum roof cover. A mechanical ventilation system was hidden behind panels next to the desks of the home office. Downstairs it was also noticeable that a lot of interventions were made. A heating unit the size of a tall fridge was installed and the light reflected in the triple glass windows. On the couch in the living room, she told me that she had been active for years in the participatory processes of the municipality in her neighbourhood. She said: "In the beginning, a couple of people had a feeling of 'something is not right, you say you want to have a discussion with us, but you want something'. And that feeling has never faded away". Of course, she and her husband had gone far in retrofitting the house in order to use less energy and have a more sustainable house, but also to avoid they could ever be forced to be connected to the heat network in the city: "I was also following the legislative agenda. Like, what is going to happen and when? Because the point was continuously brought forward of being forced [to connect to the heat network]".

6

Figure 6.2: View from roof of retrofitted house. From left to right: solar boiler, heat pump and sedum roof cover (picture by first author).

Justice concerns on public-private partnerships

The vignette above shows that residents can be driven by multiple concerns to retrofit their houses. Such concerns include not only climate change, but also critical thoughts on decision-making processes in the city. Most participants in the interviews mentioned their motivation to abate CO_2 emissions and climate change as a primary reason to participate in activities which transform heating systems. One participant even explicitly associated the transition towards low-carbon heating with climate justice. The goal to reduce CO_2 emissions can sometimes go hand-in-hand with the ambition to phase out the use of natural gas for heating, but can also be hindered by it. The replacement of natural-gas-fired heat boilers at the household level by a heat network distributing thermal energy from the incineration of gas, waste or biomass is, for example, contested in Amsterdam. This is because such a heat network can be considered to be less sustainable given the associated CO_2 emissions and material flows. Additionally, participants showed concerns about a potential 'carbon lock-in' when implementing such a heat network. A carbon lock-in means that possibilities to reduce CO_2 emissions in the upcoming decades may be limited due to the dependency of these networks on high-temperature energy sources such as the incineration of fuels.

Besides concerns on specific heating technologies, different ideas on the order of technological interventions which support energy justice best were found. The project called the 'Heat Motor' (Dutch: *Warmtemotor*) is an agreement between the municipality of Amsterdam, heat companies, and housing corporations which is aimed at connecting areas with predominantly social housing to the heat network first, in order to support families with lower incomes and to create jobs in those areas. District heating can be seen as a good heat option because individual heat pumps, which are a low-carbon alternative, often need a lot of space indoors and a connection with outdoor spaces. This is often not desirable in smaller dwellings. A heat network, which has the potential to become a low-carbon heating alternative in the future, is therefore often preferred for social housing by social housing corporations and the municipality. From the perspective of somebody from the municipality, the further expansion of the major heat networks in Amsterdam instead of other decarbonisation measures, such as insulation, was perceived as a rapid way to transition towards low-carbon heating systems, because expanding the heat network and working together with housing corporations is momentarily a straightforward thing to do for the municipality. Additionally, participants working at the municipality argued to continue the expansion of the heat network in neighbourhoods where significant renovation on underground or surface infrastructure is needed, or planned by people in the neighbourhood. The logic presented to me by a municipal civil servant was that heating systems could be first changed and that then, at "*natural moments*", buildings can be further insulated, lowering the thermal regime of the heat supply system at a later stage. This is however sometimes contradictory to what participants believed to be the cheapest and most sustainable solution, i.e. insulating first and then installing a heating system at a low thermal regime. Additionally, it can raise concerns about how to distribute renewable heating systems over the city in a fair way and whose costs will be reduced first.

6

Moreover, several concerns were found that addressed the distribution of benefits and costs of the main heat networks in the city of Amsterdam. Participants in the interviews contested that one international company exploits the network, meaning that households connected to the heat network pay this company for space heating. Multiple media outlets and participants referred to this construction as a 'monopoly', leaving less room for alternative providers of thermal energy[1]. Moreover, the audit office of the city of Amsterdam advised re-evaluating the joint venture *Westpoort Warmte* because this had not structurally been done in the past (Rekenkamer Metropool Amsterdam, 2018). Additionally, one participant questioned why the money residents pay for heating should go to an international company, instead of keeping funds within the neighbourhood. An urban professional also said that there are signals that people do not appreciate committing for a long term to one company which is experienced not to be transparent. The urban professional argued that space heating should be organised locally in order to limit long-term insecurity which comes from non-transparent companies. Some therefore envision that it would be a good solution if heat providers are utility companies who are transparent about their finances and have profits limited.

Considering justice concerns and the decision-making processes, participants in the interviews perceived decision-making processes in the city as rather top-down than bottom-up. From interviews with municipal officials and urban professionals, it was found that participation can be seen as a tool to create and increase public acceptance (Dutch: *draagvlak*). Additionally, participation was seen as a way to listen to what people want,

[1] For example: 'Stadsverwarming in Amsterdam-Noord: plan lag er al'. Episode political series 'De Hofbar', broadcast on 30-09-2020 on the Dutch public broadcasting system, and 'Zondag met Lubach: Nederland gasvrij'. Season 12, episode 8. Broadcasted Sunday 8-11-2020.

and create a plan which suits most people. The team 'natural gas free' (Dutch: *aardgasvrij*) of the municipality asks people in neighbourhoods whether they believe that the 'preferred' warmth solution or heat option stated in the Transition Vision Amsterdam is also the best solution system (see map in Figure 3.1). However, the difficulty is that these stakeholders can never be a full representation of the whole neighbourhood. A participant working at the municipality said that they are still searching for good ways to make decisions based on a good view of what the minority and majority in the neighbourhoods want. Another municipal civil servant changed from saying "*participation with inhabitants*" to "*participation with homeowners*" because the municipality can mostly only talk to building- or homeowners, since those make the decisions. In 2020, a participant told me that the municipality often starts the conversation with housing corporations because they own a lot of houses in the neighbourhoods. However, tenants sometimes also want to talk directly to the municipality instead of through the housing corporation. A participant thought that a lot of people do not like that housing corporations have scaled up and are more business-oriented in the last 20 years. The same municipal civil servant said that participation often is in the format of informing or asking questions to inhabitants of a neighbourhood, and that most 'co-creation' happens with the housing corporations. However, the civil servant did not like to call that co-creation because co-creation normally refers to collaboration with residents. In two neighbourhoods with heating cooperatives the municipal civil servant said one can talk about real co-creation.

The majority of the participants perceived that the agreements between the municipality and energy companies to expand the heat network obstructed the participatory processes of the municipality. Because of existing agreements, the municipality can be perceived as being limited by its options. One participant, for example, said there was a struggle within the municipality because they have a contract with the company Vattenfall but at the same time want to be "*a social and democratic city, which is absolutely contradictory to what they are doing*". The same participant also said: "*everything is already decided and we have nothing to choose and you are forcing this on us and we don't want it and you're not listening to what we want. [...] But it doesn't seem to be transparent or make any logical sense, right, to get this newly built environment of Sluisbuurt on the heat grid. Nobody ever would imagine they make such a decision in this city. And so it feels like Mafiosi to me.*". Another participant stated: "*The municipality seems to give the power of choice to the residents, but it is clear that the municipality has a preference for the implementation of district heating at high temperature. It therefore feels like a little play, those consultation rounds*". And one participant also linked the agreements explicitly with energy justice by saying: "*And in my view: as long as this entanglement between municipality interest and the interest of Vattenfall exists, you cannot do anything about participation and about justness. It is just undoable*".

'Commoning' the organisation of the heat transition

The energy justice concerns described in the previous section can be argued to be directed against the logics of commodification, marketization and privatisation of heating. As an alternative, collective heating initiatives are brought forward as presenting alternative forms for organising (the transition towards) low-carbon heating systems, such that the influence on decision-making processes and ownership of urban heating systems of the users themselves is increased. In this chapter, collective heating initiatives are therefore conceptualised as commoning practices that contest the prevalent rules of the game in the energy system, which seem to stimulate energy technologies that are susceptible to lock-ins, procedures that are top-down, technocratic, and with agreements with incumbent companies and organisations which hinder participation processes. In the following, it is discussed how collective heating initiatives are imagined as beneficial alternatives to ways to organise (the transition towards) low-carbon heating systems.

One motivation for local heating initiatives is to gain more control and transparency over heat provision. This is reflected in this quote: "*The added value of a co-operative is that you have and keep authority [Dutch: zeggenschap]. That is where it goes wrong with companies [...] you don't have any say there. You don't have a share [...] with which you can say 'I find the heat tariff too high, so I vote, I send the committee away or I vote against the raise of the heat tariff.' You don't have any influence*". Local heating initiatives invest in their own area and can distribute the costs, cutting out the margin that a commercial party would ask. One of the consortium members hoped that in the future the whole heat network in Amsterdam will for half be in the hand of commons. He linked the idea of local ownership with trust: "*of course, there have to be professional parties who run that network [...] But I think as a citizen of Amsterdam, you should be one of the stakeholders of the network [...] the role of the commons is important because you need to trust the system, and if you own a part of it, you have to trust it. You also trust your own car because it's yours. [...] If you own it, you probably trust it, so that's going to accelerate the spreading of these kinds of networks*".

Other participants believed as well that collective heating initiatives can help to accelerate the energy transition. One reason for this is that there can be more trust in or inspiration from local actors instead of the municipality or parties that have an interest in certain heat technologies. The following quote illustrates this point: "*You can see that when residents do that, it goes much better. That people are inspired by their neighbours and not by their housing association, so to speak. So that's why, I'm a bit impatient by nature, so that's why I don't like working at one large organisation. Because it all takes forever*". Another participant said: "*I think that the organisation of residents goes quicker if residents play a bigger role in it themselves*". Similarly, one participant said the best way to accelerate the energy transition is to choose the heat technology with the highest support in local communities rather than the solution with the lowest total costs. In the same line of thought, other benefits were also associated with local energy systems, such as self-sufficiency in energy supply. Another participant thought that having local heat sources would be good because this may increase awareness of where the energy comes from potentially resulting in a decrease in energy usage.

In other words, participants believed that neighbourhood initiatives are often good platforms to reach out to people and connect people. This is because they make use of other networks and communication channels than the municipality. Additionally, people in the same neighbourhood can feel more related to a person from the energy co-operative of that neighbourhood and believe that their interests may be more aligned. Residents themselves can have more knowledge and feel for what people in the neighbourhood find interesting or not and therefore whether a plan will catch on. These interests can also be connected to non-energy-related topics. Locally organised initiatives can "*stay with the trouble*", such as rats, rising house prices or windmills, "*optimise for* *'societal value'*" (Dutch: *maatschappelijke waarden*), and make use of the "*local intelligence*" present in neighbourhoods. Moreover, creating neighbourhood projects can also enhance that people come together, talk about their neighbourhood, and enlarge citizen engagement.

To conclude, the energy justice concerns discussed in Section 6.5.1 show that there are energy justice concerns related to transforming urban heating systems in Amsterdam and that collective heating initiatives are envisioned to make positive contributions to neighbourhoods. These initiatives increase the control and ownership of users over energy systems and can therefore be conceptualised as commoning practices. In the following, some explicit examples of activities from the case study which support collective heating initiatives are given. It is furthermore discussed how these activities can be seen as commoning practices and how these practices dynamically shape energy justice arrangements.

6.5.2. FROM COMMONING PRACTICES TO ENERGY JUSTICE: OPENING UP AND CLOSING DOWN SPACES FOR COLLECTIVE ACTION

It was still buzzing in the room. The lines on the floor and the gym rings hanging from the ceiling gave away that the event took place in the old gym room of a renovated school. Vintage chairs were placed facing the stage. The back of the stage was lit with tall window doors leading to a small garden with grey bricks and plants in their winter state. In the middle of the room, a table was filled with fresh fruits, croissants and coffee. The event started with a name round orchestrated by a host passing down the microphone from one person to the other. It had to be short because the whole audience consisted of over 40 people. Different reasons for attending the event were mentioned: entrepreneurs searching for a connection with the municipality, frustrated tenants wanting information and students wanting to start a business. The host made a remark as: "oh okay nice, you should talk to that person after the presentations" or a joke like "ah, it is good that we are being researched" after learning that there were two researchers in the room. After the name rounds, a couple of PowerPoint presentations and pitches were given. The presentations of the day were about how the renovated school acted as a hub for projects in the neighbourhood, the activities from the municipality, the upcoming labour market, organised to link people looking for a job with jobs in the energy transition, and the fix brigade who visits homes of people with small budgets to perform small insulation measures. I felt active and happy to be part of a group coming into action.

COMMONING PRACTICES WITH MULTIPLE COLLABORATING PARTIES

The vignette above shows an account of an energy breakfast. A place where people come together to engage with the energy transition by sharing knowledge, posing questions or networking. In the following, it is argued that these and other activities organised by *02025* open up spaces for collaboration among multiple actors, creating common (financial) tools, and sharing knowledge to transform the decarbonisation of space heating collaboratively. These ways of thinking, doing and organising are conceptualised as commoning practices because urban dwellers can get opportunities to increase their influence on the heat transition in Amsterdam or their ownership over urban heating systems through such ways of thinking, doing and organising (Wittmayer et al., 2022).

A first example of how collaboration among parties is supported, is that the events open up spaces for collaboration among individuals. Participants described *02025* mostly as a place to network and connect with like-minded people who are doing similar things in the energy transition. One participant described the case study initiatives as an alliance between front-runners and additionally an enjoyable (Dutch: *gezellige*) meeting place for everybody who wants to collect some "*feel good*" energy about the energy transition. It's a place where people share their 'good' activities, and the content of the presentation is of good quality. One participant described how this supported him in a process, doing things by himself, and finding people all over the city with similar experiences. Another participant did not go to many events due to limited time, but followed the newsletter and blogs for information. She thought that it was a nice platform to share the findings of the project which she was involved with.

Secondly, the events open up spaces for collaboration between urban residents and other entities. Multiple participants could not exactly describe what the *02025* does in the city, but one participant suggested that this may be a good thing, because it creates a space where people can interact without the formal roles between citizens and formal entities. An example of a collaboration between collective heating initiatives and urban professionals is that citizen-driven initiatives may enjoy the presence of an external consultant to validate their ideas. Additionally, not all collective heating initiatives want to start an energy cooperative or professionalise, but want to outsource parts of their projects or organisation to urban professionals.

Thirdly, the consortium of *02025* aims to facilitate the collaboration between collective heating initiatives and the municipality by working on a common story-line, pointing out hurdles in the decarbonisation of the built environments, and providing possible solutions, such as creating job certainties for technicians or organising events where people can find jobs in the energy sector. Multiple participants described that the municipality was both facilitating and hampering collective heating initiatives. Plans of neighbourhood initiatives can be different, e.g. in pace, than plans of the municipality. This does not directly imply that there is disagreement in the ideas between local heating initiatives and the municipality, but that people active in local heating initiatives can feel slowed down or hampered. One participant suggested that the municipality can give more trust to initiatives that have formulated the same goals as the municipality.

At last, the consortium aims to tell the community and the city of Amsterdam how much work is needed for the decarbonisation of the built environment, and to give all voluntary work and work from cooperatives more status by creating one bigger entity. In such a way collective heating initiatives can lobby for more status, resources and capacity. According to one participant, the total sum of buildings that fall under energy cooperatives is significant and the cooperatives should therefore be given more status. Citizen initiatives are picking up but experience mainly a lack of institutional support. The participant argued that the collaboration between government and industry is well established, such as the language and procedures for reporting and writing grants. The collaboration between the government and companies with collective heating initiatives is less well-established. This can, for example, lead to the feeling of individuals in collective heating initiatives not being taken seriously by energy suppliers when proposing aqua thermal projects and local heat provision. So participants from the consortium and collective heating initiatives were thinking about how to organise themselves to make sure that they are trustworthy and long-term partners for the municipality. One participant said that it is needed that 'blueprints' come available, because now it takes a lot of time to start an energy cooperative and get it funded by banks.

The spaces to collaborate can be conceptualised as a 'commons'. According to one of the founders of *02025*, a commons can be something that is shared, but with rules. She conceptualised the commons as a space where people leave behind their own interests and collaborate for one common goal. Figure 6.3 was presented by *02025* during an online conference on 'Cooperatives make the city' in the city of Amsterdam. The commons is depicted in this figure as a space where different 'stakeholders' come together for a common goal. Because commoning practices are conceptualised in this chapter as those activities increasing users' influence and ownership, it is argued that events aimed at creating such common spaces, such as energy breakfasts, can also be conceptualised as commoning practices. As described previously, energy breakfasts can open up spaces for contesting current relations between citizens, urban professionals and governmental organisations and reshape these relations.

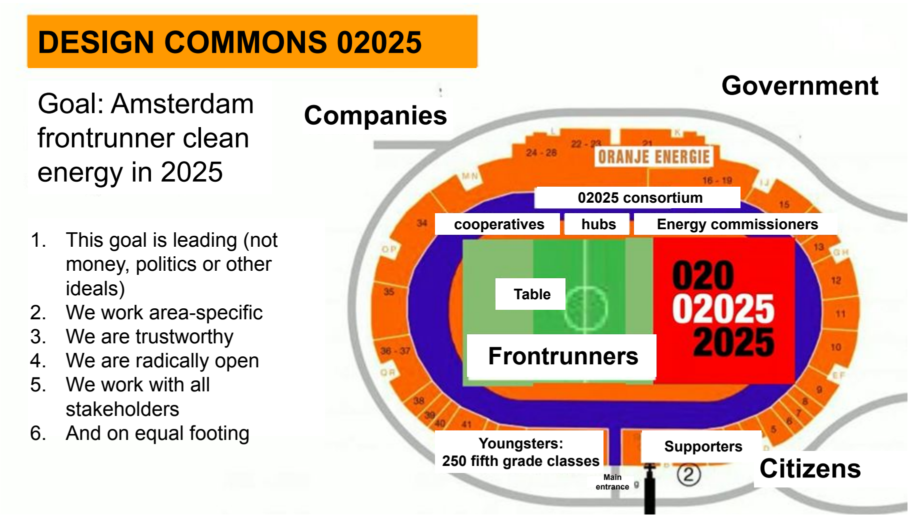


Figure 6.3: Translated slide from a presentation by the founder of *02025* envisioning *02025* as a commons with different players in the stadium (Edited picture from *02025*).

Financial means can also be conceptualised as commons and practices to restructure schemes for subsidies as commoning practices. One participant thought it was good that neighbourhood initiatives can get paid by subsidies, because it takes time to do research, meet and organise. Another participant added that giving money to volunteers in a neighbourhood can enable people to spend time on the project and create a more equal footing with other professionals. One participant additionally suggested that paying people to attend a meeting can create a sense of duty. One participant found it unfair that some projects get millions of euros of funding from governmental bodies whereas others do not, or only get 5000 euros with a lot of effort. The participant argued for a fund which is accessible for multiple initiatives and in which financial means for renewable heating initiatives are managed collectively and distributed based on mutual trust and should be accessible. The participant argued that in such a way heating collectives themselves can allocate funding based on needs. Other participants disagreed with this idea using the argument that the municipality cannot give everybody money who wants to start with an initiative for sustainability. This is also because the municipality also needs to allocate money to support other causes.

Information can also be conceptualised as a commons. A member of the consortium stressed that the space to work on the energy transition should be accessible for all and connected that idea with the notion that the sharing of knowledge should be free. Because the consortium members of *02025* do not sell energy technologies nor work directly for the municipality, they argue that they can function as independent advisers for urban dwellers who want to take part in the energy transition. Sharing knowledge for free was in one interview also connected with the notion of justice: "*We also find it important that the energy transition is accessible for everybody. You know, this is why our energy breakfasts and knowledge sessions. It is always free. If you call us with: 'Could you please help me?'. You never need to pay for that. And that is of course because we work, you know, with other volunteers. People from energy cooperatives who gladly want to share their knowledge. That is justice in the city*".

6

To conclude, the outcome of commoning practices related to *02025* are not necessarily performed by urban residents alone, but are in engagement with urban professionals and municipal officials. By its networking events, *02025* may therefore be viewed as an intermediary in the development of "*consolidating, growing, and diffusing novel [grassroots] innovations*" (Hargreaves et al., 2013, p.868). In other words, rather than fully transferring the input and ownership of urban heating systems to users of the system, commoning practices can open up spaces for collaboration between different actors including the municipality and businesses, and therefore reshape the interaction, spaces and rules between urban dwellers, professionals and municipal officials.

New energy justice questions from commoning practices

In the previous sections, a description is given on how participants link collective heating initiatives with an increase in energy justice. However, collective heating initiatives actively reshape public-private-civic relations, which may induce new energy justice concerns. Collective heating initiatives require time, money and the ability to go through complex documents from its members. Cultural-economic status of residents may therefore affect who has more influence or can engage with collective heating initiatives, creating disparities in the city. These disparities can be avenues for further energy justice research because they indicate potential inequalities in access to procedures of decision-making, institutionalised patterns of cultural value which prevent participatory parity, and unequal access to energy sources on an urban scale. By looking at commoning practices of collective heating initiatives, in this section, it is explored how inequalities in the city may potentially be (re)produced.

A first disparity is a perceived lack of diversity among people that organise or actively engage with collective heating initiatives. This disparity was mentioned during multiple interviews or events. People who do actively engage with collective heating initiatives were often described as white, theoretical educated, male and retired. One participant even typified this group of people as 'dark green', i.e. people who have the capability to free up time, are mentally available for the task, have a good social network, technological know-how, and want that the transition towards low-carbon heating takes place at a higher pace. It was also thought that this is only a small part of the society with these capabilities and wishes. As a solution to this question on diversity, a member of *02025* said that they are working hard to reach a more diverse group of people, especially to make sure that people who live on a smaller daily budget can come to ask for advice. Additionally, during a knowledge session on 'how to engage with the neighbourhood' a participant reasoned that residents in a neighbourhood can have different affinities, maybe typical 'doers' engage more with activities such as cleaning up the streets, and the thinkers go more to the energy committee. Tellingly, another participant reasoned during an interview that it is important to have a diversity of projects to engage with a diverse group of people. On an urban scale, an interviewee questioned how the municipality can make sure to not only engage with the 'front-runners' and people who are protesting against things, but with the majority of people.

A second disparity is on the potentially uneven spatial development of collective heating initiatives, considering that not in every neighbourhood active energy communities arise and continue to exist. This is in line with the idea that significant difficulties have been defined for grassroots innovations like community energy to survive (Hargreaves et al., 2013). One participant answered the question whether every neighbourhood should have a neighbourhood initiatives "*No, for sure not, [in those neighbourhoods] there are people who live there for 40, 30 years, who are well, highly educated, in the work field itself, they can organise it in this way with each other. A couple of retired people, who have a lot of time and are smart and still have a good network. In [the other neighbourhood] you have that as well. People who are well established in the network related to 'energy world' and local politics and, yes, I think that it is something for the highly educated neighbourhood*". Moreover, the financial situation of residents in the neighbourhood can create uneven spatial development of collective heating initiatives. One participant told me the story of how the owner association of the building in which the participant lived, i.e. an apartment building of four stories high with approximately eight apartments, went through the process of deciding what to do now the boiler needed an update. Similarly to other homeowners in the Netherlands, they experienced costs of retrofitting work and insecurity about the plans of the municipality as barriers to taking action and decided to wait (Ebrahimigharehbaghi et al., 2022).

A third concern is how representative the members of collective heating initiatives are of the residents of the region or buildings within the spatial boundaries of the initiatives. Collective heating initiatives may not be representative of all residents because of multiple reasons. Firstly, residents may not identify themselves with that specific neighbourhood, but rather like the anonymity of the city. Secondly, there can be multiple buildings within the neighbourhood that people of the committee may inhabit. Thirdly, residents of the neighbourhood may also have the feeling that their individual wishes may not be incorporated or pursued by the neighbourhood initiative. They can for example have the feeling that the group organising neighbourhood events can already have prefixed ideas. Alternatively, residents may find it hard to be sceptical or critical because they do not want to be excluded from the project. One participant thought that the core group of a collective heating initiative was motivated to abate CO_2 emissions for climate as soon as possible and therefore not critical towards the technical options or "*blinded by the idea of free heat*". Another participant was describing the situation in another neighbourhood as a movement in which people who did not follow the line of thinking of the local heat initiative were excluded from the project and frowned upon in the streets. Fourthly, not everybody is as engaged or wants to be as engaged.

At last, the spatial development of collective heating initiatives is influenced by the physical situation which varies between different areas of the city of Amsterdam. For example, one participant described that in some neighbourhoods a neighbourhood house is located. This can make it easier to support a neighbourhood initiative, because efforts can be made more visible and known. Another participant stated that his neighbourhood had clear boundaries because it was surrounded by water. The identity of that neighbourhood was also shaped by the fact that only three decades ago the area was redeveloped, shaping the demography of people currently living there. Similarly, there can also be reasons which make it more difficult to collaborate. A participant for example did not think a neighbourhood initiative would work because there were too few households to have an efficient collective solar power or heating system in their neighbourhood. Another reason mentioned was that nearby buildings were in different states of maintenance. Nevertheless, uneven spatial development may, according to one participant, not necessarily be negative, because it can be a good inspiration for other neighbourhoods. The municipality or housing corporations can learn from citizen-driven initiatives about "*how it is organised from a resident perspective*", and therefore inspire how energy justice concerns may be solved.

6.6. CONCLUDING REMARKS ON COMMONING PRACTICES AND ENERGY JUSTICE

The main aim of this chapter is to contribute to the understanding of collective heating initiatives in the city of Amsterdam in relation to energy justice. The technological changes needed to achieve political ambitions for reducing fossil fuel use and greenhouse gas emission create opportunities for rethinking how urban energy supply is organised, not necessarily following a strict market logic, but also creating space for empowering local communities. In this chapter, it is analysed in which way collective heating initiatives can be seen as 'commoning practices' contesting current relations between governmental bodies, businesses and urban residents, pursuing new forms of local autonomy, physical heating infrastructures and decision-making procedures. The ethnographic fieldwork has shown that (i) there are energy justice concerns related to transforming urban heating systems in Amsterdam, (ii) collective heating initiatives are envisioned to make positive contributions to neighbourhoods, increasing control of users over energy systems and other local issues, (iii) commoning practices can open up spaces to contest and reshape current relations between citizen-led, public and private parties, and (iv) new energy justice challenges do also arise from citizen-driven heating initiatives.

For further research, the concept of energy justice could be used to support establishing commoning practices which contribute to ‘just’ heating systems. Commoning practices dynamically shape and reshape the energy infrastructure and therefore energy justice arrangements. The new realities created by commoning practices do therefore not necessarily improve energy justice, but can shape or create new structures of marginalisation. The following questions could therefore be asked to study which injustices may occur through commoning practices. Can neighbourhood initiatives cause processes of in- and exclusion of people from decision-making? How to enforce democratic ways of decision-making? What are the risks associated with commercialisation or enclosure of neighbourhood-based heating initiatives? And, does a focus on the neighbourhood create or reinforce spatially distributed injustices? Moreover, this study only considers local conceptions of energy justice. To study the potential injustices that may occur through commoning practices, experienced injustices arising from the extraction, processing, transportation and disposal of energy resources in other parts of the world outside the Netherlands should also be included (Healy et al., 2019).

To conclude, the notion of commoning practices can help to discern users of infrastructures as active actors, which drive developments in the city, and enable to describe processes in which citizen-driven initiatives gain influence or responsibility over (the decision making of) infrastructures. It has been shown that commoning practices may be based on, run into, shape, and potentially create energy justice issues. Based on these insights, it is argued that the concept of commoning practices can enhance a dynamic understanding of how ideas on energy justice shape and are shaped by collective heating initiatives for urban heating systems (see Figure 6.4). Analysing the drives and practices of these initiatives can therefore help to display how urban developments are contested, potentially empowering the actual users of these systems, and working towards ideals of just policies and practices.

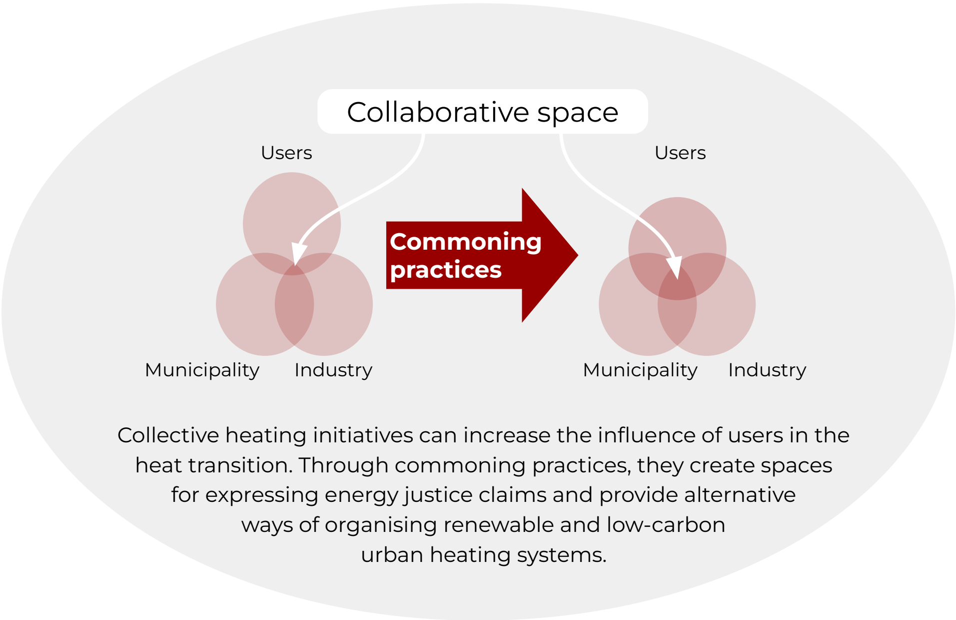


Figure 6.4: Conceptual representation of the link between collective heating initiatives and energy justice in the city of Amsterdam. Commoning practices can increase the influence of users in the heat transition by responding to and shaping (new) energy justice challenges.

7

Synthesis, discussion and research outlook

This thesis presents an exploration of social-environmental-technological transformations caused at multiple scales by a transition towards low-carbon and renewable heating systems in the city of Amsterdam. To study these changes and generate perspectives on both physical and socio-political contexts, it is proposed in this thesis to complement nexus studies with social science research methods. Furthermore, this thesis was not only intended to be a study on transformations, but also to positively contribute to transformations towards 'safe and just' urban heating systems (Raworth, 2017). In this chapter, this work is therefore discussed guided by the framework on 'transformation research' as defined by Hölscher et al. (2021). Last, an outlook on potential future avenues building upon this thesis is given.

7.1. SYNTHESIS OF RESEARCH

The aim of this thesis is to provide multiple perspectives on how urban sustainability transitions interact with social-environmental-technological transformations at different scales. This is done to inform how potential negative effects associated with those changes can be minimised. Due to the different ontological qualities of what can be traced and what is measured, it is proposed in Chapter 2, to complement nexus research with social science research approaches inspired by political ecology, interrogating questions of power, situatedness and mutual interaction between society, technology and nature. Moreover, it was proposed to take infrastructures as unit of analysis to trace social-environmental-technological changes. The infrastructures which take centre stage in this thesis are urban systems for space and tap water heating in the city of Amsterdam. The three studies presented in this thesis trace the multiscalar linkages of the transition towards renewable and low-carbon infrastructures with water use, committed emissions and energy justice. To generate these three studies, multiple advances were made in different concepts and methods. These concepts and methods are summarised in Table 7.1.

Table 7.1: Synthesis of concepts, methods and approaches applied in this thesis.

Chapter	Concepts	Approaches/Methods
4. The water use of heating pathways to 2050: analysis of national and urban energy scenarios	Water-Energy Nexus, Virtual Water Flows, Water Footprint	Multi-scale water and energy use model, scenario analysis
5. Reducing committed emissions of heating towards 2050: analysis of scenarios for the insulation of buildings and the decarbonisation of electricity generation	Committed emissions, direct and indirect carbon emissions, minimal heat density, maximal heat capacity, emission factors,	Bottom-up heat demand model, mixed-integer non-linear optimisation, scenario analysis
6. 'Commoning practices' for energy justice? A perspective on collective heating initiatives in the city of Amsterdam	Commoning practices, urban commons, energy justice, collective heating initiatives	Semi-structured interviews, participant observation, urban ethnography

In a nutshell, in Chapter 4 an extension is provided for current Water-Energy Nexus studies by assessing the water use of heating at multiple scales for different technological scenarios that are driven by underlying governance pathways for the Netherlands and Amsterdam. This study adds to the current body of literature, because water-assessment studies mostly existed for electricity production only, excluding water use for heating. In Chapter 5, existing approaches for the planning of energy systems, i.e. heat demand models and carbon footprint assessments, are integrated to find spatially explicit heat mixes with the lowest cumulative carbon emissions over time under different scenarios for the insulation of buildings and decarbonisation of electricity production. At last, in Chapter 6 advances to the concepts of energy justice and commoning practices are made by applying these concepts in urban anthropological research on how technological infrastructures shape and are shaped by new ways of thinking, doing and organising

Table 7.2: Recap research results on water use (Chapter 4), committed emissions (Chapter 5), and energy justice (Chapter 6).

	Water Use	Committed Emissions	Energy Justice
i.	The water withdrawal for heating can increase up to the same order of magnitude as the current water withdrawal of thermal power plants due to the use of ATES.	The committed emissions can be ten times lower between 2030 and 2050 if ambitious measures are taken for the insulation of buildings and the decarbonisation of electricity generation.	There are energy justice concerns related to transforming urban heating systems in Amsterdam.
ii.	The virtual water use for heating can become higher than the operational water consumption for heating.	High temperature heat options can be part of the heat mix with the lowest committed emissions.	Collective heating initiatives are envisioned to make positive contributions to neighbourhoods, increasing control of users over energy systems and other local issues.
iii.	The water use for electricity production becomes a relevant indicator for the virtual water use for heat generation because of the increase in Power-to-Heat applications.	Low temperature heating systems are optimal solutions in scenarios with ambitious insulation and decarbonisation measures for lowering committed emissions.	Commoning practices can open up spaces to contest and reshape current relations between citizen-led, public and private parties.
iv.		The minimum heat density for low temperature heat networks is not always achieved, which may lead to carbon lock-ins.	New energy justice challenges do also arise from citizen-driven heating initiatives.

(Wittmayer et al., 2022).

The main insights generated with these studies on water use, committed emissions and energy justice are summarised in Table 7.2. These insights are informative for which social-environmental-technological transformations are occurring through the implementation of renewable and low-carbon heating systems. From the study on water use, it is concluded that, due to water withdrawal by ATES systems, future heat production may increase water withdrawal up to the same order of magnitude as current water withdrawals for cooling processes during electricity production. The emphasis on water use for energy production may therefore shift from cooling practices to energy storage. Moreover, virtual water flows embedded in energy carriers made of renewable sources, such as green electricity, biogas and hydrogen, may become more dominant than those virtual water flows embedded in fossil fuels.

In the second study on committed emissions, it is shown that the modelled scenarios with the most ambitious measures for insulation of buildings and decarbonisation of electricity production can increase the update of LT heating systems, significantly reducing committed emissions, avoiding potential carbon lock-ins associated with heat networks and reducing the need for HT heating systems with natural gas, biogas, or hydrogen. A transition towards low-carbon and renewable heating systems therefore does not only require replacements of one heat generation technology by another, but also changes in building insulation, electricity production and integration of multiple thermal energy sources, distribution methods and storage options. Changes in storage options may, as indicated in the first study, increase overall water withdrawals for thermal energy storage.

The third study on energy justice describes how energy justice arrangements shape and are shaped by collective heating initiatives. These initiatives contest and transform current relations between governmental bodies businesses and urban residents through commoning practices.

All three studies show a perspective on how urban transitions shape and are shaped by social-environmental-technological transformations at multiple scales. This thesis, therefore, provides an example of how multidisciplinary research, including mathematical modelling and ethnographic research methods, can provide multiple perspectives on the entanglements between social-environmental-technical changes. In this way, the 'techno-managerial' research approaches associated with nexus research are enriched with approaches interpreting the socio-political context of these resource flows. Presenting three studies with the same infrastructures as unit of analysis facilitates conceptually connecting socio-technical networks and natural resource flows to political dynamics, recognising the strengths of different approaches to contribute to one goal, i.e. facilitating society to operate within planetary boundaries and support human well-being (Raworth, 2017). This thesis is therefore a call for more multidisciplinary work that combine quantitative modelling approaches with qualitative narratives on resource management with infrastructures as unit of analysis.

7

7.2. Discussion on transformation research

In a study on the application and interpretation of the notion of 'transformation' in scientific literature, Hölscher et al. (2018) state that research studying transformations is often intended to contribute towards desirable outcomes of change by identification of potentially detrimental implications of change and of finding ways to achieve desirable outcomes. Moreover, research on transformation interrogates what it is that is actually changing and the outcomes of these changes at a systemic level (Hölscher et al., 2018). The main question of this thesis was: *"What are the socio-environmental-technical transformations at multiple scales caused by a transition towards low-carbon and renewable heating in Amsterdam?"*. With this question, this thesis can thus be characterised as a study of transformations. To reflect on the research methodology applied in this thesis, and relate it to a broader body of literature, it will be discussed in this section to what extent this thesis can be not just qualified as 'a study on transformations', but also considered to be fitting the category of 'transformation research'.

Transformations towards improved ecosystem stewardship and global sustainability have been increasingly studied by a group of resilience scholars since the 1990s (Olsson et al., 2014). In the design of research on transitions, multiple disciplines are combined in the research design to better understand the complexity of real-world problems

(Hölscher et al., 2021). To go beyond understanding, Schneidewind et al. (2016, p.2) pledge for a 'transformative science', which is aimed at achieving "a deeper understanding of ongoing transformations and increased societal capacity for reflexivity with regard to these fundamental change processes". Tellingly, 'transformation research' itself has been slowly growing in the last two decades (Hölscher et al., 2021). Hölscher et al. (2021) define 'transformation research' as a distinct research lens focusing on transformations, with an ultimate goal to contribute to sustainability transitions. This lens has been applied in different research areas such as sustainability science, transition studies, resilience change, and social innovation (Hölscher et al., 2021).

Although transformation research is targeted at supporting the development of society towards more desirable futures, it differs from action research and research on sustainability transitions. Action research is generally applied in social sciences and seeks change by simultaneously doing research and taking action added with critical reflection. Sustainability transition research, on the other hand, has emerged over the past two decades and uses an analytical perspective on transitions for sustainability with notions such as path dependencies, regimes, niches, experiments and governance (Loorbach et al., 2017). Additionally, Hölscher et al. (2018, p.2) argue that transition research is more targeted to explain "how a shift from one state to another is supported or hindered".

Of course, the ultimate goal of this thesis was also to actually contribute to sustainability transitions. In order to reflect on this, the four 'guiding criteria' defined by Hölscher et al. (2021) for the (reflection on the) research design of transformation research will be applied to the research presented in this thesis (see Figure 7.1).

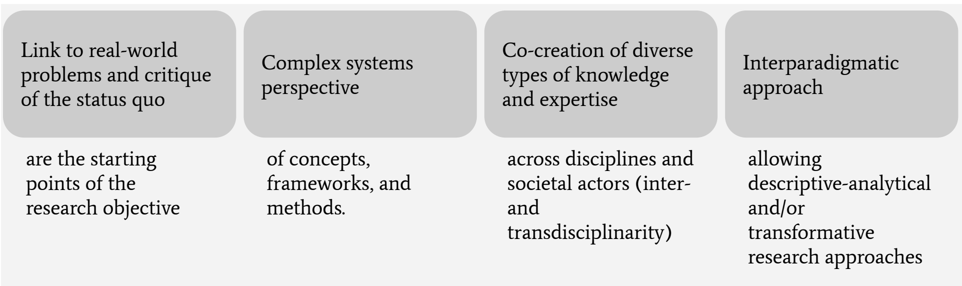


Figure 7.1: Guiding criteria for design of transformation research as formulated by Hölscher et al. (2021).

LINK TO REAL-WORLD PROBLEMS AND CRITIQUE OF THE STATUS QUO

The first criterion is that the research should be linked to 'link to real-world problems and critique of the status quo'. This implies that the starting point of transformative research contains value judgements and is thus explicitly normative. This thesis is based on the belief that a transition towards low-carbon and renewable heating systems is key to solving problems related to climate change, fuel depletion, air pollution and geopolitical relations. By assessing the changes induced by a Heat Transition on water use and energy justice, real-world problems related to water stress and energy democracy are included.

The three studies presented contain critiques on the status quo of current energy research in three ways. First, it is argued that the water use of urban heating systems should be included in the design of these systems on top of indicators such as carbon emissions and costs. Although studies for the assessment of water use of electricity production were present, this was not yet the case for heating systems. Second, it is argued that the cumulative carbon emissions over time should be leading to interventions for the decarbonisation of the built environment instead of the goal towards low carbon emissions at a certain point in time. This is important to stay within the carbon budget. At last, by taking the notion of energy justice, the study presented in Chapter 6 shows current contestations on how the Heat Transition is predominantly organised.

Complex systems perspective

Transformation research "acknowledges the complexity of systems and the difficulty this implies for describing, analysing and intervening in systems". (Hölscher et al., 2021, p.3). In a review on the meaning of complex systems across natural and social sciences, Ladyman et al. (2013) provide multiple features that are widely associated with the term, i.e. nonlinearity, feedback, spontaneous order, lack of central control, emergence, hierarchical organisation and numerosity of elements. All three studies included different complex systems perspectives to a certain extent. In the first study, multiple feedback loops are considered to account for indirect water use at different scales. Changes in the electricity mix on the national scale influence, for example, the indirect water use associated with P2H applications at both the national and urban levels. There is also a hierarchical order of local, national and global virtual water flows embedded in energy carriers. In the second study, a nonlinear model is applied to account for the criteria posed on the feasibility of infrastructures both at address and neighbourhood levels. The research discussed in the third study can be described as a systems approach in the sense that it studies how the practices of collective heating initiatives are part of urban heating systems. In order to avoid reifying different actors in the network, seeing them as separate entities, and insinuating that the intention of the research was to find certain causal relations, an assemblage perspective, as discussed in Section 2.2, is taken for this research. Assemblages are also characterised by the numerosity of (heterogeneous) elements and hierarchical organisation (McLean, 2017; Delanda, 2006).

Co-creation of diverse types of knowledge and expertise

The developed approaches were performed in collaboration with people across research disciplines and societal actors. The academic backgrounds of all the authors of the papers associated with the main chapters were: control engineering, mathematical optimisation, water resources management, energy systems, hydrology, ethics of technology, urbanism, theoretical physics, anthropology, and environmental science. Moreover, other societal actors were included, for example the Amsterdam Institute for Advanced Metropolitan Solutions (AMS Institute).

The outcomes of this PhD project were not only typical 'academic knowledge' in the shape of peer-reviewed papers and conference presentations. A policy brief was written, and the work was communicated to multiple policymakers through the context of the project in the VerDuS project and collaboration with the AMS Institute. Most knowledge transfer was done by means of written text and conference presentations.

Due to the ethnographic research methods applied in the last paper, this study was established with local knowledge and lived experiences from societal actors in the city. Although, it was asked to most participants what research questions they would like to be asked by academics, it proved challenging to co-create actionable knowledge within one research project since it requires creating space, time and resources to do so. It can also compete with other (academic) requirements, such as the pressure to publish. Moreover, the abstraction required for the generalisability of academic research may sometimes hinder the applicability of the knowledge created. To overcome some of these challenges, Hölscher et al. (2021) also included guiding questions and criteria for the research process and research results in their proposed framework. One of these is the continuous reflection on the place of institutions such as universities in society. More information on the context of the PhD project on which this thesis is based is therefore given in Chapter 8.

INTER-PARADIGMATIC APPROACH

Miller et al. (2011) argue that academic institutions seeking to produce knowledge sufficient to support sustainability transitions are characterised by epistemological pluralism. As can be read in Section 8.2, the aim of this PhD project was early on to complement nexus studies with ethnographic research methods. As discussed in Chapter 2, the taken approaches differ in paradigms ranging from post-positivism to interpretivism. The assessments on water use and committed emissions presented in Chapters 4 and 5 can be characterised by descriptive-analytical approaches, considering that they consist of computational models applied to describe and analyse potential pathways for the future. Chapter 6, however, focusing on energy justice and using ethnographic research methods is based on an interpretivist approach. As such, a multi-paradigmatic approach is applied in this thesis.

7

7.3. OUTLOOK

To build upon the work performed in this PhD project, there are multiple policy and research avenues to take. Policy and practice recommendations are presented in the front matter of this thesis (See page v). The multiple research avenues are presented in the following.

Overall, this thesis provides a contribution to multidisciplinary research by combining nexus approaches with ethnographic research methods. In this way, it is an example of how to complement nexus research with studies on the socio-political context of case studies. Following, Cairns and Krzywoszynska (2016), spaces must keep on being created to critically engage with the concept of the nexus in order to keep on broadening epistemic boundaries and incorporating multiple voices, perspectives and values. One thing that can, for example, be further explored is the conceptualisation of social-environmental-technical hybrids. Throughout the text in this thesis, it may sometimes seem that there is a clear distinction between the 'social', the 'environmental' and the 'technological'. A more extensive application of approaches in which these domains are seen as hybrids, such as political ecology, would further contribute to a more holistic understanding of how the world around us is shaped.

Moreover, research can be performed by directly extending the three specific studies presented in this thesis. From the first study, the presented framework to quantify water use at multiple scales can be used to qualify the impacts of this water use (see Appendix A.1 on a first exploration of the impacts of thermal energy extraction from surface water). This can support generating actionable knowledge for 'best practices' of water use, improving water security and supporting ecosystems. From the second study, the heat demand models can be improved in order to support the design of energy systems by including multiple building functions and heat demand profiles (Voulis, 2019). The challenge here is to develop robust maximum heat capacity criteria to assess whether heat technologies can supply sufficient amounts of thermal energy at peak demand. From the third study, urban anthropology can help to identify the continuous shaping of different contestations in the Heat Transition and how energy justice can be supported. Providing a political perspective can not only generate insights on local energy justice concerns, but can also serve to increase the understanding of how the low-carbon transition changes jobs and livelihoods globally (Bouzarovski, 2022).

Alternatively, other indicators or social domains connected to the Heat Transition can be studied to explore how urban heating systems can be improved to solve other sustainability challenges. A suggestion for a new research avenue is to explore how the generation, distribution and organisation of thermal energy can take part in a more regenerative economy, moving away from extractive business models and focusing on positively influencing ecosystems and society.

The narrative applied in this thesis is on the 'Heat Transition', i.e. a transition away from natural-gas based heating and towards low-carbon and renewable heating infrastructures. One of the challenges experienced in this thesis is that such a transition is multi-faceted, including the design of energy generation technologies, to the quality of housing and decision-making processes. Instead of taking heating infrastructures as unit of analysis, another focus point for inquiry could be comfortable indoor climates. A comfortable indoor climate in temperate climates does not only include heating, but also cooling. With rising temperatures in the Netherlands, cooling technologies may become more integrated with heating technologies. This is especially the case for most innovative networks at this moment, sometimes referred to as 5th Generation Heat networks, which are decentralised, bi-directional, close to ground temperature networks that use the direct exchange of warm and cold return flows and thermal storage to balance thermal demand and supply (Boesten et al., 2019; Buffa et al., 2019).

In the end, although this thesis is a call for the integration of multiple perspectives to support sustainability transitions, it is also an acknowledgement that society will keep on desiring new characteristics from its infrastructures based on changing values. This can stimulate the most trendy research and visions on how infrastructures, such as urban heating systems, can look like. Although I believe in the power of tinkering for innovation and the blessing of creative freedom, in my opinion, the core focus should remain on establishing structures in which basic needs, such as a warm house, can be fulfilled in a dignified manner for all while respecting planet Earth. The fight against climate change is not just a battle against greenhouse gas emissions. It is rather about navigating changes in the physical and imagined world for creating a place for all.

8

Afterword: the context of this PhD project

Miller et al. (2011) argue that academic institutions seeking to produce knowledge sufficient to contribute to 'sustainability transitions' should be characterised by reflectivity. Transformations research as defined by Hölscher et al. (2021) is purposefully aimed at shaping existing power structures, but is unavoidable, like all research, also shaped by these same structures. It is therefore explicitly a political practice, which requires critical reflection on the current ways of thinking, doing and organising that researchers are embedded in themselves (Wittmayer et al., 2022). Reflection on the research and acknowledgement of it shaping socio-political structures, and material and imaginary realities can open up space to clarify assumptions, values and interests underlying research questions explicitly (Hölscher et al., 2021). In the following, a short reflection is given on the set-up, trajectory and supportive surroundings of this PhD project.

Figure 8.1: ENLARGE research consortium. Picture taken at 14 July 2019 during the mid-term consortium meeting in Montpellier, France.

8.1. ABOUT THE RESEARCH CONSORTIUM

8

This PhD project was part of a research consortium called ENLARGE, which took place in 2018-2021 (see Figure 8.1). This acronym stands for 'ENabling LARGE-scale adaptive integration of technology hubs to enhance community resilience through decentralised urban Water-Energy-Food (WEF) Nexus decision support'. The main aim of this project was to develop models and tools to facilitate urban decision-making processes for innovations at different scales and locations. Central in our analysis was the WEF Nexus. In general, 'nexus' research is aimed at identifying links between the production and use of different material flows. This makes it possible to identify synergies, trade-offs and risks associated with sectoral transitions. The ENLARGE team assesses the impact of scenarios for metropolitan challenges at decision-relevant scales. In addition to research in the field of economic and environmental sustainability, the ENLARGE team also investigated the topics of social resilience and equity.

ENLARGE consisted of an international research consortium primarily focusing on three cities. In the city of Miami, United States of America, the role of urban agriculture in fresh food provision was studied, and in the French city of Marseille, the recycling of raw materials from wastewater and the effect of urban vegetation on urban heat islands was investigated. The Dutch part of the research consortium consisted of Dr Ir. Edo Abraham and Dr Igor Tempels Moreno Pessoa and Chelsea Kaandorp. The Dutch team focused on the social-ecological consequences of transitioning towards natural gas-free heating systems in the city of Amsterdam and worked collaborated with the AMS Institute. The consortium members are affiliated with the University of Central Florida, University of

Florida, and in France at the Institut national de recherche en sciences et technologies pour l'environnement et l'agriculture (IRSTEA), Ecofilae and Ecosec.

The ENLARGE project has received funding through the Sustainable Urban Global Initiative (SUGI) co-sponsored by the Belmont Forum, JPI Urban Europe and the European Commission. The Dutch contribution to SUGI is provided by the *Verbinden van Duurzame Steden* (VerDuS) knowledge programme Smart Urban Regions of the Future (SURF) of the Ministries of Infrastructure and Water Management, the Interior and Kingdom Relations, Economic Affairs and Climate, the Dutch Research Council, Platform31 and the National Governing Body for Practical Research SIA.

8.2. PHD PROJECT GOALS AND TRAJECTORY

After the first three months of this PhD project, the research objective as stated in the PhD Agreement was to:

"*contribute to the ENLARGE project by focusing on the Food-Water-Energy Nexus in Amsterdam. The goal is to optimally integrate and mobilise food, water and energy resources in a synergistic way to reduce water, carbon, and ecological footprints, and increase the community resilience against challenges exacerbated by climate change and population growth. The output of this project will be actionable knowledge that is useful for partners in Amsterdam, most likely Waternet and AMS. This knowledge will be produced by looking at the Amsterdam Metropolitan Area from different scales. First, an urban metabolism will be modelled for the urban scale. Secondly, the PhD Candidate will perform ethnographic methods for a certain project on a local scale. This approach will solidify the models and the research outputs by placing food-water-energy nexus research in a social contemporary context*".

Led by the ENLARGE project, the PhD project on which this thesis is based thus started with the notion of WEF Nexus in the city of Amsterdam. In the first year, I studied together with the ENLARGE team multiple urban transformations such as heating and cooling with water, resource recycling from wastewater, increasing urban green spaces as Nature-Based Solutions, and shifting urban diets. Because of my interest in water resources and the position of the supervisory team at the Water Management department of the TU Delft, at one point Edo and I asked ourselves the question of which processes have the most impact on water use in the Netherlands. We learned that most water in the Netherlands is pumped up for cooling power plants, and therefore started to question the role of renewable heating systems in the water used for energy, which resulted in the study performed in Chapter 4.

The study, presented in Chapter 4, consists of a multi-scale water and energy use model that accounts for the interdependencies between water and energy resources for current technology mixes and scenarios. It therefore considers how different political scenarios influence environmental flows (Acreman, 2016). Based on the results, it was expected that water use for electricity production would decrease in the scenarios in which thermal power plants are replaced by wind and solar energy. On the other hand, more water withdrawal was expected for the supply of heat due to an increase in ATES and hydrothermal energy extraction. From the study, it is concluded that the water withdrawal for heating can become as significant as the water withdrawal of thermoelectric power plants in 2015 if only around a tenth of the heating is supplied through ATES. This means that the water use of groundwater will change significantly. In Appendix A.1, an exploration of the implications of increased water use for heating is presented.

Another result of the insight into the strong linkages between energy and water was that the ambit of this PhD project turned out to be the Heat Transition in Amsterdam. After the first year of the PhD project, the goal of the project was to be: "*integrating spatio-temporal modelling and optimisation techniques with social science research methods to support a sustainable heat transition in the City of Amsterdam*". Besides a static model on the urban and national scale, the plan in this PhD thesis was thus to also work with spatio-temporal models with a higher resolution and optimisation techniques.

The specific idea to play with carbon emissions on the neighbourhood level was shaped during the Master's thesis project of Tes Miedema. Tes and her supervisory, team, including me, Edo Abraham and Jan-Peter van der Hoek, were looking for indicators for the sustainability, feasibility and affordability of urban heating systems. Feasibility was about whether for example enough thermal energy could be extracted from surface water. Heat demand and modelling for neighbourhoods were an important part of that. Sustainability was reflected most in the amount of carbon emissions. Estimating the amount of carbon emissions for heat technologies however deemed complex because it depends on multiple factors such as carbon intensity of electricity and heat demand at the building and neighbourhood level. One of my frustrations was also that heat networks were in some reports depicted as less carbon-intensive than electric heat pumps, which may not be the case in low-carbon electricity futures.

Building on Tes Miedema's thesis work, a bottom-up heat demand model for neighbourhoods was developed. Challenges around this bottom-up heat demand model and the maximum heat capacity criteria were addressed with help from Maéva Dang at the AMS Institute. Although different scenarios could be modelled, the results gave limited insights into the temporal interplay of changes in heat demand and decarbonisation of electricity production in the neighbourhoods. Because of the non-linear interactions between heat demand on both building and neighbourhood levels and their interaction with the criteria, the model got extended into an optimisation model with the help of Jeroen Verhagen. In this way, a multi-scale optimisation model was built to answer which heat technologies are optimal for reducing committed emissions based on different pathways for the energy transition in the Netherlands. It thus answers how changes in political ambitions influence which technology mix can be best applied to reduce committed emissions.

From the start of the PhD, the aim was to combine computational modelling approaches with ethnographic research methods to juxtapose nexus thinking with narratives on urban heating infrastructures in Amsterdam. This study proved to be the most adaptive. The first interviews for this study were already performed in October 2019, but the continuation of the study was pushed forward towards October 2020 first and later became January 2022, mostly due to the COVID pandemic. Igor, Edo and I tried to shift the research methods to online ethnography, but we were not satisfied with the quality of the data. This is why we continued with the fieldwork at the beginning of 2022. Originally, the research question was how people experience a diversity of heating systems in the city. The idea was to analyse this question with notions such as energy justice, splintering networks and social resilience. From the start of the interviews, it was clear that there was a tension between urban heat systems being a commodity but also something which is considered to be something that should be accessible for all. We heard complaints about the major district heating systems and did see citizen initiatives being brought forward as alternatives. When we decided to focus on the notion of 'commons' and citizen initiatives, the idea of 'commoning practices' came up. This is how the aim of the study was shifted towards the notion of urban commons and, more specifically, its relationship with energy justice in the context of low-carbon heating initiatives in the city of Amsterdam, resulting in the study presented in Chapter 6.

8.3. ACKNOWLEDGEMENTS

I feel privileged when thinking that society as a whole created a position which allowed me to follow my interests and work on complex societal challenges. In this section, I would like to give thanks to some individuals who have had a special role in shaping my experiences over the last couple of years.

First of all, I want to thank my promotors, Edo Abraham and Nick van de Giesen. Edo, I am grateful for the advice you gave me as a supervisor, collaborator, coach, and person. You have been present and supportive during the whole PhD trajectory, always gently pushing me to go one step further. You have given me a lot of freedom to carve out my own research direction, while at the same time being involved and asking critical questions (especially the one 'What does it mean?' in order to make sure that the research outcomes were specific and related to the research to the world around us). With your personal approach, I almost always left our meetings with a smile on my face. Nick, I enjoyed and felt supported by the way that you are down-to-earth, interested in many topics and able to see the bigger picture. Thank you for the freedom you gave me in the project and for thinking along with me about future career possibilities.

Furthermore, I had the joy to collaborate with multiple people to write the papers. Igor Pessoa, I have enjoyed our more-than-four-year-lasting collaboration. You have taught me a lot during our weekly meetings and our fieldwork together. Tes Miedema, thank you for trusting me to be your supervisor and giving your time and energy in order to work on our paper. I find your can-do mentality inspiring. Jeroen Verhagen, thank you for your ideas and modelling work on the paper on committed emissions. Udo Pesch, thank you for the advice and input on Chapter 6.

The work in this thesis has been facilitated by many researchers who shared their feedback and ideas during conferences, seminars and other events. Special thanks go out for the input from Elisabeth van de Grift, Els van der Roest, Emanuele Fantini, Jan Peter van der Hoek, Ljiljana Zlatanović, Maéva Dang, Martin Bloemendal, Maurice Ramaker, Maurits Ertsen, Nina Voulis, Tim van Emmerik, and Stef Boesten. Moreover, I thank the committee members Andy van den Dobbelsteen, Charlotte Johnson, Elisabeth Krueger, Martijn Warnier, and Wilfried Ivens for their time and constructive feedback on the dissertation. Much of the research would also not be possible without the participation of experts in the field. I thank the consortium members of *02025* for welcoming me into their organisation. I also thank all participants in the interviews.

Doing a PhD is not only about doing research but also about becoming an 'independent' researcher. I was fortunate that this PhD project was part of the ENLARGE consortium, which was an opportunity to learn about international collaborations and different research fields. I enjoyed our kick-off in Amsterdam, our mid-term in Montpellier, and our recurring meetings. I am additionally thankful for the support of VerDuS, JPI Urban Europe and Platform31 in communicating the research to stakeholders through organising events, interviews or publishing our policy briefs. I am moreover grateful for the opportunities offered by the AMS Institute to connect to other researchers, the municipality of Amsterdam, and urban professionals. I have enjoyed working at the AMS Institute's office in Amsterdam.

These last couple of years would also not be as enjoyable and rich of experiences without the colleagues at the TU Delft. Betty Rothfusz, Fleur van de Water, Lydia de

8

Hoog, Tamara Auperlé, and Petra Jorritsma, thank you for all your support. Martine Rutten, thank you for involving me in Delta Futures Lab. Erik Mostert, Marie-Claire ten Veldhuis, Miriam Coenders, Remko Uijlenhoet, Rolf Hut, Ruud van der Ent, Saket Pande, and many others, thank you for the wonderful interactions and conversations.

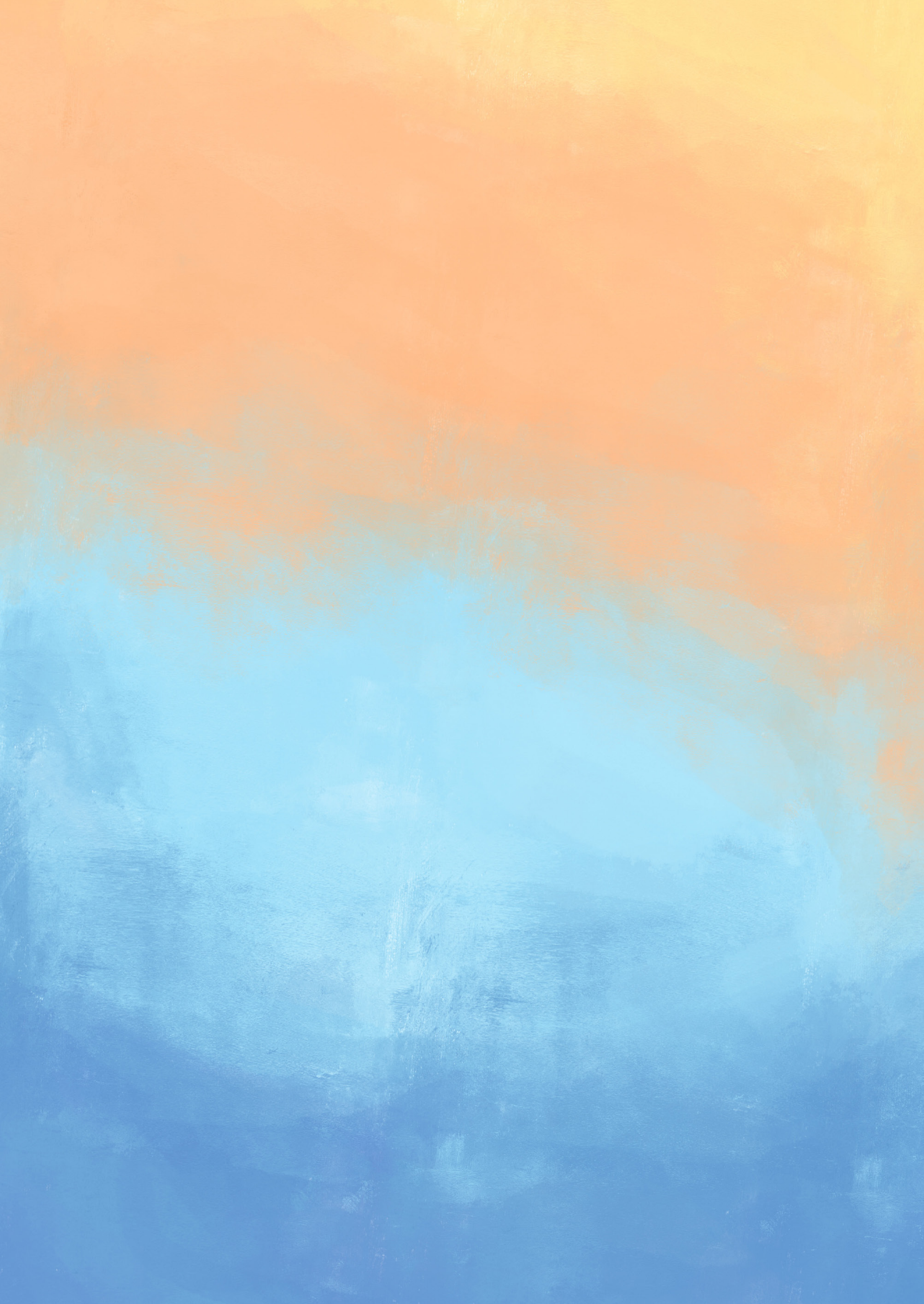
It has been a privilege to work at a university with high-quality support from HR, career counsellors, psychologists and the Sports and Culture Centre. The dance classes given by Iris and Lisa made me feel more at home in Delft in the first months and helped me stay grounded. Additionally, I am grateful for being part of a student association for dancing, D.S.D.A. Dynamic, which was founded during the COVID pandemic and grew into a vibrant society.

I have had the opportunity to share my office with great personalities. In 2018, I was welcomed into an office with Anjana Ekka, César Dionisio Jiménez Rodríguez, Elisa Ragno, and Uwacu Alban Singirankabo. I have happy memories of our conversations about food, snow and doing a PhD. Anjana, I am grateful for our tea, cooking and yoga sessions outside the office. Now, in 2023, I am sharing an office with four inspiring women: Roya Mourad, Schuyler Houser, Tessel Grubben, and Yee Mon Thu.

Beyond the office, the departments consist of a large group of PhD Candidates and Postdocs who act as colleagues, peers and friends. Alexandra Rocio Urgilez Vinueza, I am grateful for our time being neighbours at the Papenstraat. Boran Ekin Aydin, thank you for welcoming me to the team. Laurène Bouaziz, I have valued our lunch walks during the COVID-19 pandemic and I am happy that you are my paranimf. Luuk van der Valk, thank you for our coffee walks in Delft and I am happy that you are my other paranimf. Ties van der Heijden, thank you for creating more *gezeligheid* in and outside the office. Alireza Shefaei, Bahareh Kianfar, Banafsheh Abdollahi, Bart Schilperoort, Bas des Tombe, Bas Walraven, Dengxiao Lang, Fransje van Oorschot, Gaby Gründemann, Indushree Banerjee, Jerom Aerts, Juan Carlo Intriago Zambrano, Juan Pablo Aguilar López, Judith Boekee, Mónica Estébanez Camarena, Muhammad Ibrahim, Paul Vermunt, Reza Pramana, Sehouevi Mawuton David Agoungbome, Thijs van Esch, and many others, thank you for the enjoyable time spent during lunches, drinks, walks, EGU conferences and at the coffee corner. I am grateful for the happy memories and hope to see many of you in the future.

This PhD would also have been very difficult without the joyful and supportive moments shared with friends and family. Idelès, thank you for being my biggest supporter and source of inspiration. Joke, thank you for making many things in life more festive. Freek, you have been there almost every step along the way these past 5 years. I am grateful for your love and care, and look back happily to our time in Delft. Hildegard en Chris, thank you for welcoming me into your home as a daughter-in-law and for our many dinners and conversations during the past few years. Toine, thank you for your support and advice over the years. Mamma, I am writing this 25 years after attending your PhD defence as a toddler. I am proud to follow in your footsteps and I am grateful for all your support.

This thesis is dedicated in loving memory to my father, David Djir, who passed away in January 2020. He has been a great support and motivator for me, and I am grateful for his dreams, experiences, and care.



A

Supplementary Material to Chapter 4

Chapter 4 is based on the text in Kaandorp et al. (2021a). The in- and output tables provided in this Appendix can also be found in the supplementary material of Kaandorp et al. (2021a) or in the workbook uploaded at the 4TU data repository (Kaandorp et al., 2023a).

A.1. CASE STUDY ON HYDROTHERMAL ENERGY

Hydrothermal energy can be a relevant low-carbon heat source for future low-carbon heating systems in the Netherlands. A conservative estimate is that 12% of the Dutch heat demand can be provided with hydrothermal energy (Bruggers and Van Weren, 2017). By Municipality of Amsterdam (2019a), it has even been estimated that 40 to 60%, i.e. up to 15 Petajoules, of the total heat demand can be extracted from surface water (see Figure A.1). Although the potential for hydrothermal energy is high in Amsterdam, the amount of possible thermal energy extraction depends on the time of extraction and the size of the water body.

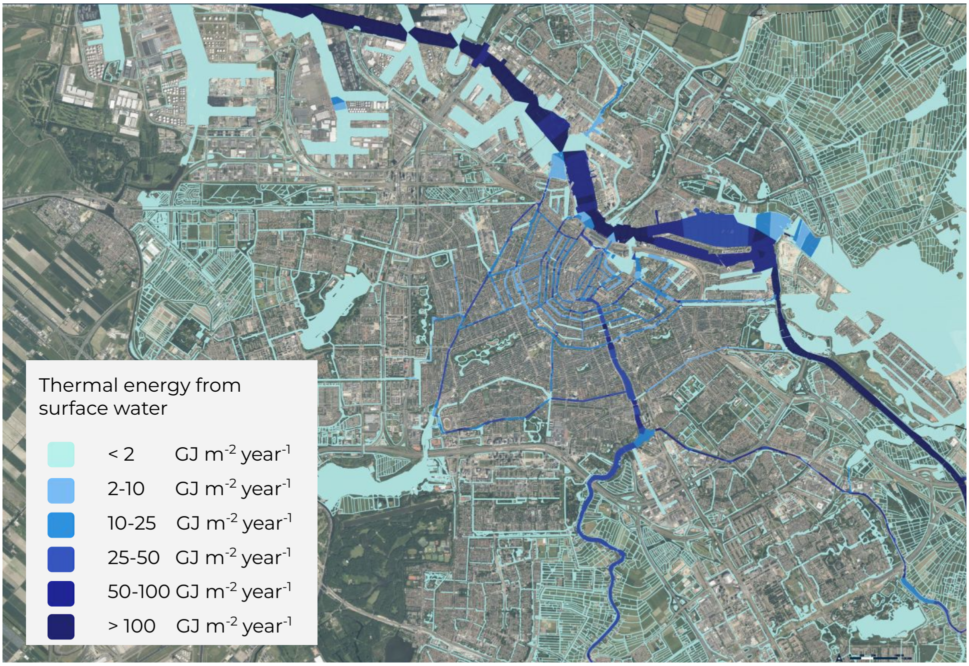


Figure A.1: Thermal energy from surface water. Edited map from the Ambient Heat map (Dutch: *Omgevingswarmtekaart*) from Waternet (2023).

Hydrothermal energy can be applied in two different ways. The thermal energy can be used directly to cool and heat buildings, or it can be stored so that the thermal energy can be used in another season. During the bachelor thesis project of Dominique Kromwijk, hydrothermal energy from water bodies in Amsterdam called *'t IJ*, *Kostverlorenvaart*, the *Amstel*, and the *Weespertrekvaart* were studied (Kromwijk, 2020). As a result, hydrothermal energy extraction with seasonal storage appears to be better for the ecology, as it cools the surface water in summer instead of heating it up. This is good for the oxygen content and reduces algae growth and botulism. Because the Kostverlorenvaart is the narrowest canal and therefore has the least surface area, less thermal energy can be exchanged with the outside air than in the other waters. As a result, the limit of thermal changes within this canal must be carefully considered. Research and regulations on the ecological impact of heating on surface water use should therefore be a main pillar for the sustainable design of future heating systems in the Netherlands.

Moreover, from the analysis performed in the Master's thesis of Tes Miedema, it is concluded that the thermal energy available from the surface water in the Felix Meritis neighbourhood is not sufficient to meet the thermal energy demand in this neighbourhood in a scenario that all buildings are insulated up to level B (Miedema, 2020). This implies that a combination of heat sources is required when hydrothermal energy is a desirable heat source in this neighbourhood.

A.2. INPUT TABLES

Table A.1: Range of values for water consumption per unit of produced energy given by literature and the used value in this research. The used values in this research are the mean values given in the literature, if not stated otherwise. All thermoelectric power plants are assumed to be cooled by once-through cooling because of the high availability of water resources in the Netherlands. The water consumption rates are assumed to be a tenth of the rates of corresponding power plants (Mekonnen et al., 2015). The values for the 'gas' technologies are taken from literature on natural gas technologies. We assume that technologies which are fuelled by a mix of natural gas and green gas use the same amount of water as those fuelled by natural gas. Abbreviations: ATES = aquifer thermal energy storage, CC = combined cycle, HP = heat pump, GM = gas motor, GT = gas turbine, PV = photovoltaic, ST = steam turbine,
References: [1] Larsen and Drews (2019), [2] Macknick et al. (2012), [3] Davies et al. (2013), and [4] Meldrum et al. (2013).
[a] The values are the averages from different mean values collected from scientific and grey literature [1].
[b] Assumed to be equal to Gas CC.
[c] Set equal to zero because water ways are not principally used for hydropower in the Netherlands. The range for water consumption and water withdrawal are based on Macknick et al. (2012) and Davies et al. (2013) respectively.
[d] ≪1 means a positive number smaller than 0.1.
[e] No range found in literature.
[f] The range is based on Macknick et al. (2012) and used value is based on Larsen and Drews (2019).
[g] Closed system.
[h] Set equal to Biomass Combined Heat and Power (CHP).

Application	Technologies	Water consumption [m^3 / TJ]			Reference
		min	max	used	
Electricity	Coal ST	2.22	392	194	[1][a]
	Hydrogen CC	21.0	105	105	[2][b]
	Hydropower	1 425	18 918	0	[2], [3][c,d]
	Gas CC	21.0	105	105	[2]
	Gas GT	52.6	357	52.6	[4][e]
	Nuclear power	105	420	343	[1][a], [2][f]
	Solar PV	1.05	27.3	6	[4]
	Wind Turbine	≪1	0.5	0	[4][d]
Combined Heat and Power	Biomass	-	-	31.5	[2][e]
	Coal ST	0.222	39.2	19.4	[1][a]
	Gas CC	2.10	10.5	10.5	[2]
	Gas GM	-	-	0	[g]
	Gas GT	5.26	35.7	5.26	[4][e]
	Waste CHP	-	-	31.5	[h]

A

Table A.2: Range of values for water withdrawal per unit of produced energy given by literature and the used value in this research. The used values in this research are the mean values given in the literature, if not stated otherwise. All thermoelectric power plants are assumed to be cooled by once-through cooling because of the high availability of water resources in the Netherlands. The water consumption rates are assumed to be a tenth of the rates of corresponding power plants (Mekonnen et al., 2015). The values for the 'gas' technologies are taken from literature on natural gas technologies. We assume that technologies which are fuelled by a mix of natural gas and green gas use the same amount of water as those fuelled by natural gas. Abbreviations: ATES = aquifer thermal energy storage, CC = combined cycle, HP = heat pump, GM = gas motor, GT = gas turbine, PV = photovoltaic, ST = steam turbine,
References: [1] Larsen and Drews (2019), [2] Macknick et al. (2012), [3] Davies et al. (2013), and [4] Meldrum et al. (2013)
[a] The values are the averages from different mean values collected from scientific and grey literature Larsen and Drews (2019).
[b] Assumed to be equal to Gas CC.
[c] Set equal to zero because waterways are not principally used for hydropower in the Netherlands. The range for water consumption and water withdrawal are based on Macknick et al. (2012) and Davies et al. (2013) respectively.
[d] ≪1 means a positive number smaller than 0.1.
[e] No range given: reference only give value from one source.
[f] The range is based on Macknick et al. (2012) and value based on Larsen and Drews (2019).
[g] Closed system.
[h] Set equal to Biomass Combined Heat and Power (CHP).

Application	Technologies	Water withdrawal [m^3 / TJ]			Reference
		min	max	used	
Electricity	Coal ST	1 940	50 000	28 800	[1][a]
	Hydrogen CC	7 883	21 020	12 000	[2][b]
	Hydropower	-	≪1	0	[2], [3][c,d]
	Gas CC	7 883	21 020	12 000	[2]
	Gas GT	-	-	462	[4][e]
	Nuclear power	26 275	63 060	35 400	[1][a], [2][f]
	Solar PV	1.05	27.3	6	[4]
	Wind Turbine	≪1	3	2	[4][d]
Combined Heat and Power	Biomass	2 102	5 255	3 680	[2][e]
	Coal ST	194	5 000	2 880	[1][a]
	Gas CC	788	2 102	1 200	[2]
	Gas GM	-	-	0	[g]
	Gas GT	-	-	46.2	[4][e]
	Waste CHP	2 102	5 255	3 680	[h]

Table A.3: Water withdrawal per unit of produced energy for combustion-free heat sources. The values are calculated with Equation 4.1 in Chapter 4. Abbreviations: ATES = aquifer thermal energy storage, BTES = borehole thermal energy storage, and HN = heat network.

Heat source	Water withdrawal [m^3 / TJ]	Remark
Aerothermal HP	0	No operational water use assumed.
ATES	59 780	$\Delta T = 4$
BTES	0	Closed system.
Electric boiler	0	No operational water use assumed.
Geothermal	5 978	$\Delta T = 40$
Hydrothermal	59 780	$\Delta T = 4$
Industrial HN	0	Closed system.
Solar heat	0	Closed system.

Table A.4: Energy Required for Energy (ERE) factors for electricity and heat production expressed in the fraction of amount of heat energy (J_h) per fuel needed for the production of either electricity (J_e) or heat (J_h). A range is given in case this was given in the reference literature. The value in brackets designates the mean value given in the reference literature and the used value in this research. Abbreviations: ST = steam turbine, CC = combined cycle, GM = gas motor, GT = gas turbine. References: [1] U.S. Energy Information Administration (2019), [2] Faaij (2006), [3] Mekonnen et al. (2015), and [4] ETM (2020).

Application	Technologies	Fuel	ERE	Reference
Electricity [TJ_h / TJ_e]	Coal ST	Coal	2.9	[1]
	Hydrogen CC	Hydrogen	1.7	[4]
	Gas CC	Natural gas & biogas	2.2	[1]
	Gas GT	Natural gas & biogas	3.3	[1]
	Nuclear power	Uranium	3.1	[1]
Combined heat and power [TJ_h / TJ_e]	Biomass plant	Biomass	2.5 - 5.0(2.5)	[2], [3]
	Coal ST	Coal	2.9	[1]
	Gas CC	Natural gas & biogas	2.2	[1]
	Gas GM	Natural gas & biogas	2.7	[1]
	Natural Gas GT	Natural gas & biogas	3.3	[1]
	Waste plant	Waste	3.3 - 6.7	[2]
Heat [TJ_h / TJ_h]	Biomass Heater	Biomass	1.1 - 1.4 (1.3)	[2]
	Coal heater	Coal	1.3	[4]
	Gas heater	Natural gas & biogas	1.0	[4]
	Hydrogen Boiler	Hydrogen	1.11	[4]
	Wood Household	Wood	10	[2]

A

Table A.5: Water Footprint per fuel type expressed in units of heat content. A range is given based on the values found in the literature. The mean values mentioned in literature are the values used in this research. References: [1] Pacetti et al. (2015), [2] Mekonnen et al. (2015), [3] Gerbens-Leenes et al. (2009), and [4] Webber (2007)
[a] In the Netherlands, biogas is mostly made by co-fermentation of manure, sewage sludge or waste Meurink et al. (2019). No water footprint is assigned to the biomass used to make biogas because we assume that these materials are not primarily produced for energy production.
[b] Residual biomass is assumed to be a byproduct from the forestry and lumber industries and does not depend on the energy demand. We therefore assign a zero water footprint to these energy carriers.

Fuel	Water Footprint [m^3/TJ_h]			Reference
	min	max	used	
Biogas	0	79 340	0	[1][a]
Biomass residual	-	-	0	[b]
Biomass wood	19 000	124 000	24 000	[2], [3]
Coal	6.6	228	15	[2]
Hydrogen	75.6	34 216	75.6	[4]
Natural gas	0.6	18	2.2	[2]
Uranium	5.7	169	20.2	[2]

Table A.6: Gas mix of natural gas and green gas in the national gas grid per technology mix. Green gas is assumed to be made from biogas without further water use. The Water Footprint of green gas is therefore set to be equal to the Water Footprint of biogas (ETM, 2020). The values are given as fractions and are therefore unitless.

Gas type	2015	International	European	National	Regional
Natural Gas	1.0	0.424	0.47	0.367	0.423
Green Gas	0.0	0.576	0.53	0.633	0.577

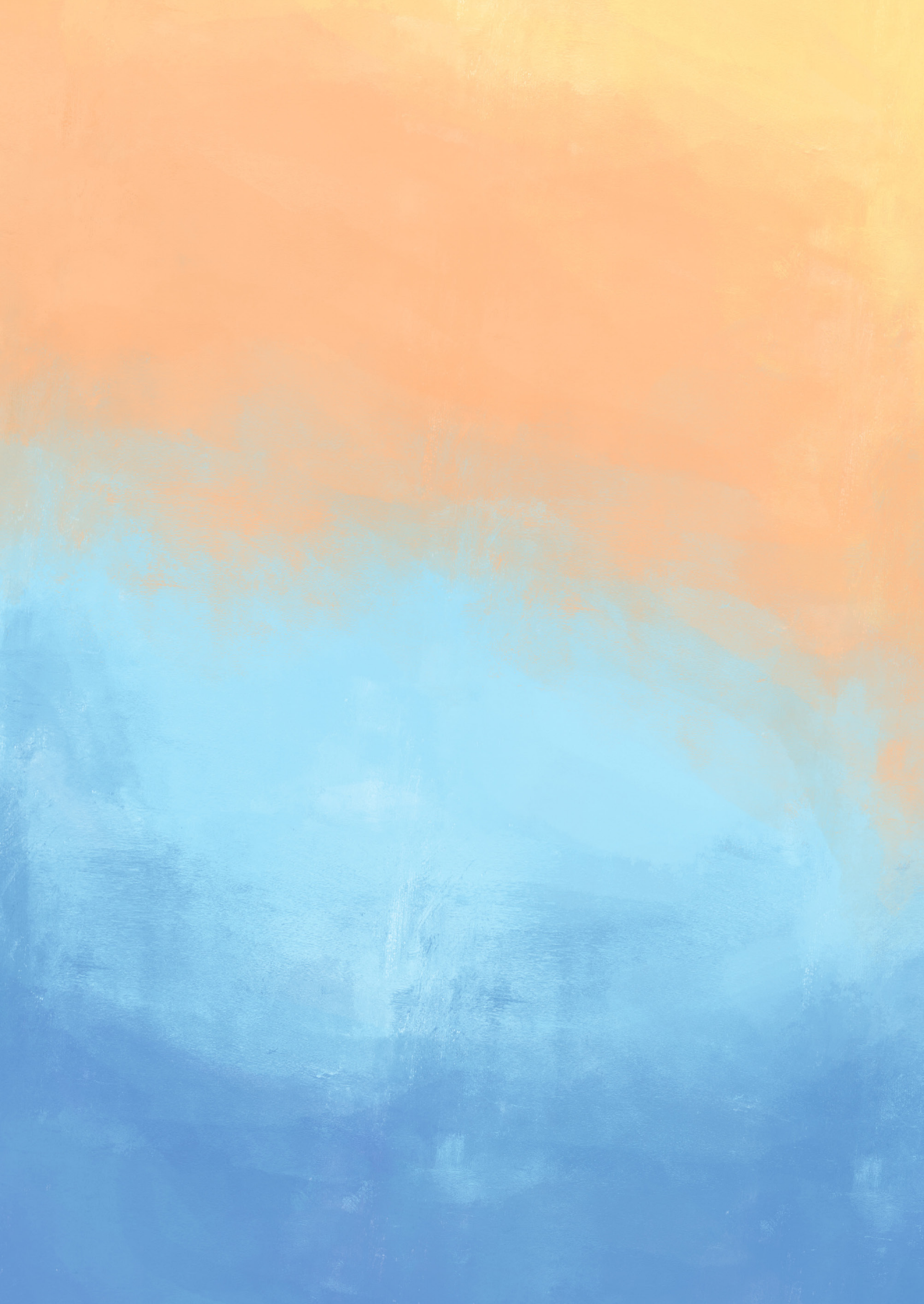
A.3. OUTPUT TABLES

Table A.7: Total national electricity production versus national electricity demand for Power-to-Heat (P2H) applications per scenario.

Scenarios	Electricity production [PJ]	P2H [PJ]
2015	391	2.08
International	450	68.1
European	474	65.0
National	1 230	450
Regional	992	174

Table A.8: Water use to produce electricity for Power-to-Heat (P2H) applications in Amsterdam. The aggregate annual electrical energy needed for Power-to-Heat (P2H) applications in the 2015 and 2050 technology mixes are 68.1 TJ and 1 310 TJ, respectively. The electricity is assumed to be supplied from the national grid. The water use to generate this amount of electricity thus depends on the technology mix of electricity scenarios nationally as shown in the table.

	Water Use for Power-to-Heat (P2H) [m^3]		
Scenarios	Water Withdrawal	Water Consumption	VW_{fuel}
2015	8.3×10^5	6.1×10^3	4.2×10^4
International	1.5×10^7	1.1×10^6	2.1×10^4
European	1.6×10^7	1.2×10^5	2.4×10^4
National	4.1×10^5	4.5×10^3	5.9×10^2
Regional	1.1×10^6	1.3×10^4	7.1×10^3



B

Supplementary Material to Chapter 5

Chapter 5 is based on the text in Kaandorp et al. (2022). The code and tables provided in this Appendix can also be found in the supplementary material of Kaandorp et al. (2022) or in the workbook uploaded at the 4TU data repository (Kaandorp et al., 2023b).

B

B.1. BOTTOM-UP HEAT DEMAND MODEL

In this section, we present the input and output data of the bottom-up heat demand model used. The input data on the size parameters per building type, the infiltration rates, the insulation specifications, and the thermal resistances are presented in Tables B.1 and B.2, Figures B.1 and B.2, Tables B.3 and B.4, respectively. The results of the modelled heat demand per building archetype are presented in Figure B.3 and compared to the results of other models in Figure B.4.

The input for the infiltration rates and the output for the heat demand per building archetype are presented for different insulation measures. Insulation measures can be performed to different degrees. We therefore define three different insulation levels: the basic, intermediate, and advanced insulation levels. The basic insulation level represents the minimal ordinary improvements that are performed in practice on the original state of buildings after their construction. The intermediate insulation level represents the more elaborate improvements that are still commonly applied in practice. The advanced insulation level represents technologically complex improvements that happen less often in practice, but are technologically feasible.

The results in Figure B.3 suggest that currently, only building archetypes with a construction year after 1995 can be heated at mid temperature (MT), i.e. the heat demand is lower than 80 kWh m^{-2} $year^{-1}$ (see Table 5.2 for a description the maximum heat capacities for low temperature (LT), MT and high temperature (HT) heating). The results also suggest that all building archetypes have a HT heat demand after basic insulation, i.e. the heat demand is higher than 80 kWh m^{-2} $year^{-1}$. This means that in practice, intermediate or advanced insulation measures need to be taken to bring the heat demand below the HT regime. After intermediate insulation, all buildings built after 1946, except for the detached buildings, have a heat demand below 80 kWh m^{-2} $year^{-1}$ and can therefore be heated with MT heat options. Four out of sixteen building archetypes even have a LT heat demand after intermediate insulation, i.e. the heat demand is lower than 50 kWh m^{-2} $year^{-1}$. This means that if intermediate insulation is applied to a whole neighbourhood, that MT and even HT heat strategies still need to be applied. The results also show that if advanced insulation is implemented, all building archetypes have a heat demand lower than LT level. This means, among other things, that all existing buildings can be retrofitted to a level which is suitable for low-temperature heat systems.

Table B.1: Size parameters per building type. The building envelope areas are extracted from a study by Agentschap NL, presently known as RVO The Netherlands Enterprise Agency (Agentschap NL, 2011).
[a] The building footprint is projected to be the ground floor size divided by 0.9.
[b] The volume is calculated by multiplying the number of floors, the floor height and the usable surface.

Building type	Number of floors [-]	Floor height [m]	Usable surface[m^2]	Ground floor size [a] [m^2]	Volume[b] [m^3]
Terraced	2	3	87	47	282
Semi-detached	2	3	110	66	396
Detached	2	3	130	93	558
Apartment	1	3	71	71	213

		Original state	Basic insulation
< 1945	Specification	Insulation measures	Insulation measures
Groundfloor	Floor with crawlspace	Non-insulated wooden floor	50 mm insulation under floor
Facade	Face without cavitywall	Brickwork no cavity wall	Brickwork no cavity wall
Panel	Panel with cavity wall	Non-insulated panel	Non-insulated panel
Roof		Non-insulated roof	50 mm roof insulation
Windows	-	Single glazing, wooden/plastic frame	HR++ glazing, wooden/plastic frame
Doors	-	Non-insulated door	Non-insulated door
Infiltration	-	No gap sealing	Improved gap sealing
Thermal bridges	-	-	-
Ventilation	-	Natural - natural	Natural-mechanical (C2)
1945-1975	Specificatie	Insulation measures	Insulation measures
Groundfloor	Floor with crawlspace	Non-insulated wooden floor	50 mm insulation under floor
Facade	Face with cavitywall	Brickwork with cavity wall	Brickwork 50 mm cavity wall insulation
Panel	Panel with cavity wall	Non-insulated panel	Non-insulated panel
Roof	Roof with cavity	Non-insulated roof	50 mm roof insulation
Windows	-	Single or double glazing, wooden/plastic frame	HR++ glazing, wooden/plastic frame
Doors	-	Non-insulated door	Non-insulated door
Infiltration	-	No gap sealing	Improved gap sealing
Thermal bridges	-	-	-
Ventilation	-	natural - natural	Natural-mechanical (C4), CO2 steering in living room
1975-1995	Specificatie	Insulation measures	Insulation measures
Groundfloor	Floor with crawlspace	Non-insulated stone-like floor	50 mm insulation under floor
Facade	Face with cavitywall	Brickwork with cavity wall	Brickwork 50 mm cavity wall insulation
Roof	Roof with cavity	Non-insulated roof	50 mm roof insulation
Windows	-	Double glazing	HR++ glazing, wooden/plastic frame
Doors	-	Non-insulated door	Non-insulated door
Infiltration	-	No gap sealing	Improved gap sealing
Thermal bridges	-	-	-
Ventilation	-	Natural - mechanical (C1)	Natural-mechanical (C4) with CO2 steering
>1995	Specificatie	Insulation measures	Insulation measures
Groundfloor	Floor with crawlspace	Minimal floor insulation	Minimal floor insulation
Facade	Face with cavitywall	Brickwork with minimal cavity wall insulation	Brickwork with minimal cavity wall insulation
Panel	Panel with cavity wall	Insulated panel	Insulated panel
Roof	-	Minimal roof insulation	Minimal roof insulation
Windows	-	HR++ glazing, wooden/plastic frame	HR++ glazing, wooden/plastic frame
Doors	-	Non-insulated door	Non-insulated door
Infiltration	-	Minimal gap sealing	Minimal gap sealing
Thermal bridges	-	-	-
Ventilation	-	Natural - mechanical (C1)	Natural-mechanical (C4) with CO2 steering

Figure B.1: Insulation specification per construction period (applied to all building types). Insulation specification for the 'original' and 'basic' insulation levels. Values are taken from the report 'Standard and Target values for existing housing' (in Dutch: *standaard en streefwaardes bestaande woningbouw*) (Cornelisse et al., 2021).

		Intermediate insulation	**Advanced insulation**
< 1945	Specification	Insulation measures	Insulation measures
Groundfloor	Floor with crawlspace	140 mm under floor	140 mm insulation according to ISSO 82.1
Facade	Face without cavitywall	Brickworkd no cavity wall	260 mm insulation according to ISSO 82.1
Panel	Panel with cavity wall	Non-insulated panel	Insulated panel
Roof		150 mm roof insulation	350 mm roof insulation according to ISSO 82.1
Windows	-	HR++ glazing, wooden frame	Triple-glazing with new windowframe
Doors	-	Non-insulated door	Insulated door
Infiltration	-	Improved gap sealing	Good gap sealing
Thermal bridges	-	-	-
Ventilation	-	Natural-mechanical (C2)	Balanced (D3), with CO2 steering
1945-1975	Specificatie	Insulation measures	Insulation measures
Groundfloor	Floor with crawlspace	140 mm under floor	140 mm insulation according to ISSO 82.1
Facade	Face with cavitywall	Brickwork 50 mm cavity wall insulation	260 mm insulation according to ISSO 82.1
Panel	Panel with cavity wall	Non-insulated panel	Insulated panel
Roof	Roof with cavity	150 mm roof insulation	350 mm roof insulation according to ISSO 82.1
Windows	-	HR++ glazing, wooden frame	Triple-glazing with new window frame
Doors	-	Non-insulated door	Insulated door
Infiltration	-	Improved gap sealing	Good gap sealing
Thermal bridges	-	-	-
Ventilation	-	natural-mechanical (C4), with CO2 steering	Balanced (D3), with CO2 steering
1975-1995	Specificatie	Insulation measures	Insulation measures
Groundfloor	Floor with crawlspace	140 mm under floor	140 mm insulation according to ISSO 82.1
Facade	Face with cavitywall	Brickwork 50 mm cavity wall insulation	260 mm insulation according to ISSO 82.1
Roof	Roof with cavity	150 mm roof insulation	350 mm roof insulation according to ISSO 82.1
Windows	-	HR++ glazing, wooden frame	Triple-glazing with new window frame
Doors	-	Non-insulated door	Insulated door
Infiltration	-	Improved gap sealing	Good gap sealing
Thermal bridges	-	-	-
Ventilation	-	natural-mechanical (C4), with CO2 steering	Balanced (D3), with CO2 steering
>1995	Specificatie	Insulation measures	Insulation measures
Groundfloor	Floor with crawlspace	Minimal floor insulation	Minimal floor insulation
Facade	Face with cavitywall	Brickwork with minimal cavity wall insulation	Brickwork with minimal cavity wall insulation
Panel	Panel with cavity wall	Insulated panel	Insulated panel
Roof	-	Minimal roof insulation	Minimal roof insulation
Windows	-	HR++ glazing, wooden/plastic frame	Triple-glazing with new window frame
Doors	-	Non-insulated door	Non-insulated door
Infiltration	-	Minimal gap sealing	Good gap sealing
Thermal bridges	-	-	-
Ventilation	-	Natural-mechanical (C4) with CO2 steering	Balanced (D3), with CO2 steering

Figure B.2: Insulation specification per construction period (applied to all building types). Insulation specification for the 'intermediate' and 'advanced' insulation levels. Values are taken from the report 'Standard and Target values for existing housing' (in Dutch: *standaard en streefwaardes bestaande woningbouw*) (Cornelisse et al., 2021).

Table B.2: Infiltration rates ($q_{v;10}$ values) in SI-units of dm^3 s^{-1} m^{-2}. Values are taken from the report 'Standard and Target values for existing housing' (in Dutch: *standaard en streefwaardes bestaande woningbouw*) (Cornelisse et al., 2021).

		Insulation level			
Building type	Construction period	Basic	Intermediate	Advanced	Current
Apartment	<1946	1.8	1.8	0.4	1.8
	1946 - 1975	0.6	0.42	0.4	0.6
	1976 - 1995	0.6	0.42	0.4	0.6
	>1995	0.6	0.6	0.4	0.6
Detached	<1946	4.2	4.2	0.4	4.2
	1946 - 1975	1.4	1.4	0.4	1.4
	1976 - 1995	1.4	1.4	0.4	1.4
	>1995	1.4	1.4	0.4	1.4
Semi-detached	<1946	3.6	3.6	0.4	3.6
	1946 - 1975	1.2	1.2	0.4	1.2
	1976 - 1995	1.2	1.2	0.4	1.2
	>1995	1.2	1.2	0.4	1.2
Terraced	<1946	3	3	0.4	3
	1946 - 1975	1	1.2	0.4	1
	1976 - 1995	1	1.2	0.4	1
	>1995	1	1	0.4	1

B

Table B.3: Thermal resistances, also known as the R-values, of the different materials of the shell for the 'current' insulation level. Values apply for the current insulation level and four different building types, i.e. 'Apartment', 'Detached', 'Semi-detached', and 'Terraced'. Values are taken from the report 'Standard and Target values for existing housing' (in Dutch: *standaard en streefwaardes bestaande woningbouw*) (Cornelisse et al., 2021).

		Terraced	Semi-detached	Detached	Apartment
< 1945	Ground floor	0.77	0.73	0.94	0.56
	Facade	0.7	0.82	0.99	0.58
	Panel	0.46	0.97	0.98	0.36
	Roof	1.24	1.2	1.42	1.00
	Windows	2.96	3.06	2.98	3.11
	Doors	3.36	3.36	3.35	3.32
1945-1975	Ground floor	0.57	0.6	0.66	0.48
	Facade	0.84	1.06	1.1	0.67
	Panel	0.61	0.9	0.86	0.46
	Roof	1.22	1.23	1.4	0.96
	Windows	2.73	2.69	2.66	2.87
	Doors	3.31	3.32	3.31	3.3
1975-1995	Ground floor	1.16	1.25	1.35	1.16
	Facade	1.53	1.61	1.69	1.66
	Panel	1.48	1.61	1.69	1.66
	Roof	1.5	1.59	1.82	1.66
	Windows	2.82	2.72	2.74	2.91
	Doors	3.33	3.33	3.3	3.32
>1995	Ground floor	2.68	2.63	2.64	2
	Facade	2.68	2.59	2.56	2.61
	Panel	2.77	2.56	2.6	2.7
	Roof	2.75	2.69	2.68	2.67
	Windows	2.1	2.16	2.14	2.16
	Doors	3.27	3.25	3.22	3.28

Table B.4: Thermal resistances, also known as the R-values, of the different materials of the shell of the houses for three insulation levels: 'basic', 'intermediate' and 'advanced'. Values apply for three insulation levels and all building types, i.e. 'Apartment', 'Detached', 'Semi-detached', and 'Terraced'. Values are taken from the report 'Standard and Target values for existing housing' (in Dutch: *standaard en streefwaardes bestaande woningbouw*) (Cornelisse et al., 2021).

		Insulation level		
		Basic	Intermediate	Advanced
< 1945	Ground floor	1.26	3.5	3.5
	Facade	0.19	0.19	6
	Panel	0.23	0.23	2
	Roof	1.33	3.5	8
	Windows	1.8	1.4	1
	Doors	3.4	3.4	1.4
1945-1975	Ground floor	1.26	3.5	3.5
	Facade	1.25	1.5	6
	Panel	0.23	0.23	2
	Roof	1.33	3.5	8
	Windows	1.8	1.4	1
	Doors	3.4	3.4	1.4
1975-1995	Ground floor	1.26	3.5	3.5
	Facade	1.47	1.79	6
	Panel	0.23	0.23	2
	Roof	1.33	3.5	8
	Windows	1.8	1.4	1
	Doors	3.4	3.4	1.4
>1995	Ground floor	1.26	3.5	3.5
	Facade	1.47	1.79	6
	Panel	0.23	0.23	2
	Roof	1.33	3.5	8
	Windows	1.8	1.4	1
	Doors	3.4	3.4	1.4

B

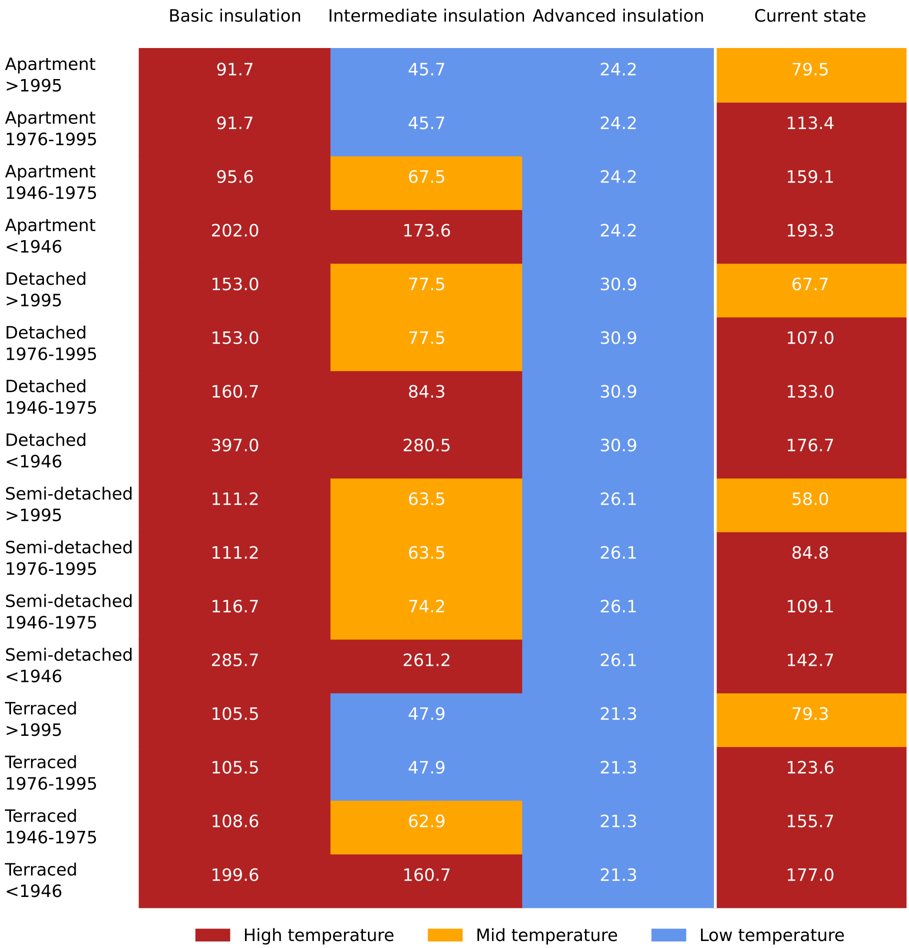


Figure B.3: Heat demand per building archetype for four insulation levels in terms of thermal energy demand per square metre of floor area per year (kWh m^{-2} $year^{-1}$). The colours depict the thermal regime in which buildings can be heated. The maximum heat density for low-temperature heating, i.e. below 40°C, is below 50 kWh m^{-2} $year^{-1}$. Mid-temperature heating at 70°C can be applied below 80 kWh m^{-2} $year^{-1}$. High-temperature heating, i.e. above 90°C, can be applied above 80 kWh m^{-2} $year^{-1}$. This heat demand at the current insulation state of a building can be lower than the heat demand for basic or even intermediate insulation because some existing buildings have already been insulated beyond that level.

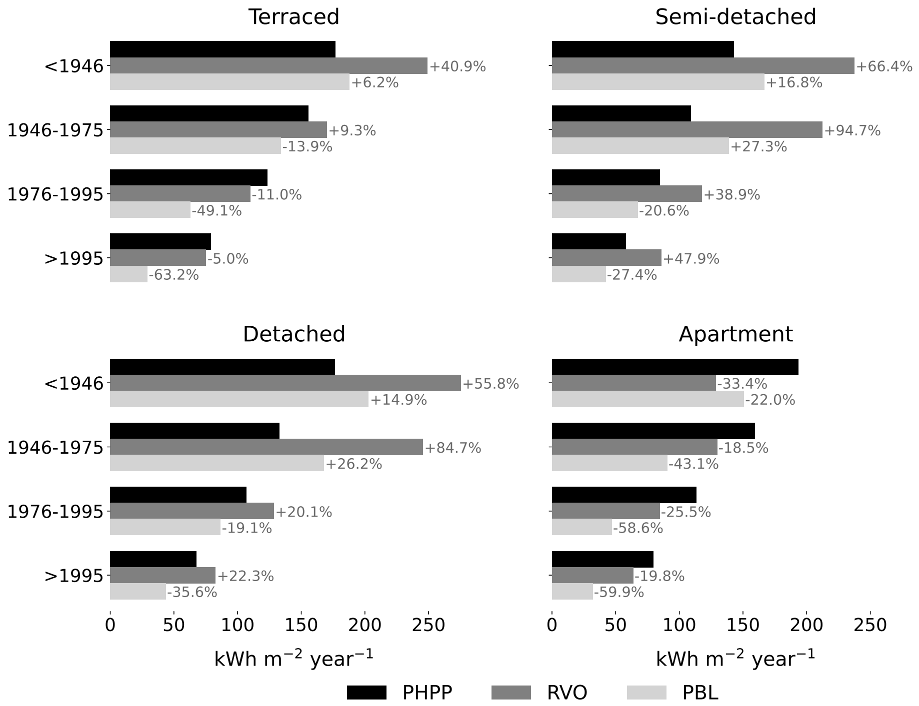


Figure B.4: Modelled heat demand with PHPP software compared to results from RVO (Netherlands Enterprise Agency) and PBL (Netherlands Environmental Assessment Agency) (Agentschap NL, 2011; Folkert and Van den Wijngaart, 2012). Heat demand is modelled for four different building types in four different time period. Heat demand is expressed in unit of energy per square meter of floor area per year. The RVO report contains different type of buildings which could be categorised as apartments, i.e. 'maisonette building', 'tenement' and 'other flat' buildings, we used the latter building type in this comparison. There are differences between the time periods defined in this Chapter 5 and in the RVO report Agentschap NL (2011). The time periods used in Agentschap NL (2011) for terraced buildings are '<1946', '1946-1964', '1965-1974', '1975-1991' and '1992-2005', and for the other building types '<1965', '1965-1974', '1975-1991' and '1992-2005'. The value shown for the construction '<1946' in the figure either corresponds to the time period '<1946' for terraced buildings or '<1965' for the other building types. The value shown for the construction period '1946-1975' corresponds with the average heat demand of time period '1946-1964' and '1965-1974' or '<1965' and '1965-1974' as given in Agentschap NL (2011). The values for the construction periods '1975-1995' and '>1995' corresponds with the construction period '1975-1991' and '1992-2005' respectively.

B

B.2. INPUT TABLES CARBON EMISSION PER HEAT OPTION

Table B.5: Emissions factors per energy carrier for the fuel supply phase and the operational phase in terms of kg CO_2 equivalents per GJ of thermal energy per energy carrier supplied. A range is given of the values found in the literature applicable to heating technologies in the Netherlands. The value between brackets is the value used for the analysis. References: [1] Zijlema (2020), [2] Wielders and Nusselder (2020), [3] Herberigs (2020), [4] Klein et al. (2021), and [5] Schepers and Scholten (2016)
[a] Biomass is assumed to be from biomass chips coming from pruning practices in the Netherlands. The value of 17.2 kg CO_2/GJ is the emission factor for wooden chips transported from Canada.
[b] The ranges show the emission factors for different types of green gas produced in the Netherlands, derived from sewage sludge or produced with fermentation of organic waste streams such as domestic and farm waste. The value chosen for fuel supply phase is the weighted average based on the mix of green gas present in the Netherlands in 2020 as given by Herberigs (2020).
[c] In Chapter 5, the assumption is made that hydrogen used for heating will be made by electrolysis with green electricity.
[d] Solar panels placed on roofs not fields.

Energy carrier	Fuel Supply [kg CO_2/GJ]	Operational [kg CO_2/GJ]	Reference
Biomass	9.2-17.2 (9.2)	109.6	[1][a]
Electricity 2018	131.94	0	[2]
Electricity Solar PV	2.53	0	[2][d]
Electricity Wind Offshore	4.08	0	[2]
Green gas	12.6 - 32.8(22.8)	84.2 - 100.7 (84.2)	[1], [3][b]
Hydrogen	9.1 - 104.3(9.1)	0	[4][c]
Natural gas	2.9	56.4	[1], [5]
Waste	0	104.4	[1]

Table B.6: Energy Required for Energy (ERE) factors rounded of two decimals places in units of energy needed from energy carrier to generate one unit of thermal energy. Abbreviations: CHP = Combined Heat and Power, HP = Heat Pump, LT = low temperature, MT = Mid Temperature, UTES = Underground Thermal Energy Storage. References: [1] Nuiten et al. (2019), and [2] Schepers and Scholten (2016)
[a] Electricity is needed for the use of heat pumps in the heat network with a coefficient of performance (COP) of 0.0072.
[b] A distribution loss of 20% for heat networks is included in the Energy Required for Energy (ERE) factors.
[c] We assume that 0.1 kWh of energy is needed to extract 1 kWh of thermal energy from residual heat sources, and is generated with an efficiency of 85% with natural gas (Schepers and Scholten, 2016).
[d] It is assumed that 20% of the delivered heat comes from a support heater burning natural gas with an efficiency of 85%. The other 80% comes from the main source.
[e] A COP of 5.1 kWh_{elec}/kWh_{heat} for a heat pump extracting heat from an aquifer is used.
[f] The heat pumps used to extract geothermal energy have a coefficient of performance (COP) of 20.
[g] Per kWh of thermal energy extracted, 0.18 kWh less electricity can be produced in comparison to a power plant with an efficiency of 50%. The amount of extra waste needed is 0.18 kWh_{elec}/kWh_{heat} divided by 0.5 kWh_{elec}/kWh_{waste}.
[h] A heat pump with a COP of 3.1 generates 60% of the heat delivered. The other 40% comes from a boiler which needs 0.0288 kWh of electricity per kWh of heat produced.
[i] An efficiency of 88% was assumed for boilers.

Substrategy	Energy carrier	ERE factor	Reference
(1a) HP Aerothermal	Electricity	0.32	[1]
(1b) HP Underground	Electricity	0.23	[1]
(2a) Residual heat LT	Electricity	0.01	[2][a,b]
	Natural gas	0.39	[2][b,c,d]
(2b) UTES	Electricity	0.20	[1][b]
(3a) Residual heat MT	Electricity	0.01	[2][a,b]
	Natural gas	0.39	[2][b,c,d]
(3b) Geothermal Energy	Electricity	0.06	[2][b,d,f]
	Natural gas	0.28	[2][b,c,d]
(3c) Biomass Heater	Biomass	1.05	[2][b,d]
	Electricity	0.01	[2][a,b,d]
	Natural gas	0.28	[2][b,c,d]
(3d) Waste CHP	Electricity	0.01	[2][a,b,d]
	Natural gas	0.28	[2][b,c,d]
	Waste	0.34	[2][b,d,g]
(4a) Green Gas hybrid	Electricity	0.21	[1], [2][h]
	Green gas	0.45	[2][h,i]
(4b) Green Gas Boiler	Green gas	1.14	[2][i]
(5a) Hydrogen Hybrid	Electricity	0.21	[1], [2][h]
	Hydrogen	0.45	[2][h,i]
(5b) Hydrogen Boiler	Hydrogen	1.14	[2][i]

B

B.3. EXTENDED SENSITIVITY ANALYSIS

In this section we present the results under different assumptions. In Figure B.5 if the maximum heat capacity of LT heating is put equal to 65 kWh m^{-2} year^{-1} instead of 50 kWh m^{-2} year^{-1}.

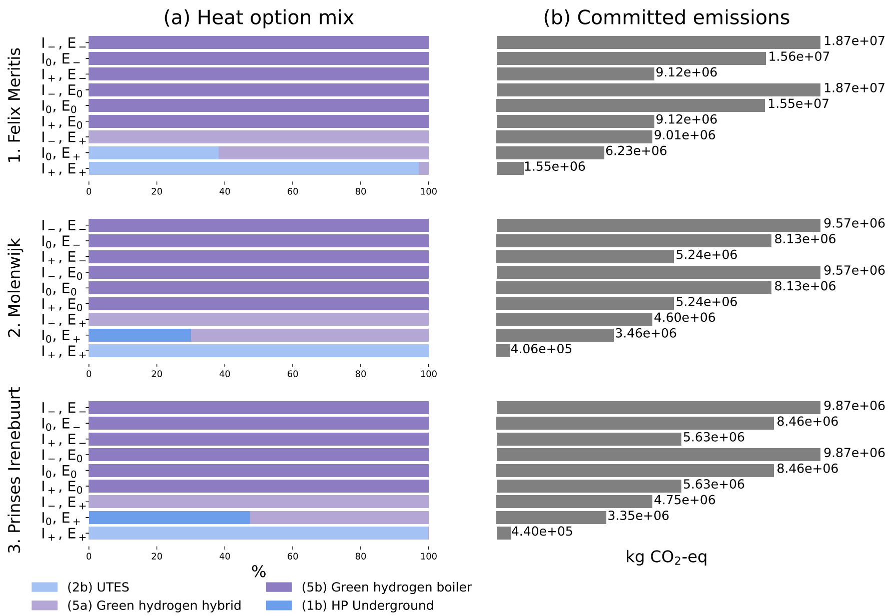


Figure B.5: Main results if the maximum heat capacity is set equal to 65 kWh m^{-2-1} instead of 50 kWh m^{-2-1} as done in Figure 5.6 of the main article.

B.4. A NOTE ON COSTS

In this section, modelling the cost for different heating strategies analysed in Chapter 5 are discussed. An example of an energy model that includes economic factors in the Dutch context, is the VESTA model which is used in a tool developed by PBL Netherlands Environmental Assessment Agency. The tool supports Dutch municipalities to compare the 'national costs' in the provision of heat, i.e. the sum of costs for investment in supply infrastructure (generation and distribution), retro-fitting of buildings, fuel supply and operations of different heat options with a reference case for the year 2030 (PBL, 2021; Henrich et al., 2021). National taxes, subsidies and levies are not included in these 'national costs', because these flows of money do not influence the total costs of all people in the nation. The tool was developed to support Dutch municipalities to perform a spatially explicit comparison of the costs of different heating systems. In Figure B.6, the modelled costs for the neighbourhoods analysed in Chapter 5 are presented.

In Figure B.6, it is shown that heat system 'LT Heat Network' is often not among the cheapest solution because, according to PBL (2021), it was the cheapest to insulate all

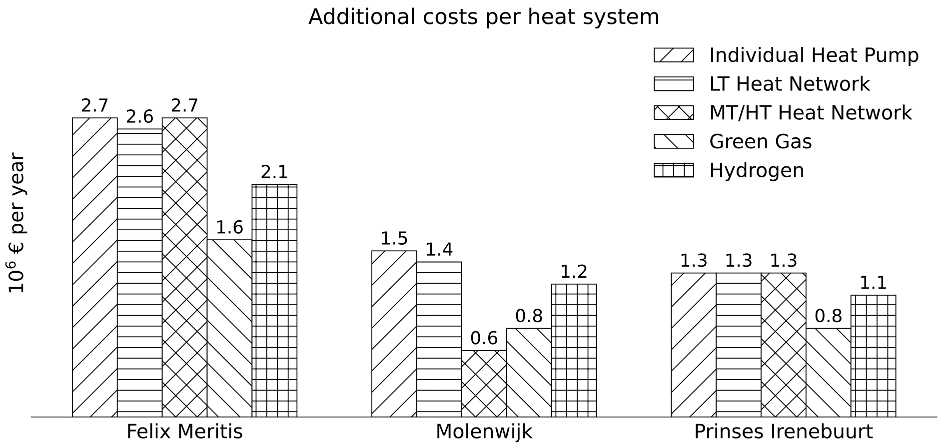


Figure B.6: Additional yearly costs per heat system in 2030 in comparison to keeping the status quo in the three neighbourhoods Felix Meritis, Molenwijk and the Prinses Irenebuurt. The values are taken from PBL (2021).

houses till at least energy label D for all heat options except for heating system 'Individual heat pump', which requires insulation to energy label B. For heat options in heating systems 'LT Heat Network' they include the costs for extra heat pumps to increase delivered heat by the heat network to 70˚C. In this way, the costs for LT heating systems 'Individual heat pump' and 'LT Heat Network' can be higher than for other heating systems. However, the results in Chapter 5 suggest that insulation of houses is an effective way of reducing carbon emissions and moreover is often a no-regret measure for decreasing carbon emissions of heating (De Oliveira Fernandes et al., 2021). Heating systems without insulation further than energy label D may therefore be cheaper now, but will have additional costs if further insulation measures will be taken in the future.

In this reference case, the variable costs are different to the current costs for heating due to assumed changes in outdoor temperatures and costs of natural gas driven by climate change. Moreover, no capital costs are assumed because potential changes to building shells or heating infrastructures are disregarded. The costs per neighbourhood can vary due to factors such as the number of buildings, building types and proximity to heat sources. The costs for heating in the reference case for the year 2030 are 4.2, 1.4 and 2.0 million euros for the neighbourhoods Felix Meritis, Molenwijk and the Prinses Irenebuurt respectively (PBL, 2021).

To assess how much each low-carbon heat option would cost in 2030, the costs were calculated for different insulation levels using the tool in PBL (2021), which considers similar heat options to the ones presented in Chapter 5, making it straightforward to use the definitions of heat options as given in Chapter 5. The costs for the heat options are presented in Figure B.6 and labelled with the name of the heating system of that heat option. In the following we will give the names of the heat options used.

The costs for different heat options vary per neighbourhood due to multiple factors such as the insulation measures needed, the amount of energy demand, and the extra costs for improvement or implementation of a electricity, gas or heat grids. According the PBL analysis, heat option '(4b) Green Gas Boiler' is the cheapest heat option in the Felix Meritis neighbourhood with yearly additional costs of 1.6 million euros compared to a 'business-as-usual' case in which a natural gas heating system is maintained until 2030 (PBL, 2021). Heat options '(5b) Hydrogen Boiler', '(2a) Residual Heat LT', '(1a) HP Aerothermal', and '(3a) Residual Heat MT' are more expensive with a yearly additional cost of 2.1, 2.6, 2.7 and 2.7 million euros respectively. The cheapest heat option in Molenwijk neighbourhood is '(3a) Residual Heat MT' with 0.62 million euros. Heat options '(4b) Green Gas Boiler', '(5b) Hydrogen Boiler', '(2b) Underground Thermal Energy Storage (UTES)', and '(1a) HP Aerothermal' are more expensive with a yearly additional cost of 0.82, 1.2, 1.4 and 1.5 million euros respectively.

The results from Chapter 5, however, suggest that heat option '(3b) Residual heat MT' is not the solution with the lowest EF_{average}. Additionally, we have seen in Figure 5.6.2a that heat option (2b) UTES can be applied to more than 30% of the addresses in this neighbourhood if ambitious rates of insulation and decarbonisation in electricity generation are applied. In the case for the Molenwijk neighbourhood, we thus see that the cheapest solution is not necessarily the solution with the least committed emissions. For the neighbourhoods Prinses Irenebuurt '(4b) Green Gas Boiler' is the cheapest option with 0.8 million euros additional costs according to PBL (2021). Other options are '(5a) Hydrogen Hybrid', '(3b) Geothermal Energy', '(1a) HP Aerothermal' and '(2b) UTES' with 1.1, 1.28, 1.31, 1.31 million euros additional costs. For this neighbourhood, the prices of some heat options are thus close to each other.

Bibliography

Acreman, M., 2016. Environmental flows—basics for novices. Wiley Interdisciplinary Reviews: Water 3, 622–628. doi:10.1002/wat2.1160.

AEB Amsterdam, 2016. Annual Report 2015. Technical Report. AEB Amsterdam. Amsterdam. URL: https://www.aebamsterdam.com/media/bbfieang/aeb160623_jaarverslag-2015.pdf.

Agentschap NL, 2011. Voorbeeldwoningen 2011 - bestaande bouw. Technical Report. Agentschap NL. Sittard.

Aksoezen, M., Daniel, M., Hassler, U., Kohler, N., 2015. Building age as an indicator for energy consumption. Energy and Buildings 87, 74–86. doi:10.1016/j.enbuild.2014.10.074.

Al-Saidi, M., Elagib, N.A., 2017. Towards understanding the integrative approach of the water, energy and food nexus. Science of The Total Environment 574, 1131–1139. doi:10.1016/J.SCITOTENV.2016.09.046.

Allan, J.A., 2003. Virtual Water-the Water, Food, and Trade Nexus. Useful Concept or Misleading Metaphor? Water International 28, 106–113. doi:10.1080/02508060.2003.9724812.

Allouche, J., Middleton, C., Gyawali, D., 2019. The Water–Food–Energy Nexus: Power, Politics, and Justice. Routledge.

Andersen, F.M., Baldini, M., Hansen, L.G., Jensen, C.L., 2017. Households' hourly electricity consumption and peak demand in denmark. Applied energy 208, 607–619. URL: https://doi.org/10.1016/j.apenergy.2017.09.094.

Andrić, I., Pina, A., Ferrão, P., Lacarrière, B., Corre, O.L., 2017. On the performance of district heating systems in urban environment: an emergy approach. Journal of Cleaner Production 142, 109–120. doi:10.1016/j.jclepro.2016.05.124.

Astola, M., Laes, E., Bombaerts, G., Ryszawska, B., Rozwadowska, M., Szymanski, P., Ruess, A., Nyborg, S., Hansen, M., 2022. Community heroes and sleeping members: Interdependency of the tenets of energy justice. Science and Engineering Ethics 28, 1–17. doi:10.1007/s11948-022-00384-3.

Bakken, T.H., Killingtveit, Å., Alfredsen, K., 2017. The water footprint of hydropower production—state of the art and methodological challenges. Global Challenges 1.

Bartolozzi, I., Rizzi, F., Frey, M., 2017. Are district heating systems and renewable energy sources always an environmental win-win solution? A life cycle assessment case study in Tuscany, Italy. Renewable and Sustainable Energy Reviews 80, 408–420. doi:10.1016/j.rser.2017.05.231.

Becker, S., Naumann, M., Moss, T., 2017. Between coproduction and commons: understanding initiatives to reclaim urban energy provision in berlin and hamburg. Urban Research & Practice 10, 63,85. doi:10.1080/17535069.2016.1156735.

Boesten, S., Ivens, W., Dekker, S.C., Eijdems, H., 2019. 5th generation district heating and cooling systems as a solution for renewable urban thermal energy supply. Adv. Geosci 49, 129–136. doi:10.5194/adgeo-49-129-2019.

Bogin, D., Kissinger, M., Erell, E., 2021. Comparison of domestic lifestyle energy consumption clustering approaches. Energy and Buildings 253, 111537. URL: https://www.sciencedirect.com/science/article/pii/S0378778821008215, doi:10.1016/j.enbuild.2021.111537.

Booth, M.S., 2018. Not carbon neutral: Assessing the net emissions impact of residues burned for bioenergy. Environmental Research Letters 13. doi:10.1088/1748-9326/aaac88.

Bouzarovski, S., 2022. Energy and labour: Thinking across the continuum. Progress in Human Geography 46, 753–774. doi:10.1177/03091325211051478.

Bruggers, M., Van Weren, B.J., 2017. Thermische energie uit oppervlaktewater: kansen voor een aardgasvrij nederland. URL: https://www.stowa.nl/sites/default/files/assets/PUBLICATIES/Publicaties%202017/STOWA%202017-33.pdf.

Bryant, R.L., Bailey, S., 1997. Third world political ecology. Routledge, New York, USA and London, UK.

Buffa, S., Cozzini, M., D'antoni, M., Baratieri, M., Fedrizzi, R., 2019. 5th generation district heating and cooling systems: A review of existing cases in europe. Renewable and Sustainable Energy Reviews 104, 504–522. doi:10.1016/j.rser.2018.12.059.

Burke, E.J., Hartley, I.P., Jones, C.D., 2012. Uncertainties in the global temperature change caused by carbon release from permafrost thawing. The Cryosphere 6, 1063–1076. doi:10.5194/tc-6-1063-2012.

Byers, E.A., Hall, J.W., Amezaga, J.M., 2014. Electricity generation and cooling water use: UK pathways to 2050. Global Environmental Change URL: http://dx.doi.org/10.1016/j.gloenvcha.2014.01.005, doi:10.1016/j.gloenvcha.2014.01.005.

Cairns, R., Krzywoszynska, A., 2016. Anatomy of a buzzword: The emergence of 'the water-energy-food nexus' in uk natural resource debates. Environmental Science & Policy 64, 164–170. doi:10.1016/j.envsci.2016.07.007.

Carrozza, C., Fantini, E., 2016. The italian water movement and the politics of the commons. Water Alternatives 9, 99–119.

CBS, 2020. Statline: Warmtepompen; aantallen, thermisch vermogen en energiestromen. URL: https://opendata.cbs.nl/statline/#/CBS/nl/dataset/82380NED/table. Accessed 17 March 2021.

CBS, 2022a. Aantal gemeenten daalt tot 342 op 1 januari 2023. URL: https://www.cbs.nl/nl-nl/nieuws/2022/52/aantal-gemeenten-daalt-tot-342-op-1-januari-2023#:~:text=Nu%20Weesp%20met%20circa%2021,grootste%20landoppervlakte%20(49e%20plaats).. version of 30-12-2022.

CBS, 2022b. Bevolking op 1 januari en gemiddeld; geslacht, leeftijd en regio. URL: https://opendata.cbs.nl/#/CBS/nl/dataset/03759ned/table?dl=39E0B. version: 30-05-2022.

CBS, PBL, RIVM, WUR, 2020. Koelwatergebruik en warmtelozing door elektriciteitscentrales, 1981-2018 (indicator 0021, version 16, 7 may 2020). URL: www.clo.nl.

CBS, PBL, RIVM, WUR, 2022. Waterwinning en watergebruik in nederland, 1976-2020 (indicator 0057, version 16, 14 june 2022). URL: www.clo.nl.

Cornelisse, M., Kruithof, A., Valk, H., 2021. Rapport standaard en streefwaardes bestaande woningbouw. Technical Report 20190115/15645. Netherlands Enterprise Agency, Nieman Raadgevende Ingenieurs B.V.. Zwolle. URL: https://www.nieman.nl/wp-content/uploads/2021/03/rapport-standaard-en-streefwaarden-bestaande-woningbouw-nieman-raadgevend-in.pdf.

Dai, J., Wu, S., Han, G., Weinberg, J., Xie, X., Wu, X., Song, X., Jia, B., Xue, W., Yang, Q., 2018. Water-energy nexus: A review of methods and tools for macro-assessment. Applied Energy 210, 393–408. URL: https://linkinghub.elsevier.com/retrieve/pii/S0306261917312242, doi:10.1016/j.apenergy.2017.08.243.

Dalakoglou, D., 2016. Infrastructural gap: Commons, state and anthropology. City 20, 822–831. doi:10.1080/13604813.2016.1241524.

Davies, E.G.R., Kyle, P., Edmonds, J.A., 2013. An integrated assessment of global and regional water demands for electricity generation to 2095. Advances in Water Resources 52, 296–313. doi:10.1016/j.advwatres.2012.11.020.

Davis, S.J., Caldeira, K., Matthews, H.D., 2010. Future CO2 Emissions and Climate Change from Existing Energy Infrastructure. Science 329, 1330–1333. doi:10.1126/science.1188566.

De Oliveira Fernandes, M.A., Keijzer, E., van Leeuwen, S., Kuindersma, P., Melo, L., Hinkema, M., Gonçalves Gutierrez, K., 2021. Material-versus energy-related impacts: Analysing environmental trade-offs in building retrofit scenarios in the Netherlands. Energy and Buildings 231, 110650. doi:10.1016/j.enbuild.2020.110650.

Delanda, M., 2006. A new philosophy of society: Assemblage theory and social complexity. Continuum, London.

Deleuze, G., Guattari, F., 1987. A thousand plateaus: capitalism and schizophrenia. University of Minnesota Press. Originally published as *Mille Plateaux*, volume 2 of *Capitalisme et Schizophrenic* in 1980 by *Les Editions de Minuit*, Paris.

Den Ouden, B., Kerkhoven, J., Warnaars, J., Terwel, R., Coenen, M., Verboon, T., Tiihonen, T., Koot, A., 2020. Klimaatneutrale energiescenario's 2050: scenariostudie ten behoeve van de integrale infrastructuurverkenning 2030-2050. Technical Report. Kalavasta and Berenschot. Utrecht. URL: https://www.rijksoverheid.nl/documenten/rapporten/2020/03/31/klimaatneutrale-energiescenarios-2050.

Dewsbury, J.D., 2011. The deleuze-guattarian assemblage: plastic habits. Area 43, 148–153. doi:10.1111/j.1475-4762.2011.01006.x.

Directorate-General for Public Works and Water Management, 2020. Klimaatmonitor. URL: https://klimaatmonitor.databank.nl/dashboard/dashboard/. accessed on 20 March 2020.

D'Odorico, P., Davis, K.F., Rosa, L., Carr, J.A., Chiarelli, D., Dell'Angelo, J., Gephart, J., MacDonald, G.K., Seekell, D.A., Suweis, S., Rulli, M.C., 2018. The Global Food-Energy-Water Nexus. Reviews of Geophysics 56, 456–531. doi:10.1029/2017RG000591.

Ebrahimigharehbaghi, S., Qian, Q.K., de Vries, G., Visscher, H.J., 2022. From collective to individual decision-making: barriers and opportunities to improve the success rate of the energy retrofits in the dutch owner-occupied sector. CLIMA 2022 Conference doi:10.34641/clima.2022.330.

Eggimann, S., Usher, W., Eyre, N., Hall, J.W., 2020. How weather affects energy demand variability in the transition towards sustainable heating. Energy 195. doi:10.1016/j.energy.2020.116947.

Endo, A., Tsurita, I., Burnett, K., Orencio, P.M., 2016. A Review of the current state of research on the water, energy, and food Nexus by. Journal of Hydrology: Regional Studies 11, 20–30.

Erickson, P., Kartha, S., Lazarus, M., Tempest, K., 2015. Assessing carbon lock-in. Environmental Research Letters 10, 084023. doi:10.1088/1748-9326/10/8/084023.

ESRI NL, 2021. Group bag - basisregistratie adressen en gebouwen. URL: https://esrinl-content.maps.arcgis.com/home/group.html?id=31ae027e6c88449cb22292d8f9ed861b#overview. group of layers based on the Addresses and Building key register. Data retrieved on 21-05-2021.

ETM, 2020. Energy transition model. URL: https://energytransitionmodel.com/. developed by Quintel Intelligence. Accessed April 2020.

European Commission, 2022. REPowerEU: a plan to rapidly reduce dependence on Russian fossil fuels and fast forward the green transition. URL: https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131. Press release by European Commission. Version: updated 18 May 2022.

Eurostat, 2022. Energy use in households in 2020. URL: https://ec.europa.eu/eurostat/product?code=DDN-20220617-1. webpage published by Eurostat on 17-06-2022.

Eyre, N., Baruah, P., 2015. Uncertainties in future energy demand in uk residential heating. Energy Policy 87, 641–653. doi:10.1016/j.enpol.2014.12.030.

Faaij, A., 2006. Modern Biomass Conversion Technologies. Mitigation and Adaptation Strategies for Global Change 11, 343–375. doi:10.1007/s11027-005-9004-7.

Feinberg, A., Ghorbani, A., Herder, P., 2021. Diversity and challenges of the urban commons: A comprehensive review. International Journal of the Commons 15, 1–20. doi:10.5334/ijc.1033.

Fisch-Romito, V., Guivarch, C., Creutzig, F., Minx, J.C., Callaghan, M.W., 2021. Systematic map of the literature on carbon lock-in induced by long-lived capital. Environmental Research Letters 6, 053004. doi:https://doi.org/10.1088/1748-9326/aba660.

Floden, R.E., 2009. Empirical research without certainty. Educational theory 59, 485–498. doi:10.1111/j.1741-5446.2009.00332.x.

Folkert, R., Van den Wijngaart, R., 2012. Vesta ruimtelijk energiemodel voor de gebouwde omgeving. Data en methoden. Technical Report. PBL Netherlands Environmental Assessment Agency. The Hague.

Foster, S.R., Iaione, C., 2015. The city as a commons. Yale Law & Policy Review 34, 281–349. URL: http://www.jstor.org/stable/43920369.

Foster, S.R., Iaione, C., 2019. Ostrom in the city: Design principles and practices for the urban commons, in: Routledge Handbook of the Study of the Commons. Routledge, pp. 235–255.

Fouladvand, J., Ghorbani, A., Mouter, N., Herder, P., 2022. Analysing community-based initiatives for heating and cooling: A systematic and critical review. Energy Research & Social Science 88, 102507. doi:10.1016/j.erss.2022.102507.

Gabrielli, P., Gazzani, M., Martelli, E., Mazzotti, M., 2018. Optimal design of multi-energy systems with seasonal storage. Applied Energy 219, 408–424. URL: https://linkinghub.elsevier.com/retrieve/pii/S0306261917310139, doi:10.1016/j.apenergy.2017.07.142.

Gerbens-Leenes, P.W., Hoekstra, A.Y., van der Meer, T., 2009. The water footprint of energy from biomass: A quantitative assessment and consequences of an increasing share of bio-energy in energy supply. Ecological Economics 68, 1052–1060. doi:10.1016/j.ecolecon.2008.07.013.

Government of the Netherlands, 2019. Climate agreement. URL: https://www.government.nl/documents/reports/2019/06/28/climate-agreement.

Gross, R., Hanna, R., 2019. Path dependency in provision of domestic heating. Nature Energy 4, 358–364. URL: http://dx.doi.org/10.1038/s41560-019-0383-5, doi:10.1038/s41560-019-0383-5.

Gurobi Optimization, LLC, 2021. Gurobi optimizer reference manual. version 9.1. URL: http://www.gurobi.com.

Hargreaves, T., Hielscher, S., Seyfang, G., Smith, A., 2013. Grassroots innovations in community energy: The role of intermediaries in niche development. Global environmental change 23, 868–880. doi:10.1016/j.gloenvcha.2013.02.008.

Harvey, D., 2012. Rebel cities: From the right to the city to the urban revolution. Verso, London, Brooklyn.

Healy, N., Stephens, J.C., Malin, S.A., 2019. Embodied energy injustices: Unveiling and politicizing the transboundary harms of fossil fuel extractivism and fossil fuel supply chains. Energy Research & Social Science 48, 219–234. doi:10.1016/j.erss.2018.09.016.

Heffron, R.J., Mccauley, D., 2014. Achieving sustainable supply chains through energy justice. Applied Energy 123, 435–437. doi:10.1016/j.apenergy.2013.12.034.

Henrich, B.A., Hoppe, T., Diran, D., Lukszo, Z., 2021. The use of energy models in local heating transition decision making: Insights from ten municipalities in the Netherlands. Energies 14. doi:10.3390/en14020423.

Herberigs, M., 2020. UPDATE Emissiecijfers groengas. Technical Report. Stimular, CE Delft. Rotterdam. URL: https://www.co2emissiefactoren.nl/wp-content/uploads/2020/01/CO2-emissies-Groen-Gas-samenvattend-document-definitief.pdf.

Hietaharju, P., Pulkkinen, J., Ruusunen, M., Louis, J.N., 2021. A stochastic dynamic building stock model for determining long-term district heating demand under future climate change. Applied Energy 295. doi:10.1016/j.apenergy.2021.116962.

Hoekstra, A.Y., Chapagain, A.K., Mekonnen, M.M., Aldaya, M.M., 2011. The water footprint assessment manual: Setting the global standard. Earthscane, London. URL: https://digitalcommons.unl.edu/wffdocs/77.

Hoff, H., 2011. Understanding the NEXUS, Background Paper for the Bonn 2011 Conference: The Water, Energy and Food Security Nexus. URL: https://www.sei.org/publications/understanding-the-nexus/.

Hölscher, K., M Wittmayer, J., Hirschnitz-Garbers, M., Olfert, A., Walther, J., Schiller, G., Brunnow, B., 2021. Transforming science and society? Methodological lessons from and for transformation research. Research Evaluation 30, 73–89. doi:10.1093/reseval/rvaa034.

Hölscher, K., Wittmayer, J.M., Loorbach, D., 2018. Transition versus transformation: What's the difference? Environmental innovation and societal transitions 27, 1–3. doi:10.1016/j.eist.2017.10.007.

Honoré, A., 2018. Decarbonisation of heat in Europe: implications for natural gas demand. Oxford Institute for Energy Studies, Oxford. doi:10.26889/9781784671105.

Hoogervorst, N., 2017. Toekomstbeeld klimaatneutrale warmtenetten in nederland. URL: http://www.pbl.nl/publicaties/toekomstbeeld-klimaatneutrale-warmtenetten-in-nederland. The Hague: report by PBL Netherlands Environmental Assessment Agency.

Hoogervorst, N., Van den Wijngaart, R., Van Bemmel, B., Langeveld, J., Van der Molen, F., Van Polen, S., Tavaras, J., 2020. Startanalyse aardgasvrije buurten. Technical Report 4038. PBL Netherlands Environmental Assessment Agency. The Hague.

IEA, 2021. Energy Technology Perspectives 2020. Technical Report. International Energy Agency. Paris. doi:10.1787/ab43a9a5-en.

IEA, 2022a. Electricity. URL: https://www.iea.org/fuels-and-technologies/electricity. accessed 31 January 2023.

IEA, 2022b. Global Energy Review: CO2 Emissions in 2021. Technical Report. International Energy Agency (IEA). Paris. URL: https://www.iea.org/reports/global-energy-review-co2-emissions-in-2021-2.

IEA, 2022c. Heating. URL: https://www.iea.org/reports/heating. tracking report: version September 2022.

IEA, OECD, 2016. Water energy nexus: Excerpt from the world energy outlook 2016. URL: www.iea.org.

IPCC, 2014a. Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Technical Report. Intergovernmental Panel on Climate Change (IPCC). Cambridge, UK and New York, NY, USA. URL: https://www.ipcc.ch/report/ar5/wg3/.

IPCC, 2014b. Summary for Policymakers. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Technical Report. IPCC. Cambridge, United Kingdom, New York, NY, USA.

IPCC, 2018. Summary for Policy makers. Technical Report October. IPCC. URL: https://www.ipcc.ch/sr15/chapter/spm/#chapter-authors.

IPCC, 2022. Summary for Policymakers [H.-O. Pörtner, D.C. Roberts, E.S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem (eds.)], in: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 3–33. URL: https://www.ipcc.ch/report/ar6/wg2/downloads/report/IPCC_AR6_WGII_SummaryForPolicymakers.pdf.

Itten, A., Sherry-Brennan, F., Hoppe, T., Sundaram, A., Devine-Wright, P., 2021. Co-creation as a social process for unlocking sustainable heating transitions in europe. Energy Research & Social Science 74, 101956. doi:10.1016/j.erss.2021.101956.

Jenkins, K., McCauley, D., Heffron, R., Stephan, H., Rehner, R., 2016. Energy justice: A conceptual review. Energy Research & Social Science 11, 174–182. doi:10.1016/j.erss.2015.10.004.

Jennings, M., Fisk, D., Shah, N., 2014. Modelling and optimization of retrofitting residential energy systems at the urban scale. Energy 64, 220–233. URL: http://dx.doi.org/10.1016/j.energy.2013.10.076, doi:10.1016/j.energy.2013.10.076.

Joint Research Centre of the European Commission, 2014. ETRI 2014 - Energy Technology Reference Indicator projections for 2010-2050. doi:10.2790/057687. JRC Science and Policy Reports.

Kaandorp, C., van de Giesen, N., Abraham, E., 2021a. The water use of heating pathways to 2050: analysis of national and urban energy scenarios. Environmental Research Letters 16. doi:10.1088/1748-9326/abede7.

Kaandorp, C., Van de Giesen, N., Abraham, E., 2023a. Multi-scale water and energy use model: Workbook accompanying the paper 'The water use of heating pathways to 2050: analysis of national and urban energy scenarios'. doi:10.4121/22257079. Dataset published on 4TU.ResearchData.

Kaandorp, C., Miedema, T., Verhagen, J., van de Giesen, N., Abraham, E., 2022. Reducing committed emissions of heating towards 2050: Analysis of scenarios for the insulation of buildings and the decarbonisation of electricity generation. Applied Energy 325, 119759. doi:10.1016/j.apenergy.2022.119759.

Kaandorp, C., Miedema, T., Verhagen, J., Van de Giesen, N., Abraham, E., 2023b. Heat and carbon emissions model for Amsterdam: Code and datasets accompanying the paper 'Reducing committed emissions of heating towards 2050: Analysis of scenarios for the insulation of buildings and the decarbonisation of electricity generation'. doi:10.4121/d5517282-b784-4d13-b9a9-120c263737f7. Collection published on 4TU.ResearchData.

Kaandorp, C., Pessoa, I., Abraham, E., 2020. Vergroot de focus: de transitie naar aardgasvrije verwarming van gebouwen bekeken vanuit de thema's 'duurzaam watergebruik' en 'een inclusieve samenleving'. URL: https://www.verdus.nl/assets/uploads/2020/12/Beleidssamenvatting-ENLARGE-2020.pdf.

Kaandorp, C., Pessoa, I., Abraham, E., 2021b. Enlarge the focus: linking policy for low-carbon urban heating with sustainable water use and social inclusion. URL: https://jpi-urbaneurope.eu/wp-content/uploads/2021/09/Policy-Brief-JPI-Eurban-Europe-ENLARGE.pdf.

Kaandorp, C., Pessoa, I., Pesch, U., Van de Giesen, N., Abraham, E., N.D. 'commoning practices' for energy justice? a perspective on collective heating initiatives in the city of amsterdam. N.D. Under review.

Kaika, M., 2004. City of flows: Modernity, nature, and the city. Routledge, New York and London.

Khan, Z., Abraham, E., Aggarwal, S., Ahmad Khan, M., Arguello, R., Babbar-Sebens, M., Bereslawski, J.L., Bielicki, J.M., Campana, P.E., Silva Carrazzone, M.E., et al., 2022. Emerging themes and future directions of multi-sector nexus research and implementation. Frontiers in Environmental Science 10, 1–11. doi:10.3389/fenvs.2022.918085.

King, C.W., Holman, A.S., Webber, M.E., 2008. Thirst for energy. URL: https://www.nature.com/articles/ngeo195.

Klein, A., Hilster, D., Scholten, P., Van Wijngaarden, L., Tol, E., Otten, M., 2021. STREAM Goederenvervoer 2020. Technical Report. CE Delft. Delft. URL: https://ce.nl/publicaties/stream-goederenvervoer-2020/.

Klimaatakoord, 2019. Klimaatakkoord. URL: https://www.klimaatakkoord.nl/documenten/publicaties/2019/06/28/klimaatakkoord.

KNMI, 2018. Ons klimaat verandert. URL: http://klimaatverandering-mra.vormgeving.com/. accessed 16 March 2021.

Koezjakov, A., Ürge-vorsatz, D., Crijns-graus, W., Broek, M.V.D., 2018. The relationship between operational energy demand and embodied energy in Dutch residential buildings. Energy & Buildings 165, 233–245. URL: https://doi.org/10.1016/j.enbuild.2018.01.036, doi:10.1016/j.enbuild.2018.01.036.

Kromwijk, D., 2020. Ecological effects of the use of hydrothermal energy from surface water: A study into the ecological effects induced by thermal changes of the use of hydro thermal energy for heating and cooling the new built environment of amsterdam. Thesis written for the fulfilment of the requirements of the degree of Bachelor of Science in Civil Engineering at the Delft University of Technology.

Krueger, E.H., Constantino, S.M., Centeno, M.A., Elmqvist, T., Weber, E.U., Levin, S.A., 2022. Governing sustainable transformations of urban social-ecological-technological systems. npj Urban Sustainability 2, 1–12. doi:10.1038/s42949-022-00053-1.

Ladyman, J., Lambert, J., Wiesner, K., 2013. What is a complex system? European Journal for Philosophy of Science 3, 33–67. doi:10.1007/s13194-012-0056-8.

Larsen, M.A.D., Drews, M., 2019. Water use in electricity generation for water-energy nexus analyses: The European case. Science of the Total Environment 651, 2044–2058. doi:10.1016/j.scitotenv.2018.10.045.

Linebaugh, P., 2008. The Magna Carta manifesto: Liberties and commons for all. Univ of California Press, Berkeley and Los Angeles, California.

Linton, J., 2008. Is the hydrologic cycle sustainable? a historical–geographical critique of a modern concept. Annals of the Association of American Geographers 98, 630–649. doi:10.1080/00045600802046619.

Loorbach, D., Frantzeskaki, N., Avelino, F., 2017. Sustainability transitions research: transforming science and practice for societal change. Annual review of environment and resources 42, 599–626. doi:10.1146/annurev-environ-102014-021340.

Macknick, J., Newmark, R., Heath, G., Hallett, K.C., 2012. Operational water consumption and withdrawal factors for electricity generating technologies: A review of existing literature. Environmental Research Letters 7. doi:10.1088/1748-9326/7/4/045802.

Majcen, D., Itard, L.C.M., Visscher, H., 2013. Theoretical vs . actual energy consumption of labelled dwellings in the Netherlands : Discrepancies and policy implications. Energy Policy 54, 125–136. doi:10.1016/j.enpol.2012.11.008.

Maselis, I., Hisschemöller, M., 2018. 'Het moet niet te avontuurlijk worden': een onderzoek naar de institutionele barrières voor een wijkgebonden warmtevoorziening in Amsterdam. Technical Report. DRIFT. Rotterdam. URL: https://drift.eur.nl/app/uploads/2018/03/ABC-rapport-institutionele-barri%C3%A8res-voor-een-wijkgebonden-warmtevoorziening-in-Amsterdam.pdf.

Mason, J., 2002. Qualitative researching. sage, London, Thousand Oaks, New Delphi. URL: http://www.sxf.uevora.pt/wp-content/uploads/2013/03/Mason_2002.pdf.

McCauley, D., Ramasar, V., Heffron, R.J., Sovacool, B.K., Mebratu, D., Mundaca, L., 2019. Energy justice in the transition to low carbon energy systems: Exploring key themes in interdisciplinary research. Applied Energy 233-234, 916–921. doi:10.1016/j.apenergy.2018.10.005.

McGrane, S.J., Acuto, M., Artioli, F., Chen, P.Y., Comber, R., Cottee, J., Farr-Wharton, G., Green, N., Helfgott, A., Larcom, S., McCann, J.A., O'Reilly, P., Salmoral, G., Scott, M., Todman, L.C., van Gevelt, T., Yan, X., 2018. Scaling the nexus: Towards integrated frameworks for analysing water, energy and food. The Geographical Journal doi:10.1111/geoj.12256.

McLean, J., 2017. Water cultures as assemblages: Indigenous, neoliberal, colonial water cultures in northern australia. Journal of Rural Studies 52, 81–89. doi:10.1016/j.jrurstud.2017.02.015.

Mehmeti, A., Angelis-Dimakis, A., Arampatzis, G., McPhail, S., Ulgiati, S., 2018. Life Cycle Assessment and Water Footprint of Hydrogen Production Methods: From Conventional to Emerging Technologies. Environments 5, 24. doi:10.3390/environments5020024.

Mekonnen, M.M., Gerbens-Leenes, P.W., Hoekstra, A.Y., 2015. The consumptive water footprint of electricity and heat: a global assessment. Environmental Science: Water Research & Technology journal 1, 285–297. doi:10.1039/c5ew00026b.

Mekonnen, M.M., Hoekstra, A.Y., 2012. The blue water footprint of electricity from hydropower. Hydrology and Earth System Sciences 16, 179–187. doi:10.5194/hess-16-179-2012.

Meldrum, J., Nettles-Anderson, S., Heath, G., Macknick, J., 2013. Life cycle water use for electricity generation: a review and harmonization of literature estimates. Environmental Research Letters 8, 18pp. doi:10.1088/1748-9326/8/1/015031.

Menkveld, M., Matton, R., Segers, R., Vroom, J., Kremer, A.M., 2017. Monitoring warmte 2015. Technical Report. ECN (Energy research Centre of the Netherlands). Petten. URL: https://www.cbs.nl/-/media/_pdf/2017/15/monitoringwarmte2015.pdf.

Meurink, A., Muller, G., Segers, R., 2019. Hernieuwbare energie in nederland 2018.

Meurink, A., Segers, R., 2016. Hernieuwbare energie in Nederland 2015. URL: https://www.cbs.nl/-/media/_pdf/2016/39/hernieuwbare-energie-in-nederland-2015.pdf, doi:10.17026/dans-x95-5p7y.

Miedema, T., 2020. The prospects of heat: urban heat modelling as a means for a sustainable and equitable heat transition in the historic centre of amsterdam. Thesis written for the fulfilment of the requirements of the degree of Master of Science in Metropolitan Analysis, Design & Engineering from the Wageningen University and Research and Delft University of Technology.

Miller, T.R., Muñoz-Erickson, T., Redman, C.L., 2011. Transforming knowledge for sustainability: towards adaptive academic institutions. International Journal of Sustainability in Higher Education 12, 177–192. doi:10.1108/14676371111118228.

Ministry of Economic Affairs, 2016. Energieagenda Naar een CO2-arme energievoorziening. URL: https://www.rijksoverheid.nl/documenten/rapporten/2016/12/07/ea.

Monstadt, J., Coutard, O., 2019. Cities in an era of interfacing infrastructures: Politics and spatialities of the urban nexus. Urban Studies 56, 2191–2206. doi:10.1177/0042098019833907.

Municipality of Amsterdam, 2019a. Het Amsterdamse bronnenboek. Technical Report. Department of Planning and Sustainability, Municipality of Amsterdam. URL: https://amsterdam.raadsinformatie.nl/document/8472488/1/09012f9782d94702.

Municipality of Amsterdam, 2019b. Routekaart Amsterdam Klimaatneutraal 2050. Stap 1: Uitnodiging aan de stad.

Municipality of Amsterdam, 2020a. New amsterdam climate: Amsterdam climate neutral roadmap 2050. URL: https://assets.amsterdam.nl/publish/pages/887330/roadmap_climate_neutral.pdf. Official contractor: Space and Sustainability Cluster, Municipality of Amsterdam.

Municipality of Amsterdam, 2020b. Transitievisie Warmte Amsterdam. Technical Report. Municipality of Amsterdam. Amsterdam. URL: https://openresearch.amsterdam/nl/page/63522/transitievisie-warmte-amsterdam.

Neirotti, F., Noussan, M., Simonetti, M., 2020. Towards the electrification of buildings heating - Real heat pumps electricity mixes based on high resolution operational profiles. Energy 195, 116974. URL: https://doi.org/10.1016/j.energy.2020.116974, doi:10.1016/j.energy.2020.116974.

Nuiten, P., Goud, J., Hoiting, H., Van Der Ree, B., Harmelink, M., Bosselaar, L., Rienstra, J., 2019. Uniforme Maatlat Gebouwde Omgeving (UMGO) voor de warmtevoorziening in de woning-en utiliteitsbouw. Technical Report. Heating Expertise Centre, Netherlands Enterprise Agency. URL: https://docplayer.nl/66489523-Uniforme-maatlat-gebouwde-omgeving-umgo-voor-de-warmtevoorziening-in-de-woning-en-utiliteitsbouw.html.

Nutkiewicz, A., Choi, B., Jain, R.K., 2021. Exploring the influence of urban context on building energy retrofit performance: A hybrid simulation and data-driven approach. Advances in Applied Energy 3. doi:10.1016/j.adapen.2021.100038.

N.V. Nederlandse Gasunie, 2018. Exploration 2050.

Ollongren, K.H., M., 2021. Isolatiestandaard en streefwaardes voor woningen. URL: www.tweedekamer.nl/downloads/document?id=1fb068ac-0f5a-48ab-8b87-cb276680f99c&title=Isolatiestandaard%20en%20Streefwaardes%20voor%20woningen%20.pdf. letter to House of Representatives of The Netherlands. Session 2020-2021, 30, 196, nr. 749.

Olsson, P., Galaz, V., Boonstra, W.J., 2014. Sustainability transformations: a resilience perspective. Ecology and Society 19. doi:10.5751/ES-06799-190401.

Olsthoorn, D., Haghighat, F., Mirzaei, P.A., 2016. Integration of storage and renewable energy into district heating systems: A review of modelling and optimization. Solar Energy 136, 49–64. doi:10.1016/j.solener.2016.06.054.

Oppermann, E., Walker, G., 2019. Immersed in thermal flows: Heat as productive of and produced by social practices. Social Practices and Dynamic Non-Humans: Nature, Materials and Technologies n/a, 129–148. doi:10.1007/978-3-319-92189-1_7.

Pacetti, T., Lombardi, L., Federici, G., 2015. Water-energy Nexus: a case of biogas production from energy crops evaluated by Water Footprint and Life Cycle Assessment

(LCA) methods. Journal of Cleaner Production 101, 278–291. doi:10.1016/j.jclepro.2015.03.084.

Patterson, J., Schulz, K., Vervoort, J., Van Der Hel, S., Widerberg, O., Adler, C., Hurlbert, M., Anderton, K., Sethi, M., Barau, A., 2017. Exploring the governance and politics of transformations towards sustainability. Environmental Innovation and Societal Transitions 24, 1–16. doi:10.1016/j.eist.2016.09.001.

PBL, 2012. Effecten van klimaatverandering in Nederland 2012. URL: https://www.pbl.nl/sites/default/files/downloads/PBL_2012_Effecten-van-klimaatverandering_500193003_0.pdf.

PBL, 2021. Startanalyse aardgasvrije buurten. URL: https://themasites.pbl.nl/leidraad-warmte/2020/#. version 2020. Last accessed: 14-10-2021.

Pellegrini, M., Bloemendal, M., Hoekstra, N., Spaak, G., Gallego, A.A., Comins, J.R., Grotenhuis, T., Picone, S., Murrell, A.J., Steeman, H.J., 2019. Low carbon heating and cooling by combining various technologies with aquifer thermal energy storage. Science of the Total Environment 665, 1–10. doi:10.1016/j.scitotenv.2019.01.135.

Pesch, U., 2021. Institutions of justice and intuitions of fairness: contesting goods, rules and inequalities. Critical Review of International Social and Political Philosophy n/a, 1–14. doi:10.1080/13698230.2021.1913887.

Pesch, U., Correljé, A., Cuppen, E., Taebi, B., 2017. Energy justice and controversies: Formal and informal assessment in energy projects. Energy Policy 109, 825–834. doi:10.1016/j.enpol.2017.06.040.

Ramaker, M., 2020. The effect of thermal energy recovery on the ecology of a small, slow flowing freshwater ecosystem: A modelling approach. Thesis project Master of Science in Environmental Science of the Open University.

Raven, R., Verbong, G., 2007. Multi-regime interactions in the dutch energy sector: the case of combined heat and power technologies in the netherlands 1970–2000. Technology Analysis & Strategic Management 19, 491–507. doi:10.1080/09537320701403441.

Raworth, K., 2017. Doughnut economics: seven ways to think like a 21st-century economist. Chelsea Green Publishing.

Ree, G.V.D., Kelfkens, J., 2019. Verkenning van de milieuaspecten van de activiteiten die onder het Staatstoezicht op de Mijnen vallen. doi:10.21945/RIVM-2018-0162.

Rekenkamer Metropool Amsterdam, 2018. Grip op westpoort warmte. URL: https://www.rekenkamer.amsterdam.nl/onderzoek/grip-op-westpoort-warmte/. version of 20 December 2018.

Rio Carrillo, A.M., Frei, C., 2009. Water: A key resource in energy production. Energy Policy 37, 4303–4312. URL: https://www.sciencedirect.com/science/article/pii/S0301421509003863?via{%}3Dihub, doi:10.1016/J.ENPOL.2009.05.074.

RVO, CBS, 2015. Protocol Monitoring Hernieuwbare Energy - Herziening 2015. Publication commisioned by the Dutch Ministry of Economic Affairs. Publication number: RVO-268-1501/BR-DUZA.

Schepers, B., Meyer, M., 2017. CEGOIA - Amsterdam: kansen voor gemeente en corporaties. Technical Report. CE Delft. Delft. URL: https://ce.nl/wp-content/uploads/2021/03/CE-Delft_3G41_CEGOIA-Amsterdam_Def_context.pdf. version August 2017. Publication number: 17.3G41.93.

Schepers, B., Scholten, T., 2016. Ketenemissies Warmtelevering - Directe en indirecte CO2-emissies van warmtetechnieken. Technical Report. CE Delft. Delft. URL: https://ce.nl/wp-content/uploads/2021/03/CE_Delft_3H06_Ketenemissies_warmtelevering_DEF.pdf.

Schippers, J., Small, J., Verbong, G., 2020. Techniek in Nederland in de twintigste eeuw. Deel 2. Delfstoffen, energie, chemie. Stichting Historie der Techniek, Walburg Pers, Eindhoven / Zutphen. chapter 4 Schaalvergroting in de gasvoorziening. pp. 161–173. URL: https://www.dbnl.org/tekst/lint011tech02_01/lint011tech02_01_0011.php.

Schneidewind, U., Singer-Brodowski, M., Augenstein, K., Stelzer, F., 2016. Pledge for a transformative science: A conceptual framework. Technical Report. Wuppertal papers. URL: https://epub.wupperinst.org/frontdoor/index/index/docId/6414.

Scott, C.A., Pierce, S.A., Pasqualetti, M.J., Jones, A.L., Montz, B.E., Hoover, J.H., 2011. Policy and institutional dimensions of the water–energy nexus. Energy Policy 39, 6622–6630. doi:10.1016/j.enpol.2011.08.013.

Segers, R., Van Den Oever, R., Niessink, R., Menkveld, M., 2019. Warmtemonitor 2017. Technical Report. CBS (Statistics Netherlands) and ECN part of TNO. URL: https://www.cbs.nl/-/media/_pdf/2019/23/rapport-monitoring-warmte-2017.pdf.

Segers, R.C., Niessink, R., Van Den Oever, R., Menkveld, M., 2020. Warmtemonitor 2019. Technical Report. CBS (Statistics Netherlands) and TNO. Den Haag. URL: https://www.cbs.nl/nl-nl/achtergrond/2020/35/warmtemonitor-2019.

Seto, K.C., Davis, S.J., Mitchell, R.B., Stokes, E.C., Unruh, G., Ürge-Vorsatz, D., 2016. Carbon lock-in: types, causes, and policy implications. Annual Review of Environment and Resources 41, 425–452. doi:10.1146/annurev-environ-110615-085934.

Smits, A., 2022. Factsheet bevolkingsprognose 2022-2050. URL: https://onderzoek.amsterdam.nl/publicatie/bevolkingsprognose-2022-2050.

Sovacool, B.K., Burke, M., Baker, L., Kotikalapudi, C.K., Wlokas, H., 2017. New frontiers and conceptual frameworks for energy justice. Energy Policy 105, 677–691. doi:10.1016/j.enpol.2017.03.005.

Sovacool, B.K., Cabeza, L.F., Laura, A., Fronzetti, A., Madani, H., Dawoud, B., Martiskainen, M., 2021a. Decarbonizing household heating: Reviewing demographics, geography and low-carbon practices and preferences in five European countries. Renewable and Sustainable Energy Reviews 139. doi:10.1016/j.rser.2020.110703.

Sovacool, B.K., Demski, C., Noel, L., 2021b. Beyond climate, culture and comfort in European preferences for low-carbon heat. Global Environmental Change 66. doi:10.1016/j.gloenvcha.2020.102200.

Spang, E.S., Moomaw, W.R., Gallagher, K.S., Kirshen, P.H., H, M.D., 2014. The water consumption of energy production: an international comparison. Environmental Research Letters 9. doi:10.1088/1748-9326/9/10/105002.

Statistics Netherlands, 2020. Statline: Watergebruik bedrijven en particuliere huishoudens; nationale rekening. URL: https://www.cbs.nl/nl-nl/cijfers/detail/82883NED. Accessed November 2020.

Statistics Netherlands, 2021. Energielevering aan woningen en bedrijven naar postcode. URL: https://www.cbs.nl/nl-nl/maatwerk/2020/33/energielevering-aan-woningen-en-bedrijven-naar-postcode. data retrieved on: 25-05-2021.

Statistics Netherlands, 2023. Welke sectoren stoten broeikasgassen uit. URL: https://www.cbs.nl/nl-nl/dossier/dossier-broeikasgassen/hoofdcategorieen/welke-sectoren-stoten-broeikasgassen-uit-. last accessed on: 13-03-2023.

Sunny, N., Dowell, N.M., Shah, N., 2020. What is needed to deliver carbon-neutral heat using hydrogen and CCS. Energy & Environmental Science 13, 4204–4224. doi:10.1039/d0ee02016h.

Swan, L.G., Ugursal, V.I., 2009. Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. Renewable and Sustainable Energy Reviews 13, 1819–1835. doi:10.1016/j.rser.2008.09.033.

Thomaßen, G., Kavvadias, K., Navarro, J.P.J., 2021. The decarbonisation of the eu heating sector through electrification: A parametric analysis. Energy Policy 148, 111929. doi:10.1016/j.enpol.2020.111929.

Tijmstra, J., Boeije, H., 2011. Wetenschapsfilosofie in de context van de sociale wetenschappen. Boom Lemma uitgevers, The Hague.

UNFCCC, 2015. Paris agreement. article 2(a). URL: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement.

U.S. Energy Information Administration, 2019. Annual electric generator report. URL: https://www.eia.gov/electricity/annual/html/epa_08_02.html. Last accessed March 2021.

Van den Brom, P., 2020. Energy in Dwellings: A comparison between theory and practice. URL: https://research.tudelft.nl/files/69716293/9789463662536_WEB.pdf. phD thesis, Delft Technical University. isbn: 9789463662536.

Van den Dobbelsteen, A., Broersma, S., Fremouw, M., Blom, T., Sturkenboom, J., Martin, C., 2020. The amsterdam energy transition roadmap – introducing the city-zen methodology. Smart and Sustainable Built Environment 9, 307–320. doi:10.1108/SASBE-05-2019-0065.

Van Der Hoek, J.P., Struker, A., De Danschutter, J.E.M., 2017. Amsterdam as a sustainable European metropolis: integration of water, energy and material flows. Urban Water Journal doi:10.1080/1573062X.2015.1076858.

Van Overbeeke, P., 2001. Kachels, geisers, en fornuizen: keuzeprocessen en energieverbruik in Nederlandse huishoudens, 1920-1975. volume 10. Uitgeverij Verloren, Hilversum. URL: https://research.tue.nl/nl/publications/kachels-geisers-en-fornuizen-keuzeprocessen-en-energieverbruik-in.

Van Uffelen, N., 2022. Revisiting recognition in energy justice. Energy Research & Social Science 92. doi:10.1016/j.erss.2022.102764.

Van Vliet, M.T.H., Wiberg, D., Leduc, S., Riahi, K., 2016. Power-generation system vulnerability and adaptation to changes in climate and water resources. Nature Climate Change 6, 375–380. doi:10.1038/NCLIMATE2903.

Vattenfall, 2019. Heat label 2018. URL: https://www.vattenfall.nl/media/consumenten/producten/stadsverwarming/warmte-etiket/warmte_etiket2018.pdf.

Vattenfall, 2022. 65% co2-reductie met stadswarmte in amsterdam in 2021. URL: https://www.vattenfall.nl/stadsverwarming/co2-reductie-amsterdam/. webpage, last accessed: 8-11-2022.

Vesterlund, M., Toffolo, A., Dahl, J., 2017. Optimization of multi-source complex district heating network, a case study. Energy 126, 53–63. URL: https://linkinghub.elsevier.com/retrieve/pii/S0360544217303766, doi:10.1016/j.energy.2017.03.018.

Von Winterfeld, U., Biesecker, A., Katz, C., Best, B., 2012. Welche Rolle können Commons in Transformationsprozessen zu Nachhaltigkeit spielen? Technical Report. Wuppertal Institut für Klima, Umwelt, Energie. Wuppertal. URL: https://www.econstor.eu/bitstream/10419/59295/1/718033531.pdf. impulse zur WachstumsWende, No. 6.

Voskamp, I.M., Spiller, M., Stremke, S., Bregt, A.K., Vreugdenhil, C., Rijnaarts, H.H., 2018. Space-time information analysis for resource-conscious urban planning and design: A stakeholder based identification of urban metabolism data gaps. Resources, Conservation and Recycling 128, 516–525. doi:10.1016/j.resconrec.2016.08.026.

Voulis, N.T.D., 2019. Harnessing Heterogeneity: Understanding Urban Demand to Support the Energy Transition. Ph.D. thesis. Delft University of Technology. Delft. doi:10.4233/uuid:9b121e9b-bfa0-49e6-a600-5db0fbfa904e.

Vásquez, F., Løvik, A.N., Sandberg, N.H., Müller, D.B., 2016. Dynamic type-cohort-time approach for the analysis of energy reductions strategies in the building stock. Energy and Buildings 111, 37–55. doi:10.1016/j.enbuild.2015.11.018.

Waternet, 2020. Infopagina omgevingswarmtekaart. URL: https://www.waternet.nl/innovatie/CO2-reductie/infopagina-omgevingswarmtekaart/. web page published on 23 September 2020.

Waternet, 2023. Omgevingswarmtekaart. URL: https://waternet.omgevingswarmte.nl/waternet#c9eaed99-a69e-48eb-9642-61c0e0b77078. image retrieved on 1 March 2023.

Webber, M.E., 2007. The water intensity of the transitional hydrogen economy. Environmental Research Letters 2. doi:10.1088/1748-9326/2/3/034007.

Werner, S., 2017. International review of district heating and cooling. Energy 137, 617–631. doi:10.1016/j.energy.2017.04.045.

Wesselink, A., Kooy, M., Warner, J., 2017. Socio-hydrology and hydrosocial analysis: toward dialogues across disciplines. Wiley Interdisciplinary Reviews: Water 4, e1196. doi:10.1002/wat2.1196.

Wiebes, E., 2018. Gaswinning. URL: https://zoek.officielebekendmakingen.nl/kst-33529-457.html. letter of Minister of Economic Affairs and Climate to the chair of House of Representatives. Session year 2017-2018. 33 529: nr. 457.

Wielders, L., Nusselder, S., 2020. Emissiekentallen elektriciteit. Technical Report. CE Delft. Delft. URL: https://www.co2emissiefactoren.nl/wp-content/uploads/2020/01/CE-Delft-2020-Memo-emissiekentallen_elektriciteit-190426-januari-2020.pdf.

Williams, J., Bouzarovski, S., Swyngedouw, E., 2018. The urban resource nexus: On the politics of relationality, water–energy infrastructure and the fallacy of integration. Environment and Planning C: Politics and Space 37, 652–669. doi:10.1177/0263774X18803370.

Wittmayer, J.M., Hielscher, S., Fraaije, M., Avelino, F., Rogge, K., 2022. A typology for unpacking the diversity of social innovation in energy transitions. Energy Research & Social Science 88. doi:10.1016/j.erss.2022.102513.

Zapata Campos, M.J., Zapata, P., Ordoñez, I., 2020. Urban commoning practices in the repair movement: Frontstaging the backstage. Environment and planning A: Economy and Space 52, 1150–1170. doi:10.1177/0308518X19896800.

Zhu, K., Victoria, M., Brown, T., Andresen, G.B., Greiner, M., 2019. Impact of CO2 prices on the design of a highly decarbonised coupled electricity and heating system in Europe. Applied Energy 236, 622–634.

Zijlema, P., 2020. Nederlandse lijst van energiedragers en standaard CO2 emissiefactoren, versie januari 2020. Technical Report. Netherlands Enterprise Agency. The Hague. URL: https://www.rvo.nl/sites/default/files/2020/03/Nederlandse-energiedragerlijst-versie-januari-2020.pdf.

List of Figures

List of Tables

Acronyms

AMS Institute	Amsterdam Institute for Advanced Metropolitan Solutions
ATES	Aquifer Thermal Energy Storage
BTES	Borehole Thermal Energy Storage
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
CO_2-eq	carbon dioxide equivalent
COP	coefficient of performance
ENLARGE	ENabling LARGE-scale adaptive integration of technology hubs to enhance community resilience through decentralised urban Water-Energy-Food Nexus decision support
ERE	Energy Required for Energy
GIS	Geographic Information System
HT	high temperature
IPCC	Intergovernmental Panel on Climate Change
IRSTEA	Institut national de recherche en sciences et technologies pour l'environnement et l'agriculture
LCA	life cycle assessment
LT	low temperature
MFA	material flow analysis
MILP	mixed-integer linear program
MINLP	mixed-integer nonlinear program
MT	mid temperature
P2H	Power-to-Heat
PHPP	Passive House Planning Package
SET	social-ecological-technological
SUGI	Sustainable Urban Global Initiative
SURF	Smart Urban Regions of the Future
UTES	Underground Thermal Energy Storage
VerDuS	*Verbinden van Duurzame Steden*
VW_{fuel}	virtual water use of fuels
WEF	Water-Energy-Food
WF	water footprint

List of Publications

- Kaandorp, C., Miedema, T., Verhagen, J., van de Giesen, N. and Abraham, E., 2022[1]. Reducing committed emissions of heating towards 2050: Analysis of scenarios for the insulation of buildings and the decarbonisation of electricity generation. *Applied Energy*, 325, 119759. Doi: 10.1016/j.apenergy.2022.119759

- Kaandorp, C., van de Giesen, N., Abraham, E., 2021. The water use of heating pathways to 2050: analysis of national and urban energy scenarios. *Environmental Research Letters* 16. Doi: 10.1088/1748-9326/abede7.

- Kaandorp, C., Pessoa, I., Abraham, E., 2020. Enlarge the focus: linking policy for low-carbon urban heating with sustainable water use and social inclusion. Policy brief: `https://jpi-urbaneurope.eu/wp-content/uploads/2021/09/Policy-Brief-JPI-Eurban-Europe-ENLARGE.pdf`

- Kaandorp, C., Pessoa, I., Abraham, E., 2020. Vergroot de focus: de transitie naar aardgasvrije verwarming van gebouwen bekeken vanuit de thema's 'Duurzaam watergebruik' en 'Een inclusieve samenleving'. Policy brief: `https://www.verdus.nl/assets/uploads/2020/12/Beleidssamenvatting-ENLARGE-2020.pdf`

- Chang, N., Hossain, U., Valencia, A., Qiu, J., Zheng, Q. P., Gu, L., Chen, M., Lu, J. W., Pires, A., Kaandorp, C., Abraham, E., ten Veldhuis, M. C., van de Giesen, N., Molle, B., Tomas, S., Ait-Mouheb, N., Dotta, D., Declercq, R., Perrin, M., Conradi, L., Molle, G. (2020). Integrative technology hubs for urban food-energy-water nexuses and cost-benefit-risk tradeoffs (I): Global trend and technology metrics. *Critical Reviews in Environmental Science and Technology*. Doi: 10.1080/10643389.2020.1759328.

- Chang, N., Hossain, U., Valencia, A., Qiu, J., Zheng, Q. P., Gu, L., Chen, M., Lu, J. W., Pires, A., Kaandorp, C., Abraham, E., ten Veldhuis, M. C., van de Giesen, N., Molle, B., Tomas, S., Ait-Mouheb, N., Dotta, D., Declercq, R., Perrin, M., Conradi, L., Molle, G. (2020). Integrative technology hubs for urban food-energy-water nexuses and cost-benefit-risk tradeoffs (II): Design strategies for urban sustainability. *Critical Reviews in Environmental Science and Technology*. Doi: 10.1080/10643389.2020.1761088.

  Contributed to:

- De Kraker, J., Kemp, R. (2021). Stedelijke duurzaamheidstransities: energie, klimaat & circulariteit. Synthesis study on Sustainability for the VerDuS SURF initiative. URL: `https://www.verdus.nl/stedelijke-duurzaamheidstransities-energie-klimaat-circulariteit/`

[1]This paper has received the Best Energy Paper 2022 Award from the TU Delft Urban Energy Institute in the category of 'Urban Energy'.

About the author

Chelsea KAANDORP

Chelsea Kaandorp was born in Amsterdam, the Netherlands, on 17 April 1994. In 2018, she started her PhD on the Water-Energy-Food Nexus in Amsterdam at the TU Delft. Before that, she finished her Master's degrees in Theoretical Physics and in Cultural Anthropology, at the University of Cambridge and Utrecht University respectively. For her master's thesis in Cultural Anthropology, she performed an ethnographic study on how notions of global climate change and local deforestation in the Kilimanjaro region in Tanzania connect to the hydrosocial cycle. During her studies, she also fulfilled a six-month internship in the Cities team at Circle Economy and a semester-long Erasmus exchange at the École Normale Supérieure in Paris, France.

Figure B.7: Picture taken of Chelsea Kaandorp in November 2018