The General and the Specifics

Heating and Cooling Strategies in Smart Energy Systems

Paardekooper, Susana

DOI (link to publication from Publisher):
10.54337/aau539408837

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

THE GENERAL AND THE SPECIFICS

HEATING AND COOLING STRATEGIES
IN SMART ENERGY SYSTEMS

BY
SUSANA PAARDEKOOPER

DISSERTATION SUBMITTED 2023

AALBORG UNIVERSITY
DENMARK

THE GENERAL AND THE SPECIFICS

HEATING AND COOLING STRATEGIES IN SMART ENERGY SYSTEMS

by

Susana Paardekooper

AALBORG UNIVERSITY
DENMARK

Dissertation submitted February 2023

.

Dissertation submitted: February 2023

PhD supervisor: Prof. Henrik Lund
Aalborg University

Assistant PhD supervisor: Associate Prof. Jakob Zinck Thellufsen
Aalborg University

PhD committee: Associate Professor Søren Løkke (chairman)
Aalborg University, Denmark

Associate Professor Kristina Lygnerüd
Halmstad University, Sweden

Director Robin Wiltshire
Heatmatters Ltd, United Kingdom

PhD Series: Technical Faculty of IT and Design, Aalborg University

Department: Department of Planning

ISSN (online): 2446-1628
ISBN (online): 978-87-7573-738-3

Published by:
Aalborg University Press
Kroghstræde 3
DK – 9220 Aalborg Ø
Phone: +45 99407140
aauf@forlag.aau.dk
forlag.aau.dk

Printed in Denmark by Stibo Complete, 2023

PREFACE

This PhD presents a synthesis of the work I have undertaken working at the Sustainable Energy Planning and Research Group at Aalborg University in Copenhagen between 2016 and 2022. Around the time that I started working at the AAU, in 2015, there was a moment of increased action on district heating and cooling, with the EU Strategy for Heating and Cooling looking towards more integrated heating and cooling at European level, and the UN Environment District Energy in Cities Initiative gaining speed. This was of course also driven by the annexation of the Crimea in 2014. The main narrative was still that heating and cooling was local and complex, but these initiatives represented an emerging recognition that they were also European and global problems. It felt like a call to action in terms of research on heating and cooling. Now that heating and cooling was making its way onto the agenda, how should it be done? It goes without saying that this is still something we are and should be trying to address.

During the past years I have had the pleasure of participating in countless discussions, presentations, conferences, workshops, and capacity building events of different flavours. More so than I expected, local motivations and objectives differ. At the same time, I have found myself having very similar conversations in wildly different settings about heat pumps, district heating ownership, cogeneration, and local policy on pipe trenches, and have been struck by how there are certain recurring themes and topics, no matter the contexts.

I set out to try and understand how to make useful heating and cooling strategies, and how much transferrable learning exists between them. My overall goal with this research was to contribute to the integration of heating and cooling in local and global energy and sustainability strategies. Looking back, there are concrete things that point to this having happened. The Heat Roadmap Europe project, which forms the basis for much of this work, is referenced in the 2018 EU Clean Planet for All analysis, and has been recalled in the context of the current energy crisis. The Heat Roadmap for Chile we developed in 2019 is was used to inform the discourse on Chile's Long-Term Energy Plan and Nationally Determined Contribution. This is how researchers dream that their hard work gets used. At the same time there are new challenges and much work left to be done, particularly given the renewed attention heating and cooling is receiving. I hope that the papers and this thesis make the results of that work relevant for other places too.

ACKNOWLEDGEMENTS

The work that this PhD is based on has received funding from European Union's Horizon2020 program (Heat Roadmap Europe, GA 695989), the United Nations Environment Programme, the UNEP DTU Partnership and Mads and Bitten Clausen Foundation, and the UNEP District Energy in Cities Initiative, the 4DH project (funded by the Innovation Fund Denmark) and the RE-INVEST (Renewable Energy Investment Strategies) project (funded by the Innovation Fund Denmark).

This research has been helped by a number of people along the way. My supervisors, Henrik Lund and Jakob Zinck Thellufsen, have been instrumental in my PhD journey. I cannot thank them enough for their continuous support, patience, guidance, and advice throughout this period. Their input has been invaluable to help structure my thoughts, see the story within, and bring the finished product forwards.

I would also like to express my deepest appreciation to my colleagues in the Sustainable Energy Planning group – past and present – for their engagement, collaboration, coffee and cake over the years. Research is not always an easy field to be in, and without the encouragement, advice, and team work we share it would not have been possible for me.

A heartfelt thanks goes to my colleagues at the UNEP Copenhagen Climate Center (formerly UNEP-DTU Partnership) and the UN District Energy in Cities Initiative, with whom I collaborated between January 2018 and November 2019. In particular, I would like to thank Zhuolun Chen and Romanas Savickas for always making me feel welcome, and sharing their enthusiasm, knowledge and experience, including the bright, dark, hopeful, and sometimes absurdist aspects of trying to get pipes in the ground.

A special thank you also goes to the project partners of Heat Roadmap Europe. Being a part of bringing together so many tools, methodologies, and perspectives on the heating and cooling sector was a great experience and I hope this work reflects how much I have learned from our discussions and exchanges.

This appreciation is also extended to the project partners in the DES Initiative. Being part of the challenges and navigating them has informed much of the research here, and a driver for trying to discern how it can be turned into something useful. Hearing how problems have and are being creatively solved has been a huge inspiration for this work.

Throughout this process, I spoken to and heard from hundreds of people, and almost always experienced a shared curiosity and commitment towards improving how we discuss heating and cooling. Some have shaped my thinking through ongoing discussions and exchanges, but often I have found myself challenged or my curiosity piqued through a single remark or question. These insights have been vital in developing the rigor of my work, and I would like to thank the broader community around district heating and energy system analysis which I have become a part of.

In finalising this project, I would also like to thank my current colleagues at the Danish Energy Agency, for supporting and enquiring about the progress. I would also like to specifically thank my (former) colleagues Uni Reinert Pedersen, Miguel Chang, and Noémi Schneider for their help with translation of the summaries.

Finally, it goes without saying that I could not have done this without the unconditional love, support, and encouragement of my family. I could also not have done this without the laughter, cheerfulness, and 'gezelligheid' along the way.

ENGLISH SUMMARY

In energy transition, strategies for heating and cooling are neglected compared to electricity and other sectors. Yet, such strategies are much needed to present concrete visions and alternatives for a more sustainable and renewable future of heating and cooling. Without them, we risk failing to realise the many opportunities for increased sustainability that heating and cooling presents, on both a local and a global scale.

This PhD thesis investigates which general elements are part of the design of heating and cooling strategies, and which are necessarily specific to the local situation. The analysis is based on the review of two 100% renewable energy strategies, the development of 14 Heat Roadmap strategies for Europe, a Heat Roadmap for Chile, and collaboration with the UN Environment District Energy in Cities Initiative to explore heating and cooling infrastructures in developing and emerging economies.

Strategies are intended to present visions in support of dialogue and decisions on the direction of transitions. In this PhD, strategies for heating and cooling are rooted in scenario design and energy system analysis. They take their conceptual point of departure in the “Smart Energy System” concept and actively include exploring the development of district energy as an enabling infrastructure that supports decarbonisation and sustainability in heating and cooling.

Combined, the studies in this PhD show that by designing heating and cooling strategies for various countries, it is possible to identify general and specific aspects. The comparative approach discusses heating and cooling strategies in terms of identifying strategic design objectives, determining design criteria, and using functional design approaches and functional design principles.

Specific reasons exist at local level that drive the need for heating and cooling strategies. These can be very particular, such as the desire to prevent air pollution from heating stoves in Chile, or phasing out natural gas use in the Netherlands. Even more universal challenges like decarbonisation, sustainable resource management and poverty reduction also play out differently at the local level. This is why strategic design objectives and criteria for heating and cooling strategies must capture the specific socio-political context to reflect and respond to local differences.

Generally, there are some good, functional approaches and principles towards addressing heating and cooling in varied contexts. Integration of the energy system, thermal grids in cities, and a focus on energy efficiency emerge as good general solutions to many problems. Smart use of storage, excess and renewable heat, and exploring cogeneration and large-scale heat pumps is also commonly valuable. While many technical solutions and mechanisms for improving the heating and cooling sector are common – and have been successfully implemented in some countries – they must be implemented in a way that addresses the specific local problems.

DANSK RESUME

I omstilling til vedvarende energi bliver strategier for varme og køling forsømt sammenlignet med el og andre sektorer. Der er dog i høj grad brug for disse strategier, således at konkrete visioner og alternativer kan opstilles for fremtidens bæredygtige og vedvarende varme og køling. Uden sådanne strategier er der risiko for, at vi ikke formår at udnytte de mange muligheder, der er, for mere bæredygtig varme og køling lokalt såvel som globalt.

Denne PhD afhandling undersøger strategier for varme og køling, herunder hvilke dele af disse strategier er generelle og hvilke er specifikt afhængige af det lokale område. Analysen baseres på review af to strategier for 100% vedvarende energi, udviklingen af 14 Heat Roadmap strategier for Europa, et Heat Roadmap for Chile, og et samarbejde med UN Environment District Energy in Cities Initiativet om udforskningen af varme- og køleinfrastruktur i udviklingslande.

Formålet med strategier er at præsentere visioner, som kan understøtte dialog og beslutningstagning i omstillingen. I denne PhD bunder strategier for varme og køling i design af scenarier og analyse af energisystemer. Deres konceptuelle udgangspunkt er "Smart Energy Systems" konceptet, og de undersøger brugen af fjernvarme som en infrastruktur, der muliggør og fremmer dekarbonisering og bæredygtig varme og køling.

Undersøgelserne i denne PhD viser tilsammen, at ved at designe strategier for varme og køling for forskellige lande er det muligt at identificere hvilke generelle og specifikke forhold der gør sig gældende. Med denne komparative tilgang diskuteres strategier for varme og køling med det formål at identificere strategiske mål i designprocessen, at opstille design kriterier, og at bruge funktionelle designtilgange og -principper.

Særlige lokale forhold skaber behov for strategier for varme og køling. Det kan være særdeles specifikke forhold, såsom ønsket om at forhindre luftforurening fra ovne i Chile, eller udfasningen af naturgas i Holland. Mere universelle udfordringer, såsom dekarbonisering, bæredygtig ressourceforbrug og reducering af fattigdom, udspiller sig også forskelligt i forskellige lokalområder. Derfor må strategiske designmål og -kriterier for varme og kølestrategier fange de specifikke socio-politiske forhold, således at de kan reflektere og tilpasses lokale forskelle.

Overordnet set findes der nogle gode og funktionelle tilgange og principper for at adressere varme og køling i forskellige sammenhænge. Integration i energisystemet, fjernvarme i byer, og fokus på energieffektivitet fremstår som gode generelle løsninger på mange udfordringer. Smart brug af lagre, udnyttelse af overskydende og vedvarende varme, samt undersøgelse af potentialer for kraftvarme og store varmepumper er også gode generelle initiativer. Selv om der findes mange gode tekniske løsninger og mekanismer til at forbedre varme- og kølesektoren, og selv om disse allerede er implementerede og velfungerende i nogle lande, så må disse almindelige løsninger implementeres på særlige måder hvor lokale områders specifikke udfordringer adresseres..

RESUMEN ESPAÑOL

En la transición energética, las estrategias de calefacción y enfriamiento son, a menudo, pasadas por alto en comparación a las estrategias de otros sectores como el sector eléctrico. Sin embargo, estas son muy necesarias para presentar visiones y alternativas concretas para un futuro más sostenible y renovable. Sin ellas, se corre el riesgo de no aprovechar las muchas oportunidades para una mayor sostenibilidad que presentan la calefacción y el enfriamiento tanto a nivel local como global.

Esta tesis doctoral investiga qué elementos generales forman parte del diseño de estrategias de calefacción y enfriamiento, y cuáles de esos elementos son específicos al nivel local. El análisis se basa en la revisión de dos estrategias de energía 100% renovable, el desarrollo de 14 Hojas de Ruta de Calefacción para Europa, una Hoja de Ruta de Calefacción para Chile y una colaboración con la Iniciativa Global de Energía Distrital en Ciudades (District Energy in Cities Initiative) del Programa de las Naciones Unidas para el Medio Ambiente (PNUMA) para explorar infraestructuras de calefacción y enfriamiento en países en vías de desarrollo y economías emergentes.

Estas estrategias están destinadas a presentar visiones que apoyen el diálogo y las decisiones sobre la dirección de la transición energética. En esta tesis, las estrategias de calefacción y enfriamiento se basan en el diseño de escenarios y el análisis de sistemas energéticos. Estos toman su punto de partida en el concepto de "Smart Energy System" e incluyen activamente la exploración del desarrollo de la energía distrital como una infraestructura facilitadora que respalda la descarbonización y la sostenibilidad en la calefacción y el enfriamiento.

En su conjunto, los casos estudiados para este doctorado muestran que, mediante el diseño de estrategias de calefacción y enfriamiento para varios países, es posible identificar tanto aspectos generales como específicos. En términos comparativos, se analizan las distintas estrategias de calefacción y enfriamiento considerando la identificación de objetivos estratégicos de diseño, la determinación de criterios de diseño, y el uso de enfoques y principios de diseño funcional.

Existen razones específicas a nivel local que impulsan la necesidad de estrategias de calefacción y enfriamiento. Estas pueden ser muy particulares, como el deseo de descontaminación atmosférica para eliminar la contaminación del aire causado por estufas de calefacción en Chile, o la eliminación progresiva del uso de gas natural en los Países Bajos. Incluso desafíos más universales como la descarbonización, la gestión sostenible de los recursos y la reducción de la pobreza se manifiestan de manera diferente a nivel local. Es por eso que los objetivos de diseño estratégico y los criterios para las estrategias de calefacción y enfriamiento deben capturar el contexto sociopolítico específico para reflejar y responder a las particularidades locales.

En general, existen algunos enfoques y principios buenos y funcionales para abordar la calefacción y el enfriamiento en contextos variados. La integración del sistema energético, las redes térmicas en las ciudades y el enfoque en la eficiencia energética surgen como buenas soluciones generales a muchos problemas. El uso inteligente de almacenamientos de energía térmica, de fuentes de calor residual y calor renovable, y la exploración de la cogeneración y las bombas de calor a gran escala también son comúnmente valiosas. Si bien muchas soluciones técnicas y mecanismos para mejorar el sector de la calefacción y el enfriamiento son comunes y se han implementado con éxito en algunos países, deben implementarse siempre de una manera que aborde los problemas locales específicos.

RÉSUMÉ FRANÇAIS

Dans la transition énergétique, les stratégies en matière de chauffage et de refroidissement sont négligées par rapport à l'électricité et à d'autres secteurs. Pourtant, de telles stratégies sont indispensables pour proposer des visions et des alternatives concrètes pour un avenir plus durable et renouvelable du chauffage et du refroidissement. Sans elles, nous risquons de ne pas saisir les nombreuses opportunités de développement durable que présentent le chauffage et le refroidissement, à la fois à l'échelle locale et mondiale.

Cette thèse de doctorat étudie quels sont les éléments généraux qui participent à l'élaboration des stratégies de chauffage et de refroidissement, et lesquels sont nécessairement spécifiques à la situation locale. L'analyse est basée sur l'examen de deux stratégies d'énergie 100 % renouvelable, l'élaboration de 14 stratégies et feuilles de route pour le chauffage en Europe, une feuille de route pour le chauffage au Chili, et la collaboration avec l'Initiative des réseaux d'énergie urbains du Programme des Nations Unies pour l'environnement pour étudier les réseaux de chaleur et de froid dans les économies en développement et émergentes.

Les stratégies visent à présenter des visions à l'appui du dialogue et des décisions sur l'orientation des transitions. Dans cette thèse, les stratégies en matière de chauffage et de refroidissement sont basées sur l'élaboration de scénarios et l'analyse de systèmes énergétiques. Elles prennent leur point de départ conceptuel dans le concept de « Smart Energy System » et incluent activement l'étude du développement des réseaux de chaleur et de froid comme une infrastructure habilitante qui soutient la décarbonation et le développement durable du chauffage et du refroidissement.

Pris ensemble, les cas étudiés dans ce doctorat montrent qu'en concevant des stratégies en matière de chauffage et de refroidissement pour différents pays, il est possible d'identifier des aspects généraux et spécifiques. Dans une approche comparative, les différentes stratégies de chauffage et de refroidissement sont analysées en termes d'identification des objectifs de conception stratégique, de détermination des critères de conception et d'utilisation d'approches de conception fonctionnelle et de principes de conception fonctionnelle.

Il existe des raisons spécifiques au niveau local qui motivent le besoin de stratégies de chauffage et de refroidissement. Celles-ci peuvent être très particulières, comme l'impératif de prévenir la pollution de l'air due aux poêles à bois au Chili, ou la suppression progressive de l'utilisation du gaz naturel aux Pays-Bas. Des défis encore plus universels comme la décarbonation, la gestion durable des ressources et la réduction de la pauvreté se manifestent également différemment au niveau local. C'est pourquoi les objectifs de conception stratégique et les critères des stratégies de chauffage et de refroidissement doivent saisir le contexte socio-politique spécifique pour refléter et répondre aux particularités locales.

En général, il existe de bonnes approches et principes fonctionnels pour aborder le chauffage et le refroidissement dans des contextes variés. L'intégration du système énergétique, les réseaux de chaleur et de froid dans les villes et un focus sur l'efficacité énergétique apparaissent comme de bonnes solutions générales à de nombreux problèmes. L'utilisation intelligente du stockage de l'énergie et de la chaleur renouvelable et de récupération, et l'exploitation de la cogénération et des pompes à chaleur sont également souvent valables. Si de nombreuses solutions techniques et mécanismes pour améliorer le secteur du chauffage et du refroidissement sont connus – et ont été mis en œuvre avec succès dans certains pays – encore doivent-ils être mis en œuvre de manière à résoudre les problèmes locaux spécifiques.

PUBLICATION LIST

This dissertation is based on a collection of papers, consisting of a chapter in an edited volume and three research articles, which form the scientific basis of this thesis. It is supported by the other work and activities carried out during the PhD period.

PAPERS INCLUDED IN THE THESIS

- (**Study 1: Storage in SES**) Paardekooper, S., Lund, R., & Lund, H. (2019). Smart Energy Systems. In R. E. Hester, & R. M. Harrison (Eds.), Energy Storage Options and Their Environmental Impact (pp. 228-260). Royal Society of Chemistry. Issues in Environmental Science and Technology, No. 46, Vol.. 2019-January https://doi.org/10.1039/9781788015530-00228
- (**Study 2: Heat Roadmap for Chile**) Paardekooper, S., Lund, H., Chang, M., Nielsen, S., Moreno, D., & Thellufsen, J. Z. (2020). Heat Roadmap Chile: A national district heating plan for air pollution decontamination and decarbonisation. Journal of Cleaner Production, 272, [122744]. https://doi.org/10.1016/j.jclepro.2020.122744
- **(Study 3: Types in Heat Roadmap Europe)** Paardekooper, S., Lund, H., Thellufsen, J.Z., Bertelsen, N., and Mathiesen, B.V. (2022). Heat Roadmap Europe: strategic heating transition typology as a basis for policy recommendations. Energy Efficiency, 15(5), [32]. https://doi.org/10.1007/s12053-022-10030-3
- (**Study 4: Motivations for DES**) Paardekooper, S., Chen, Z., Savickas, R. (2022). Smart objectives for district heating and cooling: exploring reasons for countries to engage with district energy. Working Paper, Version 2. July.

OTHER PUBLICATIONS AND PRESENTATIONS

Peer reviewed articles and working papers

- Chang, M., **Paardekooper**, S, Prima, M.G., Thellufsen, J.Z., Lund, H., Lapuente, P. (2023). Smart energy approaches for carbon abatement: Scenario designs for Chile's energy transition. Submitted to Smart Energy.
- Korberg, A.D., Thellufsen, J.Z., Skov, I.R., Chang, M., **Paardekooper**, S., Lund, H., Mathiesen, B.V. (2023). On the feasibility of direct hydrogen utilisation in a fossil-free Europe. International Journal of Hydrogen Energy, 48 (8): 2877-2891. https://doi.org/10.1016/j.ijhydene.2022.10.170
- Bertelsen, N., Mathiesen, B.V., **Paardekooper**, S. (2021). Implementing large-scale heating infrastructures: Experiences from successful planning of district heating and natural gas grids in Denmark, the United Kingdom, and

the Netherlands. Energy Efficiency, 14(7), [64]. https://doi.org/10.1007/s12053-021-09975-8
- Verschelde, T., **Paardekooper**, S., D'haselaer, W. (2021) Analysing the relation between the shares of district heating and country dependent parameters within the Heat Roadmap Europe scenarios. Working paper, version July 2021
- Maya-Drysdale, D., Mathiesen, B. V., & **Paardekooper**, S. (2019). Transitioning to a 100% renewable energy system in Denmark by 2050: assessing the impact from expanding the building stock at the same time. Energy Efficiency, 12(1), 37-55. https://doi.org/10.1007/s12053-018-9649-1

Conference presentations

- **Paardekooper**, S. (2017). Energy Efficiency in Buildings and District Energy. Presented at Aligning approaches to building energy efficiency and district energy, Co-organised by UN District Energy in Cities Initiative, Building Efficiency Accelerator and Belgrade municipality, Belgrade, 13 March 2018.
- **Paardekooper**, S. (2018). Iterations for heat savings, electrification, and district heating. Presented at 4th International Conference On Smart Energy Systems And 4th Generation District Heating, Aalborg, 13-14 November 2018.
- **Paardekooper** S. (2019). Heat Roadmap Europe: A Vision for 2050. Presented at Roadmaps are ready: now what?? Exploring the realities of the heat transition, Brussels, 13 February 2019
- **Paardekooper**, S. and Nielsen, S. (2019). Heat Roadmap Chile: A national district heating plan for air pollution decontamination and decarbonisation. Presented at workshop on Analysis of the potential to develop district energy in Chile. INACAP University Campus Sur, Santiago de Chile, 30-31 May, 2019.
- **Paardekooper**, S. (2019). Heat Roadmap Europe: Heating typology as a basis for policy recommendations. Presented at 5th International Conference on Smart Energy Systems, 4th Generation District Heating, Electrification, Electrofuels and Energy Efficiency, Copenhagen, 10-11 September, 2019.
- **Paardekooper**, S. (2019). Heat Roadmap for Scotland – Heating and cooling strategies at local, national and EU level. Presented at Research-policy workshop on heat decarbonisation, Edinburgh Centre for Carbon Innovation, Edinburgh, Scotland, 14 and 15 October 2019.

Project reports and working papers

- **Paardekooper**, S., Lund, R. S., Mathiesen, B. V., Chang, M., Petersen, U. R., Grundahl, L. et al. (2018). Heat Roadmap Europe 4: Quantifying the Impact of Low-Carbon Heating and Cooling Roadmaps. Department of Development and Planning, Aalborg University.

- **Paardekooper**, S., Chang, M., Nielsen, S., Moreno, D., Lund, H., Grundahl, L. et al. (2019). Heat Roadmap Chile: Quantifying the Potential of Clean District Heating and Energy Efficiency for a Long-Term Energy Vision for Chile. Report, Department of Planning, Aalborg University.
- Bertelsen, N., Mathiesen, B. V., Djørup, S. R., Schneider, N. C. A., **Paardekooper**, S., Sánchez García, L., et al. (2021b). Integrating low-temperature renewables in district energy systems: Guidelines for policy makers. International Renewable Energy Agency.
- Mathiesen, B. V., Bertelsen, N., Schneider, N. C. A., García, L. S., **Paardekooper**, S., Thellufsen, J. Z., et al. (2019). Towards a decarbonised heating and cooling sector in Europe: Unlocking the potential of energy efficiency and district energy. Aalborg University.
- Bean, F., Volt, J., de Groote, M., **Paardekooper,** S., Riahi, L. (2018). Aligning District Energy and Building Energy Efficiency – A View on Strategic Integrations. Buildings Performance Institute of Europe.
- Mathiesen, B. V., Maya-Drysdale, D., Lund, H., **Paardekooper**, S., Ridjan, I., Connolly, D., et al. (2016). Future Green Buildings: A Key to Cost-Effective Sustainable Energy Systems. Department of Development and Planning, Aalborg University

TABLE OF CONTENTS

TABLE OF FIGURES

LIST OF ABBREVIATIONS

3GDH – Third Generation District Heating

4GDH – Fourth Generation District Heating

AAU – Aalborg University

CHP – Combined heat and power

CO_2 – Carbon dioxide

DES – District energy systems

DES Initiative – United Nations Environment District Energy in Cities Initiative

EC – European Commission

EED – Energy Efficiency Directive

EERE - United States Government Office of Energy Efficiency and Renewable Energy

EPBD – Energy Performance of Buildings Directive

ESD – Energy Services Directive

EU – European Union

GHG – Greenhouse gas

HCFC – hydrochlorofluorocarbons

HFC - hydrofluorocarbons

HRE – Heat Roadmap Europe

IDA – The Danish Society of Engineers

IEA – International Energy Agency

LPG – Liquid petroleum gas

LSHP – Large scale heat pump

LULUCF – Land use, land-use change and forestry

MS – Member State (of the European Union)

nZEB – Near zero energy building

PELP – "Proceso de Planificación Energética de Largo Plazo", Long-term energy planning carried out for Chile by (Ministerio de Energía, 2017)

PES – Primary energy supply: all energy that is used, before conversion, as input to supply the energy system

PM – Particulate matter

RED – Renewable Energy Directive

RES – Renewable Energy Sources

SDG – Sustainable Development Goal

SES – Smart Energy Systems

UN – United Nations

VRES – Variable renewable energy sources

WtE – Waste to energy

CHAPTER 1. INTRODUCTION

1.1. BACKGROUND, FORM AND PAPERS

This paper-based PhD consists of this PhD thesis and several studies, which are very briefly summarised below and attached in the Appendices. This PhD thesis then aims to bring them together and synthesise the research from the publications, to discuss **how heating and cooling strategies can be designed for various countries within the concept of Smart Energy Systems.**

Study 1: Storage in Smart Energy Systems (Paardekooper, Lund and Lund, 2019) is a chapter in an edited volume, which investigates the role of different types of storages in (pre-existing) 100% renewable Smart Energy Systems. For this PhD, it serves to define the concept of Smart Energy Systems, review and familiarise two examples of 100% renewable energy system strategies ('IDA's Energy Vision 2050' for Denmark and 'Smart Energy Europe'), and investigate in more depth how storages function. Based on this, it becomes possible to contextualise the heating sectors, and have a better framing of how they function within 100% renewable energy system strategies.

Study 2: Heat Roadmap Chile (Paardekooper et al., 2020) is a peer-reviewed paper in the Journal of Cleaner Production. In it we develop a heating strategy for Chile. It presents the first national-level assessment for district heating in Chile, and supports long term decarbonisation and decontamination of the Chilean energy system. Methodologically, it is novel in that it applies the Heat Roadmap methodology, which combines energy mapping and energy system simulation and analysis, outside of Europe. It further advances the development of heating strategies by including an assessment of particulate matter (PM) as an indicator of air pollution, in response to the challenge Chile faces in terms of air pollution from inefficient heating stoves. In this thesis, it serves as an example of fully developing a heating and cooling strategy in response to the particular strategic objectives of a country.

Study 3: Types in Heat Roadmap Europe (Paardekooper et al., 2022) is a peer-reviewed article in the Journal of Energy Efficiency. In the Heat Roadmap Europe project we developed heating and cooling strategies for 14 European countries. This paper proposes a typology to categorise these 14 countries in a way that operationalises the energy efficiency first principle to consider demand and supply-side efficiency in the heating and cooling sector, and a particular regard for the potential of district energy. Based on this we identify 4 different types of heating strategies, with 4 corresponding sets of policy recommendations. In doing so it facilitates a level of analysis that lies between a fragmented country approach and a generic European approach, and supports transferability and the development of (local) policy based on characteristics of the heating sectors.

Study 4: Motivations for district energy engagement (Paardekooper, Chen and Savickas, 2022) is a working paper (dated July 2022). The perspective is often that district energy addresses decarbonisation and global sustainability issues, but district energy is typically a local infrastructure with local effects. To understand better how local and global objectives become aligned, we explore why countries are interested in engaging with district energy using a semi-structured narrative review, and an analytical framework based on energy cultures, planning objectives, approaches, design solutions and triggers. The analysis covers Chile, India, Serbia and Mongolia. These represent 4 countries which chose to actively engage with the UN Environment District Energy in Cities Initiative, ensuring that there is an a priori interest in developing district energy, and resulting in availability of sources describing the motivations in depth. It currently lacks further analysis on China, and would benefit from further development and discussion on the transferability of these findings before submission.

1.2. HEATING AND COOLING CAN SUPPORT SUSTAINABLE DEVELOPMENT

Heating and cooling underpins some of the key parts of our development as humanity. It is then unsurprising that many of the Sustainable Development Goals (SDGs), which were set up in 2015 with grand ambition towards addressing the world's key challenges, are either directly related to or heavily influenced by heating and cooling. Figure 1: Relevance of heating and cooling examples for the 17 Sustainable Development Goals explores the application of heating and cooling for each of the 17 SDGs. The relevance and reasons for improving heating and cooling are far-reaching and deeply entrenched with economic development, health and well-being, social equity, land-use and resource conflict, and greenhouse gas (GHG) reduction, environmental sustainability that a full recognition of the socio- and political context is required to develop a heating and cooling strategy that addresses the right needs. As a consequence, improving the way we heat and cool ourselves is not only a question of energy system transition, but also a question of sustainable development.

SUSTAINABLE DEVELOPMENT GOALS

1 NO POVERTY	Income poverty and energy poverty are strongly related. Inefficient appliances result in seasonal costs. High proportions of income going towards essential heating and cooling also result in lower productivity and worsen other dimensions of poverty.
2 ZERO HUNGER	Appliances for heating and cooking are often the same, exacerbating problems presented by inefficient stoves. Cooling and cold chains are integral parts of global food production, transport, storage and preservation. Multi-dimensional poverty is affected by energy poverty.
3 GOOD HEALTH AND WELL BEING	Heating and cooling prevent health burdens due to exposure, particularly for infants, and support overall well being. Clean heating prevents (indoor and outdoor) air pollution, with associated health impacts. Cold chains are part of stable medical supply and storage chains, including for vaccines.
4 QUALITY EDUCATION	Appropriate indoor environments through heating and cooling support cognitive functions, increase productivity and enhance learning outcomes. Safe, healthy, clean and comfortable schools encourate participation and completion.
5 GENDER EQUALITY	Indoor pollution from heating and cooking disproportionally affects women and girls. Clean and efficient heating, and improved food supply and storage chains reduce domestic work and enable time for other activities. Securing fuel in unsafe environments puts people, particularly women, at risk.
6 CLEAN WATER AND SANITATION	Reliable domestic hot water production supports sanitation. Industrial processes, cooling, and power production require large amounts of water, which may be reduced through clean and efficient design of heating.
7 AFFORDABLE AND CLEAN ENERGY	Heating and cooling provision is an integral part of affordable, reliable, sustainable and modern energy for all. Heating and cooling improvements can support efficiency and the development of renewable energy capacity and infrastructure meaningfully.
8 DECENT WORK AND ECONOMIC GROWTH	Process heating and cooling form integral parts of many industries, and present opportunities for economic growth and local retention of industries. Appropriate indoor environments through heating and cooling increase productivity and enhance worker environments.

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Industrialisation, especially at small scale, often requires effective heating and cooling that can support effective ressource use. Effective cooling is required for infrastructures like datacentres that support technology for innovation.
10 REDUCED INEQUALITIES	Inclusive access to appropriate indoor environments, reduction in energy poverty, and access to energy for industries supports growth and creates potential for increased equality.
11 SUSTAINABLE CITIES AND COMMUNITIES	Planning for provision of heating and cooling and hot water, notably through (inclusive) energy infrastructures, supports sustainable upgrading, urbanization and settlement planning. Reliable supply of cooling, particularly in cold chains, enhances resilience and disaster mitigation.
12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Inefficient heating and cooling represent wasteful consumption of energy. Cooling and cold chains enhance food preservation. Production and recycling of heating and cooling appliances with ozone-depleting substances must be soundly managed.
13 CLIMATE ACTION	Heating and cooling is responsible for high levels of greenhouse gas emissions globally. Heating and cooling are a substantial factor in nationally determined contributions, long term strategies, and climate change related planning and management.
14 LIFE BELOW WATER	Process cooling, district cooling and cooling of (thermal) power plants from coastal intake affects aquatic life. Cooling and cold chains support fishing practices and preservation. Fuel mining and production disrupts aquataic environments and has potential for contamination.
15 LIFE ON LAND	Inefficient heating and cooking practices based on biomass are causes deforestation, desertification, and land degradation, especially in the context of informal markets. Fuel mining and production disrupts environments and has potential for contamination.
16 PEACE, JUSTICE AND STRONG INSTITUTIONS	Strong institutions are integral parts of the Montreal Protocol and Paris Agreements that cover heating and cooling. Inefficient use of fuels for heating and cooking can result in land-use conflict. Fuel gathering in unsafe environments puts people, particularly women, at risk of conflict and harm.
17 PARTNERSHIPS FOR THE GOALS	Development of (inclusive) energy infrastructures supports partnership development. Heating and cooling technologies and infrastructures add to global climate financing portfolios and efficient heating and cooling can mobilise local resource use.

Figure 1: Relevance of heating and cooling examples for the 17 Sustainable Development Goals[1]

The cost of effective heating and cooling is deeply engrained with other types of poverty, as a dimension of multi-dimensional poverty, but is also strongly linked to affordable industrialisation and economic growth, so is embedded in the SDGs looking at sustainable economic growth. Since heating and cooling is a large part of the energy system (which requires transformation to reduce environmental impact, including through decarbonisation), it affects many of the SDGs which pertain to climate action, resource use, and environmental impact. From the perspective of household heating, cooling, and cooking practices, the use of fuels has strong impacts on the people, particularly women and children, who allocate time towards securing fuel and are most impacted by the impacts of inefficient heating in their living, learning, and working environments. The securing of fuels, both fossil and bioenergy, can further cause conflicts and insecurity, meaning heating and cooling affects many of the SDGs related to productivity, health, well-being, and reducing conflict. The desire to support and build sustainable cities and communities supports decentralised types of heating and cooling, by moving towards more local use of resources and employment. Finally, the role of (industrial) cooling, particularly in the form of the cold-chain, plays a specific role in preserving and ensuring supply for foods and medicines in support of several of the SDGs. In addition to geopolitical and domestic growth considerations, heating and cooling affect nearly all of the 17 SDGs, to a larger or smaller degree.

As will be discussed these many and varied reasons for transitioning the heating and cooling sector form strong drivers for change, particularly at local level. They also govern what is meant by improving the heating and cooling sector, particularly when the objectives shift beyond decarbonisation. Complexity is added because heating and cooling is so pervasive in the defining of problems and solutions to many of the world's sustainability problems. Simultaneously, the interplay between long-term, short-term, local, and global transition for heating and cooling from the perspective of sustainability shows clearly the importance and potential of addressing the issues. These many and varied reasons also all represent an opportunity to contribute to broader sustainability, by transitioning the heating and cooling sector.

1.3. HEATING AND COOLING CAN SUPPORT ENERGY SYSTEM TRANSITION

As one of the means to achieve SDG 13 (urgent action to combat climate change), the Paris Agreement was adopted at the COP21 in 2015 to reduce carbon emissions for all countries in order to keep anthropogenic climate change in check. This, combined

[1] Own elaboration, based on UN General Assembly, 2015; UN General Assembly, 2017; Ritchie, Roser, Mispy et al., 2018; Khosla, Miranda, Trotter et al., 2021.

with SDG 7 (clean energy for all) basically represents the first legally binding pact to decarbonise our energy systems in support of sustainable development.

Directly supporting this ambition is an increasing body of work, in both academia and grey literature and academia, which recognises the need to support long-term strategic planning in the context of decarbonisation and wider sustainable development. This includes establishing global renewable energy scenarios (Hansen, Breyer, and Lund, 2019; Jacobsen et al., 2017; Teske, 2019; Ram et al., 2019), global low carbon scenarios development (IEA, 2021), emissions gaps (UNEP, 2020), and new, updated, and vastly improved national plans in the form of nationally determined contributions (UNFCC, 2021). These works underline both the feasibility and the benefits that decarbonisation of the energy system can bring, but also highlight the magnitude of the transition required and challenges that may arise.

Energy system transition must include a strategy for heating and cooling. Heating and cooling represents about half of the energy used globally, but is traditionally treated as a local or individual issue. The heating and cooling sectors are also regularly excluded from renewable energy research (Hansen, Breyer, and Lund, 2019). This also means effective transition strategies for heating and cooling have been lacking (Fleiter et al., 2016; Connolly et al., 2014; IEA, 2017). This is problematic, since effective transition of the energy system is unlikely if the heating and cooling sector is left unaddressed.

As we will discuss, the complexity of the heating and cooling sector means that there is not a simple view on what a transition for the heating and cooling sector should look like. If energy systems would like to transition towards more sustainability and 100% renewability, the heating and cooling sector will have to rapidly become both more efficient and use more renewable energy. As countries increasingly more towards operationalising the aims of the Paris Agreement, this includes the need for more in-depth discussion and assessments regarding the approaches, resources, and strategies available to decarbonise the heating and cooling sectors within the context of wider sustainable development.

Transition in the heating and cooling sector is important not just for the heating and cooling sectors sake, but also in support of broader decarbonisation. There is also an increasing body of work showing that better heating and cooling strategies are an underpinning factor in creating more renewable energy systems, especially if they include district energy and 4th generation district heating (4GDH) technologies (UNEP, 2015; Connolly et al., 2016; Mathiesen et al., 2015). This is especially the case if the different energy sectors are integrated and synergies between them are exploited, as happens within the Smart Energy System concept (Lund, 2014; Connolly et al., 2013; Mathiesen et al., 2015). In this way the effective decarbonisation of the heating and cooling sector can further support decarbonisation of the wider energy system.

The importance of the heating and cooling sector to the national energy system means that heating and cooling, while inherently local, must then also be considered from a national and supra-national perspective, in order to ensure that effective strategies can be shared and decarbonisation targets are met in a cost-effective way. Strategies are needed to decarbonise the heating and cooling sector in a way which is coherent with other energy sectors, strategic with regard to the local and national planning objectives and implementation, and which can support a transition towards 100% renewability and sustainability.

1.4. HEATING AND COOLING IS LOCAL AND COMPLEX

The inclusion of heating and cooling in wider energy system planning has been a challenge for several reasons. Heating and cooling demands differ strongly by sector, and local influence is strong. Geography plays a role, both in limiting the ability to establish national markets for heat and cold directly, and because it results in varied local heating and cooling resource potentials. The current organisation of the heating and cooling sectors are typically a result of local conditions and past policies, combined with factors that interrelate deeply to socio-economic development. The complexity and fragmentation of the heating and cooling sector have made it difficult to develop effective efficiency and decarbonisation policy, and less likely to be included in energy system analysis and strategies.

The actual provision of heating and cooling is already varied. Heating and cooling is part of the residential and service sectors in the built environment, but also present in industrial sectors. The challenges posed by residential heating and heating practices compared to service and industrial heating are quite different, and achieving efficiency requires different approach (Schultze et al., 2016; Harmsen et al., 2017). In addition because industrial heat and cold demands may have specific temperatures, constraining alternative supply and efficiency options. Characteristics of the built environment also influence type and temperature of heating and cooling demands. Further, meeting comfort level demands for both heating and cooling is complicated as they are deeply based on culture and practices (Mallaband and Lipsom, 2020; Sovacool, 2020; Vlasova and Gram-Hanssen 2014; Waite et al., 2017). Since the types of demand, solutions, and drivers can be very diverse across these sectors this represents an additional layer of complexity.

The local nature of heating and cooling further results in a sector that is further diverse and complex. Because thermal energy travels badly, it is difficult to construct national markets or national infrastructures of heat or cold supply, so the sector typically results in a combination of local resources and national fuel markets being used for local heating systems (Bertelsen and Mathiesen, 2020). Because the heating sector is in many cases deeply integrated in the (national) gas and electricity sectors, the inclusion of local alternatives can be overlooked.

This is even more so the case for cooling, for which a quantified understanding is largely obscured due to its entanglement with electricity demands. Cooling is typically provided through electric chillers and air-conditioning at the building level, but particularly in residential sectors, it is difficult to estimate the prevalence of these solutions. While quantitative analyses are improving (Santamouris, 2016), this also means that the actual demands and efficiencies are hidden under electricity demands, complicating the ability to describe or assess the sector other than at the (building) level, and as part of a national electricity infrastructure.

Simultaneously local supply solutions like biomass, solar thermal, passive cooling, or district energy are difficult to capture when considering national energy systems and markets. The application of solar thermal or heat pump solutions typically requires careful consideration of the exact configuration of the building and its direct environment, which is subject to large heterogeneity (ENS, 2021). Because dwelling attributes, age and building practices and architecture are inherently to an extent local – ranging from building, neighbourhood, town or regional level - this drives local characterisation of the heating (and cooling) sectors.

Regarding district energy systems, the availability and appropriate use of renewable or excess heat/cold in district energy are also more diverse and locally specific than renewable electricity, since the consideration of physical geography has to be higher. This also means that project development and investments lack uniformity, making both technical assessments and risk assessments more difficult.

Finally policy and ownership traditions differ widely among nations and even cities, which results in heating taking place is much more diverse than other energy sectors. The way heat is currently supply is not typically explained by geography or resource availability (Fleiter et al., 2017). Rather, in addition to building attributes discussed above, heating practices are dependent on several other factors, many of which vary strongly sub-nationally. National or regional infrastructure choices (for district energy, gas, or electric-based heating) have strong influence, over many decades (Bertelsen, Mathiesen and Paardekooper, 2021; Laureti and Secondi, 2012). This is still visible for example along the former divisions of Eastern and Western Germany (Braun, 2010; Michelsen and Madlender, 2012; Fleiter et al., 2017). Past policies on building standards clearly affect neighbourhood characteristics. Income, household composition, and socio-economic status are a further driver of current heating and cooling practices across many nations (Braun, 2010; Reyes et al., 2019; Meier and Rehdanz, 2008; Laureti and Secondi, 2012; San Miguel-Bellod, González-Martínez, and Sánchez-Ostiz, 2018). The legacy of these policies on the long-term infrastructures and built environment continue to result in local differences and determinants of the heating and cooling sectors.

The combination of different types of heating and cooling demands; the influence of the built environment; inherently local characteristics of heat and cold resources and potentials; and ongoing impact of varying policies on heating and cooling result in a sector that is both highly local and relatively complex. The development of heating and cooling strategies must then recognise both the role, potential, and magnitude of heating and cooling in the national energy system, which simultaneously embracing the local problems and solutions of the heating and cooling sectors.

1.5. HEATING AND COOLING IN EUROPE

From an EU perspective, half of final energy demand is for heating and cooling, of which 75% is based on fossil fuels (Fleiter et al., 2017; Almost half of demand is supplied through natural gas, with (declining) shares of oil and coal (10% and 15% respectively), a small share of nuclear energy and increasingly renewables based on biomass supplying the remainder (Bertelsen and Mathiesen 2020). District heating represents just over 10% of heating, although shares differ significantly between different EU member states (Werner, 2017). Of concern is that, since 2019, there are several countries which have not reduced the carbon intensity of (residential) heating, and only several have done so radically (Bertelsen and Mathiesen 2020). While heating and cooling are thus an important part of the (European) energy sector and its decarbonisation, the EU has lacked a coherent approach for its decarbonisation as it has for electricity and transport.

On a member state (MS) level, the current heating sector is very diverse and the challenges faced quite different. This is compounded by the fact that good geographic knowledge of heat consumption and resources is often lacking and difficult to generate (Möller, 2018). As a result, the onus has remained on MS. For some countries this has not hindered the development of long-term strategic governance of heating and cooling (Ieul-Stissing and Karnøe, 2018). However, in the majority of countries policy frameworks for intervention in heating have also been lacking, with most countries' heating markets displaying strong path dependency and little radical change (Bertelsen, Mathiesen and Paardekooper; 2021; Roberts and Geels, 2019). This strongly risks potential gains not being or not fully being implemented – both at the detriment of local communities and at European level.

From an energy planning and policy perspective, the relative neglect of the heating and cooling sector is clear in the way heating and cooling has been treated as part of the energy European transition. Policy development relevant to heating has mostly gone through the Energy Performance of Buildings Directive (EPBD), Ecodesign Directive, Renewable Energy Directive (RED) and Energy Services Directive (ESD)/Energy Efficiency Directive (EED), with a designated heating and cooling strategy only being developed in 2016.

The EPBD, first approved in 2002, addresses heating (and to a lesser extent cooling) through the perspective of the built environment; at first through Energy Performance Certificates, then increasingly, since 2010 and 2018, nearly-zero energy buildings and long-term renovation strategies (DG Energy, 2019a). The Ecodesign Directive (from 2009) has a stronger focus on heat supply, by also setting standards for the (energy) performance of heating and cooling equipment (DG GROW, n.d.). The RED, from 2009, set shares for the renewable energy – including from heating and cooling – but with a specific renewable heat target only being set in 2018 (DG Energy, 2021). The EED, created in 2012 to replace the ESD, and amended in 2018, affects the heating and cooling sectors primarily through an emphasis on energy savings and National Energy Efficiency Action Plans. From the perspective of district energy, Article 14 and 15 and associated methodologies of comprehensive assessments is highly relevant in assessing potentials for cogeneration (DG Energy, 2019b). This collection has then mostly focussed on reducing heating demand and ensuring that equipment used is of a high quality, rather than an integrated or coherent approach towards transforming the heating and cooling towards sustainable decarbonisation.

It was not until 2016 that a strategy on Heating and Cooling was published (EC, 2016). Its approach is to provide overarching (and more integrative than previously) frameworks with regard to the energy performance of buildings, the design of heating technologies, energy use in industry, renewable energy in energy infrastructures, and energy system integration. Since non-gas heating and cooling does not have the obvious cross-border infrastructure and markets that the European gas and electricity markets have, it remains difficult to provide strong levers for EU coordination and alignment. As a result the strategy still builds on the Member States (MS) implementation of separate Directives and the framework is described as merely “supportive” (EC, 2016).

The subsequent Clean Energy for all Europeans package further strengthened the above mentioned initiatives, and further integration of heating and cooling in national energy and climate plans (DG Energy, 2017). The ‘Renovation Wave’, ‘Green deal’ and ‘Fit for 55’ package cement the commitment at European level to address the quality and efficiency of buildings, with explicit recognition of co-benefits in terms of energy poverty, quality of life, job generation, and decarbonisation (EC, 2020; EUCO, 2023). This increased pace in recasts, amendments, reviews and revisions may be indicator of acceleration and ascendancy regarding the energy performance of buildings, but also broader heating and cooling as a key topic for energy planning.

However, efforts at developing an EU heating and cooling strategy beyond the energy performance of buildings have only relatively recently been developed. Without clear perspectives on the role of supply technologies, they cannot be described as integrated heating (and cooling) planning, which would require consideration of both the demand side through the energy performance of buildings, and long-term and systemic supply technologies and infrastructures within and energy system perspective.

1.6. HEATING AND COOLING GLOBALLY

Outside of Europe, heating and cooling remains equally important. Globally speaking, in the IEA statistics residential space heating is the largest CO_2 emitter after passenger and freight traffic (IEA, 2017). Heating and cooling worldwide is highly heterogenous, but broadly speaking, outside of Europe and North America heating (and cooking) demands are primarily met through fossil fuels or inefficient biomass; cooling demands are primarily met using electricity. District energy supplies about 10% of these demands globally, but here also the heterogeneity between countries is high (Werner, 2017).

The demand for thermal energy is expected to grow, with population and economic growth as drivers for (residential and non-residential) heating and cooling demands (Ürge-Vorsatz et al., 2015). Cooling is currently not a large part of energy consumption yet, but is more under researched and addressed than heating in a global perspective (Santamouris, 2016; Khosla et al., 2021). The challenges posed to greenhouse gas emission reduction and sustainability in terms of cooling is the significant. This is largely due to the uncertain rates of growth expected, particularly in developing countries and emerging economies, driven by population and economic growth combined with anticipated climate change. This means that on a global level heating and cooling demands are of a magnitude that deserve and require appropriate attention to transition towards decarbonisation and sustainability.

While there is a growing number of sustainable heating and cooling initiatives globally, trends follow those of renewable energy and electricity targets and strategies. While there are over 100 countries with renewable electricity targets, only 22 non-EU countries have national targets for renewable heating and/or cooling (IRENA, IEA and REN21, 2020). Comprehensive city-level overviews are obviously difficult to generate, but the indications are that only a portion of cities which develop renewable ‘energy’ targets and policies include heating; and cities in developing countries and emerging economies are underrepresented (UNEP, 2015; IRENA, IEA and REN21, 2020). Overall, this means that as many countries are trying to move towards more sustainable energy systems and decarbonisation, heating and cooling is less likely to have concrete targets for renewable or clean energy, even though the sectors are significant and growing.

1.7. REPRESENTATION OF HEATING AND COOLING IN ENERGY SYSTEM MODELLING

Complexity may be the primary reason that heating and cooling has been neglected, but a strong additional factor is that the analytical tools, methodologies, and approaches for decarbonisation and sustainability in energy system planning do not represent the sectors effectively. This is in itself because the local nature and complexity of the system make data collection and generic modelling approaches notoriously difficult to gather and develop, especially where mapping is required (Novosel et al., 2020). This results in an circularly unfortunate situation where modelling heating and cooling is difficult because data and methodologies are scare – and data, methodologies, and approaches are not developed with the same level of attention due to underrepresentation and valuation in energy systems analysis.

Sustainable energy system modelling and analysis still regularly excludes heating and cooling. In 2018, only half of the 100% renewable energy studies included a sector other than electricity (Hansen, Breyer, and Lund, 2019). Cooling was not explicitly included in this otherwise comprehensive review, since it is often sits under the electricity sector. This in turn means that while it is somehow included, it often does not get the specific attention it deserves as a thermal and distinct type of demand from other electricity demands. While there has been a significant increase in multisectoral analysis since 2015, this is particularly centred on Europe and not yet the case for developing countries and emerging economies. This lack of analysis, and the geographic disparities of it, are a result of but also perpetuate the neglect of heating and cooling in terms of supporting energy system transition.

Deeply interconnected with this is that heating and cooling are also underrepresented in energy datasets and energy system modelling and analysis tools (Chang et al., 2021; Fattahi, Sijm and Faaij, 2020). While Europe has typically led development of energy models (Lopion et al., 2018), EU,national datasets have always lacked granularity for the heating and cooling sectors; Fleiter et al. in 2016 and Fleiter et al. in 2017 represent the first comprehensive and detailed data sets on different types of heating and cooling demand and supply, broken down by sector. In terms of energy system modelling, Already in 2010, Connolly et al. determined that many energy system tools did not include the heating sector, and even less so the option of district heating.

A more recent review shows that half of energy system models still do not take into account the heating sector; and nearly 4 out of five of all models exclude cooling (Chang et al., 2021). Much of this is not only due to the difficulty in accessing data at sufficient detail, but also due to the difficulty linking (or aligning) regional and national modelling tools and approaches to generate enough representation of decentralised energy systems (Fattahi, Sijm, and Faaij, 2020).As such the complexity of the heating sector and cooling sectors, and its local nature, are also represented in the data and tools that are used to analyse the energy system transition and support strategic energy planning.

The lack of available tools, data, and methodologies to discuss the heating and cooling sector limits the available knowledge (objects), visions, references and pathways that can be developed for the heating sector. This is problematic because it limits the ability to govern the heat transition (Iuel-Stissing and Karnøe, 2018). When the heat sector is not effectively included, or when the alternative visions, scenarios, technologies and infrastructures cannot be discussed at the appropriate level of detail it hinders the ability for strategic energy planning to effectively take place. For this reason, an integrated approach is needed that includes considering spatial planning, the built environment, and the wider energy system to generate comprehensive strategies.

1.8. COMMONALITIES IN HEATING AND COOLING

The challenges surrounding the effective development of strategies and knowledge around heating and cooling can be attributed to the local, decentralised, and complex nature of heating and cooling needs and solutions; the large heterogeneity between different countries, and the fragmented policy landscape where it exists. Because of the diversity between countries, regions, local areas, and even neighbourhoods, context-specificity is per definition necessary in order to both develop appropriate.

In parallel, there is a sufficient level of commonality to allow for general approaches and methodologies that we can use to inform strategic heating and cooling planning. Comprehensive heating and cooling strategies are needed that embrace both perspectives, and the theories and methodologies for designing these must be developed within the context of a Smart Energy System, in order to move towards more and fully sustainable and renewable energy systems.

The first is that it is necessary to include heating and cooling in strategic (energy) planning, because both heat and cold demands are significant, and more widespread than previously assumed. Heating and cooling demands are both geographically driven, but also not geographically determined (Connolly et al., 2012a; Werner, 2016). This is specifically the case for both heating and cooling. Firstly, industrial demands for process heating and process cooling are likely present, irrespective of climate. For heating, even when perceived demands can be low, the total absence of space heating requirements in unlikely. For example, while cooling dominates in India, space heaters, where present and afforded, are still used for 2,5 months a year (Chaturvedi et al., 2014). Similarly, even (relatively) cold climates increasingly implement comfort cooling, particularly in service sector buildings (Werner, 2016; Dittman et al., 2016). Both sectors require attention within the area of decarbonisation and sustainability, since heating and cooling demands are effectively always present.

The second commonality is that alternative, sustainable heating and cooling sources and technologies are globally abundant and already proven. This includes the use of direct renewables such as solar- or geothermal either individually, or through district energy systems (Moriarty and Honnery, 2019; Jacobsen et al., 2017; Limberger et al., 2018). District energy further allows for the integration of sources of excess heat such as industry and thermal power production, which are typically located close to human settlements. The integration of the heating and cooling sectors with the electricity sector open up further opportunities to supply heating and cooling without the direct use of fossil fuels, and can be further supported by using surface water bodies as sources of heat/cold for heat pumps. Although these solutions may not be commonly implemented in some countries, by looking globally it is clear that they are all mature and proven in terms of the technologies. The variety of these different solutions, which on the one hand contribute to the complexity of the sector, also ensure that regardless of building type, urban/rural location, or geography there are likely to be alternatives that are – from a technical perspective – available today.

The third indication that strategic heating and cooling planning can benefit from common approaches and methodologies is that density, while on the one hand very local, can also be a strong general driver for the development of infrastructure. Cities inherently thrive on density, which aggregates energy demands. By shifting the perspective of energy infrastructures to include the heating and cooling sectors – be that through the assessment of electrification of heat or development of district energy – the local nature of heating and cooling, through density, can be considered. At the same time this approach allows for infrastructure development which is likely to require local assessment of sources, but can facilitate efficiency, renewables, and flexibility.

The final support for conjecture is based on the Smart Energy System concept, which provides a general framework design for 100% renewable energy systems, generally based on the better use of local resources. This is achieved primarily through the interconnection of the (power, transport, and heating and cooling) sectors, and flexibility between different types of storage. In turn, if a connection and coordination with the other energy sectors allows for better results for energy systems, this should benefit the (local) heating and cooling sectors.

1.9. PROBLEM FORMULATION AND RESEARCH QUESTION

For a global transition towards sustainability and decarbonisation, it is necessary to transform the heating and cooling sectors. Strategic energy planning has, so far, neglected to fully include for the sustainable development of the heating and cooling sectors; both globally but also at European level. This is even more so the case for district energy. An integrated approach is needed that includes considering the spatial dimension of heating and cooling demands and resources; the built environment; the wider energy system and its decarbonisation; and further sustainability considerations. Given the magnitude, complexity and localised nature of heating and cooling, implementation has been hard and we need faster ability to act strategically at the local level is required to accelerate change.

This PhD sets out to answer **how heating and cooling strategies can be designed for various countries within the concept of Smart Energy Systems**. It identifies general learning and specific aspects of developing heating and cooling strategies, and how they can be used to support strategic planning.

As will be elaborated later, this PhD argues that while heating and cooling is inherently locally determined, commonalities of the problems and solutions do exist. Consequently there are some general approaches and methodologies that we can use to inform strategic heating and cooling planning scenarios. This includes developing an understanding of which general elements can be identified in the design of heating and cooling strategies, and which are necessarily specific to the local situation. This then supports the development of more comprehensive and appropriate policy at higher levels, and provide a framework for more detailed and context-specific strategic planning at local level.

The development of heating and cooling strategies departs from the Smart Energy System concept, resulting in an emphasis on the development and valuing of grids (including district heating and cooling) and active utilization of the heating and cooling sectors to support and exploit synergies in the wider energy system. The comparative approach in the thesis includes discussion on developing strategies that can contribute to strategic planning by identifying strategic design objectives, determining design criteria, using design approaches and applying design principles in order to identify general and specific aspects of developing heating and cooling strategies. This contributes to our understanding of where general solutions can be applied, and where and how local planners and practitioners need to focus their efforts to develop specific and bespoke solutions.

CHAPTER 2. THEORETICAL AND METHODOLOGICAL FRAMEWORK

This Chapter sets out the theoretical and methodological framework for the PhD, in order to elaborate the perspective through which heating and cooling strategies are seen and developed, and discuss the relevant methods and tools.

The Smart Energy System concept forms the basis for how the energy system is interpreted, and what change is necessary. The heating and cooling sector is presented in some depth, including setting out how district energy is framed within this. This serves partially to define some terms and present the frame that is taken in this PhD in terms of how the heating and cooling sector is conceptualised. This section on heating and cooling also explains in some more detail the complexity of the heating and cooling sector, and how this generates research interest. This chapter will also elaborate what a heating and cooling strategy actually is; how it is envisioned to contribute to strategic planning. This both serves to establish the scope for this PhD, but, as will be shown, also highlight the need for deliberative and explorative scenario and strategy development. Before moving to the discussion in Chapter 3, this chapter will also present a brief methodological consideration of energy system analysis, the use of EnergyPLAN in the PhD, and case study research, including an overview of the cases in this PhD.

Presenting these frameworks first gives a much better understanding of what the context and starting point is for the design of heating and cooling strategies is, and how the research question was approached. This also sets up the discussion, which focusses on the specific design choices to how heating and cooling strategies were made in relation to general and specific aspects.

2.1. SMART ENERGY SYSTEMS

The development of the scenarios and strategy roadmaps is heavily guided by Smart Energy System concept. **The Smart Energy Systems concept** is constructed around the idea of integrated and coherent energy planning. The approach in Smart Energy Systems is that by considering and interconnecting the different energy sectors, it is possible to exploit the synergies that arise between them and which can be exploited to bring down the costs and fuel needs of the system, create efficiency, and integrate more renewable energy (Lund, 2014). To this end, the Smart Energy Systems concept emphasises the need to consider solutions from an overall energy system perspective, rather than only the separate sectors.

Smart Energy Systems are characterised by emphasis on reducing the need for fuels; smart electric, thermal, and gas grid infrastructures; and the coupling of energy sectors (Connolly et al., 2013; Lund, 2014; Study 1: Storage in SES Paardekooper, Lund and Lund, 2019). The reduction of fuels supports the reduction of costs and primary energy, but also prevents a transition towards renewable energy that is over-reliant on biomass. This configuration, allows for an efficient transfer of energy between the sectors, and through that the possibility to use and store high volumes of renewable (fluctuating) electricity. Through this, the system can move towards 100% renewable energy and sustainability.

For this PhD, the first few sections in Study 1: Storage in SES (Paardekooper, Lund and Lund, 2019) set out how the Smart Energy System concept is synthesised in more detail. The key normative underpinnings are briefly outlined here.

- The first is to **rely only on available and proven technologies**; this to ensure transitions can be readily started and prevent delay and a reliance on the (uncertain) development of technologies. The concept is based on the assumption that 100% renewable is feasible and possible, and it is not necessary to wait for technology development to be able to achieve sustainability.
- The second is to **incorporate and balance different sustainability needs.** Achieving 100% renewability is necessary in relation to prevent catastrophic global warming, but access affordability, equitable access to energy, biodiversity and other environmental concerns, etc. are also of relevance. Related to this is to ensure fuel use is comprehensively, sustainable, which is of particular concern regarding biomass.
- Finally there is a normative imperative **to take a socio-economic perspective**, and design for what is best for society at large. While the system overall may improve, there will be sectors that are expected to emerge while others decline, and corresponding employment changed, as well as transformed cost structures for energy. To ensure equity, a mechanism for distributive justice should then be part of the strategic planning process.

These normative positions that are implicit in the Smart Energy System concept provide a useful strong basis for planning heating and cooling strategies in several ways. The congruence with sustainable development theories, largely seeking to ensure the meeting of current and future generations' need, is clear. Criteria like 100% renewability; affordability, etc. are present but because there is flexibility in the strategic objectives and criteria of the Smart Energy System it is possible to be adaptive to the needs that are identified. This makes it possible to align the design of Smart Energy Systems with sustainable development concepts and criteria.

The use and application of this concept has advanced rapidly in the past few years. It initially emerged out of the body of research developed in the context of sustainable energy planning at Aalborg University over the past few decades (Lund, 2014; Connolly et al., 2013). It has since been applied and refined, with varying applications at local, regional, national, island and European scale (Connolly et al., 2012b, Mathiesen et al., 2015; Marczinkowksi and Barros, 2020; Cabrera et al., 2021; Thellufsen et al., 2020; Connolly et al., 2016). Simultaneously, there are studies which seek to contribute the role of certain technologies, infrastructures, or solutions within a Smart Energy System concept – of which this is one – and which contribute to strengthening the depth of understanding (for example Lund et al, 2014; Ridjan, 2015, Thellufsen, 2017; Maya-Drysdale, Mathiesen and Paardekooper, 2018; Korberg, 2021). These perspectives contribute to applying the Smart Energy System concept in different contexts, and further elaborating the mechanisms and principles of it.

In a few cases, the concept has also been applied outside of the European Union. In some rare cases a renewable, integrated Smart Energy System is developed and analysed (eg. Zhao et al., 2017 and Icaza, Borge-Diez, and Pulla Galindo, 2021); in most cases, the concept is partially used. This is then done primarily as a rationale or approach to study the likely impact of a certain technology or solution within a system context (eg. Nam, Nam, and Lee, 2021). Even within these applications, the focus is mainly on the electricity sector, although there are some instances where heating or cooling is particularly analysed (eg. Zhang, 2019). District energy is often mostly considered when the infrastructure already exists. Nonetheless these new and varied applications contribute to the development and refining of the overall concept, particularly in terms of its application outside of the European context.

For the purpose of this PhD, the Smart Energy System concept provides a framework for the scenario and strategy design through the provision of more general approaches and principles, which can be applied to the heating and cooling sector. The general design approaches and principles can be understood as an abstraction of the broader mechanisms that occur in the Smart Energy System concept, particularly when looking at the heating sector, that contribute to the fulfilment of the criteria and objectives. These are the specific 'rules of thumb' that are likely and have been shown in the past to concretely lead to fulfilling of Smart Energy System objectives and criteria using the approaches. The development and description of these approaches and principles is based on the idea that designing scenarios for strategies is a strongly explorative process, and strengthened by knowledge, inspiration, and testing of different more or less established alternatives. This PhD makes some contributions to the development of approaches and principles, but it should be noted that this part of the research also serves strongly as a continuation and further contribution to already established approaches and principles of the Smart Energy System concept.

As is clear from the case studies, the work in this PhD builds heavily and broadly supports the value of an approach that considers all sectors and couples them to exploit synergies, also when looking at heating and cooling. Particularly, the studies in the PhD confirm and emphasise that thermal grids allow for flexibility and the use of more energy sources and technologies, which have consistently found that these are available and possible. This is what drives the common use of district energy in the heating and cooling strategies, also in countries that do not have an obvious or established district energy potential. These cases contribute to the general nature of the Smart Energy System concept, particularly when district energy is shown to be valuable in supporting diverse and novel strategic design objectives or in a diverse range of resource available contexts. By using the principles and approaches of the Smart Energy System concept in the design of the diverse heating and cooling strategies, there is also a contribution to the concept itself.

There is also a methodological development in Heat Roadmap Europe (Paardekooper et al., 2018 and Study 3: Types in Heat Roadmap Europe), in terms of how energy efficiency is explored. Typically, the studies in this PhD confirm the previous Smart Energy System studies that energy system fuel reductions support security of supply, reduce costs, and reduce further environmental impacts, including health and wider sustainability concerns. This means all the studies in the thesis consider minimising fuel needs to a certain extent.

Where previous Heat Roadmap and IDA studies (Connolly et al, 2013; Mathiesen et al, 2015) had used a step-wide approach, Heat Roadmap Europe 4 employed a simultaneous, ‘matrix’ approach, elaborated in conference presentation Iterations for heat savings, electrification, and district heating (Paardekooper, 2018). The previous approach methodologically investigated several scenarios for energy savings in the demand-side of buildings first, and then moved forward at a particular level to further investigate supply-side options. The iterative approach in Heat Roadmap Europe, supported by a modelling heuristic to develop 66 models per country simultaneously. By not treating them sequentially, the interplay between heat demand and supply savings was made more explicit. It also allowed, in almost all cases, for a better visualisation of the various cut-off points. This approach represents a development of how energy savings and energy efficiency is treated in the scenario design, particularly in how exploring the role of demand- and supply-side efficiency can reduce fuel needs.

2.2. HEATING AND COOLING

Given the inclusion of all sectors in the energy system, it is key to understand that both heating and cooling are considered as a key part of the Smart Energy System. This inclusion if two-fold. Firstly, it ensures that the heating and cooling sector are included in the development of the energy system, including energy access, decarbonisation, and other strategic objectives. Approaches that take the ‘energy system’ to only be the ‘electricity system’ inevitably fail to fully decarbonise, for obvious reasons. Heating and cooling should be decarbonised and made sustainable as part of the energy transition, and to do it must be included in an energy system perspective.

In addition to that, taking the heating and cooling sectors into account is an integral part of the Smart Energy System concept, since it can actively act in support of further decarbonising other sectors. A coherent scope allows for the finding and development of synergies between the sectors. Including the heating and cooling sector is important not just for its own sake but in support of more flexibility, electrification options, and storage options. In this way, the inclusion of the heating and cooling sectors supports the (further) development of the other energy sectors towards sustainability. Including the heating and cooling sector is a key part of operationalising the Smart Energy System.

2.2.1. PERSPECTIVE ON HEATING AND COOLING DEMANDS

Defining heating and cooling demands can be done from various perspectives, the main of which are in terms of sector, end-use, and location. Integral to the complexity of the heating and cooling sector is the variety of different types of heating and cooling demands. These different categorisations all contribute to a different dimensions of understanding and quantifying energy demands. They also reflect both the local nature and the dependency on the wider energy system that is inherent to the heating and cooling sector.

- **Energy demand by sector**: This categorisation describes who the thermal energy is used by (conform Fleiter et al., 2017a). This is broadly split into residential demands, service sector demands, and industrial demands. The key sub-categorisations in the residential sector are typically single-family and multi-family houses; these can then be further subdivided by age and type of building. For service and industry sub-sectors can also be increasingly specific (see also Persson et al., 2014). Understanding who is using the energy is important in order to be able to understand how their demands can be influenced.
- **Energy demand by end-uses**: Describing demand by end-use is a form of describing how the energy is used (Fleiter et al., 2017a). This represents a split between space heating/cooling, (domestic) hot water demand, and process heating/cooling. Further subdivisions along temperature can be important, particularly with regard to process heating and cooling. Identifying how the energy is used is important because it determines in large parts what kind of energy efficiency and alternative energy conversion technology options are available.
- **Energy demand by location**: Because thermal energy travels badly, it is relevant to understand where energy is being used. Depending on the required level of resolution, this can be by region (eg. Persson, Möller and Werner, 2014) down to hectare (eg. Persson et al., 2019) and building level (eg. Grundahl and Nielsen, 2019; Kuriyan and Shah, 2019). The location and density of heating and cooling demands are of particular relevance to the

planning and assessing of the infrastructures that are necessary to supply the energy.

2.2.2. TERMINOLOGY OF HEATING DEMANDS

The terminology on energy demands is sometimes conflicting: the United States Government Office of Energy Efficiency and Renewable Energy, Eurostat, and several energy primers all use slightly differing definitions (EERE, n.d.; Eurostat, 2018; Hulscher, 1991; Energy Education, n.d.). This is especially the case for heating and cooling, where both building-level and energy system level perspectives come together. In addition to causing confusion, comparisons are difficult when energy demand and changes in energy demand become criteria and indicators of efficiency but mean different things. For this reason, Figure 2 outlines the definitions of primary energy, final energy, delivered energy and useful energy used throughout this research.

This research uses delivered energy as the main parameter for discussing heating and cooling demands. By taking this perspective, it is possible talk about the improvement of buildings and energy-demanding processes separately from the supply of energy, and associated efficiencies or energy sources. This is opposed to, for example, a final energy, which concerns itself with the amount (and renewability) of energy required at the building envelope. This is discussed in depth in Maya-Drysdale, Mathiesen, and Paardekooper (2018). Based on Figure 2 and (Fleiter et al., 2017a) delivered energy is considered energy 'that the unit needs to provide to heat/cool the building or process'. In a building, this can be a boiler, heat pump, heat/cold exchanger, chiller, etc. This excludes conversion efficiencies, but included losses in local distribution.

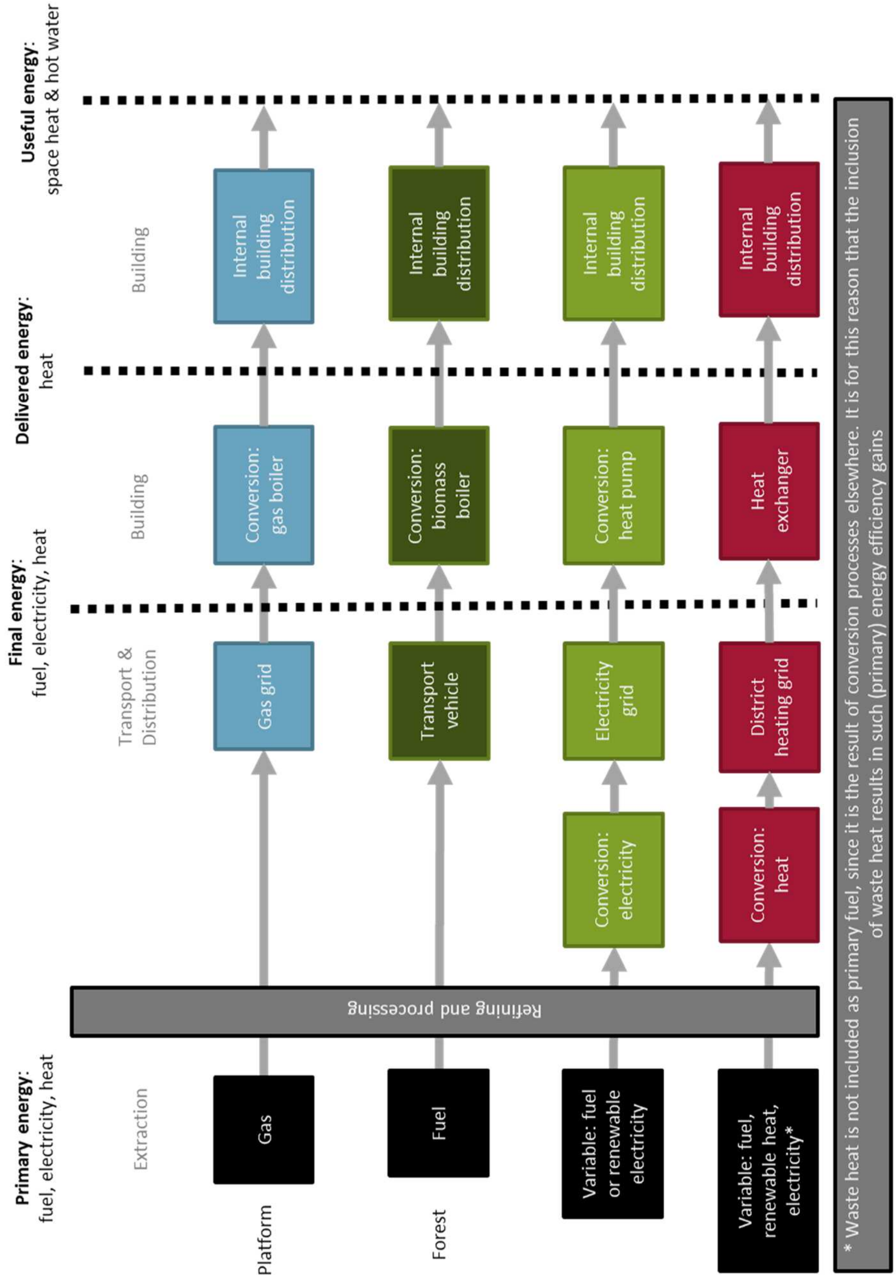

Figure 2: Overview of relationships between primary, final, delivered and useful energy demands including conversions and transport, using several simple heating examples.

There are several points which arise from Figure 2, and contribute to the perspective of heating and cooling as complex and a part of the wider energy system. Firstly, the terminology and need for clarification is a product of the complexity of the sector. It is clear that the position of heating and cooling brings together local (building) level conditions, and larger, even national infrastructures which consider energy delivered at the building to be ‘final’. Taking the building envelope as final disregards any (in)efficiency that comes with local conversion and distribution. This also reflects on the one hand the perspective of the energy performance of buildings which support energy efficiency by reducing demands, and on the other hand the supply perspective, where efficiency gains are possible by using produced energy with more results. Thus the complexity in terminology is inherent with the complex position of heating and cooling as both local and integrated in the energy system.

Figure 2 highlights the importance of energy infrastructures to ensure primary energy can be transported to the final stage. This is the case for all examples mentioned, not only district heating. Particularly in residential heating heat pumps, gas boilers, and biomass boilers are often categorised as ‘individual’ technologies, but they are equally dependant on electricity and gas grids, as well as fuel transport systems. This is also the case for cooling, which typically relies on the electricity grid. Because of the required infrastructures and systems, it is not possible to assess heating and cooling without an energy system perspective.

A third observation is the difficulty in placing where waste heat sits within the overview presented in Figure 2. Waste heat, either from industry, electricity production, or otherwise, is not included as primary fuel, since it is the result of conversion processes elsewhere. In a simplified overview as this, it appears within the district heating grid, and in doing so can displace the primary energy required to supply the district heating grid. It is for this reason that the inclusion of waste heat results in such (primary) energy efficiency gains, but this largely only becomes apparent using an energy-wide perspective.

Following from this is that district heating and electrification both represent an introduction of (additional) conversion technologies that are not at building level, which require energy system analysis to be adequately captured. This means that it is no longer as easy to ascertain what the primary energy (or indeed, renewability or sustainability) of a heating choice is, since it becomes dependant on other conversion and fuel arrangements within the energy sector. This is a natural result from increased interconnection of the sectors, but means that it becomes harder to compare between heating options directly along basic criteria without reference to the wider energy system design. Considering heating and cooling from an energy system reflects these interrelationships and allows for their coherent assessment.

2.2.3. DISTRICT ENERGY

District energy is likely the least well-known of the infrastructures described above. District energy is a well-developed, established and proven technology which has played a role in contributing to several countries' energy system efficiency for many years (Werner, 2017), but clarity on how it is conceptualised is warranted. The maturity of the technology obscures that as an infrastructure, district energy is still unknown in many countries. While district energy is well-established and well-understood in some countries, there are other countries and regions where it application and development is now gaining more attention and is the subject of more research. An increasing amount of attention being paid to district heating and cooling has brought with it an increasingly diverse discourse (Sulzer et al., 2021). In order to ensure clarity, this section outlines briefly what vocabulary will be used in reference to district energy, and how it is conceptualised.

District energy can take the form of district heating, district cooling, or a combined form of district heating and cooling. Of the three, district heating is by far the most common, and the combination of district heating and cooling can be considered as an emerging technology within the framework of the next generation of district energy (Werner, 2017; Lund et al., 2021). Over the last 100 years the large scale implementation of district heating systems in particular having resulted in a transformation from inefficient 1st generation steam systems to the 3rd and 4th generation district heating systems that are considered standard today (Lund et al., 2014).

Following Frederiksen and Werner (2013), district heating is considered to be an infrastructure that enables the

> "use [of] local fuel or heat resources that would otherwise be wasted, in order to satisfy local customer demands for heating, by using a heat distribution network of pipes as a local market place" (Frederiksen and Werner, 2013).

The implication of this is that district energy is a technology that enables efficiency and renewability by bridging the wider energy system with local demands.

Using this definition as a point of departure has as a logical consequence that modern and effective implementation of district energy is based on a recognition of the role of excess or waste heat, as heat that would otherwise be wasted, as a first priority. This includes waste heat from thermal power production (in the form of cogeneration); waste heat from industrial processes; and waste heat from other energy system technologies, for example electrolysis and green fuel production. This conceptualisation of district energy fits within the Energy Efficiency First principle as worked out by the European Commission, to anchor an effective use of energy within energy planning (Regulation 2018/1999). Typical in illustrating this point is that made in Connolly et al., which specifically highlights how losses in thermal power production and one of the main reasons primary energy demand in the EU doubles end use demand (2014). Using these sources of energy, which would otherwise be wasted, has the potential to displace thermal energy without the need to introduce more energy into the energy system, supporting overall efficiency.

Secondary to this is the ability of district energy to introduce renewable energy sources into the energy system, particularly types of renewable energy that could otherwise not be harvested to the same extent. This can include geothermal energy; large-scale solar thermal; cooling from lakes or rivers; or even combusting biomass without emitting prohibitive levels of particulate matter (PM). Indirectly, this can be through the use of wind or solar power in large-scale heat pumps or chillers. In these cases district energy is considering to be enabling the integration of additional sources of renewable energy.

This can create a sense of contradiction if the waste heat comes from a process which is not renewable or sustainable: for example, power production and industrial processes that are based on fossil fuels. From a coherent energy system perspective, fossil processes should of course be replaced as part of the energy system transition, but while they exist the most effective measure is to indeed consider the recovery of the waste heat. Not doing so simply results in a less efficient use of the resource overall, even though it may not be directly renewable or sustainable.

Considering district energy as an enabling infrastructure towards long-term sustainability addresses this problem both from a broad, energy system perspective and from a local perspective. From a system perspective this includes ensuring strategies for system-wide transition, to address the source of waste heat. This is operationalised, for example, by ensuring that combined heat and power (CHP) plants operate to satisfy the electricity market, and that strategic (district) energy planning ensures that sector-specific strategies, policies and incentives exist to ensure appropriate transition in the long-term, for example for industry. This highlights the importance of the energy system perspective for coherent energy planning in order to ensure both efficient use of (current) resources and realising energy transitions.

On a local level, the consideration of integrating waste heat from a fossil or unsustainable energy source is highly dependent on the integration within a long-term, strategic energy plan. The idea of using district energy as a connecting infrastructure to create a market place – be it one where technologies' lifetimes dictate that long-term commitments are the norm, energy sources can be substituted and replaced. For example, this means that for the duration of the remaining lifetime of a power plant a retrofit to CHP may well be preferable, since it can substitute other sources. Simultaneously, an alternate future heat supply should be identified or developed to ensure that the district energy system does not undeservedly rely on an unsustainable source. Using waste heat at a local level, even if from a fossil or unsustainable source, can contribute to immediate energy efficiency and decarbonisation, but should be done within the framework of a long-term local strategy that identifies sustainable and renewable long-term options.

While the goal of decarbonisation is also present in current (and future) generations of district energy, it does not substitute the goal of increased efficiency (Sulzer et al., 2021). The dual recognition is considered to be important, because efforts to combine these two into a sense of 'efficient' district heating partially based on renewable shares, or 'clean' based on high efficiency heat production (eg. Jiménez Navarro, 2020) unnecessarily confound the specific ways in which district energy contributes to decarbonisation and sustainability. Both the Energy Efficiency First principle and energy system and local dynamics indicate that district energy should be seen as an enabler for efficiency and renewable energy, within the framework of long-term and coherent strategic energy planning.

2.3. STRATEGIES FOR HEATING AND COOLING

The term 'strategic' in energy planning has slowly become cognate with some other broad attributes such as smart; long-term; renewable; and generally that which is normatively advisable. This section draws on strategic planning literature to explore some of the concepts related to the process of strategic planning, and their regard to their relevance to the development of strategies. It clarifies the scope of a strategy, how it sits in a strategic (energy) planning frame, and explains the role of scenarios in supporting strategy development.

2.3.1. HEAT ROADMAPS AS STRATEGIES

In this thesis the concrete design of heating and cooling strategies is done through the development of Heat Roadmaps. The term 'Heat Roadmap' was devised in 2012 as counterpart to the EU Energy Roadmap (EC, 2011), which presented six scenarios for decarbonisation, of which none considered district heating (Connolly et al, 2012; Connolly et al., 2014). This resulted in a series of four main Heat Roadmap Europe (HRE) projects, which set out and refined the strategies and associated methodologies. In its subsequent iterations the Heat Roadmaps for Europe and European countries were used to contribute to discussions concerning wider heating strategies and demand vs. supply side energy efficiency (Connolly et al., 2013); local heat strategies (Connolly et al., 2015; Paardekooper et al., 2018); and applying the energy efficiency first principle for holistic heating and cooling strategies (Paardekooper et al., 2018). The methodologies and approaches which were developed and advanced in this process were progressively applied also to cooling (Connolly et al., 2015; Paardekooper et al., 2018) and to non-European countries (partially Xiong et al, 2015; Paardekooper et al., 2019; Study 2: Heat Roadmap Chile: Paardekooper et al., 2020).

Titling these heating and cooling strategies as Heat Roadmaps has had two benefits. The first, mostly relevant for European Heat Roadmaps, had the pragmatic advantage of more easily aligning with the strategic planning discourse and narratives on energy visions at EU level. This means that the strategy, as a knowledge artefact, is more likely to contribute to the collective reimagining of energy futures in strategic planning. The second is that through the iterations and various publications associated with it, the title has come to represent the particular normative and methodological approaches and principles which the heating and cooling strategies rely on. Consistency is provided by grouping the strategies under the same name that have been designed using broadly the same theories and methodologies.

2.3.2. STRATEGIC PLANNING

A simple definition of 'strategic planning' is difficult. Bryson et al. describe clearly how strategic planning is in and of itself intangible, since it covers a scala of combined processes, concepts, procedures and tools that in turn represent varied and different interpretations of strategic planning (2018). Albrechts and Balducci point out that the ephemeral nature of 'strategic-ness' is in part a result of its rise as a response to the dual challenges of simultaneous increased globalisation and decentralisation of issues, and increased complexity and fragmentation (2013). This echoes strongly the challenges and developments in the heating and cooling sector. Secondly, because strategic planning means to address complex planning issues in an inclusive manner, a definition must inherently be adaptable.

Albrechts and Balducci (2013), based strongly on several works by Healey, give a definition that can be synthesised into the following three parts, to act as a working definition of strategic planning for the purposes of this PhD;

- Strategic planning includes a (social) process of co-creating plans and processes between diverse actors.
- Strategic planning creates space for new ideas and new processes for their development.
- A deliberate re-imagination of the future, and subsequent identification of priorities for transition in terms of investments, focus areas, and regulations.

Using this as a framework for strategic planning allows for a better understanding of how heating and cooling strategies fit within this, and how heating and cooling strategies can be best shaped to contribute to strategic (energy) planning. In line with Bryson et al., these three elements describe process, participation, principles, and to some extent results and drivers for further strategic planning. The idea of a strategic planning space, where strategies, strategic processes and strategic practices come together is clearly recognised in literature (Mazza, 2013; Albrechts and Balducci, 2013; Maya-Drysdale, Krog Jensen, Mathiesen, 2020). It should be clear from this that heating and cooling strategies do not represent the complete strategic planning proposal or process. Strategic energy planning is not something which is taking place in this research. Rather, the development of strategies is considered to take place in a wider strategic planning arena, and should be designed to facilitate contribution towards these wider processes.

To support the use of the strategy within the strategic energy planning arena, clarity and transparency about the normative nature of the strategies is important. This includes the concepts, notions, objectives, criteria, approaches, and principles which underpin the design of the heating and cooling strategies; what, if any, participatory processes have taken place; and methodological considerations for the actual scenario development. These qualifiers ensure that the contributions that strategies make are well-understood and can be discussed appropriately within the strategic planning arena.

2.3.3. STRATEGIES IN STRATEGIC PLANNING

Concretely, strategies support strategic planning by contributing artefacts which present (alternative) visions for the future, and identifying key areas of intervention to support their achievement. As Mazza (2013) points out, a fully collective (presumably ongoing) co-designing of a common future in a single strategy is not a realistic expectation. This is also what drives the need for multiple strategies to be presented, and ensure that real choices become available in strategy-making (Lund, 2014). In doing so, strategies can create awareness for alternative solutions, explore new ideas in depth, include the perspectives of different actors, and otherwise contribute viewpoints to processes of determining strategic planning directions. The contribution of the strategies is the perspective which they add to the wider strategic planning process.

Strategies precede implementation mechanisms by establishing visions towards the future. This approach is based on the need to be able to break from current trends; introduce radical changes, alternatives, be able to think freely in 'what if' scenarios in order to uninhibitedly re-imagine the future and explore possibilities (Healey, 2013; Maya-Drysdale, Krog Jensen, and Mathiesen, 2020). This is utilising the strategies cf. Ricard and Borch (2011), and closer to what Albrechts and Balducci (2013) would consider first term strategic analysis. There is sufficient evidence that disruptive technologies, non-linear diffusion of infrastructures, etc. take place; also in heating and cooling (eg. Bertelsen, Mathiesen and Paardekooper, 2021; Roberts and Geels, 2019). Strategies should not only reflect this, but support the envisioning of radical change in strategic planning

The vision-making includes identifying key areas that require transition and restructuring; physically, economically, in terms of investment needs/financing; and with regard to planning traditions. This supports a specific inclusion of district energy as an infrastructure which can support decarbonisation and sustainability. It also provides scope for alignment with the idea of roadmaps in technology management, since it specifically analyses the potential, roles, needs and to an extent market requirements of a specific set of technologies and infrastructures (Ricard and Borch, 2011). This also supports quantification of the strategies, to simulate inclusion of heating and cooling and district energy into future energy system visions, and particularly investigate the (broad) strategic infrastructure investments and priority actions necessary support more sustainable energy systems.

The purpose of a strategy is not to create a plan for implementation. This type of conceptualisation of strategies is also reflective of the idea that the long-term strategies analysed here are not plans which present an itinerary and command left and right turns at pre-determined intervals. Based on strategies, other strategic planning processes and practices are required to transform existing institutional frameworks and organisations to facilitate a preferable energy system (Hvelplund and Djørup, 2017). In terms of concrete (multilevel) policies, these should specifically be designed in response to the challenges and opportunities surrounding energy strategies and scenarios, which contrasts with trying to identify pathways towards renewability and sustainability within the current institutional and organisational frameworks. In alignment with radical transition theories, strategies relate to unrestrained the vision-creating and ideation aspects of strategic planning and not the methods of realisation.

2.3.4. SCENARIOS AS PART OF STRATEGIES

Technical scenarios are used to help quantify strategies, and give indications of magnitudes of transition to help reach these goals (Lund et al., 2017). There is an interplay between putting forward an image of the future, and the exploratory nature of scenarios which allow for generation and quantified assessment of alternatives. Scenarios represent the interface between deeply political, complex, and normative assumptions and concrete exemplification of the future which is needed to move forwards. This recognises the interconnected nature of analytic/technical work, planning work, and strategy-making (Healey 2013). Technical scenarios are then presented as part of a strategy, where they bridge the (normative) strategic objectives and desires with quantified indications for futures.

Scenario work is, per definition, exploratory, with many different scenarios (typically representing different uncertainties and choice options) being developed. In putting forward a vision, strategies do and should often present one scenario as desirable and more advantageous – but in this work this is not as an ’optimal’ scenario in the sense of optimisation. The variety of objectives, criteria, and complexity in strategic planning and energy systems analysis means that presenting an optimised solution can be overly reductionist to trade-offs that are being made (Østergaard, 2009). This is especially the case since many of the objectives that are relevant to heating, cooling, and energy scenarios are non-transitive, further complicating the choice of a single criterion.

Recommendations arise not from one 'optimal' solution from the series of investigated scenarios. The proposed scenario in the heating and cooling strategies is the product of exploratory simulations with many scenarios, rather than the development of one or several optimised scenarios (Lund et al., 2017). To explore mechanisms and allow for the simulation of different imagined ideas and futures, an exploratory approach with many different sets of scenarios can make different assumptions explicit. This more reflective of the fact that they result from and represent a certain normative framework.

This allows for comparative advantages, deeper understanding of the mechanisms under which outcomes change, and the magnitude of various uncertainties. The (final) proposed scenario then does not stand by itself, but represents also the scenarios behind it and the process of having developed the scenario. Purposefully designing also aligns more strongly with the weight put on ideation and diverse exploration in strategic planning (Healey, 2013). Based on this a recommended scenario as input to the vision and strategy is not only possible but can deeply support the choices and understanding that is required for roadmap and strategy development.

In summation, the development of a heating/cooling strategy cannot, inherently represent the comprehensive 'set' of strategic (energy) planning procedures or practices, but contributes to this discourse by presenting visions and identifying areas, technologies, and infrastructures that require particular prioritisation or transition. Strategies act as ideation, proposals, and synthetic development of diverse and alternative visions to generate choices and dialogue allow for the identification of navigational targets and broad destinations for the future.

2.4. ENERGY SYSTEM ANALYSIS FOR SCENARIOS

Methodologically, the development of technical scenarios of the energy system takes place through energy system analysis. This represents a pragmatic approach towards the complex relationships and interactions within the energy system. Scenarios have to represent energy systems, so it is important to be able to model its elements, connections, regulations, and interactions in recognition of the complexity with which they come together. There are several characteristics that underpin the forming the methodological framing for the development of these heating and cooling strategies throughout.

Firstly, whole energy system analysis is an important characteristic. As discussed in 2.1 above, this congrues with the Smart Energy System concept that heating and cooling strategies must be designed and considered with relevance to the wider energy system. This is both to support decarbonisation of heating and cooling, but also to further facilitate the decarbonisation of the other energy sectors. This means that the analysis underpinning the scenarios should also be conducted using whole energy system analysis. In the heating and cooling strategies created in this PhD it is evident that more analytical attention has been paid to the heating and cooling sectors, typically followed by the electricity sectors and with changes in the transport sector mostly taken from references. This partially reflects the influence that the heating sector, particularly through increased electrifications, CHPs, LSHPs, and storage can have on the electricity sector – and then further through the system. By including the other sectors, it still becomes possible to identify points of interaction and opportunities when developing scenarios. An analysis of the energy system, and heating and cooling in it, prevents solutions being put forward that may make sense for the sector, but result in system-wide suboptimality.

A second characteristic of the energy system analysis supporting the design of technical scenarios is appropriate time resolutions: Because future energy systems are expected to have and benefit from the integration of high levels of variable renewable energy sources (VRES), time resolutions that can appropriately simulate that variance are required. This facilitates designing strategies that have the right levels of flexibility, storage, and operational regulations to be able to analyse how VRES affects the energy system analysis. The scenarios developed in this PhD use an hourly basis, allowing for ample consideration of the temporal differences in 100% renewable energy y systems and detailed assessment of adequate (peak) capacity and storage needs.

Finally, scenario simulation and energy system analysis for the purpose of strategy development should allow for independent design of scenarios, without intertemporal constraints. To be able to generate alternatives that reflect radical re-imagining and can support (potentially participatory) co-creation described in section XX in relation to strategic planning, it is important that the scenarios can be developed with a high level of user input and for any given time period. This is discussed in depth in Lund et al. (2017). Rather than merely present one option as the optimal solution, the energy system analysis should allow for the consideration of radical changes, technology substitutions, sensitivities, and the inclusions of many various alternatives to support dialogue planning and the discussion of alternatives as input for strategies.

2.4.1. ENERGYPLAN SIMULATION MODEL

The overlarge majority of the modelling work presented in this PhD uses EnergyPLAN as an advanced energy system analysis tool that can fulfil these requirements (Lund et al., 2021). This section gives a brief overview of the models and its advantages for this research, but the particular applications of EnergyPLAN in the PhD (and how it is respectively aligned to other tools and data available) are discussed in Study 1: Storage in SES (Paardekooper, Lund, and Lund, 2019) and Study 2: Heat Roadmap Chile (Paardekooper et al., 2020), with Paardekooper et al.

(2018) also being a relevant reference to understand how the energy system analysis was conducted in support of Study 3: Types in Heat Roadmap Europe (Paardekooper et al., 2022).

EnergyPLAN has been specifically designed to be able to simulate scenarios that consider radical technology and infrastructure change and the interconnection (and emergent properties of interconnections) between the sectors (Figure 3). This aligns strongly with the Smart Energy System concept, particularly with regard to shifting towards a system that can take advantage of the synergies that emerge from the development of different types of smart grids and connecting the electricity, transport and thermal sectors to support efficiency and flexibility (Lund et al., 2021). Using EnergyPLAN for heating and cooling strategies thus ensures that the wider energy system is considered, and that the role that heating can play within it can be made fully explicit and appreciated.

A second key characteristic of EnergyPLAN, from the perspective of this PhD, is the advanced ability to model (district) heating and cooling. (Connolly, Miguel) show this is not always the case. Specifically, being able to set out (hourly) heating demands and simulate the district heating system with regards to excess heat, CHP, large scale heat pumps, boilers, and thermal storage on an hourly basis gives good insight into how district heating is working within the energy system. Similarly, the ability to model district cooling in detail allows for a much better insight on the dynamics that surround it. This also supports alignment with the Smart Energy System, and allows for the development of heating and cooling strategies that can reflect the potentials of district heating and cooling well.

Finally, as discussed with regard to scenarios and scenario development, simulation models are best placed to generate scenarios for strategies and support dialogue model planning and strategic planning (Lund et al., 2017). This is particularly the case for backcasting approaches. EnergyPLAN optimises the (technical) operation of the system on an hourly level, but the scenario is not based on a forecasting or constrained optimisation pathway; rather, it fully reflects the modellers' choices with regards to the technologies and infrastructures used. Since it is a deterministic model, it also does so consistently allowing for better comparison and a more effective scenario development process.

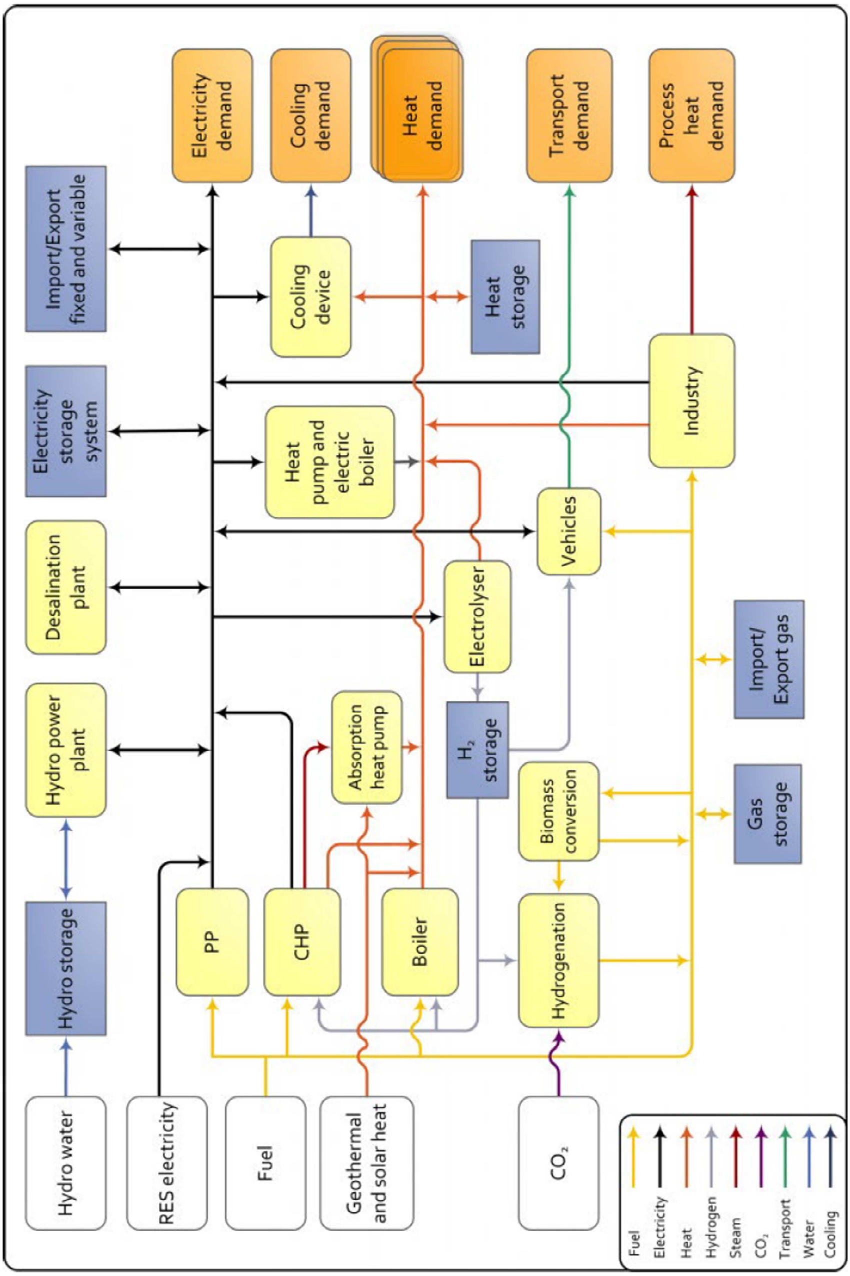

Figure 3: Diagrammatical overview of the energy system as basis for simulation and modelling in the EnergyPLAN tool. Based on Lund et al., 2021 and Korberg, 2021.

Secondly, as will be discussed a major feature of the scenarios and strategies designed in this research are subject to a variety of strategic design objectives and criteria. Heating and cooling particularly combine local and global needs, desires and preferences. This makes the ability to easily, iteratively, and exploratively simulate and develop the scenarios in EnergyPLAN particularly valuable. (Pouls article) shows that there are several regularly used criteria, but the simulation also allows for the assessment of other, particular criteria. For example, the user may easily choose to also consider required peak electricity or boiler capacity, load factors in CHP, or any of a huge variety of other factors. This type of simulation analysis not only supports the development of appropriate and better heating and cooling strategies, but, as the discussion will show, also supports discourse and engagement around what the aims and objectives of the strategy should be.

2.5. HEATING AND COOLING STRATEGIES AS CASE STUDIES

The research question sets out to identify general and specific aspects of heating and cooling strategies, and implicitly uses cases to do so. The comparative approach to using cases to ascertain generalisations and specifics in this PhD is heavily guided by Flyvbjergs 'Five Misunderstandings About Case-Study Research' (2006), which presents the methodological value of well-examined, varied cases for the development of generalisations and valuable scientific knowledge. While his arguments are aimed at social sciences, the value for the fields covered in this PhD are clear.

Cases are used in this PhD to generate depth of knowledge, particularly in response to the complexity (and variety) of the heating and cooling sector. Because heating and cooling is local and context dependant, rule-based models of knowledge only are unlikely to lead to satisfactory results. This is obvious for example during site visits with planners and experts; the first reaction to seeing, for example, a waste to energy (WtE) plant is the discussion of how it was developed in its context – and what the visitor's context would mean for its development there. This is not to say that general 'rules' cannot be made – and, as this PhD argues, can have value – but a predictive theory for heating and cooling seems unlikely, given the complex interwovenness between physical and geographical local characteristics, socio-political contexts, and specific relation to other parts of the energy system with their own particularities. Cases are also used to generate examples that be used to generate or test hypotheses in other cases; in doing so support or falsify assumptions. This contributes to the ability to generalise and develop (general) scientific knowledge overall, as long as it is placed within the right contexts.

2.5.1. CASE SELECTION

To give meaning to the research question, cases should then be selected and compared with the explicit perspective of generalisation and specificity. Effectively using cases in this way requires a relatively in-depth understanding of the context, and what it means for the broader understanding of heating and cooling in relation to what is specifically being studied. To support generalisation (or falsification), Flyvbjerg (2005: mostly page 230) distinguishes between:

- Cases selected for their extremity, which can both include presenting extreme versions of the problematics being studied or especially well-solved cases.
- Cases selected for maximum variation along certain dimensions, which allows for investigation of particular circumstantial effects.
- "Critical cases", in terms of being able to establish a logical reasoning. This can include both formats along the lines of 'it if it the case here, it probably should be the case everywhere (least-likely)' and 'if this is not the case here, it probably should not be so anywhere (most likely)'.
- Cases which can act as paradigmatic examples, which present general characteristics and serve as useful metaphors. The emergence of a case as paradigmatic is difficult to predict, so advance selection is not straightforward.

There are several important points to note with regard to case selection. The first is that, as Flyvbjerg outlines, cases can act in several of the functions described above dynamically, as the research progresses. In relevance to this he makes reference to the non-linear processes of research and research design, and that the framing of cases and their role in developing, generating and testing knowledge can change. He specifically highlights how this can happen when the case is related to other cases, showing the importance of a comparative approach. Because case studies are most applicable in contextualised and dynamic situations, the emergence of new knowledge, perspectives, and insights as to how the case functions may be more likely than for example studying natural sciences. The way in which case studies are then used can change, depending on how the research and strategic planning processes develop and other cases emerge.

As a result, researchers and the research community must and typically do confront their own preconceptions, actively seek challenging and critical perspectives, and consider the dissonance and feedback that case studies elicit, also to address confirmation bias. For this reason, I have found the combination of research with the applied work as an associate to the DES Initiative to have greatly influenced my thinking during this PhD, in terms of being able to discuss ideas and observations with practitioners, and other people in what Flybjerg terms 'the Field'. This has been both the case for working with consultants and engineers that have in-depth knowledge and established experience with energy, heating and cooling, and district energy but also with professionals in adjacent areas of expertise, and in policy and planning areas. With this in mind, the use and development of case studies in complex and rich areas such as heating and cooling, is then a dynamic process which benefits from discussion and consideration, tying in neatly with the emphasis on discourse and multiplicity of perspectives which is valued in strategic planning.

The second point is that in the realisation of PhD research, case selection is also guided by access to the means to conduct research, so complementing case selection is also the process of giving meaning to cases that are or become available. Means is both in terms of access to sufficiently rich available data and information on the cases as well as the availability to spend time and resources on the research. Chapter 9 refers to potential further research, which would benefit most from the development or more in-depth assessment of more cases, particularly in developing countries and emerging economies. A similar project for Study 2: Heat Roadmap Chile but developed for Serbia, India, or Colombia would provide a good case for enrichment in terms of methodology development and more refined adjustment to different contexts, but was not possible. Secondly, being able to connect and leverage a sufficiently engaged network of practitioners to both be able to support the generation of contextualised, rich knowledge, but also ensure it will be actively used. Case selection and research design for case studies is then partially a proactive process, but also requires responsiveness and framing to give meaning to the cases that become available.

2.5.2. OVERVIEW OF THE CASES

Section 1.1 outlines the cases used in the studies in this PhD. They are set out here with relevance to their particular role towards addressing generalisations and specifics of heating and cooling in this thesis. Additionally in the thesis, cases are used from other publications developed in the context of this thesis. In particular these are from Maya-Drysdale, Mathiesen and Paardekooper (2018), which investigates in more depth the role of near zero energy buildings (nZEBs) in a Smart Energy System for Denmark, and Bertelsen, Mathiesen and Paardekooper (2021) which investigates how the (historic) development of large-scale heating infrastructures towards extremely high market shares for Denmark, the United Kingdom, and the Netherlands. Through these examples, it becomes clear that the value of cases, and effective use in generating knowledge, is also largely in the way that the cases and their findings are selected, discussed, contextualised and related to each other.

Study 1: Storage in SES (Paardekooper, Lund and Lund, 2019) uses ‘IDA’s Energy Vision 2050’ for Denmark (Mathiesen et al., 2015) and ‘Smart Energy Europe’ (Connolly et al., 2012b). Since the purpose was not to develop the strategies, but better understand them the use of pre-existing cases and models served to expedite the research. These cases serve several functions in this PhD. Firstly, they represent two cases of 100% renewable, Smart Energy Systems. While the other cases are all developed within the framework and using the notions of Smart Energy Systems, the scenarios developed in Study 2: Heat Roadmap Chile and for Study 3: Types in HRE are not 100% renewable and do not represent complete Smart Energy Systems. Being able to review how re-designed heating and cooling sectors look and function within the frame of strategies specifically designed for 100% renewable energy systems facilitates the design of the other strategies towards this aim.

Secondly, the use of these cases allows some further investigation of the use of thermal storages in comparison to other storages within a Smart Energy System. The two cases represent Smart Energy Systems in the European context, but there are some obvious significant differences in terms of scale and geography. A major motivation of the design approach of interconnecting the different energy sectors – particularly the electricity sector with the thermal sector – is the availability of cheap thermal storage. The cases here exemplify this, with particular regard to the varying roles of electrofuel production (and subsequent storage). Denmark as a country without hydroelectric storages, in combination with district heating, is especially important to show alternate means of flexibility (see also Askeland, Johnson Brygg, and Sperling, 2020 for more detailed discussion on challenges and particularities on determining exact combinations). Looking at these different scales and how storages operate within them allows for a better perspective of the role and magnitude of the thermal sector in a Smart Energy System, without the need to develop it completely.

Study 3: Types in HRE (Paardekooper et al., 2022) is based on the 14 European countries we analysed in depth in the Heat Roadmap Europe project between 2016 and 2019. It sets out some of the key differences between the development of heating sectors and the built environment, infrastructures, and planning traditions which also highlights local differences. They are the 14 largest EU countries in terms of heat demand and collectively represent 90% of the EU's heating demand, meaning that there is sufficient grounds to also say something about the EU's situation overall. Again, the choice for 14 countries is based on balancing detailed strategy development with pragmatism. To have done all 28 countries would have effectively doubled the analytical work required, since each strategy is based on intensive, explorative, and as such iterative and repeated scenario development. At the same time, this would only have added small significance to the overall European perspective, so the 14 cases are used as a way to both manage to make detailed heating and cooling strategies and be able to allow for analysis at European level.

In terms of the cases, European countries are in many ways very similar. There are some strong common historical, cultural, and political developments and shared experiences, also outlined in Section 1.5. For heating and cooling specifically, the EU level policies mentioned (particularly the EPBD, RED, EED, and Ecodesign Directives) ensure a certain level of cohesion between all MS, as has decades of free trade to enable the diffusion of heating and cooling equipment and technology suppliers. This also results in an overall relatively high level of energy transition literature and management and available data for strategy development. Because the discourse is already present, and the data available, this means that the 14 cases from the Heat Roadmap Europe projects are thus collectively also used as best-examples for strategy development.

This uniformity is complemented by particular differences, and Study 3: Types in HRE investigates these in more detail. In grouping the cases the study aims to both explore the variance between the cases and support eventual paradigmatic cases (Paardekooper et al., 2021). In accordance with strategy development and the generation of alternate future visions, the cases are described and categorised along the lines of what the state of the heating and cooling sector is now, where they are headed, and where they could go (ibid). Three dimensions represent the heating sector: energy demands for the built environment; energy supply in terms of infrastructures and technologies and energy supply in terms of energy carriers for district energy. These dimensions of the cases are used establish four types, to represent the variation between the cases, and the investigation of particular circumstances and policies that effect the development of the heating and cooling sectors. Within the types, country cases are also used to highlight representativeness where appropriate, particularly in the discussion of certain dimensions. In this way the cases individually in Study 3: Types in HRE are both used to investigate variation and establish representativeness.

Study 2: Heat Roadmap Chile (Paardekooper et al., 2020) uses Chile as a case for developing a strategy for heating. Chile represents a fairly singular case in that the heating sector is currently largely based on biomass, so strategies are more based around the development of access to energy and combatting of PM as a result of inefficient combustion common in heating currently. It is relatively singular since it is one of the first cases of a heat strategy being developed in the frame of a Smart Energy System outside of Europe, and the first time the methodology addressed air pollution quantitatively. In addition, it presents the first instance of district heating being nationally assessed for Chile. These all present contrasts with the cases discussed in the EU context, and give weight to the more general applicability of the findings.

Using Flyvbjerg's frame of case selection it is particular in several more ways. Methodologically, Chile provides some strong contrast with the other cases in terms of the extent to which data is available. As a critical case, the flexibility and adaptation of the methodologies showed that even with limited data, it is possible to develop a Heat Roadmap that includes district heating. Similarly, the use of Chile as a critical case confirmed the importance of a high level of local engagement (also discussed in Study 4: Motivations for DES) to shape the strategy in terms of workshops to discuss and present results, providing another critical dimension to the case. In terms of findings, Chile was a 'least-likely' case for decarbonisation to be a major driver of the heating strategy, since heating is mostly based on (renewable) biomass. However, even here, decarbonisation was found to be an important part of re-designing and transforming the heating sector. Because it varies quite strongly from the other cases analysed, the case of Chile can be used in several different ways to discuss the different aspects of developing heating strategies.

Chile is included together with Serbia, India, and Mongolia in Study 4: Motivations for DES (Paardekooper, Chen and Savickas, 2021). From a case selection perspective, the aim was to be able to create a rich narrative review on the backgrounds and motivations in the case countries, so the primary criterion for inclusion was a documented expressed and developed interest in (district) heating and cooling development. Further from this the aim was to combine some extreme cases and provide variety through the set. The cases include a range of existing district energy infrastructure (in Serbia and Mongolia) and (quasi-) non-existing district energy sectors in Chile and India. Both heating and cooling are included, with Serbia and Mongolia focussing mostly on heating, India on cooling and Chile increasingly considering cooling in addition to the primary focus of heating. While all countries face resource management challenges in terms of fuels for heating (coal in the case of India, Serbia and Mongolia; biomass in the case of Chile), the ways in which these dynamics manifest differ. These variations allow for some good comparisons between the cases.

In addition, each case has its own particularities and in some ways presents an extreme problematic or context. The particular issues of Chile are discussed above. India represents a case where growth is a primary driver – of energy demands, capacities, urbanisation, and cooling demands. This lessens the importance of eg. renovating existing buildings, which dominates the discourse in many countries, and heightens the awareness on the interactions between the electricity and thermal sectors. Mongolia presents an extreme in terms of climate, and in terms of low population density. This is in direct contract with findings from the European cases, where population density is a better predictor of district energy infrastructures than climate. In addition, Mongolia presented a case where an in-depth gender and social assessment had taken place and an action plan had been developed, which is uncommon. The interest in Serbia is partially in terms of the specific approaches and principles towards further developing district energy, but also as a case where the EU legislation is in the process of being aligned and thus driving change in a different way. As a set, these cases then provide both a broad variety to each other and present some interesting extremities in several dimensions, which allows for a more broad assessment of what aspects are more of less general in heating and cooling strategy development.

CHAPTER 3. STRATEGIC DESIGN OBJECTIVES

The strategic design objectives are the first aspect of heating and cooling strategies that will form the discussion. The strategic design objectives set out the overarching planning goals for the (energy) system, and serve to identify the political and social context of the heating and cooling strategy. These strategic design objectives identify what the purpose of re-designing the heating and cooling sector is, in alignment with wider developments. In some cases, this means addressing current problems, such as decontamination of the Chilean heating sector by eliminating harmful air pollution. Alternatively, it can be addressing the emergence of future problems, such as increased and anticipated growth of energy demands in India. Strategic design objectives can identify what problems the current system presents, and what (aspirational) elements the re-design of the heating and cooling system must address.

These types of driving motivations are typically relatively non-concrete, and describe the directionality of moving forward towards a more sustainable future, that the sustainable heating and cooling strategy is aiming to support. When introducing the relevance of heating and cooling, Figure 1: Relevance of heating and cooling examples for the 17 Sustainable Development Goals in Chapter 1 explored interactions between heating and cooling and all of the UN Sustainable Development Goals (SDGs). This is also the level at which strategic design objectives operate, although they are not limited to the SDGs exclusively. Notably, these strategic design objectives are purposefully broad, because they represent how energy, and heating and cooling specifically, fits within wider social, economic, geo-political, and sustainability transitions.

Establishing clear design objectives is particularly relevant for heating and cooling, since it does intersect strongly with many broader planning objectives. When introducing the relevance of heating and cooling, Figure 1: Relevance of heating and cooling examples for the 17 Sustainable Development Goals illustrated how, to some degree, heating and cooling affects all of the SDGs, although this may not be the case in every instance. Geopolitical events and desires to support domestic growth have in the past provided strong design objectives for energy systems to reduce reliance on external fuels, and support the development of local employment and economy. The relevance and reasons for improving heating and cooling are far-reaching and deeply entrenched with economic development, health and well-being, social equity, land-use and resource conflict, and environmental sustainability that a full recognition of the socio- and political context is required to develop a heating and cooling strategy that addresses the right needs.

3.1. USING STRATEGIC DESIGN OBJECTIVES FOR HEATING AND COOLING STRATEGIES

In heating and cooling strategies, the design objectives govern with what perspective the re-imagining of the future will take place. Because strategies are designed to address the challenges that arise from decentralisation, globalisation, and increased complexity, the development of clear strategic design objectives is necessary in order present an improved vision for the future. By providing a normative context, reflecting social and political objectives, design objectives determine what the purpose of the heating and cooling strategy is.

There are several implications from the broad variety of strategic objectives that exist. Identifying the right strategic design objectives ensures that the heating and cooling strategy aligns well with the political and social context, and can contribute effectively to strategic planning processes. The scenarios and strategies developed in the Heat Roadmap Europe project series are all geared towards addressing slightly differing design objectives and in doing so address different questions; firstly of technical feasibility, then of affordably achieving similar energy efficiency, and then in the final two iterations of increased efficiency and decarbonisation. So, even though the overall results are not radically different between the projects, they address different aspects of the developing contexts of (strategic) planning discourse at European level between 2012 and 2019.

Given the diversity and breadth that strategic design objectives can have, it is not likely that all strategic design objectives will carry equal weight. It is important to be able to prioritise, and identifying several of the most salient issues or objectives. These are, inherently, normative choices, and are thus a reflection of the prioritisation of the wider strategic planning objectives that are appropriate in the context.

Simultaneously, the diversity of Goals and aspects that are affected by heating and cooling means that there must be some consideration to ensure that there are no adverse effects to other objectives or aims. In recognition of the complexity and systems thinking that is required in the design of heating and cooling strategies, the prioritisation of certain strategic design objectives may lead to proposed strategies that so not consider other impacts of the energy systems and heating and cooling. For example, incoherent assessments of waste incineration for combined heating and cooling may lead to decarbonisation, but could also adversely affect the efficient use of resources in the broader system, and detract from indicators on sustainable consumption and resource use. This is an issue that has been investigated in the context of Danish waste incineration plants in some detail (WtE refs Marie/Amalia). Similarly, in Serbia and Mongolia, the heating sector is mostly fuelled by locally mined coal, so direct decarbonisation should be complemented with strategies to support and transitions local employment. An integrated perspective, that recognises other strategic objectives than the main priorities, is required.

Thirdly, by functioning as normative recognition of the (socio-political) objectives and priorities, the strategic objectives are direct representations of stakeholders' perspectives. Since stakeholders' priorities are likely to differ, the development of strategic objectives includes an exercise of establishing rapport and including and incorporating various stakeholders' positions. In the case of developing heating and cooling strategies for Europe, the inclusion of a network of local governments for sustainability (ICLEI), different industry associations, and several other different representative organisations was particularly valuable in providing perspectives and feedback, in addition to in-person workshops, events, and round-tables to discuss the development of the heating and cooling strategies. Similarly, in the development of the Heat Roadmap for Chile, collaborations with local partners and workshops allowed to shape the strategic design objectives. This is especially relevant for heating and cooling, since there are both strong local and (inter-)national considerations and perspectives to be considered. This also means that careful selection of the heating and cooling strategies design objectives can build support and standing for the strategy in the strategic planning process.

Strategic design objectives form the starting point of designing heating and cooling strategies, by identifying the purpose of the strategy, within the political and social context. Strategic design objectives can combine aspirational and problem-solving, and allow for prioritisation of how energy, heating, and cooling intersect with social, economic, geo-political, and sustainability transitions. As a result of the normative nature of strategic design objectives, their choice and development also represents a link between stakeholders' perspectives and the development of heating and cooling strategies.

There are several strategic design objectives that are common as priorities for heating and cooling strategies. Given the deliberately universal nature of the SDGs, high degree of adherence to the Paris Agreement, Montreal Protocol, and several other international frameworks and cooperatives that govern sustainable development, this is expected. It also emphasises the global nature of several of the issues that a transition towards sustainability and decarbonisation must address. However, while these strategic objectives may be generally present, there are still differences between the cases considered in this thesis in terms of how they are utilised. As a result there is a huge diversity and specificity in the strategic design objectives for heating and cooling strategies at local level.

3.1. SECURITY OF SUPPLY AND ENERGY RESOURCE MANAGEMENT

Increased and ongoing attention to the heating and cooling sector currently is in large part driven by the trade interruptions and security of supply concerns following the outbreak of war between Ukraine and Russia. A generally present strategic design objective is the sustainable management and domestic reliance on energy resources and robustness to fuel shocks through security of supply.

Outside of Europe, this is also one of the key themes in establishing a framework on motivations for energy planning more broadly and district energy specifically in Study 4: Motivations for DES. Based on Stephensen, Sovacool and Inderberg (2021), it considers the dependence on (fossil) fuels in terms of supplying the energy system, and in terms of import and export reliance.

Again, the way in which these objectives take shape differ quite broadly in different contexts and result in some quite specific strategic design objectives. This strategic objective presents one of the most political and complex problematics to relate heating and cooling strategies to, because it directly touches on geopolitical relations (and sometimes geopolitical conflicts), domestic resource management, and domestic employment. Consequently the shape it takes at local level varies strongly.

The objective of developing a heating and cooling strategy that is robust to fuel shocks can be driven by a desire to prevent foreign dependence on fuels. Since the beginning of 2022, this has been highlighted by the war in Ukraine and subsequent effects on the fuel and particularly gas market.

These are often based on experienced events rather than long-term pressures, as implied by the idea of fuel shocks. In the case of Denmark and IDA's Energy Vision, this is particularly strong since the field of Danish energy and heat planning was established largely as a response to the OPEC crises in the 1970's (Rüdiger, 2014; Bertelsen, Mathiesen and Paardekooper, 2021). This dynamic continues to inform a particular attention in the design of 100% renewable and heating and cooling strategies towards diminishing reliance on foreign fuels – be that fossil or imported biomass resources (Lund, 2007, Mathiesen et al., 2015). For the IDA Energy Vision reviewed in Study 1: Storage in SES, there is then an explicit strategic objective to reduce reliance on fuels.

To a lesser extent, the objective to reduce reliance on foreign fuels is also present in the 100% renewability and heating and cooling strategies for the EU. This is then often particularly in the form of gas, about half of which is currently imported from Russia. At the beginning of this PhD, during the 2014/2015 Russia-Ukraine gas disputes, there seemed to be a stronger political emphasis on geopolitical security. However, it should be noted this to an extent dissipated and a shift away from natural gas was framed largely through decarbonisation measures in the intermediate (EC, 2020). In the Smart Energy Europe study reviewed in Study 1: Storage in SES, the complete phase-out of gas (and coal) is based on the decarbonisation objective. In the Heat Roadmap Europe studies, contrastingly, the degree of remaining gas usage is partially driven by domestic availability. It goes without saying the strategic objective to reduce reliance on foreign resources is now present again, salient due to explicit trade interruptions.

Chile experienced a concern around disruption of natural gas supplies from Argentina around 2004. Gas trade with neighbour Bolivia has traditionally been interconnected with other longstanding geopolitical frictions, so natural gas imports are largely dependent on Argentina. Since 2004 there have been periodic episodes of concern over Argentina's ability to fulfil their supply contracts, so in the short term there has been so has an active policy of diversifying and minimising reliance, for example by developing LPG terminals, and establishing (electricity) interconnectors to Peru. In the long term, these experiences support a strategic objective to be able to improve robustness to fuel shocks and price disruptions, and reduce single reliance on imported energies.

The strategic objective to reduce (future) reliance on imported energy to is also present in India, although in many ways secondary to others and only occasionally made explicit (Study 4: Motivations in DES, Paardekooper, Chen and Savickas, 2021). While India is still the world's second largest importer of coal, import dependency has been decreasing. This is partially due to a deliberate policy of diversification, and partially the development of domestic resources. While not the major strategic objective addressing the problematics of increased power and coal consumption, it is periodically present and can be considered in terms of developing strategies for energy and cooling in India.

Serbia stands out as a case in terms of foreign dependence on fuels, and its strategic role for heating and cooling objectives. There is a distinct foreign dependence (gas supplies the majority of district heating and is imported mainly from Russia), but the development and plans for several gas transmission infrastructures through Serbia also present an opportunity to present it as a 'regional hub' for gas trading. This shifts the perspective away from foreign reliance towards fuel towards integration in global markets, and associated market power and choices. There is a recognition that this is not completely without geopolitical implications, but it means that from the perspective of formulating strategic design objectives for heating, a high degree of resources being traded internationally is not considered a key problematic.

A second category of strategic objectives relating to energy resource management and trading is the management of domestic reserves, and how this informs the strategic design objectives for heating and cooling strategies. This is especially the case for countries which have significant energy resources of their own.

The development of natural gas grids in the Netherlands provides a retrospective example of heating and cooling strategy objectives based on this, described in Bertelsen, Mathiesen and Paardekooper, 2021. In developing an approach to the management of the largest gas field in Europe, found in Groningen, during the late

1950s and early 1960s, there was an initial perspective of extracting the resource fully as soon as possible. The reasoning was that the imminent development of cheap, super-abundant nuclear energy could make fuels like natural gas redundant (and thus worthless), so extracting and using the resource quickly would ensure its value (Verbong and Schippers, 2000). Developing natural gas grids for domestic heating and hot water thus served both a dual purpose of providing volume in the market for sales and improving the standard of living and quality of heating for many people during the initial phases.

Similarly, when fuel prices rose and resources globally became scarcer during the OPEC crisis a decade later, the strategic direction of heating shifted towards increased insulation and energy efficiency, to support larger exports of gas and capitalise on higher global energy prices. Since, the strategic objectives in the Netherlands for heating and cooling have radically changed towards a natural gas phase-out in heating in response to the combined challenges of decarbonisation ambitions and increasing induced seismicity due to overexploitation. In its retrospective, the natural gas management and heating sector development in the Netherlands provides a good example of the strategic objectives of a heating and cooling policy being strongly guided by domestic energy resource management, and changing over time in response to both global and local developments.

Applied to more current cases, the discourse on how to manage domestic (fossil) fuel reserves and how this impacts the heating and cooling sector is echoed in Serbia and Mongolia, which both have significant coal reserves and heating sectors that currently use these resources. The review in Study 4: Motivations for DES touches on some of these implications, including (in Mongolia) the effect of global fuel and commodity prices on domestic income; implications of providing employment opportunities and quality of work in mining and extraction sectors (in both Serbia and Mongolia), and the diversification and reduction in reliance on foreign fuels that coal can provide (also in both Serbia and Mongolia). It seems clear from this that the political context of domestic resource management and exploitation has a large effect on how strategic objectives for heating and cooling are developed, and are strongly linked to geopolitical and resource trade positioning.

3.2. ACCESS TO AFFORDABLE ENERGY

Across all the heating and cooling strategies, there is a clear common strategic design objective that in developing the vision for the strategy, the heating and cooling sector should provide affordable access for all. Recalling Figure 1: Relevance of heating and cooling examples for the 17 Sustainable Development Goals outlining the relevance of heating and cooling to the SDGs, this is unsurprising. Because of the impacts of good heating and cooling on health and well-being and productivity in educational and professional settings, addressing energy poverty and ensuring comfort through heating and cooling relates to much broader socio-political objectives regarding equity and economic and sustainable development. While it seems like the most universal question when discussing alternative scenarios and strategies is to ask what it costs, the exact context and form that concepts like affordable and accessible energy take differ widely over the cases.

Improving access to quality heating stands out most strongly in the case of Mongolia, discussed in Study 4: Motivations for DES, because of the extremely high level of underheating identified – also in educational and professional settings. A social assessment for low-carbon heating and cooling identified instances of schools and kindergartens being heating to 13°C during the heating season (Erdenebat, 2019). In this case the strategic objective to be able to provide practical and economic access to heat is of course paramount, and the driving purpose of the strategy.

In the case of India, access to cooling is clearly identified to be growing hand in hand with economic growth. This is ascribed to increased electrification rates, increased ownership of cooling appliances, population growth and in many cases increased urbanisation and expansion of the building stock taking place in the context of a tropical climate. Summer peak electricity due to cooling can be as high as 40% in some of the larger cities like Mumbai and Dehli (Chen et al., 2020). In much of the literature reviewed in Study 4: Motivations on DES this is actually identified as the major driver for engaging with district energy, but also the need for short- and long-term strategic planning around heating and cooling.

The perspective of equitable access to cooling as a key strategic design objective here is interesting, because in almost all the other cases studied it is not considered a key strategic objective to access cooling – the emphasis is typically on heating. Even in the warmest parts of Europe, heating demands are still typically expected to outweigh cooling demands in 2050 (Paardekooper et al., 2018; Fleiter et al., 2017). However, there are reasons to consider a more broad inclusion of access to cooling to strategic design objectives. This first is clearly that there despite efforts are likely to be changes in climate and temperatures globally over the coming decades leading to episodic high temperatures; this is the case in India but likely to be the case elsewhere too. Secondly, even where heating demands are more prominent and under-heating the dominant form of energy poverty, heat waves have impacts on public health and can disproportionally affect certain groups of people. From this perspective it could be interesting to consider access to cooling as a strategic design objective where possible, even in cases where it is currently not a priority.

The strategy developed on Study 2: Heat Roadmap Chile also has a relatively explicit strategic design objective to achieve affordable heating and access for all. Mostly, the driver for this is addressing under heating practices, particularly in buildings with bad thermal quality. Equitable and affordable access is also important in relation to the two main strategic design objectives determined in the Heat Roadmap for Chile (decarbonisation and decontamination through reduction of air pollution). Because affluent neighbourhoods are less likely to suffer as much from air pollution from heating, there is an implicit need to address equity and ensure that the better and cleaner heating options are also available to those and those neighbourhoods where they are most needed. This strongly links the strategic objective of affordable access to energy with the other strategic objectives of decreasing PM emissions from heating.

For all of the cases in Europe (including Smart Energy Europe, IDA Energy Vision, and the Heat Roadmap Europe countries) one of the main strategic objectives is to minimise energy system costs, in order to support an affordable and cost-effective transition towards sustainability. The strategic objective to provide affordable energy is very implicit, because the strategies take the desire to minimise the cost of the energy system as a strategic design objective. The further analysis of how a reduction in energy system costs is framed will take place in Section 4.4. There is an implicit assumption that the re-designed heating and cooling system will provide adequate comfort temperatures, but the majority of the cases this is not emphasised as a major challenge or point of discussion in discourse, so the overall cost of the system is the leading strategic design objective in this regard.

3.3. DECARBONISATION AND 100% RENEWABILITY

Decarbonisation is a strategic design objective in all of the heating and cooling strategies, and an important topic for all of the other countries encountered. One of the key findings is the consistency in which the Paris Agreement forms a basis for increased efficiency and decarbonisation, even where there is already high renewability, or no express desire to go towards full renewability. What is surprising is the differences in the way it is interpreted and applied, since in every case the particular interpretation and construction of a decarbonisation strategic design objective is different.

The purpose of reducing fossil fuel consumption and their associated CO_2 emissions from the heating and cooling and energy sectors is to prevent and reduce catastrophic results of climate change over the coming decades. Simultaneously, the use of fossil fuels also poses secondary threats to sustainability in terms of environmental impacts during production, source of land-use and geopolitical conflict, and health impacts from PM as a result of combustion. The global nature of this problem means it is fairly universal, but it is applied differently in the different heating and cooling strategies.

It is relevant to note here that the distinction between decarbonisation and 100% renewability is not always clear for the heating and cooling strategies developed. The strategies discussed here typically have as an additional strategic objective to give preferential treatment to safe, proven and known technologies, in line with the Smart Energy System concept (see Section 2.1). As a result carbon capture storage technologies and nuclear energy are not used to decarbonise the energy system. The main approach to decarbonisation is the exclusion of fossil fuels, meaning that here, decarbonisation and renewability are effectively synonymous. This is not always the case; the current EU ambition to be carbon-neutral by 2050 allows for use of fossil fuels and carbon capture, and does not necessarily lead to decarbonisation through 100% renewable energy. Similarly, the role of waste heat and its implications towards renewability, sustainability and decarbonisation have been discussed in Section 2.2.3. This highlights that while decarbonisation is a common design objective, its interpretation varies depending on the context.

The IDA Energy Vision and Smart Energy Europe study, reviewed in Study 1: Storage in SES, are unique in this PhD because they represent the only fully renewable energy systems considered. The IDA Energy Vision purposefully set out to establish an energy system without fossil fuels for 2050, in alignment with the formal government goal (Mathiesen et al., 2015). This included complete decarbonisation of the heating, cooling, power, transport, and industry sectors. The Smart Energy Europe explicitly set out to explore the feasibility and impacts of a 100% renewable energy system – even though this is (still) not a formal objective of the European Union (Connolly et al., 2016). The IDA Energy Vision and Smart Energy Europe study both have as primary design objective to present 100% renewable energy visions.

However, even though both had 100% renewable energy and full decarbonisation as a primary design objective, their positioning and intent still reflects different (political) contexts. In its full renewability, the IDA Energy Vision was aligned with other scenarios (developed by the Danish Energy Agency) which were also fully renewable in their objective, but different in other objectives and approaches, in particular bioenergy usage and local investments. In the Smart Energy Europe study, the use of full decarbonisation as primary design objective was intended to support expansion of strategic planning to better include fully decarbonised and renewable energy options. In this way the strategic design objective of 100% renewability, though the same, recognises the different political contexts and serves a different purpose in terms of positioning the strategy and contributing to strategic energy planning.

The strategic objective for decarbonisation in the Heat Roadmap Europe strategies (discussed in Paardekooper et al., 2021) is explicitly in line with the Paris Agreement, but less clear. This is less strict than full renewability, since at the time of development, the EUs commitment to the Paris Agreement was formally between 80%-95% decarbonisation of the energy system – which is of course in and of itself not a very clear goal. In addition, it allowed for carbon capture and storage – which the Heat Roadmap design objectives did not. Given the relative difficulty in decarbonising heavy industry and transport, for these strategies the objective was interpreted to mean a full decarbonisation of the heating and cooling sector, implying no direct use of fossil fuels for heating and cooling and maximum support for renewability in the electricity sector to support decarbonisation. In this sense the specific design objective was full decarbonisation of the heating and cooling sector, and maximum decarbonisation of the electricity sector as a result of a redesign of heating and cooling.

The strategic objective of decarbonising the heating and cooling sector was here used to further the strategic planning discourse on decarbonisation altogether. The vision presented was that by redesigning the heating and cooling sector using certain principles and approaches, it is possible to decarbonise further and faster than the commitments in the Paris Agreement – without having even made major changes to planned approaches for transport, non-thermal industry, and other sectors that were not the explicit focus of the heating and cooling strategies. While the strategic objective was not full decarbonisation or renewability, the goal of increased decarbonisation does support strategic planning discourse towards full decarbonisation and renewability.

The Heat Roadmap Chile strategy, described in Paardekooper et al., 2020, specifically set out to combine the strategic objective of decarbonisation with decontamination, in recognition of a heating sector already largely based on renewable energy. As a case this is significant, because it highlights that decarbonisation of the energy system is likely always relevant – even where the system currently is renewable – but may take the form of preventing the introduction of fossil fuels as heating and cooling systems transition.

This also reflects the large share of heating (globally) that already takes place using renewable energy, but contravenes many of the SDGs in terms of environmental, health, and resource efficient sustainability. Specifically, heating based on (inefficient) biomass combustion may be renewable, but does not represent sustainability. In this context the strategic objective of decarbonisation means ensuring that the heating and cooling system remains fossil-fuel free and decarbonised, and supports greater implementation of renewables in the other energy sectors, notably the electricity sector.

In the case of Chile, the double focus on decontamination and decarbonisation both responded to a context of increase gas used in heating, and a further integration of the heating sector looking towards developing strategies and scenarios for net-zero energy systems by 2050, in recognition of the signing of the Paris Agreement. Including decarbonisation allowed for clear recognition that while natural gas may be cleaner (addressing the objective of decontamination), it contravenes the long-term planning objectives clearly laid out and agreed by successive governments. Secondly, the inclusion of energy system-wide decarbonisation allowed for the strategy to explicitly address the role of bioenergy in a future energy system, and show the potential of positing the heating system as an interconnected and supportive part of further decarbonisation. In this way, the objective of decarbonisation raised the relevance of a re-imagined and designed heating sector, but also raised the relevance for wider and more integrated strategic energy planning.

In terms of identifying immediate drivers for change and strategic design objectives, decarbonisation and 100% renewability in Study 4: Motivations for DES diverge quite strongly. One aspect that unites the cases of Serbia, Mongolia and India is how decarbonisation and Paris Agreement targets function not (or not only) to displace fossil fuel consumption, but to increase the efficiency of using fossil fuels. An example is Mongolia, where coal is expected to continue to play a role, but inefficient combustion is deeply problematic. In India, this objective of curbing the growth rather than eliminating fossil fuels (and particularly coal) combines partial decarbonisation in the traditional sense with the desire to prevent further introduction of fossil fuels. Better using existing fossil fuel resources, then becomes a strategic objective in and of itself. This obviously does not lead to 100% renewability, but represents diminishing or preventing the further use of fossil fuel as a different way of interpreting decarbonisation.

3.4. SUSTAINABLE USE OF BIOENERGY

A strategic design objective present in many of the heating and cooling strategies is the sustainable use and management of bioenergy. Retaining limits on the use of bioenergy is important from an environmental perspective to reduce impacts of deforestation, soil and land degradation, desertification, and broader upset of ecosystem and biodiversity sustainability (see also review in Study 1: Storage in SES [Paardekooper, Lund and Lund, 2019]). In addition to the environmental concerns, the informal nature of many biomass markets results in further endangerment of environmental sustainability but also dimensions of health, safety, agricultural sustainability and adequate work. There are universal concerns about overuse of bioenergy, and broadly speaking in the future its use should be reserved for the sectors that are most difficult to decarbonise and where few alternatives exist (Lund, 2014). Simultaneously the specific sustainability aspects are relatively locally determined. As a result bioenergy is both in many cases both a viable source of renewable energy, but its limitation also an important strategic design objective for heating and cooling strategies.

A clear example of the influence of a design objective using a conservative approach to sustainable bioenergy is the Smart Energy Europe study in Study 1: Storage in SES. In scoping, the study reviews some different bioenergy potentials for Europe, with particular regard to different parameters of sustainability in terms of available fuels (Connolly et al., 2016; Paardekooper, Lund and Lund, 2019). The objective here was to look specifically at sustainable bioenergy availability in Europe locally, often from forestry. A European market for bioenergy is assumed, in recognition of the fuel markets that allow for free transfer of bioenergy today. Simultaneously, the design objective was also to not exceed global per capita limits, in order to ensure a global solution could be enabled. The resulting design objective was a relatively constrained use of bioenergy, in particular given the complementary objectives of using no nuclear and CCS technologies for decarbonisation, and 100% renewable energy.

The resulting – conservative – estimate effectively posited that a transition to decarbonisation and full renewability was possible for the whole energy system, without an overt reliance on bioenergy as a direct substitute for fossil fuels today. In particular, the combination of the objective to constrain bioenergy with the objective of initiating with technologies that have scientific and political consensus, results in a strategy that demonstrates clearly where bioenergy can be used, where alternatives are possible and preferable, and what dynamics emerge. This then also contextualises what the scope of bioenergy usage can be, if potentials are expanded or contract. This is particularly the case for the heating sector, where it is clearly shown that choices which involve high levels of bioenergy are not necessary or beneficial. By combining the two strategic objectives, the Smart Energy Europe strategy allows for a better understanding of how 100% renewable energy can be achieved, and how dependant it is on bioenergy within the European strategic energy planning space.

Similarly, the strategic objective to constrain and minimise bioenergy usage in the IDA Energy Vision in Study 1: Storage in SES shapes much of the strategy's alternative message that 100% renewability can be done using less biomass (Mathiesen et al., 2015). Again, based on a review of (domestic) bioenergy resources, including a differentiation between bioenergy types (and particularly bioenergy crops and algae production for bioenergy), a design objective was developed that set out to reduce bioenergy reliance, compared to other strategies being developed in the strategic energy planning space. As a result, the strategy put forward in the IDA Energy Vision demonstrates clearly that a renewable energy system – including heating and cooling – is feasible and benefits from approaches that avoid the need for bioenergy crops and rely on (further) development of bioenergy production methods. In this case designing the strategy with the objective of minimising bioenergy in combination with 100% renewability allowed for a Vision that emphasises the feasibility and potential of intermittent renewable energy sources.

While the sustainable use of bioenergy was not one of the main strategic design objectives considered in Heat Roadmap Europe, the need to respect limits to sustainable biomass was respected (Paardekooper et al., 2018). The choice not to focus on minimising bioenergy as a design objective was driven by several motivations. Firstly, on a pragmatic level the design of the Heat Roadmap strategies was in some ways concurrent to the revision of land use, land-use change and forestry (LULUCF) regulations at EU level (Regulation 2018/841), but too late to effectively contribute to the policy discourse on this. Secondly, the strategies main design objectives were to show the potential of a re-designed heating and cooling strategy based on proven technologies and a redesign of the heating and cooling sector; this in many ways included avoiding the use of (inefficient) bioenergy combustion already. Thirdly, once developed, much of the bioenergy utilisation was outside of the direct heating and cooling sector, so in many ways outside of scope. As a result, any radical proposals for bioenergy usage overall would have been difficult to constructively draw into strategic energy planning discourses, and required redesigns that were not a part of the specific desire to redesign heating and cooling. Nonetheless, the strategic objective not to exceed certain biomass limits shaped Heat Roadmap strategies, in providing additional motivations to avoid overt reliance on bioenergy for the heating and cooling sectors.

Using bioenergy sustainably is one of the primary design objectives in Study 2: Heat Roadmap Chile. The per capita biomass availability in Chile relatively high, even using relatively stringent norms of environmental sustainability. It also differs quite strongly from the strategies discussed above in that the focus is more on how to use the bioenergy in a way that facilitates other dimensions of sustainability, such as quality of local employment, biodiversity, and equitable distribution of resources. This calls for a more intricate approach towards sustainable use rather than only trying to constrain or reduce usage.

Because of this, the strategic objective to use bioenergy sustainable was considered from an environmental perspective, but even more strongly so from an emissions perspective and from the perspective of developing a formal market for biomass that supports local employment, reduces conflict, and support the development of the sector towards high-quality products and growth. However, much of this work had already been developed for the context of energy planning. In reference of the work already done in the Process of Long-Term Energy Planning (PELP), bioenergy was aligned with usage in the reference scenarios (Ministerio de Energía, 2017). In addition to adhering to those quantities, usage was directed specifically towards more centralised facilities, in line with the facilitation of more formalised of biomass markets, and the additional design objectives of minimising PM emissions.

3.5. ADDRESSING AIR POLLUTION FROM HEATING

Many of the heating and cooling strategies developed have an explicit strategic design objective to address current problematics of air pollution as a result of PM emissions in the heating sector. In all cases the cause is inefficient combustion of solid fuels, either in older centralised plants for district heating, or in individual stoves at the building level. The impact of air pollution on health is well documented throughout the cases, and has a tendency to affect children and elderly disproportionally, meaning it also represents an equity issue. In some cases, there is also a gender dimension if women are more likely to spend time indoors. As such the strategic design objective of diminishing air pollution from heating is strongly related to wider sustainability objectives to improve well-being, health, and support the reduction of inequalities and explicitly put forward in many of the heating and cooling strategies.

In Chile, addressing PM emissions from heating is the main strategic design objective for the strategy developed in Study 2: Heat Roadmap Chile and also identified as the primary driver for engagement with district energy in Study 4: Motivations for DES. Chile sees almost 3500 deaths annually as a direct result of air pollution on a population of 19 million, and high pollution events can be double the level experienced in Beijing (Ministerio del Medio Ambiente, 2018; see also Paardekooper et al., 2020). This pollution is caused by inefficient combustion of wood for heating – because of inefficient stoves and boilers, but also because of high levels of humidity and quality concerns about the biomass being used. In addition, high pollution events lead to prohibitions of biomass combustion, resulting in discomfort and under heating. Combined, this context results in the main strategic design objective for a heating and cooling strategy for Chile being decontamination of the heating sector through the reduction and elimination of PM emissions.

Addressing PM emissions and air pollution is also identified as one of the main drivers for improving and redesigning the heating sector and engaging with district energy in Mongolia (Study 4: motivations for DES). Here, pollution is primarily caused by inefficient combustion of coal – both in individual stoves, but also in 1st and 2nd generation district heating installations. This echoes literature investigating air pollution from coal in district heating, for parts of Eastern Europe (eg Wojdyga et al., 2014), Sweden (eg Fahlén and Ahlgren, 2012), but mostly for China (eg. Li et al., 2019; Zhang et al., 2018). Similar to Chile, the impacts to health and wellbeing are considered in Mongolia, and the improvement thereof recognised as a major reason for engaging towards an improved heating sector.

The only place where air pollution reduction is not a significant strategic design objective is for large parts of Europe. This includes the Heat Roadmap Europe strategies (on which Study 3: Types in HRE) is built or the Smart Energy Europe and IDA's Energy Vision strategies (reviewed in Study 1: Storage in SES). In many cases, the relatively low emphasis on air pollution reduction in the heating and cooling strategies for Europe is because the strategies are not proposing displacement of technologies that emit high levels of PM. Individual burning of solid fuels is relatively rare in the countries considered in Heat Roadmap Europe, and as mentioned the discourse of air pollution from district heating in urban areas has been studies as part of the transition between generations. Additionally, many of the places that do suffer from air pollution and high PM emissions, particularly in urban areas, the main source comes from the transport sector so it does not feature strongly in terms of designing a heating and cooling strategy. As a result, there is not a particularly strong focus on reducing air pollution or PM emissions in the heating and cooling strategies made for Europe.

To an extent, this may be an oversight and better emphasis is needed. In Serbia also air pollution from heating is increasing when (mostly) gas fuelled district heating is substituted by alternative solutions in the form of (individual) coal and biomass combustion (Bean et al., 2018). In Study 3: Types in HRE, certain 'refurbishment heating countries' are identified which would benefit hugely from shifting from 1st and 2nd generation district heating technologies towards more modern and cleaner heating, but the direct link towards more broad health implications is not made, even though they are likely to be true. In this case, further development of heating and cooling strategies might support a more coherent strategic planning discourse if they included an explicit strategic design objective to consider air pollution and PM reduction.

3.6. REDUCTION IN HFCS

An example of a design objective present only in one country is the explicit inclusion of trying to reduce and phasing down hydrofluorocarbons (HFCs) in India, discussed in Study 4: Motivations for DES. HFCs are gasses which have a high global warming potential, and are commonly used as refrigerants – for example in cooling, refrigeration, and for heat pumps. With the Kigali Amendment to the Montreal Protocol coming into force in 2019, there has been an increased level of attention for how to reduce HFC and HCFC usage in the cooling sector. This transition and refrigerant management challenge is particularly visible in the case of India, where it serves as an explicit strategic design objective in terms of developing cooling strategies. Avoiding the use of HFC containing refrigerants is considered both in terms of in-kind substitutions (of cooling technologies and refrigerants), and energy efficiency measures to reduce demand and necessary capacities for cooling equipment.

Its singularity could partially be that the immediate attention regarding HFCs and HCFCs is related to cooling, which is far more prevalent in India than the other cases considered. In Europe, there has been active phase-out of HFCs (and other measures to address additional fluorinated gasses, which also have global warming potentials) since 2014, with some small effects on what types of heat pump technologies are foreseen (see also Hoffman and Pearson, 2011 and David et al., 2017). As a result, most of the technology data forecasts simply adopt alternative refrigerants as the standard, which may also explain why it is not a major objective for energy system analysis there.

However, it is easy to see how this strategic design objective could become relevant in other cases too. Firstly, the strategies developed in Heat Roadmap Europe see an exponential growth in cooling, even as energy efficiency measures are put in place (Paardekooper et al., 2018). Secondly, all the strategies developed foresee a large role for electrification through heat pumps, either at building level or on a large scale for district energy (Study 2: Heat Roadmap Chile and Study 3: Types in HRE). Increasing the market share of heat pumps to such an extent could likely necessitate more attention towards the impact of used refrigerants than is currently taken. Finally, the current standards for commitments mostly concern phase-downs (rather than complete eradications) and include some notable exemptions, and to actively combat climate change as we approach 2050 it may be necessary and indeed possible to make more stringent commitments. For these reasons, it may be that the strategic design objective to reduce and consider HFC use could become more relevant and be applied more generally.

3.7. SUMMARY

This Chapter 3 on strategic design objective investigates how general and how specific the reasons and socio-political contexts for the development of heating and cooling strategies are. The relevance and reasons for improving heating and cooling are far-reaching and deeply entrenched with broader planning objectives. These include geopolitical concerns, economic development, health and well-being, social equity, land-use and resource conflict, and environmental sustainability. Given the deliberately universal nature of the SDGs, high degree of adherence to the Paris Agreement, Montreal Protocol, and several other international frameworks and cooperatives that govern sustainable development, this is expected. It also emphasises the global nature of several of the issues that a transition towards sustainability and decarbonisation must address.

Through the cases it becomes clear that while it is possible to identify some general themes in the strategic design objectives, their translation to a local context differs widely. Objectives around access to affordable energy, decarbonisation, security of supply, and sustainable bioenergy management are present in all cases, but there is a large heterogeneity on what they mean in the context. Addressing air pollution are also present themes in several cases, but because the sources (and extent) of pollution differ, the specific challenges to the heating and cooling sector differ too. Addressing an HFC phase-down is an explicit objective for India, but could also be considered more broadly. As a result, what drives the needs and ambitions for a redesigned heating and cooling sector are different in the different contexts. Of the aspects considered, this is where the results are most specific, even though there are some more general themes. To incorporate this, a full recognition of the socio- and political context is required to develop a heating and cooling strategy that addresses the right needs.

CHAPTER 4. STRATEGIC DESIGN CRITERIA

The strategic design criteria for a heating and cooling strategy are the indicators to the design objectives. The quantification of the scenarios in the strategies is useful to be able to assess the extent to which the vision contributes to achieving the various strategic design objectives identified for the heating and cooling strategy. This also supports comparison to other visions and knowledge objects created in the strategic planning process, allowing a basis for comparison and discussion. In some cases, this means quantifying impacts (such as emissions), but this can also include quantifying energy capacity and quantity needs and potentials. In the energy system modelling for heating and cooling scenarios, strategic design criteria translate the broad strategic objectives into the specific (quantifiable) goals that the system should achieve.

The heating and cooling strategies benefit from the use of tangible scenarios to support concretisation and quantification of the vision presented, and strategic design criteria are used for quantification to both develop and present the vision. Doing this well enables the strategy to support strategic planning. Using good indicators for this increases the value of the heating and cooling strategy towards actively addressing the socio-economic context of the heating and cooling strategy and contributing constructively to the strategic planning process.

Where the strategic design objectives are often more abstract in terms of describing the broad goals and aspirational directionality, the strategic design objectives distil these to a more positivist, concrete (and preferably quantifiable) level. To an extent, this means reducing complex and broad concepts like affordable access to energy, decarbonisation, and security of supply to more narrow indicators. In order to prevent reductionism, the complementarity between the strategic design objectives and the strategic design indicators should be highlighted. It is also important that this is recognised in the discussion in transitioning from the heating and cooling scenarios to the heating and cooling designs, in order to re-contextualise the more narrow strategic design criteria towards their strategic design objective counterparts.

4.1. USING STRATEGIC DESIGN CRITERIA IN DESIGNING HEATING AND COOLING STRATEGIES

The design criteria are used in two main ways to support the design of the heating and cooling strategies. As outlined in Sections 2.3 and 2.4, technical scenario development and modelling for strategies in a largely exploratory process. Using clear indicators and criteria during this process allows for the systematic comparison of the performance of different scenarios throughout the modelling, particularly in simulation modelling (see also Lund et al., 2017). This not only supports the development of improved scenarios (since there is an ongoing process of assessment throughout the iterative scenario design and development process) but also generates a more in depth understanding of the mechanisms that drive changes in the system and design. A clear set of design criteria supports the modelling, design and development process of scenarios in support of strategies.

Additionally, the strategic design criteria are used in presenting the final vision and scenario that the heating and cooling strategy puts forward. The criteria can then represent the basis for comparison and entering strategic discourse. By quantifying the vision to give indications of magnitudes of transition, it becomes possible to actively compare with other scenarios, strategies, and knowledge artefacts that are part of the strategic planning area. In this way the quantified scenarios play a large role in putting forward the concrete alterative in the vision of the heating and cooling strategy.

Much of the scenario development is aligning and comparing different design criteria. The way in which the strategic design criteria are functionally used aligns strongly with the methodological choices towards iterative simulation modelling, also outlined in Lund et al., 2017 and Østergaard, 2009. The specificity and varying importance of different strategic design objectives, combined with complexity means that presenting an optimised solution can be overly reductionist to trade-offs that are being made. Because of this, developing scenarios and strategies is largely a process of comparing and developing according to many different criteria.

In the simulation modelling, each criteria is assessed differently. As the following sections will show, some criteria are used to constrain the scenarios by effectively including or excluding certain options; for example excluding fossil fuels to indicate 100% renewable energy system scenarios. Between most of the criteria, there is an interplay between trying to maximise or minimise, while balancing the others. Because some of the scenarios have 10 or more different criteria, optimisation strategies are not practicable or transparent, so the strategy benefits more from a clear explanation of the (positive and normative) underpinnings of the different criteria.

4.2. CO_2 EMISSIONS

Because atmospheric CO_2 is the largest source of greenhouse gas emissions, it is used as one of the key criteria for decarbonisation, combined with the level of fossil and renewable fuels in the energy system. The heating and cooling strategies in this PhD are all presented as being part of an energy system which is decarbonised to a certain extent.

The criteria upon which the decarbonisation of the heating and cooling strategy is assessed is then based on the CO_2 emissions of the entire energy system. Presenting the CO_2 criteria from an energy system perspective achieves several things. The first is conform the Smart Energy System concept and aligning with the approach that the heating and cooling system is an integral part of the energy system, and its decarbonisation cannot be seen outside of this integrated concept. The second is to recognise that accounting for where in the energy system carbon is emitted, is complex. This relates to the extent to which carbon emissions in the electricity sector should be accounted for in the heating and cooling sectors, if heating and cooling is electricity based, or the extent to which carbon emissions in industry and electricity production should be accounted for in the heating sector if waste heat is used. Recalling Section 2.2.3 on the role of waste heat and cold in district energy, it is important to note that there are other perspectives and other methods of carbon allocation (see eg. Jiménez Navarro, 2020). Taking a system wide perspective diminishes the relative importance of allocations for these sector distinctions, and recognises the inherently interconnected nature of heating and cooling in the broader energy system.

The same metrics are used in different ways to indicate different perspectives on decarbonisation and align to different strategic planning discourses. In the case of Study 2: Heat Roadmap Chile, this means presenting a scenario where the entire energy system emits 82 Mt of CO_2 emissions annually, compared to a reference scenario for 2050 based on PELP which emits 124 Mt of CO_2 annually (Paardekooper et al., 2020). Here, only CO_2 emissions from the energy system are considered, and the comparison is made to the alternative 2050 scenario. In the case of the Heat Roadmap Europe strategies (Study 3: Types in HRE) this represents an energy system which reduces total carbon emissions by 86% compared to 1990 levels (Paardekooper et al., 2018; Paardekooper et al., 2021). The emissions from the energy sector are nearly eliminated here; however, CO2 emissions from agriculture, land use, land-use change and forestry, and other (chemical and building) sectors are also included and the 1990 base year used, in order to align with the calculation methodology used for the Paris Agreement. These represent different perspectives, and allow for different comparisons to be made.

4.3. PRIMARY ENERGY SUPPLY

Understanding the Primary Energy Supply (PES) of the energy system allows for further development of several criteria, including decarbonisation, sustainable management of energy resources, and an assessment of other strategic design criteria. PES represents all energy that is used, before conversion, as input to supply the energy system. This includes (fossil and bioenergy-based) fuels and energy from renewables in the form of different electricity or thermal energy sources.

As a first order, PES can be used to make an overall indicative assessment of the fuel efficiency of a system. Efficiency can of course be a criterion in and of itself, but in the studies in this PhD it typically serves in function of almost all the strategic design objectives and criterion, rather than being a strategic design objective and criterion in and of itself. Reducing energy typically reduces the need for fuels, the need for imports, and the need for production and conversion capacity so the need for costs. As such, PES is a good way to measure how to do more with less, supporting more specific criteria.

4.3.1. PES TO INDICATE DECARBONISATION

In addition to CO_2 emissions, the level of fossil fuels and level of renewables in the energy system is a criterion for decarbonisation. The strategic design objectives for decarbonisation can be interpreted differently. As a result the strategic design criteria that represent that case of 'decarbonisation' can also differ. As discussed in Section 3.3, factors that can change the operationalising of decarbonisation criteria are net-zero carbon/carbon neutrality criteria; carbon capture storage, carbon offsetting, etc. Zero CO_2 emissions and 100% renewable energy systems may not mean the same things, so the heating and cooling strategies consider both PES and CO_2 emissions.

In Study 2: Heat Roadmap Chile, the redesign of the heating and cooling sector significantly reduces coal and oil usage, leading to the reduction in CO_2 emissions presented above. At the same time, there are remnants of coal and oil, as well as a considerable level of natural gas left in the PES of the final scenario (see also Table 1 from Study 2: Heat Roadmap for Chile Paardekooper et al., 2020). Coal is phased out of power production (following government policy; from a modelling perspective this represents the most major difference between Paardekooper et al., 2019 and Paardekooper et al., 2020). Further changes than were already present in the reference scenario for 2050 (based on PELP) to the energy carriers for industrial and transport demands were not made. Simultaneously, the natural gas is retained in the electricity sector to not exceed bioenergy potentials. As a result the heating and cooling strategy contributes to decarbonisation, but also balances other criteria and does not eliminate all fossil fuels from the energy system.

		Combo Ref 2050	**Heat Roadmap Chile 2050**
Fuels (including transport)	Coal	118	36.46
	Natural gas	223	219
	Oil	114	58
	Biomass	133	153.43
Fuels Total (TWh/year)		**588**	**467**
CO2 emissions (including transport)		**123.75**	**82.26**

Table 1: Main types of fuel consumption and resulting CO2 emissions for the energy system scenarios for transport, heating and electricity in Heat Roadmap Chile Used directly from: Study 2: Heat Roadmap for Chile (Paardekooper et al., 2020)

A similar dynamic is seen in the strategies developed in the context of Heat Roadmap Europe, where coal and oil were largely eliminated from PES, and gas largely reduced compared to both today and in a 'Conventionally Decarbonised' scenario[2] (see also Figure 4). In this case also, a significant amount of the fossil fuels in the energy system have already been phased out but further reductions in transport and industry were not actively pursued. However, the increased efficiency of the energy system (and higher proportion of wind, solar and other renewable power) allowed for further phasing out of natural gas – particularly in the heating and electricity sector. The resulting CO_2 emissions (here only from energy) are shown, but by combining them with an itemised understanding of what renewable and what fossil fuels are being used, the criteria for assessing decarbonisation and increased renewability become clearer.

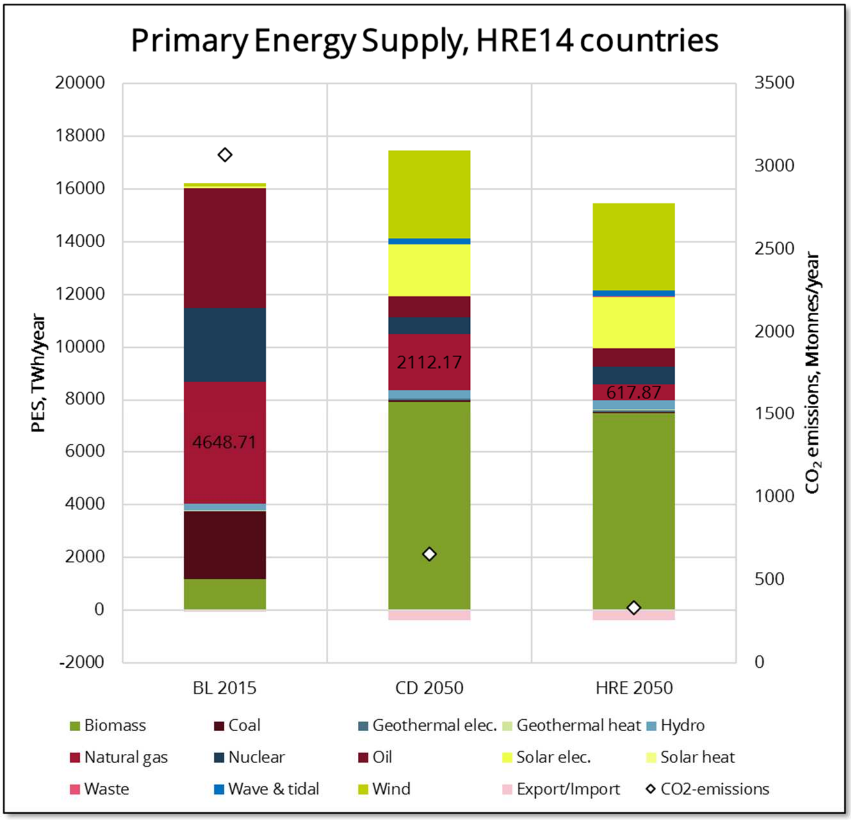

Figure 4: Primary energy supply currently, in the conventionally decarbonised scenario and the Heat Roadmap scenario. Note particularly the reduction in natural gas use. Adapted from: Paardekooper, S. et al., (2018).

[2]The BL 2015 scenario represents a baseline for 2015; the Conventionally Decarbonised (CD) 2050 scenario represents the development of the energy system under a framework that encourages renewables, but does not radically change the heating and cooling sector.

4.3.2. PES TO INDICATE SECURITY OF SUPPLY

A detailed understanding of PES, combined with background information on the way fuels are obtained, also allows for a deeper assessment of the security of supply when it comes to fossil and biofuels. This includes an understanding to what extent the system is dependent on fuels (clearly obtainable from Table 1and Figure 4), and where the fuels are being sourced. This second aspect of security of supply is more difficult to determine quantitatively, since the scenario development does not necessarily take into account (future) global fuel market flows and exchanges. Similarly, Study 4: Motivations for DES clearly demonstrates that while countries may be net importers or exporters of fuel, it is possible and indeed common to both produce a fuel for export and import it simultaneously. This means that PES for future energy systems can be indicators for future fuel (import) needs, but these must be contextualised with trade and resource extraction strategies.

Both Study 2: Heat Roadmap Chile and the countries in Study 3: Types in Heat Roadmap Europe allows for these kinds of criteria to be determined. The reductions in fossil fuel use in Chile are a strong indicator that Chile could both reduce coal imports and benefit from higher resilience to global price fluctuations and geopolitical issues. It also makes it possible to either reduce domestic coal extraction, or increase imports. This is dependent on the development of global fuel markets, and price developments. However, it also raises more strategic questions regarding not only energy security, but also resource management and economic development regarding the role of coal extraction and trade in the national economy. In this way, PES provides an indicator to energy security and resource management strategies, but also reflects much broader and more complex design objectives.

Similarly, one of the secondary criteria put forward in the scenario development behind Study 3: Types in HRE was the reduction of gas use, beyond the point of contemporaneous gas imports. The elimination of gas in heating, and significant reduction of natural gas use overall was used to indicate fulfilment of the strategic design objective to increase security of supply in terms of price fluctuations, but also in terms of geopolitical concerns. As outlined in Section 3.4, the salience of this strategic design objective had at that point in time reduced but presenting PES as a criterion of strategic design can be used to operationalise the strategic objective.

4.3.3. PES TO INDICATE SUSTAINABILITY LIMITS TO BIOENERGY

A fuel that requires particular indicators in future energy systems, and thus the design of heating and cooling strategies, are bioenergy resources. To fulfil sustainability criteria, and as an indicator of the strategic design objective of ensuring sustainable use of bioenergy discussed in Section 3.5, typically there is simply a limit to biomass usage in the heating and cooling strategies. This is also assessed based on the PES of the overall system, which means there is no strict allowance for the development of natural resource management strategies and global (fuel) markets, but allows for an insight on how to best avoid an over-reliance on bioenergy in the design of heating and cooling strategies.

In Smart Energy Europe and IDA's Energy Vision (discussed in Study 1: Storage in SES) and Study 3: Types in Heat Roadmap Europe, the limits to biomass are most salient, since the decarbonisation of the overall system results in more pressure being put on the use of solid, liquid, and gaseous fuels. In Study 2: Heat Roadmap Chile, there both a quantitative and a qualitative discussion regarding the use of bioenergy and sustainability, since Chile is relatively rich in bioenergy sources, but current bioenergy markets can be informal, and bioenergy resources used inefficiently. Here the fuel distribution also served to inform discussion on how bioenergy resources should be used, rather than simply a quantity given.

The results in the Heat Roadmap Europe studies, particularly Paardekooper et al, 2018, highlight that criteria for sustainable biomass usage are likely to be a moving target as strategies and scenarios are further developed towards changing strategic design objectives. As mentioned, there were developments in LULUCF even at the time; this has only increased in the intervening period, and will likely continue to do so. This highlights the need to both set constraints for biomass, but also work to minimise where possible, in order to support and align with a trend of increasing understanding of the ecosystem impacts of bioenergy usage.

4.4. ENERGY SYSTEM COSTS

In terms of affordability and competitiveness, the heating and cooling strategies largely use annualised socio-economic energy system costs as the criteria. These are reported as euros or US Dollars, but can of course be done in whatever appropriate currency. Costs are considered from an energy system wide perspective and annualised to represent equivalent annual costs. As in the case of allocating fuels or emissions, this recognises the interconnected nature of heating and cooling in the wider energy system, and ensures that any synergies created between the sectors are recognised. Annualised costs are a mechanism that both allows for the consideration of costs for technologies with different expected lifetimes and discounting to reflect the time-value of money during that period.

Using annualised socio-economic energy system cost (sometimes also referred to as equivalent annual costs) as a metric and criteria for assessing the performance of the energy system inherently assumes that there will be eventual strong redistributive and risk sharing effects. Normatively, using socio-economic costs has some normative implications towards the standing of the heating and cooling strategy, in terms of whose perspective is being assessed, and in terms of scope. The role of the heating and cooling strategies is not to mimic a current pathway, but to design an improved energy system in order to show the impacts, feasibility and necessity of a socially more desirable system. The use of a social cost perspective in the heating and cooling strategies reflects this aim and allows for modelling that can inform strategic discourse on what is best for society overall.

As a first point, the use of a socio-economic perspective is exclusive of subsidies and taxes. These are redistributive measures that represent ways in which governments either attempt to internalise the cost or value of externalities (for example, by taxing fossil fuels or subsidising flexibility measures), supporting employment, or to generate revenue. While they are real and experienced costs to consumers, they do not represent 'costs' of the energy system so are not included. Rather, following Hvelplund and Djørup, 2017, taxes and subsidies should be considered methods to work towards incentivising and achieving visions that have been strategically agreed and established. This aligns with the idea of strategies putting forward visions that are able to radically depart from todays' socio-economic and political contexts, as well as the recognition that strategic planning should, principally, include everyone and be in society's broadest best interest.

This means that the link between the strategic design objective of affordable access to energy and strategic design criteria – typically to design the cheapest system possible – rests on some strong assumptions of redistributive action. As a result, using energy system costs as a criterion allows for the design of a heating and cooling strategy that can make energy cheaper and more affordable for consumers, but this is reliant on the institutional framework that supports the energy system transition. The design of heating and cooling scenarios and strategies assumes that a cheaper energy system overall means that the consumer will benefit from gains made in all parts of the energy system (including consumers and building owner/occupiers but also sectors concerned with fuel extraction , handling, and trading; utilities and energy companies; transmission and distribution; technology developers). Additionally, a high level of risk-sharing and access to capital is assumed, given the ambition of the strategy to set out a direction for support and implementation. While a cheaper energy system can lead to lower consumer prices, this is reliant on a supportive framework and redistributive action where necessary to ensure that there is access to affordable energy.

As a design criterion, this means that it may be desirable to further segment what the changes are in annualised costs. In the heating and cooling strategies considered in this PhD, particular attention is paid to the level of investments in technologies (and installation of technologies) and levels of expenditure on fuels. Typically, shifting expenditure away from fuels and towards investments opens for further analysis on employment types: for example, Study 2: Heat Roadmap Chile identified several sectors where high-skilled labour demands could present opportunities for domestic and local employment looking towards 2050 and biomass management. In the shorter term, a social impact assessment in Mongolia discussed the different changing opportunities in the energy sector (Erdenebat, 2019). This breakdown can be especially useful where the strategic design objectives concerning domestic resource management and quality of work are also present.

Distinguishing between types of costs as a design criteria in terms fixed costs (in terms of long-term investments and infrastructures) and variable costs (in terms of fuels, and to a lesser extent operation and maintenance) opens opportunities to consider security of supply factors. Non-fuel renewables are far more resistant to price shocks and commodity market fluctuations, simple because once standing they do not rely on them. On a much smaller scale, increased insulation and less variable costs increase predictability and reduce the monetary impact of extreme weather events on individuals and households. This is because a higher proportion of the consumers' costs are going towards long term investments and actions that reduce the impact of price fluctuations. This also makes differentiating between fuel and non-fuel costs a relevant criterion for security of supply and reliable access to energy objectives.

In terms of developing strategies and identifying main areas for transition, the quantification of the required annual investment of different sectors plays a key role in terms of operationalising the strategies. This was done both in Study 2: Heat Roadmap for Chile and in the Heat Roadmap Europe project supporting Study 3: Types in Heat Roadmap Europe (see also Figure 5 and Figure 6, presenting these results directly from Paardekooper et al., 2019 and Paardekooper et al., 2018). Here, annual energy systems costs and their changes – either compared to today or compared to a different expected future – show the areas where changes are the most radical and allow for identification of key areas for investment.

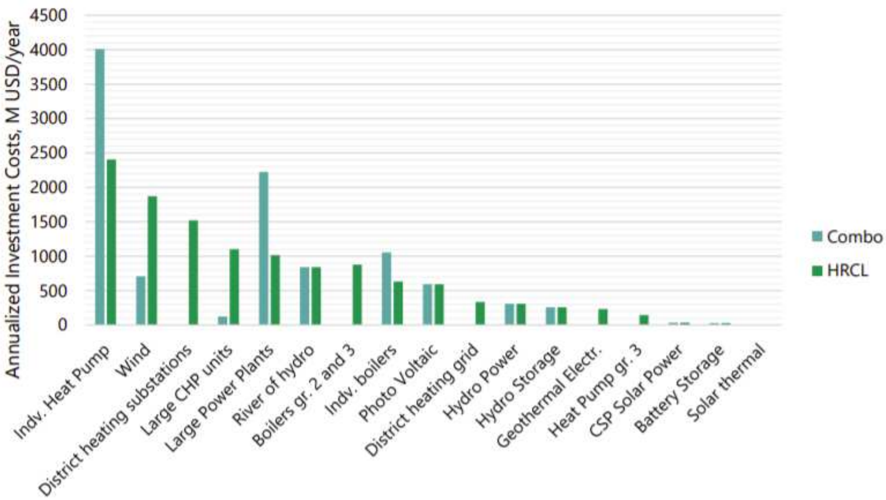

Figure 5: Changes in investment costs for selected technologies for the 'conventional' 2050 scenario and redesigned Heat Roadmap Chile scenario, including decreasing significance (such as large power plants), obvious growth sectors under a heating-sector redesign (such as

district heating components), but also indirect growth sectors (such as wind power technologies). Used directly from Paardekooper et al.(2019).

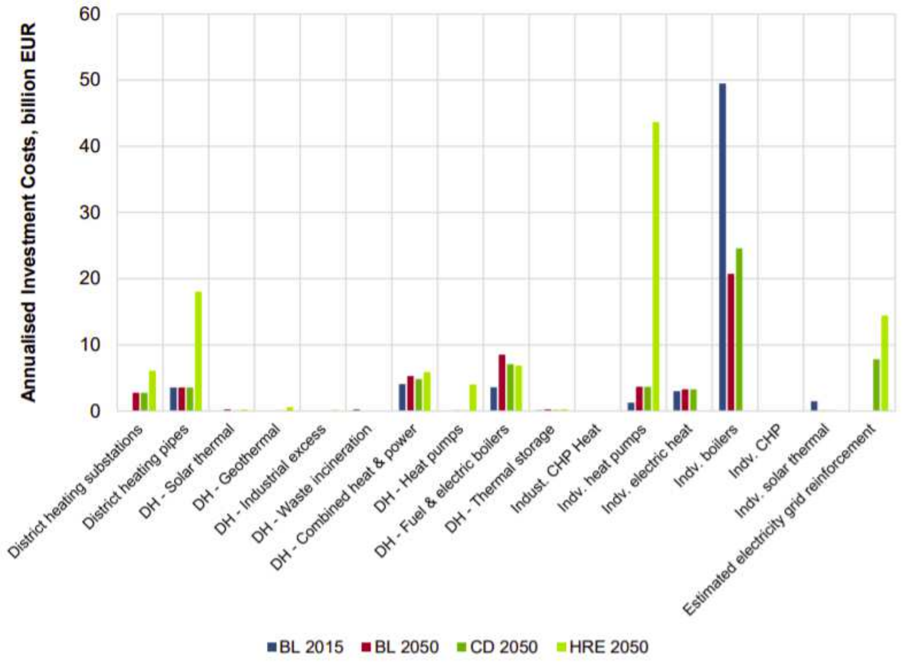

Figure 6: Changes in investment costs for selected technologies for the 2015 and 2050 Baseline scenarios, 'conventional decarbonisation' 2050 scenario and redesigned Heat Roadmap Europe scenario, including the complete phase-out of individual boilers, growth of individual boilers, and emphasis on the relative scales of investments needed for collective infrastructures and individual installations. Used directly from Paardekooper et al.(2018)

Improving on this, further analysis is possible, potentially using value chain analysis (see for example Hvelplund and Djørup, 2017; Leire, Korberg, 2021). This allows for a better differentiation between different stakeholders and groups' individual losses and gains, and understanding of the magnitude of the transitions that are necessary. Based on that, it also becomes possible to see what types of interventions can be made, in support of a broader implementation plan and other strategic planning processes, to develop the subsequent steps from strategy development.

4.5. PARTICULATE MATTER AND AIR POLLUTION

Study 2: Heat Roadmap Chile developed a methodology to use the outputs of the energy system scenario modelling in EnergyPLAN to calculate levels of PM2.5 and PM10. This meant that is was possible to use a concrete measure to indicate broader strategic design objectives, particularly relating to air pollution and health. Particulate Matter was calculated from fuel balances and technologies, excluding the transport sector. This approach was taken because of the scope of the project was to develop a heating and cooling strategy, so this is where the analytic efforts were based, rather than methodological considerations.

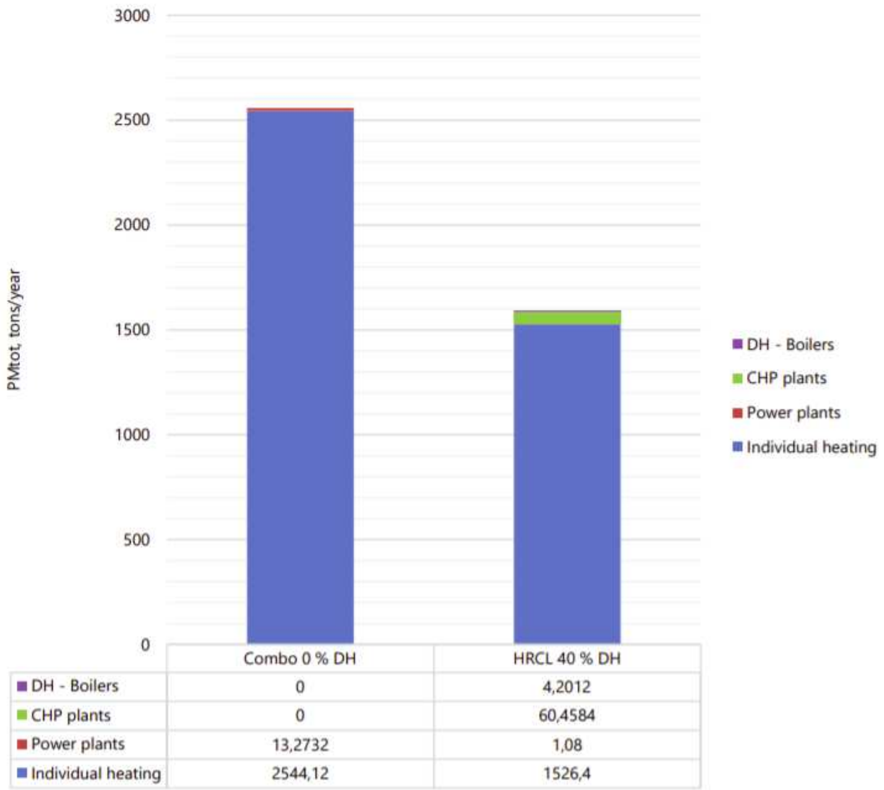

Figure 7: Total PM emissions from heating and electricity by source in the 'conventional' and Heat Roadmap Chile scenario. Used directly from Paardekooper et al. (2019).

Figure 7 shows the results of this analysis. In particular, the role of the heating sector in terms of PM emissions is highlighted in both the conventional scenario (which uses primarily high-efficiency and clean individual biomass boilers in buildings) and Heat Roadmap Chile scenario, in which heating in rural and less densely populated areas continues to take place with those same high-efficiency biomass boilers. The machinism is that through centralisation, better flue gas and ash cleaning processes and dust filters are available and cost-effective, so the centralised combustion of biomass becomes a hugely effective way of eliminating PM emissions from heating and electricity.

While it remains difficult to then take PM emissions on to quantify local health impacts, overall emissions can be calculated and give a strong indication as to the changes in air pollution. If desired, the hourly modelling that supports the scenario can further be used to identify peak pollution emission events – although it should be noted that weather plays a large role in generating peak pollution events themselves. Finally, PM and other emissions resulting from coal combustion can also play a significant role in heating and cooling strategies, since they also affect many of the same strategic design objectives as those affected by PM emissions from biomass combustion. For example, this issue is also flagged in Serbia, Mongolia, China, and several countries in Eastern Europe throughout Study 4: Motivations for DES and Study 3: Types in Heat Roadmap Europe. Here, of course, the same criterion can be relevant to concretely address the effectiveness of a heating and cooling strategy to address the prevention of air pollution.

4.6. LOCALLY RELEVANT, SPECIFIC DESIGN CRITERIA

There is of course scope to develop other relevant criteria, based on what relevant (local or broader) design objectives are present. In order to support the strategic development of scenarios, the value of this is likely determined directly by the understanding and appreciation of the relevance and importance of the different strategic objectives, and their role in the discourse for vision making.

As outlined in section 3.6, following the Kigali Amendment to the Montreal Protocol, it could be highly relevant to include a reduction or phase-out of HFCs and HCFCs into a quantified scenario. Also using India as an example, Study 4: Motivations for DES identifies the desire in India to avoid peak power capacity as an element for strategic objectives for cooling strategies, since they represent expensive, seasonal peak loads. Similarly, including or excluding certain technologies could better support strategies; this could for example be the case regarding WtE, or the inclusion/exclusion of nuclear power. Where relevant, the SDG indicators could also be used to develop specific and locally relevant criteria. Often, these types of data are easily retrievable or constructible within a quantified scenario, but for them to be impactful, it should be clear how they are contributing to the future vision and strategy development, so they can support the shaping of the strategy towards fulfilling the strategic design objectives.

4.7. SUMMARY

This Chapter 4 on strategic design objectives investigates how general and how specifically the strategic design criteria can be used to shape heating and cooling strategies are. By providing concrete indicators for the strategic design objectives, design criteria can both support performative assessment of different scenarios and strategies and provide more concrete and detailed visions to contribute to the strategic process. While many criteria are recurring, it is often useful to discuss the criteria with particularly relevance to how it represents the strategic objective, and how it related to the other criteria. This means that while the indicators seem quite common, there is a highly relevant scope for specific discussion, if they can be contextualised in the frame of the strategic objectives.

This is demonstrated through the cases, by looking at the function and influence of CO2 emissions as an indicator of decarbonisation; primary energy supply to further discuss decarbonisation objectives, security of supply objectives, and wider sustainability issues; and energy system costs as an avenue to address and develop scenarios in response to objectives related to affordability and competitiveness. Particulate matter and HCFC emissions are further highlighted as specific criteria, which can be used to develop heating and cooling strategies that address the specific strategic objectives required for the strategy to be a meaningful support to policy development.

The treatment of the design criteria in the heating and cooling strategies is then strongly linked to the development of relevant, socio- and politically contextualised strategic objectives, in order to fulfil their role as convincing indicators. There are several commonly used criteria, since they function as a point of simplification and comparison (and indeed many occur in all or almost all of the strategies). However, by linking the design criteria to the strategic objectives, the same criterion may carry a different weight or indicate something different altogether. As a result, more general use of strategic design criteria can still address and represent relatively specific aspects of heating and cooling strategies.

CHAPTER 5. CONCLUSIONS

In energy transition, strategies for heating and cooling are neglected compared to electricity and other sectors. Yet, such strategies are much needed to present concrete visions and alternatives for a more sustainable and renewable future of heating and cooling. Without them, we risk failing to capitalize on the many opportunities for increased sustainability that heating and cooling presents, on both a local and a global scale.

This PhD thesis investigates which general elements are part of the design of heating and cooling strategies, and which are necessarily specific to the local situation. It is based on the premise that heating and cooling strategies need to be specific and tailored to the local context and geography, but that there are enough similarities and general features of effective heating and cooling strategies that it is possible to identify some specific and some general features.

To do this, this PhD sets out to answer how heating and cooling strategies can be designed for various countries within the concept of Smart Energy Systems. It identifies general learning and specific aspects of developing heating and cooling strategies, and how they can be used to support strategic planning.

Study 1: Storage in Smart Energy Systems investigates the role of different types of storages in 100% renewable Smart Energy Systems, and concludes in more depth how storages function. Based on this, it becomes possible to contextualise the heating sectors, and have a better framing of how they function within 100% renewable energy system strategies.

Study 2: Heat Roadmap Chile develops a heating strategy for Chile. It shows it is possible to present the first national-level assessment for district heating in Chile, and supports long term decarbonisation and decontamination of the Chilean energy system. Methodologically, it is novel in that it applies energy mapping and energy system simulation and analysis outside of Europe, and advances the development of heating strategies by including an assessment of particulate matter (PM) as an indicator of air pollution. In this thesis, it serves as an example of fully developing a heating and cooling strategy in response to the particular strategic objectives of a country.

Study 3: Types in Heat Roadmap Europe synthesises the work of the Heat Roadmap Europe project, during which we developed heating and cooling strategies for 14 European countries. This paper proposes a typology to categorise these 14 countries in a way that operationalises the energy efficiency first principle to consider demand and supply-side efficiency in the heating and cooling sector, and a particular regard for the potential of district energy. The paper concludes 4 different types of heating strategies, with 4 corresponding sets of policy recommendations. In doing so it facilitates a level of analysis that lies between a fragmented country approach and a generic European approach, and supports transferability and the development of (local) policy based on characteristics of the heating sectors.

Study 4: Motivations for district energy engagement is a working paper critically discussing the perspective that district energy addresses decarbonisation and global sustainability issues, but district energy is typically a local infrastructure with local effects. To understand better how local and global objectives become aligned, we explore why countries are interested in engaging with district energy using a semi-structured narrative review, and an analytical framework based on energy cultures, planning objectives, approaches, design solutions and triggers. The analysis covers Chile, India, Serbia and Mongolia. These represent 4 countries which chose to actively engage with the UN Environment District Energy in Cities Initiative, ensuring that there is an a priori interest in developing district energy, and resulting in availability of sources describing the motivations in depth. The preliminary conclusions of this work are further echoed in Chapter 3 and 4 of this thesis.

These studies are complemented by published and unpublished research further exploring some research questions surrounding the direct research question. This includes expanding heating strategies to a decarbonised energy system (Chang et al, 2023); hydrogen in heating (Korberg et al, 2023); planning of large-scale heating infrastructures (Bertelsen, Mathiesen and Paardekooper, 2021); green buildings and building stock changes (Maya-Drysdale, Mathiesen and Paardekooper, 2019), and others.

Strategies for heating and cooling present concrete visions and alternatives for the future of heating and cooling. They identify key areas for intervention and support dialogue and decision making on the direction of transitions. The way that heating and cooling strategies are designed in this PhD is rooted in the Smart Energy System concept, and scenario design using energy system analysis. As a result there is a particular focus on the development of district energy as an enabling infrastructure that supports decarbonisation and sustainability in heating and cooling. The comparative approach then discusses heating and cooling strategies in terms of identifying strategic design objectives, determining design criteria, and using functional design approaches and functional design principles.

By designing heating and cooling strategies for various countries, it is possible to identify general and specific aspects of heating and cooling strategies. The analysis is based on the review of two 100% renewable energy strategies, the development of 14 Heat Roadmap strategies for Europe, a Heat Roadmap for Chile, and collaboration projects with the UN Environment District Energy in Cities initiative to explore heating and cooling infrastructures in developing and emerging economies.

Specific reasons exist at local level that drive the need for heating and cooling strategies. These can be very particular, such as the desire to prevent air pollution from heating stoves in Chile, or phasing out natural gas use in the Netherlands. Even more universal challenges like decarbonisation, sustainable resource management and poverty reduction also play out differently at the local level. This is why strategic design objectives and criteria for heating and cooling strategies must capture the specific socio-political context to reflect and respond to local differences.

Generally, there are some good, functional approaches and principles towards addressing heating and cooling in varied contexts. Integration of the energy system, thermal grids in cities, and a focus on energy efficiency emerge as good solutions to address many problems. Smart use of storage, excess and renewable heat, and exploring cogeneration and large-scale heat pumps also have value in almost all cases. While the principle technical solutions and mechanisms for improving the heating and cooling sector are common – and have been successfully implemented in some countries – they must be implemented in a way that ensures that the heating and cooling strategy addresses the varied and specific local problems.

The combined results of the studies and thesis show that effective heating and cooling strategies can generate alternative visions for a sustainable future and contribute towards energy security and the achievement of the 2030 Sustainable Development Goals and 2050 Paris Agreement ambitions. By looking at how heating and cooling strategies can be developed for different countries, this research identifies general and specific aspects of heating and cooling strategies. This highlights diversity in problems and challenges that the heating and cooling sector faces at local level, but also supports planners and practitioners in being able to apply general approaches and principles to find solutions to their specific problems.

CHAPTER 6. FUTURE WORK

This PhD presents some clear answers to the questions of general and specifics of heating and cooling strategies, but also outlines the need for more and better understanding of heating and cooling in transition towards sustainability. As identified in Chapter 1, energy system science is heavily focussed on Europe, and heating and cooling are still heavily under researched. This is even more so the case for district energy. This section uses the conclusions presented above and work undertaken in the PhD to broaden back out, and present some related areas for further research. Different research designs and directions that could be used to expand on the work that is presented here, organised by opportunities to integrate more knowledge on cooling, from the how the strategies can contribute to strategic planning, and the perspective of improving energy and heating and cooling scenario modelling.

It should be noted that all these perspectives would benefit from more scientific analysis being done and particularly applied to more countries. In the preparation phase of Study 4: Motivations for DES (Paardekooper Chen, and Savickas, 2021), literature reviews were done to identify resources on heating and cooling for several countries eventually not discussed in the paper. In trying to identify more countries, we were surprised how little material was available. Even for some of the countries included, scientific articles are far more scarce than expected. Similarly, the discussion in Chapter 2 highlights the scarcity of complete Smart Energy System studies outside of Europe. Studies on both more and more diverse countries can both contribute to the development of heating and cooling in more countries, particularly within the context of scientific research processes. However, the development of knowledge on heating and cooling in specific contexts also furthers the general understanding of how heating and cooling can be redesigned, and can strengthen or refine the common body of knowledge on heating and cooling to support its development elsewhere.

6.1. BETTER UNDERSTANDING OF COOLING

The first area to expand the research presented here would be to take a more refined approach to cooling. Unfortunately, as in other research, the focus is still strongly on heating when heating and cooling strategies are discussed. In many cases, and particularly the Heat Roadmaps developed for Europe, this is partially justified since the heating sector is larger in terms of energy, fuel demands, and cost; has more impact in terms of emissions; and could benefit more from strategic redesign. However, there are many countries where that is not the case, and where heating and cooling strategies both deserve more analytical attention. Based on the research done in this PhD, there are several concrete proposals on how cooling could be better included.

- The first is to develop more explicit methodologies and approaches for ‘Cooling Roadmaps’ that include energy system analysis and district cooling. Cooling was included in the Heat Roadmap Europe projects, and different supply options for district and individual cooling were considered with a methodology mirroring the heat sector, but this was not given as much analytical effort as cooling. India, Colombia, or relevant European countries would be interesting case studies for this, and allow for a more in-depth exploration of the necessary methodological alternations necessary, relevant indicators, and final impacts of national cooling scenario and strategy development.
- As discussed in Chapter 2,, there is not a wealth of literature on the interaction between heating and cooling demands; particularly when also taking into account the energy performance of buildings. Indicative results also show that the combination between these factors could focus future research efforts better. In the Heat Roadmap Europe strategies, an extensive assessment of different types of energy savings measures (to reduce cooling demands) was considered, but very few were found viable since cooling is typically produced quite efficiently already (compared to heating) (see also discussion in Paardekooper et al., 2018). However, this did not explicitly include the impacts of warming climate, urban heat islands, or changes in cooling demands due to building improvements in response to heating demands. Additionally, this analysis focussed strongly on the European building stock where renovation is far more central than new developments. With these factors in mind, the interaction between these three and their aggregated effect on the national energy system is an area that could benefit from further exploration, to assess what the impacts are.
- Where cooling was explicitly included in heating and cooling strategy simulation in this PhD, only a limited amount of options were investigated in terms of the configuration of district cooling systems. This contrasts quite strongly to many of the proposed district cooling systems and proposed designs which exist, or even which were reviewed in Study 4: Motivations for DES (Paardekooper, Chen, and Savickas 2021). A better approach towards how the various options available for system design, including trigeneration, ‘free’ cooling using lake- or seawater, cooling from waste heat, etc. could be integrated into broader, national heating and cooling strategies would allow for a much more detailed discussion on the role of cooling.

6.2. STRATEGIES FOR STRATEGIC PLANNING

This PhD takes the perspective that heating and cooling strategies are designed to contribute to a strategic planning space, where (many) different visions for the future are discussed; considered, and eventually create a consensus on what is needed. This is underlined by the discussion on the need for inclusive and diverse visions in Chapter 2. Taking that point of departure, there should be an ongoing desire to ensure that strategy-making can best support the processes taking place around the strategic (energy) planning. The strategies that this PhD build on clearly share this aim (as Study 3: Types in Heat Roadmap Europe and Study 4: Motivations for DES (Paardekooper et al., 2020 and Paardekooper, 2021) explicitly discuss), but it is possible to identify several ways in which vision-making for strategies could be improved.

- More, better attention to what the context is for strategic energy planning, and strategic heating and cooling planning in general would improve heating and cooling strategies. This includes taking into account and making explicit more of the different dimensions of sustainability. As discussed, the focus for heating and cooling is still very much on decarbonisation and affordability. The research has shown specific examples of how broader impacts from improved heating and cooling can occur, and strategies should make an explicit effort to address these in their visions and quantifications. The potential for strategies to more systemically explore and better show the impacts of redesigned heating and cooling on employment changes, resource management, gender, and other environmental impacts has been discussed already. Further examples could be the effects of increased indoor well-being, higher productivity and other mentioned in the table developed in Chapter 1, relating heating and cooling to all 17 SDGs. This would contribute better to strategic discourse on energy system change and analysis, and align better with (long and short term) planning objectives.
- An additional area where future and ongoing research could contribute to strategic planning, is by supporting active, ongoing use of the strategies to continue contributing to dialogue in the strategic energy planning discourse. For example, the long-term process for energy planning in Chile which Study 2: Heat Roadmap Chile (Paardekooper et al., 2020) was aligned with is progressing towards the next iteration, with heightened focus on geothermal energy, waste heat, and thermal storage. In addition there are proposals for interconnectors and production of hydrogen and electrofuels. This means that a further exploration on how heating and cooling could support the ongoing development could be warranted. Similarly, scenarios and strategies explicitly addressing the more recent discourse of hydrogen for heating and a hydrogen economy in European countries could be warranted. Previous work and literature reviews show little prospect for the advantages of hydrogen-based heating, but this could and should be explicitly addressed in heating and cooling strategies so the discourse can evolve beyond it (see also Korberg et al, 2022 and review in Study 4: Motivations for DES, Paardekooper et al., 2021). These are

examples of ways in which strategy development could and should continue to evolve and respond to ensure relevance and active contributions to strategic energy planning processes.

- Finally, a natural progression from the research presented here on heating and cooling strategy development is to look towards the development of more concrete heating and cooling plans. This research uses a fairly constrictive definition of what a 'heating and cooling strategy' is, as discussed in Chapter 1. The perspective is used that strategies and vision put forward redesigned and imagined futures, and identify the main priority areas of change in order to achieve them. In this view, that is distinct from a plan, which outlines intermediary steps and puts forward concrete actions to achieve this. For this, theoretical and methodological perspectives on transition are necessary to both understand how to achieve change, and inter-temporal analysis to consider when change is necessary; these elements are both not covered in the heating and cooling strategies presented here, which focusses on what kinds of change could improve heating and cooling. This should also consider existing literature on how strategies and plans are used (eg. using Bertelsen et al., 2021a). This shift, taking energy strategies towards more concrete energy plans, would present a very logical next step building on the research presented in this thesis.

6.3. SCENARIO DEVELOPMENT AND ENERGY SYSTEM MODELLING

Much of the development of heating and cooling strategies is guided by scenario development, which can help quantify, assess, and develop the image of the future that the strategy builds on. There are endless choices between different models types, different models, different data, and different approaches towards model development and inclusion. Given the methods and models used in this thesis and the collection of papers that accompanies it, there are several observations in terms of obvious modelling improvements in future work leading on from this PhD.

- Firstly, following on the theme of recognising the broader sustainability implications of heating and cooling strategies, there are several concrete ways in which these could be further included in terms of design criteria for energy system modelling. Previously mentioned are developing methods to integrate data and be able to calculate the ozone-depleting substances that are subject to the Kigali Amendment of the Montreal protocol, and better model and quantify the impacts of increased heat pumps and cooling. On a national level, such analysis would appear to be novel (Singh Gaur, Fitiwi, Curtis, 2021). Similarly, more explicitly integrated assessment on how employment and value chains would change (for example, inspired by Hvelplund and Djørup, 2019) could benefit both the exploratory nature of scenario modelling and the interpretation of results. Including such indicators and criteria in recognition of the broader sustainability impacts would allow for more detailed quantification, and both support better analysis and better scenario design.

- A second avenue for further research would be to link the (typically aggregated) results of the energy system scenarios back to a more disaggregated, and often local, level. The identification of heat synergy regions in the Heat Roadmap Europe projects is a first step in this, and (inspired by Persson, Müller and Werner, 2014) could be an important link on bringing national energy modelling back to local levels. Similarly, further analysis towards how recommended energy savings can be redistributed over different building types and ages, and kinds of heat sources is another. This would contribute to both the scenario and strategy development by being able to put forward more precise visions of what changes are required where, and support the initial stages of planning.
- Finally, much of the research presented in this PhD can form a point of departure for further analysis on how specific elements within the strategy and scenario design work. Chapter 6 outlines some of the key functional principles for heating and cooling strategies, but there is much scope to further develop these. For example, Study 1: Storage in SES (Paardekooper, Lund and Lund, 2019) touches on the role that more or less pumped hydroelectric storage could have on thermal storage, but does not explore this in depth. The role of bioenergy availability per country (and potential for renewable heating) is briefly mentioned in Study 3: Types in Heat Roadmap Europe (Paardekooper et al., 2021), but could be explored in much more depth, and with relevance to other energy sectors (informed by Korberg, 2021). Using the scenarios created, it becomes possible to investigate such mechanisms and inferences for different principles, while still retaining the context of (national) integrated energy system analysis. Further research here could help better refine energy system scenario principles, and help inform the discourse on how we talk about certain technologies and infrastructures.

CHAPTER 7. LITERATURE

Output style APA 6. edition)

Albrechts, L. and Balducci, A (2013) Practicing Strategic Planning: In Search of Critical Features to Explain the Strategic Character of Plans, disP - The Planning Review, 49:3, 16-27, DOI: 10.1080/02513625.2013.859001

Askeland, K., Johnsen Rygg, B., & Sperling, K. (2020). The role of 4th generation district heating (4GDH) in a highly electrified hydropower dominated energy system: The case of Norway. International Journal of Sustainable Energy Planning and Management, 27(Special Issue), 17-34. https://doi.org/10.5278/ijsepm.3683

Bean, F., Volt, J., de Groote, M., Paardekooper, S., Riahi, L. (2018). Aligning District Energy and Building Energy Efficiency – A View on Strategic Integrations. Buildings Performance Institute of Europe.

Bertelsen, N., Caussarieu, M., Petersen, U.R., Karnøe, P. (2021a). Energy plans in practice: The making of thermal energy storage in urban Denmark. Energy Research & Social Science 79, 102178. https://doi.org/10.1016/j.erss.2021.102178

Bertelsen, N., Mathiesen, B.V. (2020). EU-28 Residential Heat Supply and Consumption: Historical Development and Status. Energies 13:1894. doi:10.3390/en13081894.

Bertelsen, N., Mathiesen, B. V., Djørup, S. R., Schneider, N. C. A., Paardekooper, S., Sánchez García, L., et al. (2021b). Integrating low-temperature renewables in district energy systems: Guidelines for policy makers. International Renewable Energy Agency.

Bertelsen, N., Mathiesen, B.V., Paardekooper, S. (2021). Implementing large-scale heating infrastructures: Experiences from successful planning of district heating and natural gas grids in Denmark, the United Kingdom, and the Netherlands. Energy Efficiency, 14(7), [64]. https://doi.org/10.1007/s12053-021-09975-8

Braun, F.G. (2010). Determinants of households' space heating type: A discrete choice analysis for German households. Energy Policy. 38:10, 5493-5503. https://doi.org/10.1016/j.enpol.2010.04.002

Bryson, J.M., Edwards L.H., Van Slyke, D.M. (2018) Getting strategic about strategic planning research. Public Management Review, 20:3, 317-339. https://doi.org/10.1080/14719037.2017.1285111

Cabrera, P., Carta, J.A., Lund, H., Thellufsen, J.Z. (2021). Large-scale optimal integration of wind and solar photovoltaic power in water-energy systems on islands. Energy Conversion and Management 235, 113982. https://doi.org/10.1016/j.enconman.2021.113982.

Chang, M., Thellufsen, J. Z., Zakeri, B., Pickering, B., Pfenninger, S., Lund, H., & Østergaard, P. A. (2021). Trends in tools and approaches for modelling the energy transition. Applied Energy, 290, 116731. https://doi.org/10.1016/j.apenergy.2021.116731

Chaturvedi, V., Eom, J., Clarke, L.E., Shukla, P.R. (2014). Long term building energy demand for India: Disaggregating end use energy services in an integrated assessment modelingFida framework,Energy Policy 64, 226-242. https://doi.org/10.1016/j.enpol.2012.11.021.

Chen, Z., Hickman, B., Riahi, L., and Zhang, Y. (2020). Regulations and Incentive Policy Framework for District Energy System Development: an Analysis in India. In Energy Efficiency in Developing Countries - Policies and Programmes. Eds. Tavares da Silva, S., and Prata Dias, G., 1st Edition. London, https://doi.org/10.4324/9780429344541.

Connolly D, Hansen K, Drysdale D, Lund H, Mathiesen BV, Werner S, et al. (2015). Enhanced Heating and Cooling Plans to Quantify the Impact of Increased Energy Efficiency in EU Member States - Main Report.

Connolly D., Lund H., Mathiesen B.V. (2016). Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union. Renew Sustain Energy Rev 60:1634–53. https://doi.org/10.1016/j.rser.2016.02.025

Connolly D., Lund H., Mathiesen B.V., Leahy M. (2010). A review of computer tools for analysing the integration of renewable energy into various energy systems. Applied Energy 87(4),1059-1082.

Connolly, D., Lund, H., Mathiesen, B.V., Werner, S., Möller, B., Persson, U., et al. (2014). Heat Roadmap Europe: Combining district heating with heat savings to decarbonise the EU energy system. Energy Policy 2014;65:475–489. https://doi.org/10.1016/j.enpol.2013.10.035

Connolly, D., Lund, H., Mathiesen, B.V., Østergaard, P.A., Möller, B., Nielsen, S., et al. (2013). Smart Energy Systems : Holistic and Integrated Energy Systems for the era of 100% Renewable Energy. Denmark: Sustainable Energy Planning Research Group, Aalboberg University.

Connolly, D., Mathiesen, B. V., Dubuisson, X., Lund, H., Ridjan, I., Finn, P., & Hodgins, J. (2012b). Limerick Clare Energy Plan: Climate Change Strategy. Available at: https://vbn.aau.dk/en/publications/limerick-clare-energy-plan-climate-change-strategy

Connolly D, Mathiesen B V, Østergaard PA, Möller B, Nielsen S, Lund H, et al. (2012a). Heat Roadmap Europe 1: First pre-study for EU27. Aalborg University, Halmstad University, and Euroheat & Power. Available at: http://Vbn.Aau.Dk/Files/77244240/Heat_Roadmap_Europe_Pre_Study_1.Pdf

Connolly D, Mathiesen B V, Østergaard PA, Möller B, Nielsen S, Lund H, et al. (2013) Heat Roadmap Europe: Second pre-study. Aalborg University. Available at: https://vbn.aau.dk/en/publications/heat-roadmap-europe-2-second-pre-study-for-the-eu27

David, A., Mathiesen, B.V., Averfalk, H., Werner, S., Lund, H. (2017). Heat Roadmap Europe: Large-Scale Electric Heat Pumps in District Heating Systems. *Energies*, 10(578). doi:10.3390/en10040578

Dittmann, F., Rivière, P., Stabat, P., Paardekooper, S., Connolly, D. (2016). *Space Cooling Technology in Europe*. Available at: https://heatroadmap.eu/heating-and-cooling-energy-demand-profiles/

DG Energy (2017). Clean energy for all Europeans package. Available at: https://ec.europa.eu/energy/topics/energy-strategy/clean-energy-all-europeans_en

DG Energy (2019a). Energy performance of buildings directive. Available at: https://ec.europa.eu/energy/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en

DG Energy (2019b). Energy efficiency directive. Available at: https://ec.europa.eu/energy/topics/energy-efficiency/targets-directive-and-rules/energy-efficiency-directive_en

DG Energy (2021). Renewable energy directive. Available at: https://ec.europa.eu/energy/topics/renewable-energy/directive-targets-and-rules/renewable-energy-directive_en

DG GROW (n.d.). Sustainable product design. Available at: https://ec.europa.eu/growth/industry/sustainability/product-policy-and-ecodesign_en

EC (2011). Energy Roadmap 2050 (COM(2011) 885 final of 15 December 2011).. Available at:

https://ec.europa.eu/energy/sites/ener/files/documents/2012_energy_roadmap_2050_en_0.pdf

EC (2020).A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives - COM(2020) 662 final. Available at: https://ec.europa.eu/energy/sites/ener/files/eu_renovation_wave_strategy.pdf

EERE (n.d.). Energy Intensity Indicators: Terminology and Definitions. Available at: https://www.energy.gov/eere/analysis/energy-intensity-indicators-terminology-and-definitions

ENS (2021). Technology Data for Heating Installations. Danish Energy Agency and Energinet. Available from: http://www.ens.dk/teknologikatalog

Energistyrelsen (2013). Strategisk Energiplanlægning i kommunerne - Vejledning I analyser af systemændringer og scenarieanalyser. Available at: https://ens.dk/sites/ens.dk/files/Varme/system_og_scenarieanalyse_vejledning_081013.pdf.

Energy Education (n.d.). End use energy. Available at: https://energyeducation.ca/encyclopedia/End_use_energy

Erdenebat, B. (2019). Social Assessment in Scaling-up of Implementation of Low Carbon District Heating Systems in Mongolia project by Green Climate Fund.

Eurostat (2018). Glossary:Final energy consumption. Available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Final_energy_consumption

Fahl_en, E., Ahlgren, E.O. (2012). Accounting for external environmental costs in a study of a Swedish district-heating system - an assessment of simplified approaches. J. Clean. Prod. 27, 165e176. https://doi.org/10.1016/j.jclepro.2011.12.017.

Fattahi, A., Sijm, J., Faaij, A. (2020). A systemic approach to analyze integrated energy system modeling tools: A review of national models, Renewable and Sustainable Energy Reviews 133. https://doi.org/10.1016/j.rser.2020.110195

Fleiter T., Steinbach J., Ragwitz M. (2016). Mapping and analyses for the current and future (2020 - 2030) heating/cooling fuel development (fossil/renewables). Available from: https://ec.europa.eu/energy/sites/default/files/documents/mapping-hc-excecutivesummary.pdf

Fleiter, T., Elsland, R., Herbst, A., Manz, P., Popovski, E., Rehfeldt, M., et al. (2017). Baseline scenario of the heating and cooling demand in buildings and industry in the 14 MSs until 2050. Available at: https://heatroadmap.eu/project-reports/

Fleiter, T., Elsland, R., Rehfeldt, M., Steinbach, J., Reiter, U., Catenazzi, G., Jakob, M., Rutten, C., Harmsen, R., Dittman, F., Rivière, P., Stabat, P. (2017a) *Profile of heating and cooling demand in 2015.* https://heatroadmap.eu/project-reports/

Flyvbjerg, B. (2006). Five Misunderstandings About Case-Study Research. Qualitative Inquiry 12(2), 219-245. DOI: 10.1177/1077800405284363.

Grundahl, L., & Nielsen, S. (2019). Heat atlas accuracy compared to metered data. International Journal of Sustainable Energy Planning and Management, 23, 3-13. https://doi.org/10.5278/ijsepm.3174

Hansen, K., Breyer, C., & Lund, H. (2019). Status and perspectives on 100% renewable energy systems. Energy, 175, 471-480. https://doi.org/10.1016/j.energy.2019.03.092

Harmsen, R., Van Zuijlen, B., Manz, P., Fleiter, T., Elsland, R., Reiter, U., et al. (2017). Report on cost-curves for built environment and industrial energy efficiency options. Available at: https://heatroadmap.eu/project-reports/

Healey, P. (2013) Comment on Albrechts and Balducci "Practicing Strategic Planning", disP - The Planning Review, 49:3, 48-50, DOI: 10.1080/02513625.2013.859008I

Hoffman, K., and Pearson, D.F. (2011). Ammonia Heat Pumps for District Heating in Norway – a case study. Published by The Institute of Refrigeration, available from http://www.ammonia21.com/web/assets/link/Hoffman7thApril2011London%20colour.pdf

Hulscher, W.S.(1991) Chapter 1 - Basic energy concepts. In: Energy for sustainable rural development projects – Vol. 1: a reader. Food and Agriculture Organization of the United Nations, Rome.

Hvelplund, F. K., & Djørup, S. R. (2017). Multilevel Policies for Radical Transition: Governance in a 100 % Renewable Energy System. Environment and Planning C: Government and Policy, 35(7), 1218-1241. https://doi.org/10.1177/2399654417710024

Hvelplund, F., Søren Djørup, S. (2019). Consumer ownership, natural monopolies and transition to 100% renewable energy systems. Energy, 181, 440-449. https://doi.org/10.1016/j.energy.2019.05.058.

RENA, IDEA and REN21 (2020). Renewable Energy Policies in a Time of Transition: Heating and Cooling. Available at: https://www.irena.org/publications/2020/Nov/Renewable-energy-policies-in-a-time-of-transition-Heating-and-cooling

Icaza, D., Borge-Diez, D., Pulla Galindo, S. (2021). Proposal of 100% renewable energy production for the City of Cuenca- Ecuador by 2050. Renewable Energy, 170, 1324-1341. https://doi.org/10.1016/j.renene.2021.02.067.

IEA (2017). IEA Energy Efficiency Indicators Highlights (2017 edition). Int Energy Agency 2017:102. doi:10.1017/CBO9781107415324.004

IEA (2021), Net Zero by 2050 A Roadmap for the Global Energy Sector, IEA Publications. Available at: https://www.iea.org/reports/net-zero-by-2050

Iuel-Stissing, J., & Karnøe, P. (2018). Competing knowledge assemblages in Danish heat governance. In The Politics of Urban Sustainability Transitions: Knowledge, Power and Governance (1 ed.). Routledge. Available at: https://www.routledge.com/The-Politics-of-Urban-Sustainability-Transitions-Knowledge-Power-and/Stissing-Jensen-Cashmore-Spath/p/book/9781138479654

Jiménez Navarro, J.P. (2020). Efficient District Heating and Cooling Technical Background Approach towards a possible clarification of definition: CA EED.

Jacobson, M.Z., Delucchi, M.A., Bauer, Z.A.F., Savannah, C., Chapman, W.E., Cameron, M.A. et al. (2017). 100% Clean and renewable wind, water, and sunlight (WWS) all- sector energy roadmaps for 139 countries of the world By 2050. Joule 1, 108–121. http://dx.doi.org/10.1016/j.joule.2017.07.005

Khosla, R., Miranda, N.D., Trotter, P.A. et al., (2021). Cooling for sustainable development. Nat Sustain 4, 201–208. https://doi.org/10.1038/s41893-020-00627-w

Korberg, A. D. (2021). From the production to the utilisation of renewable fuels – pathways in an energy system perspective. Aalborg Universitetsforlag. Ph.d.-serien for Det Tekniske Fakultet for IT og Design, Aalborg Universitet

Krog Jensen, L. (2019). Coordinated planning for renewable smart energy systems: How strategic energy planning could help meet local and national goals. Aalborg Universitetsforlag. Ph.d.-serien for Det Tekniske Fakultet for IT og Design, Aalborg Universitet.

Kuriyan, K., Shah, N. (2019). A combined spatial and technological model for the planning of district energy systems. International Journal of Sustainable Energy Planning and Management, 21, 111-131. http://dx.doi.org/10.5278/ijsepm.2019.21.8

Laureti, T., Secondi, L. (2012). Determinants of Households' Space Heating type and Expenditures in Italy. International Journal of Environmental Research, 6(4), 1025-1038. doi: 10.22059/ijer.2012.573

Li, H., You, S., Zhang, H., Zheng, W., Zou, L. (2019). Analysis of the impacts of heating emissions on the environment and human health in North China. J. Clean. Prod. 207, 728e742. https://doi.org/10.1016/j.jclepro.2018.10.013

Limberger, J., Boxem, T., Pluymaekers, M., Bruhn, D., Manzella, A., Calcagno, P., Beekman, F., Cloetingh, S., Van Wees, J. (2018) Geothermal energy in deep aquifers: A global assessment of the resource base for direct heat utilization. Renewable and Sustainable Energy Reviews 82(1) 961-975. https://doi.org/10.1016/j.rser.2017.09.084.

Lopion, P., Markewitz, P., Robinius, M., Stolten, D. (2018) A review of current challenges and trends in energy systems modeling. Renewable and Sustainable Energy Reviews, 96 156-166, https://doi.org/10.1016/j.rser.2018.07.045.

Lund, H. (2007). Introduction to Sustainable Energy Planning and Policy. I L. Kørnøv, M. Thrane, A. Remmen, & H. Lund (red.), Tools for Sustainable Development (s. 439-462). Aalborg Universitetsforlag

Lund H. (2014). Renewable Energy Systems : A Smart Energy Systems Approach to the Choice and Modeling of 100% Renewable Solutions. vol. 2. Burlington, USA: Academic Press

Lund, H., Arler, F., Østergaard, P.A., Hvelplund, F., Connolly, D., Mathiesen, B.V., Karnøe, P. (2017). Simulation versus optimisation: theoretical positions in energy system modelling. Energies 10, 1e17. https://doi.org/10.3390/en10070840.

Lund, H., Duic N., Østergaard, P.A., Mathiesen, B.V. (2016). Smart energy systems and 4th generation district heating. Energy, 110, 1-4. https://doi.org/10.1016/j.energy.2016.07.105.

Lund, H., Østergaard, P.A., Nielsen, T.B.,Werner, S., Thorsen, J.E., Gudmundsson, O., Arabkoohsar, A., Mathiesen, B.V. (2021). Perspectives on fourth and fifth generation district heating. Energy, 227, 120520. https://doi.org/10.1016/j.energy.2021.120520.

Lund, H., Thellufsen, J. Z., Aggerholm, S., Wittchen, K. B., Nielsen, S., Mathiesen, B. V., & Möller, B. (2014). Heat Saving Strategies in Sustainable Smart Energy Systems. International Journal of Sustainable Energy Planning and Management, 4, 1-15. https://doi.org/10.5278/ijsepm.2014.4.2

Lund, H., Thellufsen, J.Z., Østergaard, P.A., Sorknæs, P., Skov, I.R., Mathiesen, B.V. (2021). EnergyPLAN – Advanced analysis of smart energy systems. Smart Energy, 1 [100007]. https://doi.org/10.1016/j.segy.2021.100007.

Mallaband, B., Lipson, M. (2020). From health to harmony: Uncovering the range of heating needs in British households. Energy Research & Social Science, 69. https://doi.org/10.1016/j.erss.2020.101590

Marczinkowski, H. M.; Barros, L. (2020). Technical Approaches and Institutional Alignment to 100% Renewable Energy System Transition of Madeira Island—Electrification, Smart Energy and the Required Flexible Market Conditions. Energies 13,17: 4434. https://doi.org/10.3390/en13174434

Mathiesen, B. V., Bertelsen, N., Schneider, N. C. A., García, L. S., Paardekooper, S., Thellufsen, J. Z., et al. (2019). Towards a decarbonised heating and cooling sector in Europe: Unlocking the potential of energy efficiency and district energy. Aalborg Universitet.

Mathiesen B.V., Hansen K., Ridjan I., Lund H., Nielsen, S. (2015). Samsø Energy Vision 2030 - Converting Samsø to 100% Renewable Energy. Aalborg, Denmark

Mathiesen, B. V., Maya-Drysdale, D., Lund, H., Paardekooper, S., Ridjan, I., Connolly, D., et al. (2016). Future Green Buildings: A Key to Cost-Effective Sustainable Energy Systems. Department of Development and Planning, Aalborg University

Mathiesen, B.V., Lund, H., Connolly, D., Wenzel, H., Østergaard, P.A., Möller, B., et al. (2015). Smart Energy Systems for coherent 100% renewable energy and transport solutions. Appl Energy;145:139–54. doi:10.1016/j.apenergy.2015.01.075.

Mathiesen, B.V., Lund, H., Hansen, K., Ridjan Skov, I., Djørup, S, Nielsen, S., et al. (2015). IDA's Energy Vision 2050. Copenhagen: Aalborg University.

Maya-Drysdale, D., Krog Jensen, L., and Mathisen, B.V. (2020). Energy Vision Strategies for the EU Green New Deal: A Case Study of European Cities. Energies 13, 2194. doi:10.3390/en13092194.

Maya-Drysdale, D., Mathiesen, B. V., & Paardekooper, S. (2019). Transitioning to a 100% renewable energy system in Denmark by 2050: assessing the impact from expanding the building stock at the same time. Energy Efficiency, 12(1), 37-55. https://doi.org/10.1007/s12053-018-9649-1

Mazza, L. (2013) If Strategic Planning Is Everything, Maybe It's Nothing, disP - The Planning Review, 49:3, 40-42, DOI: 10.1080/02513625.2013.859006

Meier, H.and Rehdanz, K. (2008). Determinants of residential space heating expenditures in Great Britain, Kiel Working Paper, No. 1439, Kiel Institute for the World Economy (IfW), Kiel

Michelsen, C.C., and Madlener, R. (2012). Homeowners' preferences for adopting innovative residential heating systems: A discrete choice analysis for Germany. Energy Economics 34(1271-1283). doi:10.1016/j.eneco.2012.06.009

Ministerio de Energía (Ministry of Energy) (2017). Proceso de Planificación Energética de Largo Plazo (Process of Long-Term Energy Planning). https://www.energia.gob.cl/planificacion-energetica-de-largo-plazo-proceso (accessed 03.06.20)

Ministerio del Medio Ambiente (Ministry of the Environment) (2018). Cuarto Reporte del Estado del Medio Ambiente 2018 (Fourth Report on the State of the Environment 2018). https://sinia.mma.gob.cl/wp-content/uploads/2019/01/Cuarto-reporte-del-medio-ambiente-compressed.pdf . accessed 03.06.20.

Möller, B., Wiechers, E., Persson, U., Grundahl, L., & Connolly, D. (2018). Heat Roadmap Europe: Identifying local heat demand and supply areas with a European thermal atlas. Energy, 158, 281-292. https://doi.org//10.1016/j.energy.2018.06.025

Moriarty, P., Honnery, D. (2019). Global renewable energy resources and use in 2050. Ch 6 in: Trevor M Letcher (ed) Managing Global Warming: an interface between technology and human behaviour. Elsevier, London

Nam, H., Nam, H., Lee, D. (2021). Potential of hydrogen replacement in natural-gas-powered fuel cells in Busan, South Korea based on the 2050 clean energy Master Plan of Busan Metropolitan City. Energy, 221: 119783, https://doi.org/10.1016/j.energy.2021.119783.

Novosel, T. Pukšec, T., Duić, N., Domac, J. (2020). Heat demand mapping and district heating assessment in data-pour areas. Renewable and Sustainable Energy Reviews, 131, 109987. https://doi.org/10.1016/j.rser.2020.109987.

Østergaard, P. A. (2009). Reviewing optimisation criteria for energy systems analyses of renewable energy integration. Energy, 34(9), 1236-1245. https://doi.org/doi:10.1016/j.energy.2009.05.004

Østergaard, P.A. (2015). Reviewing EnergyPLAN simulations and performance indicator applications in EnergyPLAN simulations. Appl Energy;154:921–33. doi:10.1016/j.apenergy.2015.05.086.

Paardekooper, S., Chang, M., Nielsen, S., Moreno, D., Lund, H., Grundahl, L. et al. (2019). Heat Roadmap Chile: Quantifying the Potential of Clean District Heating and Energy Efficiency for a Long-Term Energy Vision for Chile. Department of Planning, Aalborg University.

Paardekooper, S., Lund, H., Chang, M., Nielsen, S., Moreno, D., & Thellufsen, J. Z. (2020). Heat Roadmap Chile: A national district heating plan for air pollution decontamination and decarbonisation. Journal of Cleaner Production, 272, [122744]. https://doi.org/10.1016/j.jclepro.2020.122744

Paardekooper, S., Lund, R. S., Mathiesen, B. V., Chang, M., Petersen, U. R., Grundahl, L. et al. (2018). Heat Roadmap Europe 4: Quantifying the Impact of Low-Carbon Heating and Cooling Roadmaps. Department of Development and Planning, Aalborg University.

Paardekooper, S., Lund, R., & Lund, H. (2019). Smart Energy Systems. In R. E. Hester, & R. M. Harrison (Eds.), Energy Storage Options and Their Environmental Impact (pp. 228-260). Royal Society of Chemistry. Issues in Environmental Science and Technology, No. 46, Vol.. 2019-January https://doi.org/10.1039/9781788015530-00228

Paardekooper, S., Lund, H., Thellufsen, J.Z., Bertelsen, N., and Mathiesen, B.V. (2022). Heat Roadmap Europe: strategic heating transition typology as a basis for policy recommendations. Energy Efficiency, 15(5), [32]. https://doi.org/10.1007/s12053-022-10030-3

Persson, U., Möller, B., Werner, S. (2014). Heat Roadmap Europe: Identifying strategic heat synergy regions. Energy Policy 74, 663-681. http://dx.doi.org/10.1016/j.enpol.2014.07.

Persson, U., Wiechers, E., Möller, B., & Werner, S. (2019). Heat Roadmap Europe: Heat distribution costs. Energy, 176, 604-622. https://doi.org/10.1016/j.energy.2019.03.189

Ram, M., Bogdanov, D., Aghahosseini, A., Gulagi, A., Oyewo, A.S., Child, M., et al. (2019). Global Energy System based on 100% Renewable Energy – Power, Heat, Transport and Desalination Sectors. Study by Lappeenranta University of Technology and Energy Watch Group, Lappeenranta, Berlin. Available at: http://energywatchgroup.org/wp-content/uploads/EWG_LUT_100RE_All_Sectors_Global_Report_2019.pdf

Ricard, L. M., & Borch, K. (2011). From Future Scenarios to Roadmapping: A practical guide to explore innovation and strategy. In The 4th International Seville

Ritchie, H., Roser, M., Mispy, J., Ortiz-Ospina, E. (2018). Measuring progress towards the Sustainable Development Goals. Available at: www.SDG-Tracker.org

Conference on Future-Oriented Technology Analysis (FTA): List of FTA Briefs European Commission. Joint Research Centre.

Regulation 2018/1999 on the Governance of the Energy Union and Climate Action, (…). European Parliament, Council of the European Union. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018R1999&from=EN

Regulation (EU) 2018/841 of the European Parliament and of the Council of 30 May 2018 on the inclusion of greenhouse gas emissions and removals from land use, land use change and forestry (…) and Decision No 529/2013/EU. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.L_.2018.156.01.0001.01.ENG

Ridjan, I. (2015). *Integrated electrofuels and renewable energy systems*. Department of Development and Planning, Aalborg University.

Roberts, C., & Geels, F. W. (2019). Conditions and intervention strategies for the deliberate acceleration of socio-technical transitions: lessons from a comparative multi-level analysis of two historical case studies in Dutch and Danish heating. Technology Analysis & Strategic Management, 31(9), 1081–1103. https://doi.org/10.1080/09537325.2019.1584286

Rüdiger, M. (2014). The 1973 Oil Crisis and the Designing of a Danish Energy Policy. Historical Social Research, 39(4), 94–112.

San Miguel-Bellod, J., González-Martínez, P., Sánchez-Ostiz, A. (2018) The relationship between poverty and indoor temperatures in winter: Determinants of cold homes in social housing contexts from the 40s–80s in Northern Spain, Energy and Buildings, 173 428-442. https://doi.org/10.1016/j.enbuild.2018.05.022.

Santamouris, M. (2016). Cooling the buildings – past, present and future, Energy and Buildings 128, 617-638. https://doi.org/10.1016/j.enbuild.2016.07.034.

Schulze, M., Nehler, H., Ottosson, M., Thollander, P. (2016). Energy management in industry – a systematic review of previous findings and an integrative conceptual framework. Journal of Cleaner Production 112(5) 3692-3708. https://doi.org/10.1016/j.jclepro.2015.06.060.

Singh Gaur, A., Fitiwi, D.Z., Curtis, J. (2021). Heat pumps and our low-carbon future: A comprehensive review. Energy Research & Social Science, Volume 71, 101764. https://doi.org/10.1016/j.erss.2020.101764.

Sovacool, B.K., Osborn, J., Martiskainen, M., Anaam, A., Lipson, M. (2020) Humanizing heat as a service: Cost, creature comforts and the diversity of smart heating practices in the United Kingdom, Energy and Climate Change, Volume 1. https://doi.org/10.1016/j.egycc.2020.100012.

Stephenson, R.J., Sovacool, B.K., Inderberg, T.H.J. (2021). Energy cultures and national decarbonisation pathways. Renewable and Sustainable Energy Reviews, 137, 110592. https://doi.org/10.1016/j.rser.2020.110592.

Sulzer, M., Werner, S., Mennel, S., Wetter, M. (2021). Vocabulary for the fourth generation of district heating and cooling, Smart Energy, Volume 1, 100003. https://doi.org/10.1016/j.segy.2021.100003.

Teske, S. (2019). Achieving the Paris Climate Agreement Goals Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5°C and +2°C. Springer Open: https://doi.org/10.1007/978-3-030-05843-2

Thellufsen, J. Z. (2017). Contextual Aspects of Smart City Energy Systems Analysis: Methodology and Tools. Aalborg Universitetsforlag. PhD Series, Technical Faculty of IT and Design, Aalborg University

Thellufsen, J. Z., Lund, H., Sorknæs, P., Østergaard, P. A., Chang, M., Drysdale, D., Nielsen, S., Djørup, S. R., & Sperling, K. (2020). Smart energy cities in a 100% renewable energy context. Renewable and Sustainable Energy Reviews, 129, [109922]. https://doi.org/10.1016/j.rser.2020.109922.

UNEP (2015). District Energy In Cities: Unlocking the Potential of Energy Efficiency and Renewable Energy. United Nations Environment Programme. Available at: https://www.unep.org/resources/report/district-energy-cities-unlocking-potential-energy-efficiency-and-renewable-energy

UNEP (2015). District Energy In Cities: Unlocking the Potential of Energy Efficiency and Renewable Energy. . Available at: https://www.unep.org/resources/report/district-energy-cities-unlocking-potential-energy-efficiency-and-renewable-energy

UNEP (2020). Emissions Gap Report 2020. UNEP: Nairobi. Available at: https://www.unep.org/emissions-gap-report-2020

UNFCC (2021). NDC Synthesis Report (FCCC/PA/CMA/2021/2). Available at: https://unfccc.int/documents/268571

Ürge-Vorsatz, D., Cabeza, L.F., Serrano, S., Camila Barreneche, C., Ksenia Petrichenko, K. (2015). Heating and cooling energy trends and drivers in buildings, Renewable and Sustainable Energy Reviews 41, 85-98. https://doi.org/10.1016/j.rser.2014.08.039.

Verbong, G. P. J., & Schippers, J. L. (2000). De revolutie van Slochteren. In J. W. Schot, H. W. Lintsen, A. Rip, & A. A. A. de la Bruhèze (Eds.), Techniek in Nederland in de twintigste eeuw. Deel 2. Delfstoffen, energie, chemie (pp. 202–

219). Eindhoven: Stichting Historie der Techniek / Walburg Pers, Zutphen. https://www.dbnl.org/tekst/lint011tech02_01/lint011tech02_01_0014.php

Vlasova, L., & Gram-Hanssen, K. (2014). Incorporating inhabitants everyday practices into domestic retrofits. Building Research and Information, 42(4), 512–524.

Waite, M., Cohen, E., Torbey, H., Piccirilli, M., Tian, Y., Modi, V. (2017). Global trends in urban electricity demands for cooling and heating, Energy 127, 786-802. https://doi.org/10.1016/j.energy.2017.03.095

Werner, S. (2016). European space cooling demands, Energy 110, 148-156. https://doi.org/10.1016/j.energy.2015.11.028.

Werner, S. (2017). International review of district heating and cooling. Energy 137, 617-631. 10.1016/j.energy.2017.04.045

Wojdyga, K., Chorzelski, M., Rozycka-Wronska, E. (2014). Emission of pollutants in flue gases from Polish district heating sources. J. Clean. Prod. 75, 157e165. https://doi.org/10.1016/j.jclepro.2014.03.069.

Xiong W, Wang Y, Mathiesen BV, Lund H, Zhang X. (2015). Heat Roadmap China: New heat strategy to reduce energy consumption towards 2030. Energy 81 274-285. http://dx.doi.org/10.1016/j.energy.2014.12.039.

Zhang, Y., Li, X., Nie, T., Qi, J., Chen, J., Wu, Q. (2018). Source apportionment of PM2.5 pollution in the central six districts of Beijing, China. J. Clean. Prod. 174, 661e669. https://doi.org/10.1016/j.jclepro.2017.10.332.

Zhang, H., Zhou, L., Huang, X., Zhang, X. (2019). Decarbonizing a large City's heating system using heat pumps: A case study of Beijing. Energy, 186: 115820. https://doi.org/10.1016/j.energy.2019.07.150.

Zhao, G., Guerrero, J.M., Jiang, K., Chen, S. (2017). Energy modelling towards low carbon development of Beijing in 2030. Energy, 121: 107-113. https://doi.org/10.1016/j.energy.2017.01.019.

SUMMARY

In energy transition, strategies for heating and cooling are neglected compared to electricity and other sectors. Yet, such strategies are much needed to present concrete visions and alternatives for a more sustainable and renewable future of heating and cooling. Without them, we risk failing to realise the many opportunities for increased sustainability that heating and cooling presents, on both a local and a global scale.

This PhD thesis investigates which general elements are part of the design of heating and cooling strategies, and which are necessarily specific to the local situation. The analysis is based on the review of two 100% renewable energy strategies, the development of 14 Heat Roadmap strategies for Europe, a Heat Roadmap for Chile, and collaboration with the UN Environment District Energy in Cities Initiative to explore heating and cooling infrastructures in developing and emerging economies.

Generally, there are some good, functional approaches and principles towards addressing heating and cooling in varied contexts. Integration of the energy system, thermal grids in cities, and a focus on energy efficiency emerge as good general solutions to many problems. Smart use of storage, excess and renewable heat, and exploring cogeneration and large-scale heat pumps is also commonly valuable. While many technical solutions and mechanisms for improving the heating and cooling sector are common – and have been successfully implemented in some countries – they must be implemented in a way that addresses the specific local problems.

Specific reasons exist at local level that drive the need for heating and cooling strategies. These can be very particular, such as the desire to prevent air pollution from heating stoves in Chile, or phasing out natural gas use in the Netherlands. Even more universal challenges like decarbonisation, sustainable resource management and poverty reduction also play out differently at the local level. This is why strategic design objectives and criteria for heating and cooling strategies must capture the specific socio-political context to reflect and respond to local differences.

ISSN (online): 2446-1628
ISBN (online): 978-87-7573-738-3

AALBORG UNIVERSITY PRESS