Thesis in the MSc Sustainable Energy Technology program

Potential tariff structures for Fifth-Generation District Heating and Cooling

AN EXPLORATORY STUDY OF TARIFF STRUCTURES THAT CAN SIMULATE EFFICIENT AND SUSTAINABLE HEATING AND COOLING FOR DUTCH HOUSEHOLDS

By Mitchel Knipscheer

FAKTON ENERGY

TU Delft
Delft University of Technology

Potential tariff structures for Fifth-Generation District Heating and Cooling

An exploratory study of tariff structures that can stimulate efficient and sustainable heating and cooling for Dutch households

by Mitchel Knipscheer

Thesis in the MSc Sustainable Energy Technology program at Delft University of Technology

Student number		4220536
Thesis report		Oct-2021
Thesis committee	Dr. A.F. Correljé	Chairman
	Prof.dr.ir. A.A.J.F. van den Dobbelsteen	Supervisor
	Dr. Ir. I.W.M. Pothof	Supervisor
External supervision	S. Geerts	Fakton Energy
	P. Vlek	Fakton Energy

PREFACE

For my master thesis, I wanted to study a topic that covered areas beyond merely the technological challenges of the energy transition. I reviewed my knowledge and aimed to gain as much new knowledge as possible in my final project. And so I started a thesis that incorporated fifth district heating and cooling – a very recent innovation in a field that I had not studied before – and combined it with tariff design: which is a multi-disciplinary field itself, as I soon discovered. Now, this mix provided everything I asked for.. and more.

I believe I have learned more skills and knowledge than I could have anticipated at the beginning. For that, I can honestly say I am proud of what this final hurdle of the master Sustainable Energy Technology has taught me. However, none of it could have been possible without the support and help of the people around me. Some I met during this research, others have supported me throughout my entire studies.
First of all, my committee of supervisors. I would like to thank Aad, Ivo and Andy for your valuable insights, your patience and motivating words when I needed them. Although this might have been an unusual mix of committee members – as your research areas are not commonly combined in graduation projects – I believe the variety of angles contributed a unique value to this study. I would like to sincerely thank you for your supervision.

Furthermore, I would like to thank Saskia and Peter for their guidance at Fakton Energy and their unconditional efforts to think along and help out in any way I needed. This actually goes for all my colleagues at Fakton Energy. Without you this would not have been the memorable experience it was, both on a professional level as on a social level. Fakton Energy offered me the opportunity to study this topic without any expectations nor requirements. I would like to thank them for the opportunity to conduct this study and to allow me to participate in day-to-day business in every way. I felt welcome and comfortable from the moment I started. I really appreciated that.

I was lucky to receive help and support from many of my friends. It would be impossible to compliment everyone with the credit they all truly deserve, but I do want to highlight a few. Tirza, Eliza and Ineke: thanks for being my visual design crew. Without your efforts, this report and its visuals would not have been this sophisticated. In my opinion, your efforts added a lot of value to this report and I hereby want to express my gratitude. Next, I would like to thank Nino for his modelling skills and Chaturika for reviewing my report and grilling my English grammar (which was justified). I also would like to thank all my friends from the master program, who have made these years unforgettable. Alice, Chaturika, Jorn, Kristin, Luca, Martijn, Svenja and Yannick: you are all amazing and stating I enjoyed our time together would be an understatement.

Saving the best for last: my family. My parents and sister have supported me through all the years of my education and now they can finally experience the end result. Without their support I would not have been able to finish my studies. I am sure they are as exciting as I am for my next chapter: starting a professional career dedicated to creating a sustainable future energy system.

SUMMARY

Introduction

This report explores potential tariff structures to enable roll-out of 5GDCH systems to decarbonise thermal energy provision for Dutch households. In the face of rising global temperatures and other negative effects of global warming, policies and goals have been set to decarbonize our society. As roughly 50% of the current global energy consumption is for heat production, which accounts for 40% of energy-related greenhouse gas emissions, this sector is set to transition its energy mix. Moreover, cooling demand is rising sharply each year, having tripled globally since 1990. The collective heating and cooling demand poses challenges to maintain a both sustainable and habitable indoor climate for current and future households.

The recent development of a fifth-generation DHC technology offers the opportunity to optimally harness sustainable low-temperature thermal energy sources while enabling bidirectional heating and cooling supply. However, this novel DHC technology currently lacks experience and projects. One of the identified research gaps has led to the focus for this study being: to expand the knowledge of 5GDHC tariff design and potential incentives. Insight into the complexity of 5GDHC and how it affects its tariff design is needed, since 5GDHC is based on fundamentally different principles than traditional DHC systems. Harnessing 5GDHC's full potential can be supported by appropriately designed tariffs, but currently the lack of experience and knowledge of the complexity of 5GDHC tariffs design is hindering its roll-out.

Research methodology

First, a research design that identified a relevant research questions was created. This main research design addresses the problem as described before through four research questions that collectively answer the main research question:
Main Research Question What tariff structures can facilitate 5GDHC networks to stimulate efficient and sustainable heating and cooling for Dutch households?

In the second research phase a literature review is carried out to explore the complexity of 5GDHC form an multi-disciplinary perspective and how it affects the trajectory of its tariff design. The insights are used as input for a empirical 5GDHC tariff design, where simplifications were deemed necessary to align with the exploratory nature of current 5GDHC research and to test the required parameters without the complexity of the system causing a hindrance. Therefore tariff design focused mainly on cost-reflectivity, efficiency, and sustainability objectives and did not fully incorporate all potential economic perspectives. The proposed tariff structures are tested in a model that was created to serve as a testing environment for tariff structures. This model was inspired by DeZONNET research: a 5GDH study in The Netherlands. The tariff structures are tested under several scenarios were tested, based on the following parameters:

- Customer types: conventional and dynamic, i.e. load shifted, heating routines.
- Energy label: Energy label B and – after energy saving measures – label A households.
- Energy mix: PVT supported by either aquathermal energy or a waste heat source.

Results

Insights into the complexity of 5GDHC tariff design: an important result in this study. Firstly, the smart grid features of a 5GDHC: it is based on fundamentally different principles than traditional DHC. It includes decentralized production by prosumers, bi-directional thermal energy exchange and potentially demand side management. Secondly, different economic perspectives provide different economic lenses which can be applied to equip tariffs with design for values and tariff objectives. Finding and maintaining a trade-off goes beyond only structures and is shaped by the planned role for 5GDHC systems in the future. It operates in a multi-disciplinary field where tariff design integrates technological, economic and institutional angles. Finding and including all relevant (f)actors is a challenging assignment as is. Additionally, smart grid technologies like 5GDHC offer great potential but rising value conflicts threaten their social acceptance. 5GDHC tariff design should factor in, try to solve or at least not exemplify these potential conflicts.

The empirical 5GDHC tariff design a utility perspective was adhered to align with a cost-plus strategy as proposed in pending Dutch legislation. The prioritized objectives are cost-reflectivity,

efficiency and sustainability. Consequently, tariff structures that motivate peak shaved thermal load profiles as much as possible align with these goals. As a result, three-tier tariff structures are proposed and tested compared to a two-tier reference tariff. The proposed tariff consists of:

- A variable demand charge [€/kW(th)];
- An either flat or Time-Of-Use structured energy charge [€/kWh(th)], and;
- A fixed standing cost[€/year]. Alternatively, the latter combines a pure volumetric flat energy charge and fixed standing cost.

The tests demonstrate that a variable demand charge – with subscription levels based on desired individual kW(th) capacity – promotes cost-reflectivity and enables 5GDHC to utilize local low-temperature thermal energy sources. A Time-Of-Use structured energy charge performed slightly better – around 1% - on cost reflectivity. Sustainability was tested by running thermal load profiles of energy label A instead of the originally tested label B households. For this test, the reduced energy consumption was rewarded most in the reference tariff.

From an operator's perspective, peak shaved demand profiles result in higher load factors which allows for more efficient operation and a reduction of the required network capacity. Operators can therefor either reduce network capacity for future networks and thus reduce up-front investment, Additionally, they can increase revenues through connecting more customers during operation without grid reinforcements. This is especially the case for existing networks.

Discussion and reflection

The discussion is split in two parts: The first discusses how the modelling results should be interpreted. The second reflects on the implications of simplifying 5GDHC tariff design and performing explorative research like this 5GDHC study.

First, interpreting the modelling results shows that cost-reflectivity and efficiency is promoted more strongly in the proposed 5GDHC tariff structures than for the reference tariff. However, the effectivity of the tariffs is determined by whether demand or local production is the limiting network design variable. Customers can reduce their annual charges by adjusting their heating and cooling routines: shift thermal loads as much as possible so that thermal peaks are maximally reduced. Alternatively, they can insulate their house or install thermal energy storage, e.g. a domestic hot water buffer. Sustainability is rewarded more strongly in the reference tariff than in the proposed three-tier tariff structure. This was to be expected, since the thermal load profiles of an energy label A have larger reduction on overall energy consumption (53%) than peak reduction (36%). Adjusting subscription levels for label A houses could show different outcomes.

From an operator's perspective, cost-reflective tariffs guarantee the recuperation of costs. The added Time-Of-Use structure results in slightly higher returns that result in a small margin of profit. The proposed three-tier tariff structures encourage customers to actively contribute to load shifting. The tariffs are based on expected consumption, deviations result in losses or profits. Active customers reduce network peak which could:

- Reduce the required network capacity and thus investment cost for future networks
- Free up space for extra network connections without grid reinforcements of existing networks

Practical implementation is subject to the level of the desired control. Achieving peak shave profiles can be done manually or through automation. The latter is more is the more attractive option from an optimization and system stability point of view. Participation can be motivated by providing tariff modules that incorporate options for increased comfort levels and cost savings.

Secondly, reflecting on this 5GDHC tariff design shows that it was mainly focussed on technological and efficiency-based mechanisms. This left several economic perspectives and their corresponding theories, unused. For instance, role distribution and reallocation of property and decision rights, which were identified as important features, were not considered. However, the most pressing question that remains: what future role is imagined for 5GDHC systems? As the answer determines the tariff objectives and thus the corresponding tariff design. The guarantees that follow from the answer decide which tariff objectives should be prioritised.

Furthermore, the relation between transaction costs versus the level of interaction needed for the 5GDHC system and the designed tariffs to work is noted. The benefits should outweigh the cost for it to make sense. The amount of data required for operation depends on how active customers are expected to be. In short, the smartness within 5GDHC requires data gathering, storing, managing and securing which raises both transaction cost and privacy concerns.

Conclusion

To answer the main research question it is first repeated below:

Main Research Question What tariff structures can facilitate 5GDHC networks to stimulate efficient and sustainable heating and cooling for Dutch households?

The results of this thesis research show that a three-tier tariff structure containing a variable demand charge, an either flat or a TOU structured energy charge, and fixed standing cost can promote cost-reflective, economic efficient and sustainable heating and cooling for Dutch households by 5GDHC. Optionally, rebates to increase participation in automated operation can be included. As demonstrated in the modelling exercise, the three-tier tariffs outperformed the flat volumetric reference tariff reference on cost-reflectivity and efficiency. The results show that dynamic customers will pay less than conventional customers in the proposed three-tier tariff structures.

However, energy saving measures were rewarded more strongly in the reference tariff. This outcome is acceptable since the proposed three-tier tariffs enable increased roll-out of 5GDHC. The latter is expected to have the biggest impact in the efforts to decarbonise the residential sector. In relation to the future role of 5GDHC systems: if a utility principle with a cost-plus approach is selected, regulation should focus on sending out efficiency incentives for the operator. Since cost-reflective tariffs provide a guaranteed cost recuperation.

Recommendations

Recommendations are made in respect to the proposed three-tier tariff structures, 5GDHC tariff design in general and urban energy planning. The ones most noteworthy are listed below while suggestions for future research are found in the full report.
Recommendations specifically related to the three-tier tariff structures:

1. Incorporate incentives for automated control without disrupting customer autonomy too gravely
2. Add energy feed-in and cooling components to the tariff structure. After completing the proposed three-tier tariffs, test them in more advanced models and/or pilot projects.
3. Check compatibility with and impact on other existing and future DHC networks. Their business case has designed based on current tariff structures. It could enable the roll-out of (U)LT DHC in general.
4. Elaborate on the operator's perspective. If the tariff structures are not accepted by operators, the tariff structure will not become common practise.

Other recommendations for tariff design in general:

5. More attention for the impact of data usage and the required level of interaction in smart grid technologies like 5GDHC
6. Incorporate flexibility in tariff design for early adopters. Adjust for lessons learned during operation/ possibility to annually correct and adjust for changes and lessons learned.
7. Consider the future role for rooftop areas of energy prosumers. PV and PVT applications are essentially competing for the same surfaces. Individual benefits could clash with those of the general public. Recognizing this development and contributing research could lead to policies e.g. one that promote either PV, PVT or otherwise for specific types of households.

Suggestions for future research:

- Explore other 5GHDC tariff design paths parallel to a utility-based ideology
- Combine with SG(e) research and smart charging of electric vehicles as inspiration
- Study spill-over effects of sector coupling
- Explore tariff design for non-residential 5GDHC users

CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

3GDH	Third-Generation District Heating
4GDH	Fourth-Generation District Heating
5GDH	Fifth-Generation District Heating
5GDHC	Fifth-Generation District Heating and Cooling
ATES	Aquifer Thermal Energy Storage
COP	Coefficient Of Performance
CPP	Critical Peak Pricing
CPR	Critical Peak Rebates
DR	Demand Response
DSM	Demand Side Management
DSO	Distribution System Operator
HT	High Temperature
LT	Low Temperature
MT	Medium Temperature
NCE	Neoclassical Economics
NIE	New Institutional Economics
OIE	Original Institutional Economics
PT	Photo Thermal
PV	Photo Voltaic
PVT	Photo Voltaic Thermal
RTP	Real Team Pricing
SCOP	Seasonal Coefficient Of Performance
SG	Smart Grid
SG(e)	Electrical Smart Grid
SG(th)	Thermal Smart Grid
TCE	Transaction Cost Economy
TES	Thermal Energy Storage
TOU	Time-Of-Use
TSO	Transmission System Operator
ULT	Ultra-Low Temperature
VPP	Variable Peak Pricing

1. INTRODUCTION

Decarbonizing the heating and cooling provision

In recent years, the urgency to fight climate change has become the main driver for the transition towards clean energy. The Paris Agreement of 2015 established the goal to avoid a global temperature increase of more than two degrees Celsius. The recently published IPCC report stipulates the importance to speed up our collective efforts to limit human-induced global warming (IPCC, 2021). Much of those efforts have been aimed at the power sector, where a considerable amount of energy consumption takes place. However, transforming power mixes and reducing emissions only from power generation is not enough to reach the sustainable energy goals on its own. Approximately 50% of the current global energy consumption is for heat production, and this is responsible for 40% of energy-related greenhouse gas emissions, as well as intense levels of air pollution that threaten the environment and public health (IRENA, IEA, & REN21, 2020). The heating sector is thus obligated to decarbonize too.

Decarbonizing heating supply is not the only challenge. Cooling demand is also drastically rising as it has tripled globally compared to 1990. It is increasing most rapidly in developing and emerging economies driven by expanding wealth and population, changing lifestyles, and extreme weather patterns caused by climate change (IRENA et al., 2020). With rising temperatures and better insulated buildings it is expected that cooling will not just be a luxury commodity for better comfort. Even in Northern European countries like the Netherlands, cooling supply will be a necessity to keep the indoor climate of households habitable (W/E-Adviseurs, 2018).

Roll-out of the next generation district heating and cooling systems

District heating and cooling (DHC) networks have the potential to increase efficiency and reduce the use of fossil fuels, particularly in dense urban areas. Recently, a new innovative DHC technology has been attracting attention in research and in urban energy planning. The so-called fifth generation district heating and cooling (5GDHC) systems allow for high levels of energy efficiency by operating at ultra-low temperatures while enabling a bidirectional and decentralized flow of thermal energy. Moreover, these smart grid features allow for increased integration of renewable thermal energy sources. The 5GDHC technology is relatively new and lacks insight into its optimal implementation and widespread roll-out.

The Dutch sector

The Dutch DHC sector is a specifically interesting case for a number of reasons. Firstly, the Dutch government has agreed to transition from natural gas-fired heating to sustainable alternatives for the built environment by 2050 (Klimaatakkoord, 2019). Alternative heating solutions are thus expected to increase significantly. Secondly, this transition has led to a review of the existing Dutch Heat Act for collective heating systems, such as DH. A new Heat Act is being drafted while this 5GDHC research is being conducted. It aims to revise tariff regulation and organizational structures, among others (Wiebes, 2020). In that regard, alignment with 5GDHC developments has been noted in the public consultation of the first draft of this new legislation (Warmtecoalitie, 2020). Thirdly, the Dutch climate is changing as cooling is becoming increasingly important in the built environment. New legislation forces all new housing projects in The Netherlands to consider overheating and meet certain cooling standards (Bouwmeester, 2020).

Research objective

The aim of this research is to provide insight into 5GDHC tariff design and potential tariff structures to support 5GDHC roll-out and encourage the uptake of renewable energy in the DHC sector. If 5GDHC roll-out is to take off, the system needs a clear economical, organizational and institutional framework that facilitates its development and deployment. New business models and tariff structures could mitigate high investment costs and gain social acceptance of 5GDHC (Buffa, Cozzini, D'Antoni, Baratieri, & Fedrizzi, 2019) and thus contribute in this effort. Tariffs are a fundamental piece of the aforementioned framework as tariffs represent the monetary flow between the parties that organized themselves as an active or passive actor of 5GDHC systems. Standardized 5GDHC tariffs have not yet been designed and currently charged tariffs are not originally created to handle 5GDHCs features, such as bidirectional energy flows and decentralized production. Hence the need for research and exploration of 5GDHC tariff design, to which this research aims to contribute.

Report outline

The report is structured as follows: Chapter 2 discusses the research design, the research context, the problem statement and the research questions will be stated in this chapter. Next, the literature review will be presented in Chapter 3. Chapter 4 will discuss the process of tariff design by deducting from the earlier presented theoretical concepts. It introduces how the complexity of 5GDHC tariff design will be dealt with in this study. Chapter 5 will align the design of tariff structures with the technical features and actor characteristics of a 5GDHC system. The potential 5GDHC tariff structures are tested in the following chapter, Chapter 6. Here a modelling exercise is introduced to test these proposals. Chapter 7 discusses the results of this modelling exercise and of this study in general. The results and the impact of the proposed 5GDHC tariff structures are discussed in Chapter 8. Finally, conclusions and recommendations will be presented in Chapter 9.

2. RESEARCH DESIGN

The research design will be introduced in this chapter. It aims to describe the process of this research, from the objective to the approach and final deliveries. It will provide the reader with a structured overview of the research.

Section 2.1 will discuss the exploration that started the research design. The following section 2.2 will present the problem statement and the objective of the research. Research questions are extracted from the problem statement in section 2.3. The scope is defined in section 2.4 and the relevance of the research is elaborated on in section 2.5. Finally, the research strategy in section 2.6 presents the research phases, methods and the outputs.

2.1 Exploration

2.1.1 Initial literature scan

The research design is based on an initial literature scan and iterative meetings with both academics of the Delft University of Technology and Fakton Energy employees. The literature scan revealed insights into what 5GDHC actually is and existing research gaps that ought to be addressed. This new innovative technology is still in early phase of development and implementation is scarce. Research gaps are found in the technological framework and in the alignment with economical and organizational characteristics. To indicate the motives for this research a few important contributions to the field are highlighted: Lund et al. (2014a) stated the development of an institutional and organisational framework to facilitate suitable cost and motivation structures would be required for future thermal smart grids to function. Buffa et. al (2019) that new business models and tariff mechanisms are needed to mitigate the high investment costs and increase public support for 5GDHC. However, recent DHC research merely reviews tariff design from a broader DHC perspective or it does not integrate and connect all relevant sectors for 5GDHC tariff design. It has not focussed on 5GDHC specifically or it does not elaborate on the framework for tariff design in detail yet (Li, 2020)(Li, Wallin, & Song, 2017) (Cozzini et al., 2017). The result of this initial scan provided a starting point for the research design.

2.1.2 Exploratory research

Before starting this research, it has been clear that this study will be of an exploratory nature. Tariff structures and embedding motivational structures for both consumers and producers in smart energy systems has been topic of research in the power sector for almost a decade now. Knowledge and experience of these applications is less advanced in DHC research, and for 5GDHC especially. Since 5GDHC is a relatively recent development, its tariff design is still in an exploratory phase. Optimizing design and operation is dubbed to be 'a non-trivial process' (Boesten et al., 2019). Based on the literature scan, it is safe to say that finding potential 5GDHC tariff structures is a complex task. Simplifications and limitations are necessary to maintain an effective scope during this research. Thus, the complexity of 5GDHC tariff design is researched and evaluated but not fully accounted for in the tests and results. This is recognized and deemed acceptable for the exploratory phase of current 5GDHC research. The discussion and recommendations will be used to reflect upon the complexity and the assumed simplifications.

2.2 Problem statement and research objective

From the literature scan the problem statement was deferred. It is stated as follows:

Problem statement

5GDHC is based on fundamentally different principles than traditional DH systems, that have shaped design of the existing tariff structures. Harnessing the 5GDHC's full potential can be facilitated by appropriately designed tariffs. However, the lack of experience and knowledge of 5GDHC and the complexity of its tariffs design hinders widespread roll-out.

The aim of this research is to create insight into 5GDHC tariff design and potential tariff structures to support 5GDHC roll-out and encourage the uptake of renewable energy in the DHC sector. The 5GDHC system is lacking a clear economical, organizational and institutional framework that facilitates its development and deployment. Tariff design is inherently a part of all three frameworks. Exploring potential tariff structures and the corresponding triangle of the economical, organizational and institutional framework will support 5GDHC development and roll-out.

2.3 Research questions

To define research problems and research questions, a method has been adopted which provides structure and a proper framework. A general problem is defined, from which several sub-problems are obtained. For each sub-problem a research question is defined so that there is a proper alignment between sub-problems and research questions. The answer to a research problem should provide the solution to the corresponding sub-problem. This should eventually lead to the answer to the general problem, when the single solutions are combined(Lubbe, 2012). When applied to this this research, this approach results in the following structure, as deferred from the general problem statement. From this general problem, the following sub-problems can be characterized:

P.1	*5GDHC is still a recent innovation and insight into the complexity of its tariff design is not extensively researched and/or documented.*
P.2	*Tariff objectives and value trade-offs for 5GDHC are not yet defined.*
P.3	*The requirements of potential tariff structures that should be satisfied to align with the technological features of 5GDHC and its actors are not defined.*
P.4	*The impact of new tariffs and the implementation i.e. operational features on actors and the organisational an institutional embedding is a complex and vast assignment*

To keep to this alignment, the same number of research questions are obtained from the proposed sub-questions:

Q.1	***What makes tariff design for 5GDHC complex?***
Q.2	***What criteria are considered in tariff design?w***
Q.3	***What are potential 5GDHC tariff structures?***
Q.4	***What is the impact of implementing potential 5GDHC tariff structures?***

Together, they define the main research question of this research:

Main research question

What tariff structures can facilitate 5GDHC networks to stimulate efficient and sustainable heating and cooling for Dutch households?

The research questions mention general notions that may need clarification, because these seemingly similar notions may be explained slightly different in other reports or fields of study. To understand what is meant in upcoming chapters, the meaning of those notions which will be adhered for this report are briefly explained:

Tarif structure refers to a criterion of charging single customers. The price that customers are charged is built of several price components, representing all production activities.

Tariff design is the process towards creating the preferred structure that align with the set tariff objectives. The design requires several choices to be made to best satisfy the predefined objectives of pricing a commodity.

2.4 Research scope

2.4.1 Sustainable heating and cooling provision for the residential sector

For some time, heating and cooling have not been the focus of the energy transition on our path to decarbonisation of our energy supply. Since it has become clear that heating represents a considerable amount of the final energy consumption in the European Union, research activities have seen an increase in this particular topic. Meanwhile, cooling demand is expected to rise considerably due to better insulated houses and rising temperatures due to climate change(IEA, 2018). Research attention for sustainable energy technologies to decarbonize our heating and cooling provision in the built environment has increased seen an increase. 5GDHC, as mentioned before, 5GDHC has presented itself as one that could contribute considerably. The built environment itself consists of multiple building types and in this research the residential sector has been the focus. Thus, neighbourhoods containing households.

The Netherlands is a particularly interesting case in this regard, since the government set goals to phase out natural gas to heat the buildings in the built environment by 2030 (Klimaatakkoord, 2019). Additionally, a new Heat Act is being considered which will make considerable changes in tariff regulation and the institutional and organizational framework (Wiebes, 2020).

2.4.2 Tariff design for 5GDHC systems

For innovations like 5GDHC to fulfil the significant role they have been attributed, new business models and tariff mechanisms are needed to mitigate the high investment costs and increase public support for this new DHC technology (Buffa et al., 2019). The formulation 'tariff mechanisms' can be explained as the process of tariff design and the organisational and institutional framework that facilitates this process. The focus of this research is to evaluate potential tariff structures for 5GDHC that follow from the tariff design process. The impact of potential tariff structures on the organisational and institutional framework will be discussed and reflected on.

2.4.3 Multi-disciplinary study – technologic, economic and institutional perspectives

As reflected in the research questions, this research takes multiple angles from several disciplines into consideration. It aims to encompass a multi-disciplinary approach to evaluate the potential tariff structures. Technologic, economic, and institutional angles are considered whilst executing this study. One could argue this inherent in any tariff design process. These different disciplines have been explored simultaneously in the analysis of tariff design for 5GDHC. This stems from the ambition to gain insights beyond the technical barriers of the energy transition and, in this study, that of 5GDHC networks. These insights are meant to ease the uptake of 5GDHC and a rise of the implementation rate. The latter is a field of research by itself: implementation science. It is defined as a 'scientific study of methods is used to promote the systematic uptake of research findings and other evidence-based practices into routine practice, and, hence, to improve the quality and effectiveness of services and technologies'(Eccles & Mittman, 2006). Implementation research requires multi-disciplinary research teams that include members who are not routinely part of the design process. An in-dept analysis of the implementation dynamics is outside the scope of this research, but tariff design is a multi-disciplinary itself. In line with the research objective, implementation science methodologies could be applied for 5GDHC too in future research.

2.5 Relevance of the research

2.5.1 Scientific relevance

Projected innovation and new knowledge

First, the added value of this specific 5GDHC research and the new knowledge it intends to yield is important to note. In short, this study sheds light on the complexity of 5GDHC tariff design. An extensive overview has not been found in literature yet and could prove to be a useful basis for future more in-dept studies into 5GDHC and its potential tariff design. Furthermore, a number of simplifications are applied to explore and propose new tariff structures for residential customers. The proposed tariff structures are – much like 5GDHC systems themselves – not used in practise yet. The newly proposed tariff structures provide input for further research and possibly pilot projects.

Relation with other research projects

The topic itself fits into a broader development within several scientific fields. Smart energy systems, smart grids and thus thermal smart grids have gained scientific interest over the recent years. In that light, the innovation of 5GDHC along with its applications is hardly a surprise as the corresponding concepts have penetrated the field of power electronics for some time already. Based on the literature scan, conducted research does covers a number of aspects that are overlap with this 5GDHC study:

- Creating smart networks - Nowadays, 'smartness' and data-driven optimization is applied in many sectors. When narrowing it down to the energy sector, a few trends come to mind. For one, the shift towards decentralized systems and the rise of prosumers. While most institutional and organisational frameworks have been shaped by centralized production, these trends disrupt the status quo. Due to these looming changes, corresponding legal and economic mechanisms, e.g. tariff design, are being reviewed.
- Incentives for flexibility – A number of developments contribute to the need of flexibility in the energy networks. The changing energy mix - higher ratios of intermittent renewable energy sources - the increasing energy demand and the fact that reinforcement of energy networks is a long and expensive measure. These developments pose threats to the security of supply. Multiple sectors conduct research into how to promote and reward flexibility.
- Sector coupling – Research within the energy sector tends to increasingly focus on system integration. This results in systems where various sectors are coupled and their operation and design becomes an integrated task.
- Harnessing sustainable low-temperature sources – 5GDHC is a specific case of a (ultra) low-temperature network that enables utilization of these sustainable thermal energy sources. Insights and knowledge contributions achieved in this study, can inspire DHC research in general. For example, tariff structures for 5GDHC can be transferred and or modified to align with similar ULT DH and DHC systems.

2.5.2 Societal relevance

As societies are faced with the effects of climate change, efforts to decarbonize our energy system are made to avoid or at least dampen its impact. While scientific research is contributing to new knowledge and innovations, policy makers are faced with the planning of the energy system of the future. As for heating and cooling in the residential sector, alternatives for natural are generating more attention and research is much needed. Consequently, households and homeowners are faced with trade-offs concerning their energy usage which has only recently become a concern. The PBL believes that the national government should encourage the development of sustainable district heating systems to persuade citizens to replace their natural gas connection with a connection to the DH system, because citizens are more likely to switch if they know they are contributing to the zero emission energy system of the future (Hoogervorst, 2017). Studying how the tariff design of DHC systems could boost sustainability while still ensuring social acceptance is thus of great – if not vital – value to society.

2.6 Research approach and outline

The research approach was divided into four different steps, each with their own applied method. An overview is depicted in Figure 2.1.

To setup a research design, a preliminary literature scan was carried out. Thereafter, the first phase is characterized by exploration of the research topic. For this purpose, a literature review was carried out to define the gaps in research and to create insight into the complexity of 5GDHC tariff design.

The second phase has a more empirical approach, where theoretical concepts from the previous phase are selected, discussed and aligned with 5GDHC systems and actors. It leads to the proposal of 5GDHC tariff structures.

The third phase is characterized by testing and reflecting on the impact of the tariff structures. A testing environment will be designed to test the performance of the proposed tariff structures based on the objectives set in the previous phase. What will be required for implementation and the anticipated impact of implementation will be reflected upon in the discussion.

Finally, conclusions and recommendations will be presented in the final phase, where the restated answers to the research sub-questions will build up to the answer the main research question.

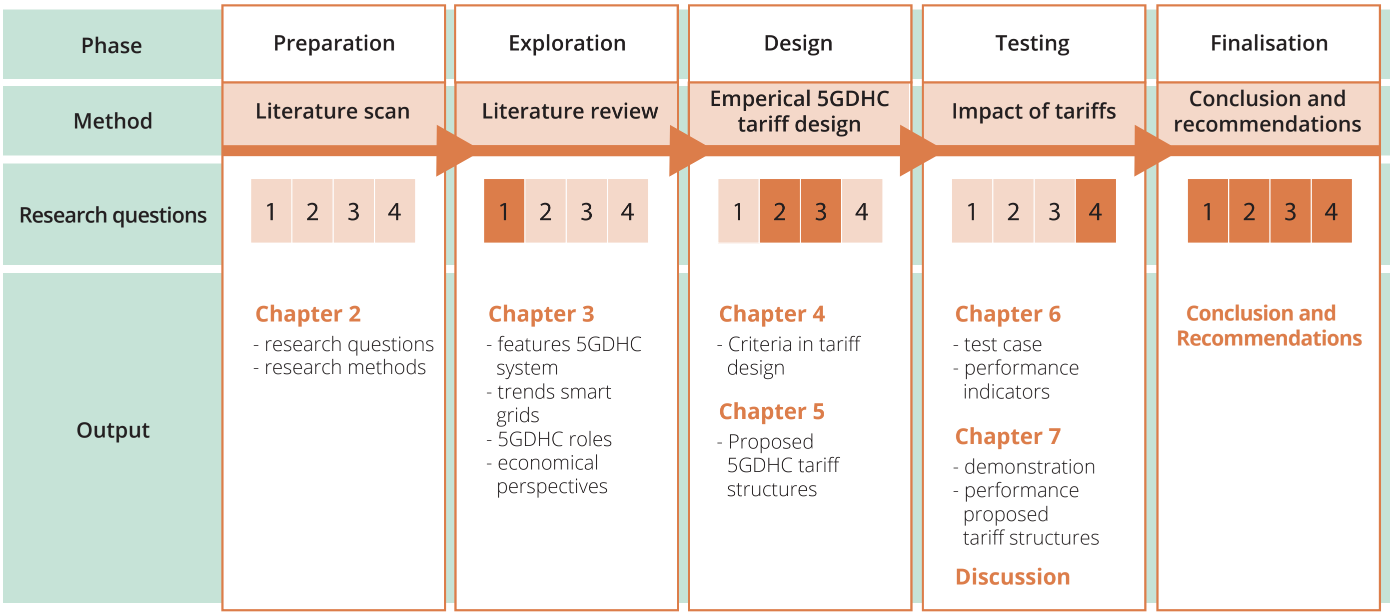


Figure 2.1 - Research design depicting phases, methods research questions and expected output

3. LITERATURE REVIEW

This literature review introduces the concept of fifth-generation district heating and cooling and its potential benefits and possibilities. It aims to clarify its technical features and potential benefits. The review is supposed identify research gaps and give insight into the tariff design for 5GDHC. Finally, this review should provide insight into the complexity of the tariff design as the first research question is phrased:

Q.1	***What makes tariff design for 5GDHC complex?***

Section 3.1 provides a technological background of DHC systems in general and introduces 5GDHC and its features. Section 3.2 discusses trends and challenges in the developing smart grid technologies. It discusses both electrical and thermal smart grids, collectively referred to as 'smarter energy networks'. Economic perspectives are reviewed in section 3.3. Role distribution in the district heating and cooling sector is discussed in section 3.4 and finally, a conclusion to why 5GDHC tariff design is complex is drawn in section 3.5.

3.1 Technological background of fifth-generation district heating and cooling

3.1.1 Introduction to the generations

The development of district heating networks and the label of generations was introduced by Lund et. al in 2014. In their paper they discussed the development of traditional DH in three generations and proposed a new innovative generation of DH systems. Moreover, this paper introduced the concept of future of smart thermal grids SG(th) and discussed the challenges for future networks. Their evolution of DH networks and corresponding key features is depicted in Figure 3.1, with the extension of a fifth generation.

The first generation of district heating networks (1GDH) dates to the 1880s. These networks made use of steam that was produced in boilers, that were primarily used for power production. This high temperature waste heat was fed to a network of pipes through radiators. 1GDH was mostly used for industrial processes. The network was not efficient nor sustainable: heat losses were significant and the heat supply was fed with fossil energy sources.

After the 1930s, a new generation district heating (DH) replaced the heat carrier steam by pressurized water to reduce heat losses, though operating temperatures remained high. Combined with the rise of combined heat and power plants, this second-generation district heating (2GDH) networks enabled an overall increase in efficiency. Typical components were water pipes in concrete ducts, large tube-and-shell heat exchangers, and material-intensive, large, and heavy valves (Vasek & Dolinay, 2017).

The third generation is the most widespread technology amongst them and was mainly the result of increased building efficiency. This allowed for lower temperatures and eliminated the need to pressurize the water. The previously installed steal carrier pipes were replaced by prefabricated jacket pipes in the distribution network for further cost reduction (Buffa et al., 2019)(Rhein et al., 2019).

The proposed fourth generation was an advancement that provided opportunities to decarbonize the DH sector. In combination with the concept of SG(th), it marked a new development in the DH sector. the goal for this new DH technology was to overcome the challenges and identify necessary tools to reach a future renewable energy-based heat supply in the broader context for an overall sustainable energy system of the future. 4GDHC was defined as follows by Lund et al. (2014b):

> *"The 4th Generation District Heating (4GDH) system is consequently defined as a coherent technological and institutional concept, which by means of smart thermal grids assists the appropriate development of sustainable energy systems. 4GDH systems provide the heat supply of low-energy buildings with low grid losses in a way in which the use of low-temperature heat sources is integrated with the operation of smart energy systems. The concept involves the development of an institutional and organisational framework to facilitate suitable cost and motivation structures"* (Lund et al., 2014).
>
> **BOX 3.1**

Following the trend of reducing temperature levels and integrating ever increasing energy flows into one energy system, the concept of a fifth-generation district heating and cooling was published. One of the main differences between 4GDH and 5GDHC can be found in method of heat production. 5GDHC enables connected customers to produce their own thermal energy and share it in the network, whereas 4GDH has a more centralized approach. Moreover, in 5GDHC all thermal energy sources can directly share that thermal energy on even lower temperature levels than 4GDH, as can be seen in the overview provided in Figure 3.1. Another feature is the ability to supply both heating and cooling. Research is not in unanimous agreement about the fundamental differences between the two technologies, but the overview in Table 3.1 provides features that indicate the differences found in literature. Buffa et al. (2019) investigated a set of 40 existing networks in Europe that provide both heating and cooling and proposed a uniform definition for a 5GDHC label:

"A 5GDHC network is a thermal energy supply grid that uses water or brine as a carrier medium and hybrid substations with Water Source Heat Pumps (WSHP). It operates at temperatures so close to the ground that it is not suitable for direct heating purpose. The low temperature of the carrier medium gives the opportunity to exploit directly industrial and urban excess heat and the use of renewable heat sources at low thermal exergy content. The possibility to reverse the operation of the customer substations permits to cover simultaneously and with the same pipelines both the heating and cooling demands of different buildings. Through hybrid substations, 5GDHC technology enhances sector coupling of thermal, electrical and gas grids in a decentralized smart energy system" (Buffa et al., 2019).

Box 3.2

Alternatively, five key features can be identified to classify a 5GDHC as such(D2Grids, 2020):

1. Close the energy loop
2. Using low-grade sources for low-grade demand
3. Decentralized & demand-driven energy supply
4. Integrating energy flows
5. Local sources as a priority

This five-point guideline leaves room for more diversity in 5GDHC network configurations. For this research, the definition in Box 3.2 will be considered the guideline for 5GDHC terminology, but other configurations will be reviewed.

3.1.2 The possibilities of 5GDHC

The development of 5GDHC networks has been discussed and introduced as a technology that could aid in the challenge to significantly reduce emissions in this sector. This subsection elaborates on its potential benefits.

Integrating renewable energy sources whilst reducing thermal losses

The low operating temperatures of 5GDHC allows integration of more low temperature renewable energy sources. Thermal energy sources that did not align with the required operating temperature levels in predeceasing generations DH networks. Examples of low temperatures sources are: geothermal energy, waste heat from data centres or other connected buildings, or seasonal sources like solar collectors, PVT panels or aquathermal energy.

An important observation is that the grid itself does not need to irectly supply the required temperature. The WSHPs located in every energy station are there to generate the required temperature, right at the point of demand. Every building gets exactly what it needs, nothing more. The decentralized, low-temperature network configuration of 5GDHC reduces distribution losses to 5% while 25% is not uncommon in traditional DH (D2Grids, 2020).

The ability to address two different thermal loads

For long, decarbonisation seemed to focus on electricity demand only. Today, the importance to decarbonize the heat provision in the built environment has been recognized by many. This challenge will soon be followed by another: cooling. With rising temperatures and better insulated buildings it is expected that cooling will not just be another luxury. It will be a necessity to maintain a habitable indoor climate (W/E-Adviseurs, 2018). In recent Dutch legislation, cooling measures to prevent overheating is made a requirement for new building projects (Bouwmeester, 2020).

Since 5GDHC supplies both heating and cooling, it holds a unique selling point compared to alternative technologies discussed in the context of the previous section. Heat demand corresponds to a cooling surplus and vice versa, 5GDHC promotes the exchange of thermal energy surpluses between its users to increase energy efficiency. The systems works best if demand for heat and cooling exactly cancel each other out. Usually, this cannot be guaranteed a 100% of the time and renewable energy sources and thermal energy storage facilities are connected to cover the imbalances.

A flexible and robust smart energy system through power grid integration and thermal storage

The distribution of WSHPs in individual energy stations enables sector coupling of heating, cooling and electricity. It allows the optimisation of these

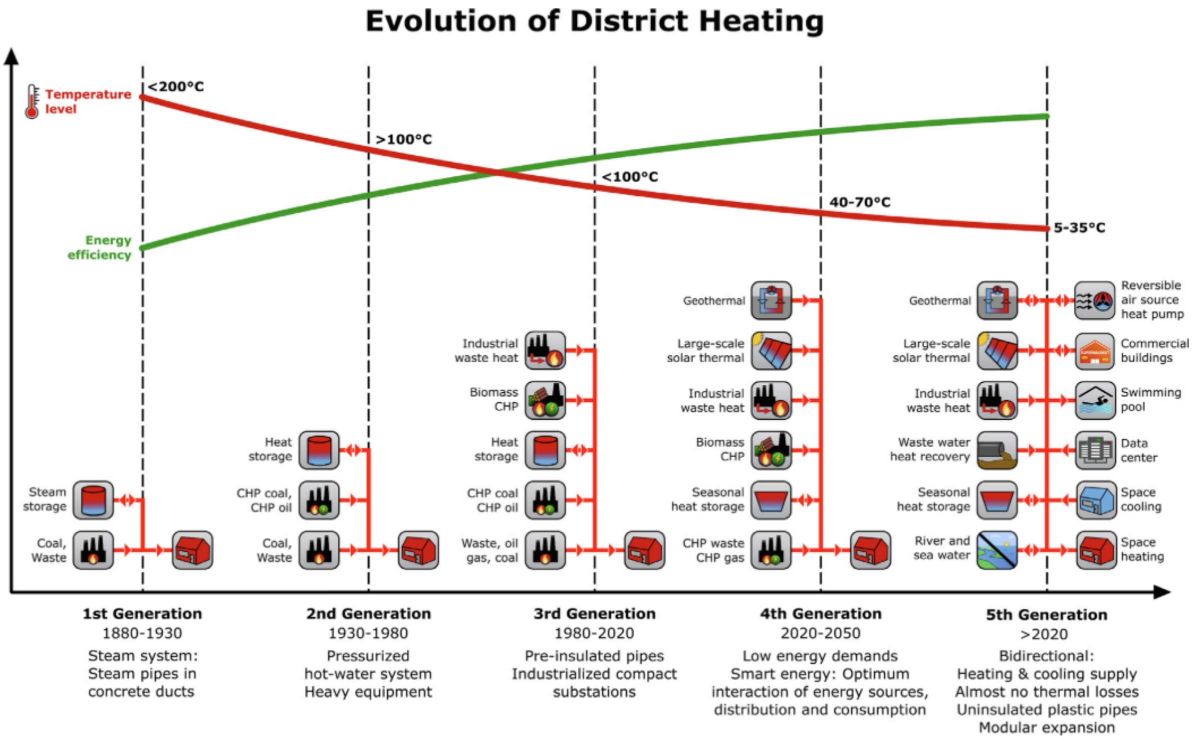


Figure 3.1 – Evolution of DH and DHC generations with 5GDHC as the latest available stage (Wirtz et. al, 2020a)

Table 3.1 – Detailed features of the different DH generations (Roossien, Barkmeijer, & Elswijk, 2020)

	1st gen	2nd gen	3rd gen	4th gen	5th gen
Heat carrier	Steam	Pressurized water	Pressurized water	water	Water
Indicative temperature	150 – 200 °C	100 – 140 °C	70 – 100 °C	35 – 70 °C	< 35 °C
Control parameter	Pressure	Pressure	Supply temperature	Supply temperature	Temperature difference
Circulation system	Steam pressure	Central pumps	Central pumps	Central and decentralized pumps	Decentralized pumps
Energy efficiency	Low	Mediocre	Mediocre	High	Very high
Cooling	No	No	No	No	Yes
Best available	1880-1930	1930-1980	1980-2020	2020-2050	In development

traditionally separate areas. Additionally, coupling enables electricity demand reduction that avoid overloading the power grid. This is due to the higher coefficient of performance (COP) for WSHPs in 5GDHC compared to the HPs commonly used in all-electric heating solutions as they operate with higher Seasonal Coefficients of performance (SCOP) (De Jonge-Baas, 2020). This means they are more efficient, because they need less electricity to supply the same level of heat.

Coupling also allows the exploitation of electricity production from sun and wind surpluses, storing the energy in the form of thermal energy, heat or cold. If weather predictions foresee a period of scarcity in the power grid, it is possible to prepare by preheating buildings, water boilers, the water in the grid itself, and other storage facilities.

Data is a key asset in optimizing the computerized operation between all components. This feature was introduced in the conceptualisation of 4GDH systems and is further developed into 5GDHC systems, where energy flows have increased even more. The integration of heating, cooling and electricity facilities, the thermal mass in buildings or the grid itself and the availability of thermal energy storage at different temperatures and time scales provides 5GDHC systems with a high level of flexibility. Optimizing 5GDHC systems is a non-trivial task, as the complexity and different temperature levels introduce a large number of degrees of freedom (Boesten et al., 2019). Adapting data to forecast optically match production and demand offers a solution to optimize operation of 5GDHC. The system becomes more effective with a smart computerized control system that optimizes these energy flows, so that peaks in the demand and/or supply are dealt more efficiently(D2Grids, 2020). Moreover, 5GDHC is a very adaptable system which can be implemented at a small scale first and then be extended, according to the needs for heating and cooling.

3.1.3 5GDHC labelled networks: the differences

Although definitions have been proposed in literature, variations of 5GDHC labelled networks can be found in practise and literature. Network topologies of multiple hierarchical levels that can differ in the number of pipes, the temperature levels and installed network components have been documented. This subsection elaborates on a number of design differentiations for 5GDHC systems.

Hierarchical networks

The topology of 5GDHC is no longer tree-structured, but for connecting local networks into larger district heating and cooling systems a hierarchal approach can still be found useful. The system and its connections

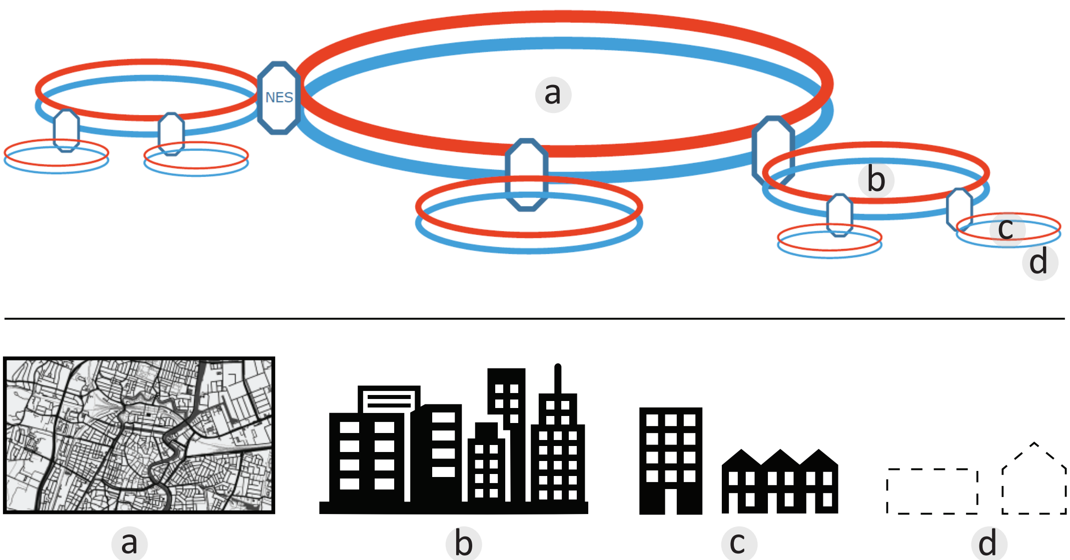
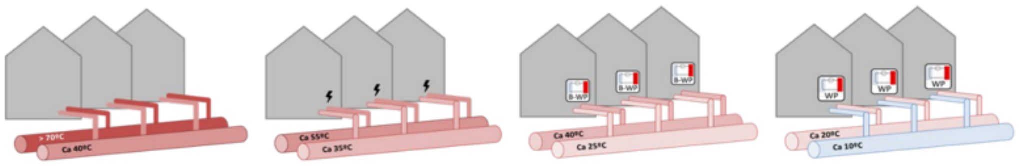


Figure 3.2 – The 5GDHC hierarchical levels: (a) the district or backbone, (b) urban block, (c) street and building unit level, adapted from (Jansen et al., 2019).



HT High Temperature	MT Medium Temperature	LT Low Temperature	ULT Ultra-Low Temperature
Hot > 70 °C Cold ~ 40 °C	Hot = 45 – 70 °C Cold ~ 30 – 40 °C	Warm = 30 – 45 °C Cold = 18 – 30 °C	Warm = 10 – 30 °C Cold = 5 – 18 °C
Direct supply of hot water	Additional solution for hot water	Direct space heating, booster HP for DHW	HP for space heating and DHW

Figure 3.3 – Temperature levels in DH systems, adapted from (Jansen et al., 2019)

can be divided into four scales which are defined as (a) district or neighbourhood level, also often referred to as the backbone, (b) the urban block level, (c) the street level and finally: (d) the building unit level as can be seen in the overview in Figure 3.2.

Different design choices can be made for different levels, creating DHC networks consisting a variety of temperature levels with configurations for the number of pipes and features each scale.

Temperature levels

DH networks are often defined by their temperature level, as was introduced in section 3.1.1. The concept of 5GDHC lowers the operating temperature below 35 oC in the warm pipes, which is referred to as ultra-low temperature (ULT). Other temperature levels and their corresponding labels can be seen in Figure 3.3. ULT is usually insufficient for direct use and water temperatures are thus boosted in or near the building unit.

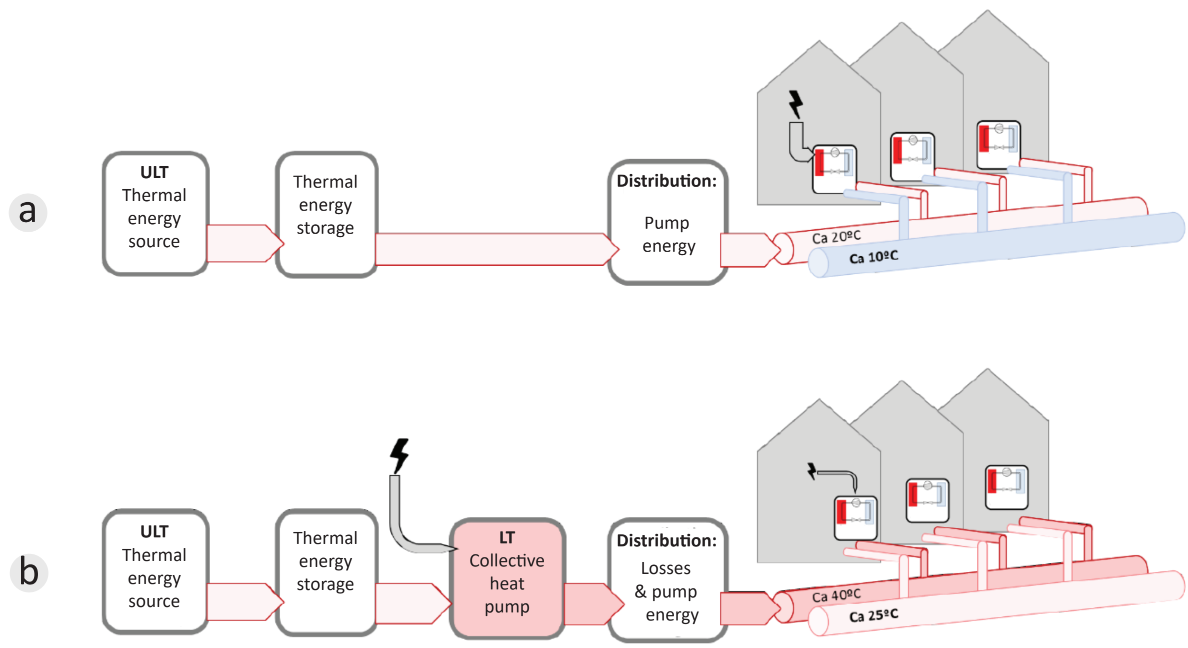


Figure 3.4 – (U)LT configurations and temperature levels at building level, adopted from (Jansen & Verhoeven, 2020)

The specific location where temperature is boosted is where a distinction can be found. It can either be boosted at the local building level or at a connection point for multiple buildings. This creates two different configurations, as can be seen in Figure 3.4.

A reversible WSHP at the individual building level is able to supply both space heating, cooling and domestic hot water demand. Boosting the ULT level can also be achieved one sub-level higher: on a street level. A collective HP means boosting at the building unit level can be achieved by a booster HP, since the supply temperature is high enough to supply space heating directly. However, since the cold pipe temperature at the building units' level is considerably higher, circa 25 °C instead of 10 °C, means cooling cannot be supplied directly. The optimal solution is case-dependent and is determined by the building features, available thermal energy sources and spatial parameters and requirements set for heating and cooling options for the connected buildings. The choice for either active or direct (passive) heating and cooling affects the boosting requirements at the building unit level.

Direct or active heating and cooling

If the required supply temperature level is met by the warm pipe of the 5GDHC network, it can be used for heating directly, meaning it does not need any additional boosting equipment. This option is referred to as direct heating and it works equally for the cold pipe and cooling. When temperature of the cold pipe allows cooling without additional equipment, it is referred to as direct cooling. However, if additional boosting equipment is necessary to achieve the required supply temperatures, operation is then referred to as active heating and active cooling correspondingly.
Based on the indicative temperatures for direct (passive) or active heating and cooling, a number of typical temperature levels for heating and cooling networks can be distinguished. Only two-pipe configurations are displayed to align with the 5GDHC definition in Box 3.2.

1. **Direct cooling and active heating**
   a. T hot pipe < 24 °C
   b. T cool pipe 8 - 12 °C
2. **Active cooling and direct heating**
   a. T hot pipe 35-45 °C, sufficient for direct space heating
   b. T cool pipe = T warm pipe – 10 °C
3. **Active cooling and active heating**
   a. T hot pipe 20-30 °C
   b. T cool pipe 12-17 °C

Although direct space heating is enabled in the second configuration, it still requires a booster HP to lift temperatures for DHW utilization. Additional information on two, three and four pipe configurations

Table 3.2 – Potential thermal energy sources with corresponding temperature level (Jansen & Verhoeven, 2020)

Thermal energy source		Temperature level	Notes
Aquathermal energy			
	From surface water	2-24 °C	Seasonal dependence
	From wastewater	8-25 °C	Locational, operational and seasonal dependence
	From drinking water	10-18 °C	
Solar energy			
	Vacuum collector	60-90 °C	In general: increasingly higher required output temperatures result in decreasing number of full load hours
	Flat plate collector	40-60 °C	
	PVT	15-40 °C	
	PVT + heat exchanger	-10-30 °C	
Lucht			
	Outside air	-10-30 °C	Seasonal dependence
	Exhaust air from e.g. parking, metro	15-30 °C	Seasonal dependence
Waste heat from industry			
	Various options	20-90 °C	Depends on the industry
	Datacentres	20-40 °C	Depends on cooling mode

and their respective pros and cons can be found in (Jansen & Verhoeven, 2020). When there is abundancy of (U)LT heat sources and supply exceed demand in the network, designing for passive cooling is arguably not the optimal solution. In this case, opting for active cooling and passive heating is recommended.

Other Network components

Building mix

The efficiency and profitability of 5GDHC strongly depends on the heating and cooling demand structure in the connected buildings. Their thermal energy surpluses can be used to optimally balance within the network. In an ideal bidirectional LT network like 5GDHC, heating and cooling demands are of the same magnitude and occur simultaneously (Wirtz et al., 2020a). However, it is to be expected that many households dominated neighbourhoods do not have equal heating and cooling demand, which can be compensated with either thermal energy sources and thermal energy storage facilities.

Thermal energy sources

When balancing is not enough, thermal energy sources and storage facilities can be utilised. For 5GDHC this means prioritizing efficient utilisation of the locally available ULT thermal energy sources. Different thermal energy sources and their corresponding temperature ranges are presented in Table 3.2. Thermal energy sources higher than ULT can be connected. However, this would mean a loss of thermal energy and is therefore not recommended. When balancing is not enough, thermal energy sources and storage facilities can be utilised. For 5GDHC this means prioritizing efficient utilisation of the locally available ULT thermal energy sources. Different thermal energy sources and their corresponding temperature ranges are presented in table 3.FIXME. Thermal energy sources higher than ULT can be connected. However, this would mean a loss of thermal energy and is therefore not recommended.

Thermal Energy storage (TES)

Daily and seasonal imbalances between heating and cooling demand and generation can be solved with thermal energy storage (TES). TES are available on various time and space scales. The short term or daily TES is commonly installed on a building level, to smoothen peaks mainly caused by domestic hot water usage. Long-term or seasonal storage can be installed to compensate seasonal fluctuations on the demand and supply side. Typical technologies for long term storage are e.g. phase change materials, thermochemical storage and underground heat-cold-storage (Roossien et al., 2020). The latter often needs to be replenished approximately every five years.

Balancing Station

The purpose of a balancing station or BAS is to balance the mass flow and thermal energy flow in a network. Balancing stations can be combined with network exchange stations, by either by integrating them or by being physically present in the same building, but with its own network connection.

Network exchange station

The network exchange station allows thermal energy transfer between two networks, while keeping them hydraulically separated. The design, operation and objectives for a NES varies depending on the topology of the system and the intend of the designer

3.2 Trends and challenges of smarter energy networks

5GDHC is considered a consequence of recent smart grid developments. The concept of designing a 'smart grid' originates from the power sector, where it has been a research topic for almost a decade now.

> *"a* **Smart Grid (SG)** *is one that incorporates information and communications technology into every aspect of electricity generation, delivery and consumption in order to minimize environmental impact, enhance markets, improve reliability and service, and reduce costs and improve efficiency" (El-hawary, 2014).*
>
> **Box 3.3**

Transforming our traditional centralized energy networks into smart energy networks has several advantages and a great potential for energy savings and decarbonisation. Meanwhile, this new DHC technology is based on fundamentally different concepts and implementation presents new challenges and complications. This section aims to clarify the smart grid concept as referred to in this report, its features and the corresponding challenges it faces.

3.2.1 The rise of smart electrical and thermal grids

The concept of electrical smart grid (SG(e)) has been defined as seen in Box 3.3. The development of information and communication technologies have spiked the smart grid research and the components that collectively form and operate as a smart grid. Concepts like Distributed Energy Resources (DER), Demand Side Management (DSM), Demand Response (DR) Smart Metering (SM), Smart Homes (SH), and Smart Appliances (SA) are considered SG applications. More detailed information about these concepts can be found in (El-hawary, 2014). Nowadays, SG technologies have grown beyond the power sector. A promising outlook on what our energy sector could look like presents entirely integrated smart energy network: e-mobility, electricity, heating and cooling appliances are communicating on a real-time basis to enable the most efficient operation, and prosumers actively take part in a smart energy environment.

> **Smart Thermal Grid, SG(th)**: *"a network of pipes connecting the buildings in a neighbourhood, town centre or whole city, so that they can be served from centralized plants as well as from a number of distributed heating and cooling producing units including individual contributions from the connected buildings" (Lund et al., 2014).*
>
> **Box 3.3**

Consequently, SG concepts have also sparked an interest within district heating and cooling research. So-called thermal smart grids (SG(th)) have been defined by Lund et. al in (Lund et al., 2014).

Thermal smart grids (SG(th) and electrical smart grids (SG(e)) face slightly different challenges. They differ in the sense that they face different challenges. The biggest challenge for SGs(th) is the utilisation of LT thermal energy sources and the interaction with low-energy buildings. SGs(e)'s biggest challenge is to ingrate the fluctuating and intermittent electricity production from the various renewable sources (Lund et al., 2014). Identifying their differences and similarities provides insight into the possibilities and limitations for both technologies. It provides insights into the dos and don'ts that can be applied for SG(th)s.

The first important difference is that TES is more mature and less expensive than storing electricity, especially for long-term applications. Implementing batteries on a household level is neither as affordable nor as widespread as its thermal counterpart. Long-term storage of electricity is even more challenging.

Additionally, the availability of thermal mass offers more flexibility to the system. Cutting power supply causes instant discomfort to its users, while temporarily limiting heating and/or cooling supply can stay unnoticed for four to eight hours, depending on building insulation.

Another important difference is that electricity household demand is driven by numerous different electrical appliances. Each with their own brand, own operating system and software. For heating and cooling, this number is significantly lower, which indicates making these appliances smarter and communicative promises to be less complex.

3.2.2 Demand side management

Demand side management is a feature of SGs that could minimize cost and increase the share of renewables by reducing thermal peaks. It means modifying the demand of end-users, mainly utilized to reduce gaps between demand and production. Existing DH networks are designed to facilitate the highest coinciding network peak. In practice, this critical network peak is usually only achieved during the coldest winter day, if at all. Implementation of renewable energy sources is hampered when load profiles with significant oscillations and peaks create a mismatch between demand and supply that drives up cost and requires fossil back-up facilities. There are a number of options to overcome this problem (Guelpa & Marincioni, 2019):

1. Install short- and long-term thermal energy storage facilities
2. Exploit the thermal inertia of the DHC network and the connected buildings
3. Implement demand side management (DSM)

The first two are fundamental parts of 5GDHC systems, whilst DSM is a feature which can be exploited before or during 5GDHC operation. Experience in this research area has been gained mostly in the electricity sector so far but has started to gain interest in the field of DHC too. DSM is a method to reshape the thermal load profiles.

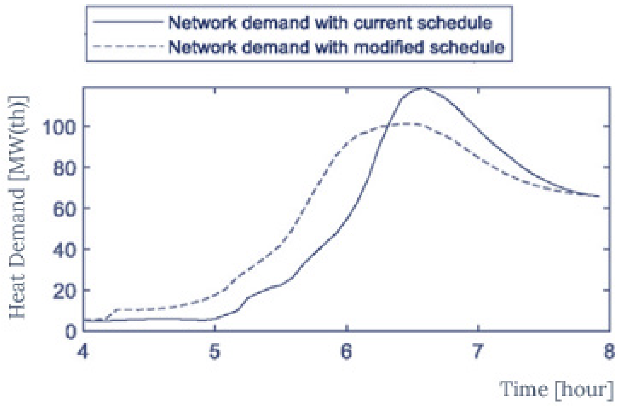


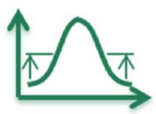
Figure 3.5 – An illustrative network thermal load profile before and after DSM: about 30% peak demand reduction (Guelpa & Verda, 2021).

Different goals can be selected for DSM such as security of supply, cost minimisation or best integration of renewable sources. As depicted in Figure 3.5, DSM can reduce network thermal peak demand by about 30%. Depending on the objective, reducing thermal peaks does not necessarily have to be the best strategy to achieve the best possible outcome. This is subject to local conditions, such as availability of thermal energy sources, the DHC network design and the connected buildings. Some objectives do experience overlap, as thermal peak reduction is argued to reduce costs for existing and future DHC networks, whilst contributing to a more sustainable heating and cooling provision at the same time (Menkveld et al., 2021). An overview of potential DSM effects on DHC systems can be found Appendix D, this section focusses on the impact of thermal peak reduction.

Reducing thermal load peaks is in line with the ambition increase of the share of renewables in the DHC sector. The heating and cooling sector is undergoing a shift from fossil-based HT or MT DH networks towards LT and ULT DHC networks where high ratios of renewable energy utilisation are desired. The current heat demand is highly volatile, at both seasonal and daily timescales. Meanwhile, base load and seasonal LT sources are available, but at low energy density and often with limited capacity. On the other hand, storing thermal energy is relatively cheap, compared to storing electricity. This combination makes DSM rather attractive from the LT TES utilisation perspective too. This is true for existing and future networks. 5GDHC and 4GDH systems are by definition equipped with the technological tools to facilitate the high level of control and data exploitation that DSM requires. The effects of DSM systems can potentially increase 5GDHC implementation and therefor lead to a higher share of renewable LT thermal energy sources in our heating and cooling provision.

Reducing thermal peaks can be used to achieve lower infrastructure and operational costs of SGs(th). The overall network capacity for future networks can

Table 3.3 – Adjusted load profiles as a result of DSM (Eid et al., 2016)

Thermal load profile	DSM strategy	Thermal load profile	DSM strategy
	Peak clipping		Load shifting
	Valley filling		Flexible load shapes (dynamic energy management)
	Load building (strategic load growth)		Strategic conservation (energy efficiency)

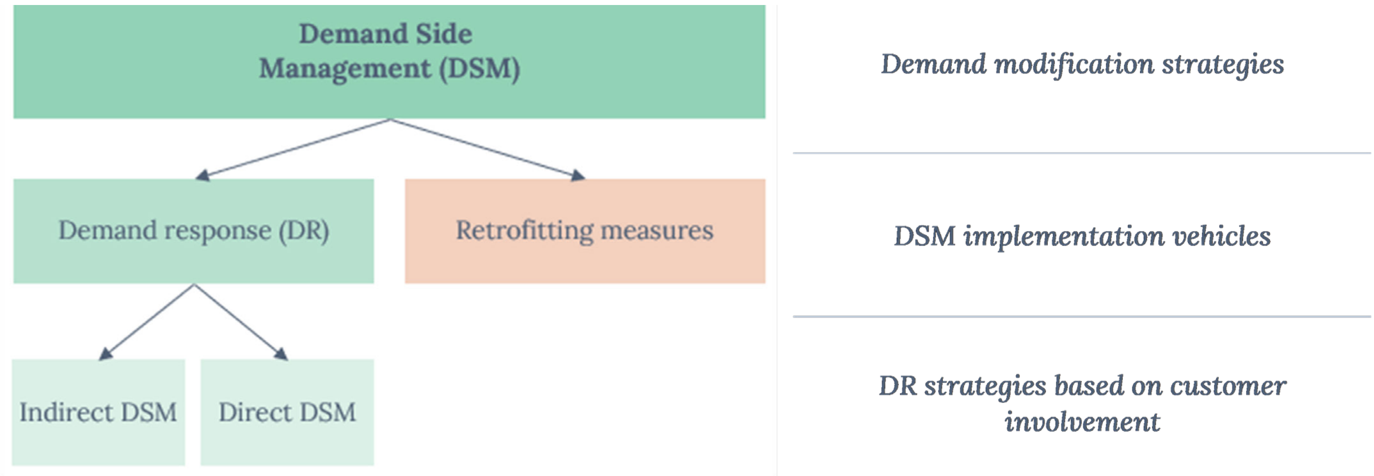


Figure 3.6 - DSM terminology and implementation, adapted from (Respond-Project, 2021)(Guelpa & Verda, 2021)

be reduced or more buildings can be connected onto existing networks without additional pipelines. Expensive peak and back-up facilities are less or not needed anymore to step in when critical network peaks occur. In operation, electricity consumption of network pumps can be reduced and lower network temperatures are enabled. These potential cost reductions due to DSM could boost 5GDHC implementation, given that the gains of DSM outweigh the cost (Menkveld et al., 2021).

DSM Implementation and tariff implications

Adjusting thermal load profiles can be done by retrofitting, direct and indirect DSM. Retrofitting means permanently modifying connected buildings for example applying insulation. It is considered DSM, but is subcategorized as energy efficiency measures as depicted in Figure 3.6. Retrofitting is an interesting option to increase suitability of buildings for direct or indirect DSM. Indirect DSM uses tariff structures with incorporated incentives to motivate customers to adjust their thermal load profiles. Using direct DSM or direct load control, means thermal loads in the network are managed and controlled by an operator. Several points can be made for to opt one or the other. For instance, while indirect DSM has more uncertain outcome, direct DSM requires levels of automation of control that some customers are not comfortable with.

3.3 Economic perspectives in the energy transition

This section is meant to present different economic perspectives on value related issues in the energy transition. These perspectives are presented and discussed to set up a conceptual framework to prepare for the more empirical tariff design steps. This is a necessary step before starting the tariff design process, because the logic behind the choices in this more empirical process are derived from the perspectives linked to this conceptual framework.
The first section will introduce three schools of economics: Neoclassical Economics (NCE), New Institutional Economics (NIE) and Original Institutional Economics (OIE). It illustrates the different economic lenses through which different perspectives on energy policy and public values are demonstrated. The next section discusses how one would deal with value related issues in the energy sector through these different lenses. Finally, the last section discusses how these different economic perspectives relate to the tariff design process.

3.3.1 Introduction to the economics

Neoclassical Economics

Neoclassical Economics (NCE) is considered a base for much of the economic theories that are developed over time and often considered ‘mainstream economics’.

In NCE both producers and individual consumers are considered rational actors who have access to all the relevant information to maximize their profit or utility and have access to the corresponding means to do so. Anyone can perform their own cost benefit analysis to determine the price they are willing to pay. The market mechanism is at the core for realizing an equilibrium between demand and supply, for which fundamental conditions need to be met to guarantee the establishment of an equilibrium.

In that process, the market is a mechanism that enables the most efficient solutions to survive (Groenewegen, 2004). In this equilibrium, where a certain amount of goods is traded at an equilibrium price that is accepted by both consumers and producers. This competitive environment forces suppliers to produce at minimal cost (productive efficiency) according to the preferences of the consumers (allocative efficiency) (Correljé & Groenewegen, 2009). In NCE, corrective action should (re)establish competition and a new equilibrium if any problems occur and the market is not functioning as described (Correljé et al., 2014).

New Institutional Economics

Another perspective can be found in the school of New Institutional Economics (NIE), where the presumed perfect market conditions of NCE do not apply. In NIE, the line of reasoning of NCE is maintained: the actors maximize profits and utility while minimizing costs. However, the focus of this economic lens is different. It focusses on the question why institutions exist and why do they matter? (Correljé et al., 2014). In contrast to NCE, NIE introduces the existence uncertainty and risks into its perspective of markets and transactions. Not every aspect of relevant information is known, accessible or evenly distributed amongst all actors in the imperfect market NIE considers. This so-called 'bounded reality' means actors have limited access to retrieve, process and utilize relevant information to maximize their utility.

The Transaction Cost Economy (TCE) is one of the pillars of NIE. The purpose of transaction cost economics (TCE) is to understand why different modes of governance exist to coordinate economic transactions(Correljé et al., 2014). Coase (1937) describes transaction costs as the costs of seeking out price information, negotiating, and establishing the terms of the transaction in a contract. This definition was broadened to include the costs of preparing, monitoring and enforcing those contractual relationships (Eggertson, 1990). Institutions exist to reduce transaction costs. Figure 3.7 present the institutional order. The upper levels set the conditions for the lower levels.

Values, norms, traditions in society are considered informal institutions. This first level sets the boundaries for the formal institutions of laws and regulation at the second level. The formal institutions like laws and regulations are subject to the so-called "first order economizing": governance structures as a typically NIE dictated level. The different distributions of property rights are key in this second level. For each configuration impacts the behaviour of actors differently and results in different outcomes. Given the institutional embedding and the formal rules of the game, the third level concerns the question of how then actors organize their transactions. Several options like market contracts, organisations or via hybrids like public-private-partnerships can be arranged. Theoretically, so-called second order economizing will ensure the governance structures

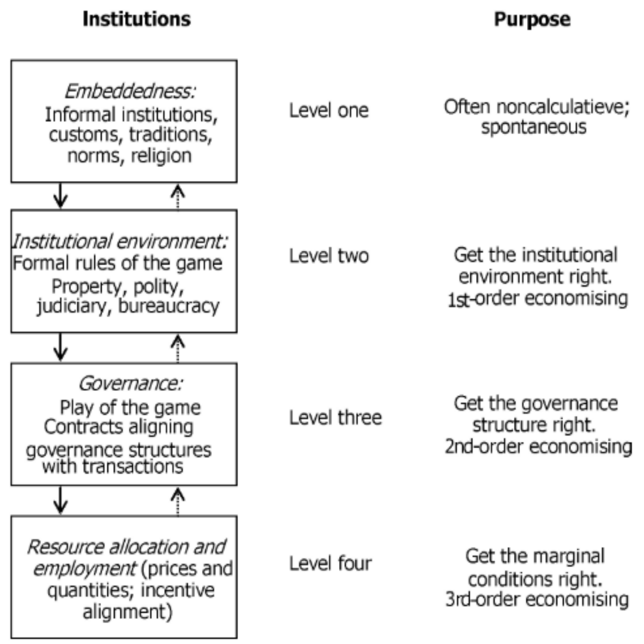


Figure 3.7 - The Economics of Institutions (Williamson, 1998)

that minimize the transaction costs will prevail. Third order economizing is found at the final and fourth level, where market participants allocate their resources from a NCE perspective so that they minimize costs and maximize profit or utility.

Original Institutional Economics

NCE/NIE-based perspective of efficiency-driven market creation and facilitation was predominant until halfway through the first decade of the twenty-first century (Correljé et al., 2014). An alternative approach can be found in Original Institutional Economics (OIE) which starts out with heterogeneous actors, with preferences that are influenced by formal (level 2 in Figure 3.7) and informal institutions (level 1) (Correljé & Groenewegen, 2009). OIE approaches markets and nonmarket allocation mechanisms differently. It starts by finding societies' collective values: what ought to be and what is the end. The mismatch between the two is then a starting point for further action like re-allocation of rights for example. The analysis of processes is the core of OIE. What ought to be can have different outcomes when asked different groups in society. This may change over time too which is why social welfare is considered a phenomenon that is identified, articulated, developed and operationalised in a socio-political process at a given society and time(Correljé & Groenewegen, 2009). This a fundamental difference from NCE and NIE.

3.3.2 Value perspectives in a sustainable and smart energy system

The economic perspectives provide different lenses which can be applied to energy policy for renewables in general and SG(th) implementation. The corresponding approaches provide the context in which tariff design operates, without solely focusing on the tariff structures themselves. Where an NCE/NIE focused approach is typically efficiency based, the OIE approach demonstrates a broader perspective, where some virtues are considered more "right" by societal standards than others. Here, the preference for any mechanism does not solely depend on its efficiency, but also on its positive or negative impact on other values and norms supported by a society. For collective action to be effective and efficient, it is necessary to not only apply the efficiency perspective of NCE and NIE, but because the change in working rules (implicitly) implies a re-allocation of rights there should also be a careful assessment of the implications for all actors, as potential winners and losers (Correljé & Groenewegen, 2009). This applies to the energy sector as a whole, as much as the implementation of new innovative technologies such as SGs(th).

The energy system

The presented economic perspectives differ in their approach to energy policy. Depending on the perspective, different tasks are carried out to achieve the best value trade-off. For the energy system as a whole, the traditional value trade-off is commonly referred to as the "Energy Trilemma" (Carbon-Brief, 2013). This trilemma balances affordability with security of supply and environmental sustainability. The Energy trilemma is an example of value trade-offs that arise when different economic perspectives are applied. The economic perspectives represent different interpretations of the optimal outcome and the corresponding course of action to follow up.

A NCE economist would focus on corrective measures to be taken by the relevant authorities. Corrective actions like enabling access to relevant information for its participants or correcting companies that behave anticompetitively. Follow-up action of a NIE economist would result in complementary advice for firms and public authorities on how to arrange the best institutional framework to facilitate that specific market. In short, the preference for any outcome does not only depend on its efficiency but also on its positive or negative impact on other values and norms supported by a society. An OIE would thus focus on individual and collective values that emerge and which can change over time and place. The resulting value trade-offs have consequences for the well-being of the different societal groups and can be judged as acceptable, while future (r)evaluations may alter that verdict. The tariff design objectives follow from the accepted compromise and exists by the grace of social acceptance.

Aside from the Energy Trilemma, other often discussed values in the context of (smart) energy networks commonly debated are (Pfeiffer, 2017) (De Wildt et. al, 2019) :

- **Reliability or security of supply:** the system is capable of performing without failure under a wide range of conditions.
- **Environmental sustainability:** the system does not burden ecosystems, so that the needs of current generations do not hinder future generations.
- **Competitiveness:** The system offers an economic advantage
- **Efficiency**: The system has high effective operation as measured by a comparison of production and cost (as in energy, time, and money).

- **Safety and health**: The system does not harm people.
- **Justice**: The system is just, impartial, or fair.
- **Privacy:** The system allows people to determine which information about the need to control is used and communicated.

These values are often translated to regulatory principles and consequential measures when the desired level of fulfilment is not fulfilled.

Conflicting values in smart grid environments

SGs are considered a key enabler in the energy transition, while their deployment could be jeopardized by looming social acceptance issues. Social acceptance issues could originate from conflicting values and the inability of current regulatory and institutional framework to solve these conflicts. Tariff design could sooth or intensify social acceptance issues. Wildt et. al (2019) selected seven key values to study to anticipate social acceptance issues for SG(e)s and encountered five conflicts. The seven studied values are: reliability, environmental sustainability, competitiveness, efficiency, safety & health, justice and privacy. Based on these key values, Wildt et. al (2019) identified five groups of value conflicts that are connected or affected by the deployment of the SGs(e): consumer values versus competitiveness, IT enabled systems versus data protection, fair spatial distributions of energy systems versus system performance, market performance versus local trading, and individual access versus economies of scale. The value conflicts that result from the seven studied key values are relevant for SG(th)s too, as most conflicts can be expected to apply

Table 3.4 – Illustration of acceptance issues resulting from value conflicts (Wildt et al., 2019)

	Socio-political acceptance issues	Community acceptance issues	Market acceptance issues
B1 - IT enabled systems versus data protection	- Inadequate privacy standards - Rejection of legislation by legislative bodies	- Tensions between individuals - Resistance from local authorities	- Limited consumer adoption - Limited investments by industry
B2 – Individual access versus economies of scale	- Protest movements on national level - Mistrust for governmental institutions - Rivalry between governmental institutions - Inadequate policies for technological development - Lack of political commitment	- Tensions between individuals and communities - Resistance from local authorities	- Limited consumer adoption - Limited investments by industry - Path dependencies leading to socially undesirable technologies
B3 - Market performance versus local trading	- Inadequate technology standards - Mistrust for governmental institutions	- Tensions between individuals	- Limited consumer adoption - Limited investments by industry
B4 - Fair spatial distributions of energy systems versus system performance	- Inadequate special planning - Mistrust for governmental institutions	- Opposition against building permits - Tensions between individuals and communities - Protest movements on local level	- Limited investments by industry - Non-involvement of consumers
B5 - Consumer values versus competitiveness	- Inadequate technology standards - Mistrust for governmental institutions - Inadequate policies for technological development - Rejection of legislation by legislative bodies	- Tensions between individuals and communities	- Limited consumer adoption - Limited investments by industry - Lobbying against new legislation

for SG technologies in general. An overview of the value conflicts subdivided using the triangle of social acceptance as proposed by Wüstenhagen, Wolsink, & Bürer (2007). Consequent social acceptance issues can be found in Table 3.4.

3.4 Role distribution in district heating and cooling

After the institutional embedding is established, the framework in which different structures and role distribution can be organized is ready. A NIE perspective suggests that transaction costs minimisation is the main determent for choosing the optimal structure. The OIE perspective suggests a reallocation of rights can be considered when public values are not safeguarded in the NIE based optimum. A division can be made between property rights (ownership) and decision rights (control).

When applied to the DHC systema and the market in which it operates, there are several different roles to be fulfilled in DHC systems. The different actors involved, the technological features and the nature of its corresponding transactions play a role in matching the suitable parties for role distribution. Depending on the tariff design objectives possible configurations of one or more parties can be designed. First, the value chain and how potential configurations line-up in the current Dutch legal system are discussed.

3.4.1 DHC market

Several roles and corresponding responsibilities can be recognized when examining the DH system and its value chain (Wiegerinck, 2020). As depicted in figure 3.8, the first role is that of the producer of thermal energy. The thermal load planner is responsible for balancing supply and demand. A Distribution System Operator (DSO) transports the thermal loads to the consumers. In case of a backbone or transmission grid, a Transmission System Operator (TSO) facilitates the feed in of thermal energy into the distribution grid. The provider sees to the delivery and billing of heating and cooling. Traditionally, the consumer would be the final stage where heating and cooling is consumed.

Four straightforward organisational structures can be thought off: private, public or public/private partnerships. The schematic overview of figure 3.9 provides a rough idea of what those set-ups would look like for a simplified role distribution. The responsibility of production and transport to through

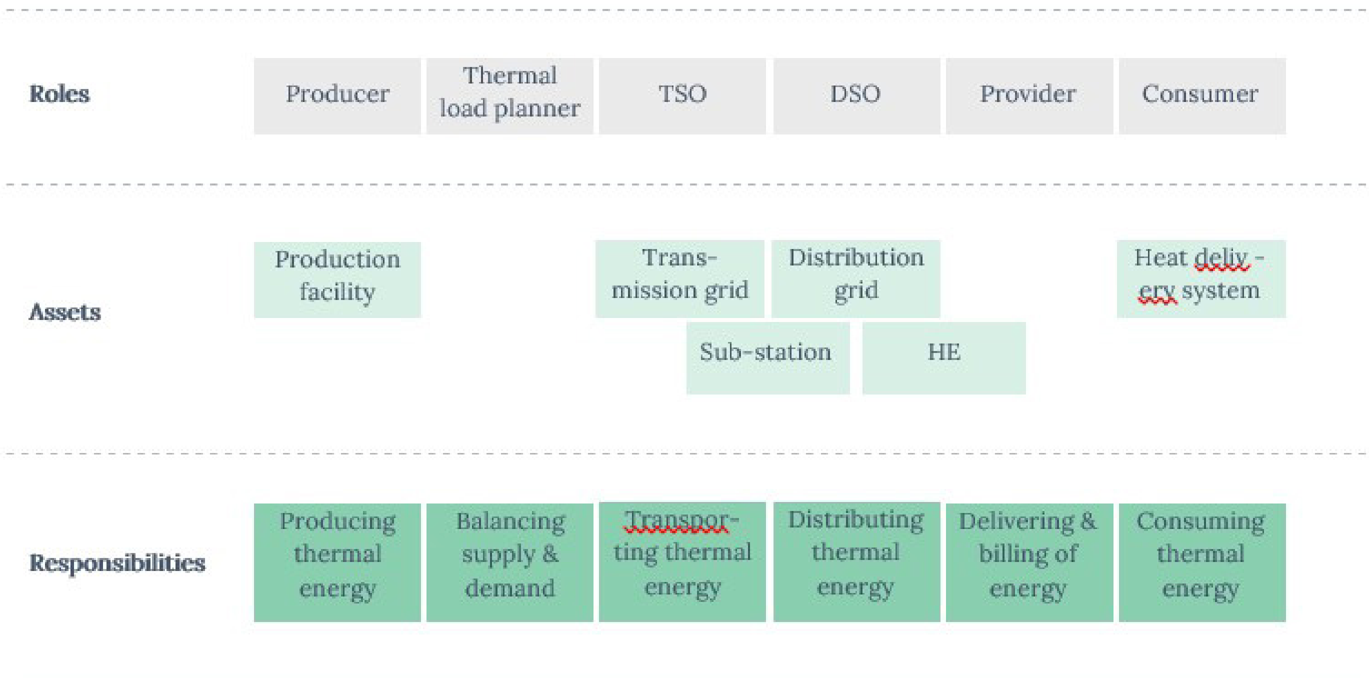


Figure 3.8 – The value chain for DH systems, per role, assets and main responsibility, adapted from (Wiegerinck, 2020)

Organizational structures (Actors) / Function	Production & transport	Distribution	Delivery	Consumption
Private	Company	Company	Company	Building owner
Public	Governmental	Municipality	Municipality	Building owner
Private / public	Company / Governmental	Company / Governmental	Company / Governmental	Building owner
Private (small-scale)	Company		Company	Building owner

Figure 3.9 – Basic examples of organisational structures for DHC systems, adapted from (Fakton-Energy, 2020)

the backbone to the distribution grid are combined into one role.

5GDHC systems are essentially a network of prosumers: consumers who both consume and produce. Table 2 displays roles for 5GDHC systems as a part of the KoWaNet research, where a number role definitions are added, split and/or slightly adjusted compared to traditional roles. Parties can fulfil one or more roles, bounded by legislation and regulation in the institutional environment.

To carry responsibility for a specific function does not automatically mean that one has to actually carry out the execution. Execution can be outsourced to one or multiple parties. Depending on the market model and cooperation structures, different functions can coincide.

3.4.2 Allocation of property and decision rights in 5GDHC

Property rights are a pillar of NIE theory. In NIE, firms and other relevant actors will negotiate about finding a comprise where re-allocation of rights is agreed at the price that the other is willing to pay to exercise the others' property right. When the NIE optimal outcome is not aligned with societal preferences, a re-allocation can be enforced to safeguard public values. Alternatively, decision rights can be contractually arranged to empower relevant actors that could not effectively exercise power otherwise. Reallocation of property and decision rights can thus be motivated from an OIE perspective. When the governance structure is not resulting in satisfactory value trade-off to all actors in the system, shifting property and decision rights can increase public support.
For 5GDHC systems, the allocation of decision rights impacts (Müller et. al., 2020):

- Decisions on tariff design;
- Choice of thermal energy sources;
- Decisions to expand or reinforce the network or to connect it to other network(s);
- Allocation any profits;
- Decisions on management and maintenance and outsourcing thereof
- Decisions to dispose (parts of) the network

An example of reallocation rights to compensate for a suboptimal outcome from an OIE perspective can be found in DeZONNET research. Possible organisational structures for 5GDHC systems within the Dutch context were examined with special attention for property and decision rights. The report suggests that limited individual freedom of choice can be compensated through creating transparency and allocating decision rights to the community through participation in a local energy firm ("Marktmodellen

DeZONNET", 2020).

3.4.3 Monopolistic nature of DHC

A DHC system is by definition of monopolistic nature. As the average costs of operation in DHC decreases with the volume of the heat transported, the infrastructure shows the characteristics of a natural monopoly. Additionally, switching to alternatives is hard for its connected customers.

Table 3.5 – Functions of 5GDHC (Jansen & Verhoeven, 2020)

Function	Explanation
Thermal load planner	Party which determines how much thermal energy is produced and transported at each specific moment in time by which sources and to which customers.
System operator	Party which ensures that the correct amount of heat or cooling within the requirements is distributed from one palce to the other.
Market operator	Party which facilitates market place for supply and demand, from which a daily (or similar) program follows that system operator and producers implement.
Balancing	Party which instantaneously creates balance of heating vs. cooling supply and demand by using IT enabled control mechanisms.
Metering	Party which performs measurements to facilitate billing and account for thermal losses in the network.
Supplier	Party which purchases heat and cooling from producers and sells it to customers and is responsible for security of supply.
Producer = consumer	Party which purchases heat and cooling from producers and sells it to customers and is responsible for security of supply.
Consumer = producer	Party which consumes heat or cooling as an end-user.
Network owner	Party that owns the 5GDHC network (possibly with multiple shareholders) and allows for the construction, maintenance, access and expansions of the network.
TES owner	Party which owns the the TES facility.

Thus price inelasticity is low due to high transition cost to alternative technologies. Due to the monopoly nature, the objective to protect its customer from monopolistic power has been a main focus of DHC regulation and play a role when allocating property and decision rights.

3.5 Conclusion: Why is 5GDHC tariff design complex?

This literature review introduced the concept of fifth generation district heating and cooling and its potential benefits and possibilities. This SG(th) technology allows for cost reductions and increased sustainability by balancing thermal energy flows and optimisation through SG applications, such as DSM and DG by prosumers. Tariff structures for these innovative networks is complex for a number of reasons. The concluding statements support the hypothesis that 5GDHC tariff design is indeed a complex process which was phrased as the first sub-question for thesis research:

Q.1	*What makes tariff design for 5GDHC complex?*

Its complexity is caused by many factors. F**or one, 5GDHC tariff design is new. Guidelines, documentation and operational experience of 5GDHC systems is very limited. 5GDHC combines technological features – e.g., DG, DSM, prosumers - that are not commonly incorporated in DHC systems and its tariff design yet.** It is an innovative technology that enjoys increasing attention in the field of research, but is still lacking widespread operational experience. For one, 5GDHC systems are designed to optimally adapt to local conditions which allows for a wide variation of network configurations based on available TES and building mix. These differentiations should be taken into consideration when designing tariff structures, because different impacts of tariffs can occur when proposing a tariff based on a few reference 5GDHC systems. These differences can be better quantified when more experience is gained by pilot projects and/or other realized 5GDHC systems.

Secondly, c**hanging existing tariff structures and the corresponding institutional framework will result on winners and losers of that change.** Each economic perspective has their lense on how to view energy policy and safeguard public values. Selecting the appropriate tariff objectives is a trade-off between NCE/NIE driven efficiency objectives and OIE originated social values. In general, moving away from fossil-based energy systems, means re-establishing this trade-off. Finding a compromise that satisfies all active and passive actors involved while creating flexibility to respond to future (r)evaluations is a difficult task. Altering the status quo has implications that are beneficial for some groups and detrimental to others. Without careful consideration, public resistance could grow and hinder successful implementation.

Thirdly, t**ariffs can sooth or exemplify social acceptance issues of 5GDHC due to looming value conflicts in 5GDHC and for smart grid environments in general.** Any tariff structure and corresponding institutional and regulatory embedment of 5GDHC tariff design should reflect on social acceptance issues. These issues, such as fairness and privacy in particular, can jeopardize roll-out of thermal smart grids like 5GDHC, which backfires the objective of new tariff structures all together: support 5GDHC implementation. Adding the 'right' incentives to support 5GDHC is a complex assignment. By iteration, the impact of new tariff structures should be evaluated and analysed to check whether its performance is acceptable.

Additionally, d**esigning and implementing tariff structures is not a stand-alone task. It requires a multi-disciplinary approach to facilitate their deployment.** All in all, 5GDHC tariff design is embedded in a technological, economic and institutional framework. Identifying and understanding the relation between the different disciplines, their overlap and how their characteristics impact one another is a complex task. When the objectives are agreed upon and tariff design is carried out, implementation of those newly designed tariffs structures cannot be seen without considering the multi-disciplinary framework in which they operate. This results in a wide set of variables to be studied in this and follow-up research.

This literature review has highlighted the motivation for 5GDHC research, addressed the research gaps and presented the theoretical framework. This theoretical framework and its corresponding concepts can be used to perform the more empirical task of designing tariff structures for 5GDHC, where an effort is made to equip tariff structures with the appropriate incentives.

4. TARIFF DESIGN AND OBJECTIVES

The literature review in the previous chapter provided a technological background of the technology 5GDHC, several economic perspectives and their corresponding concepts to illustrate the complexity of 5GDHC tariff design. The aim of this chapter is to link the theoretical concepts presented in the literature review to the trajectory of a tariff design process. That will answer the second sub-question:

Q.2	*What criteria are considered in tariff design?*

Aside from answering this research question that concerns tariff design from a more general point of view, this chapter will yield another important insight. The complexity of 5GDHC tariff design is reduced through a number of simplifications to be able to explore its potential tariff structures.

This chapter is structured as follows: First, Section 4.1 will introduce the variety of options in tariff design based largely on a step-by step framework. The decisions made in the tariff design process are determined by the tariff objectives a, which are introduced and reviewed in section 4.2. Section 4.3 will elaborate on current DHC tariffs and Section 4.4 will argue which tariff objectives will be the main focus for 5GDHC tariff design. Section 4.5 will provide an answer to the research question and the conclusions.

4.1 Tariff design

Tariff design is used in the total process that determines the financial transactions between the users of the system. It should cover the different production activities of 5GDHC that have been discussed in Subsection 3.4. Different approaches for network tariffs can be seen which results in a variety of options. To introduce the concept of tariff design the framework for SG(e) tariff design proposed by Petrov & Keller (2009) is used. This framework consists of five questions:

1. What should be priced?
2. What is the major pricing concept?
3. How to allocate costs for tariff setting?
4. What is the tariff structure?
5. Who should pay?

This section will discuss each step separately.

4.1.1 Step 1 - what should be priced?

A starting point is to clearly define the allowed total income which has to be recovered through tariffs. This total income is the result of adding the allowed incomes for the different activities involved in the supply chain where value is created (Reneses et al. 2011). For energy networks this usually includes cost components related to (1) generation, (2) the transport of energy, (3) the distribution of energy, (4) necessary modifications and (5) renovations at the user connection point and the energy usage of the energy. For a given component, different cost drivers can be distinguished: costs driven by energy usage [€/kWh(th)], by (peak) power [€/kW(th)] or reoccurring costs that are independent of these factors, like maintenance for example. This division is depicted in an schematic overview in Figure 4.1.

4.1.2 Step 2 - What is the major pricing concept?

Pricing paradigms can be divided into the two main classes marginal and average cost pricing. The latter is common practise in network tariffs to charge users according to estimated cost imposed by their consumption. The disadvantage is that it sets no incentives for the reinforcements of the networks since all cost will recovered. Alternatively, marginal pricing concepts face complex cost estimation and the probability of over- or under-pricing can lead to unfavourable outcome: either exorbitant profits or an unattractive investment climate. Hybrid proposals have been studied, like an equivalent marginal cost

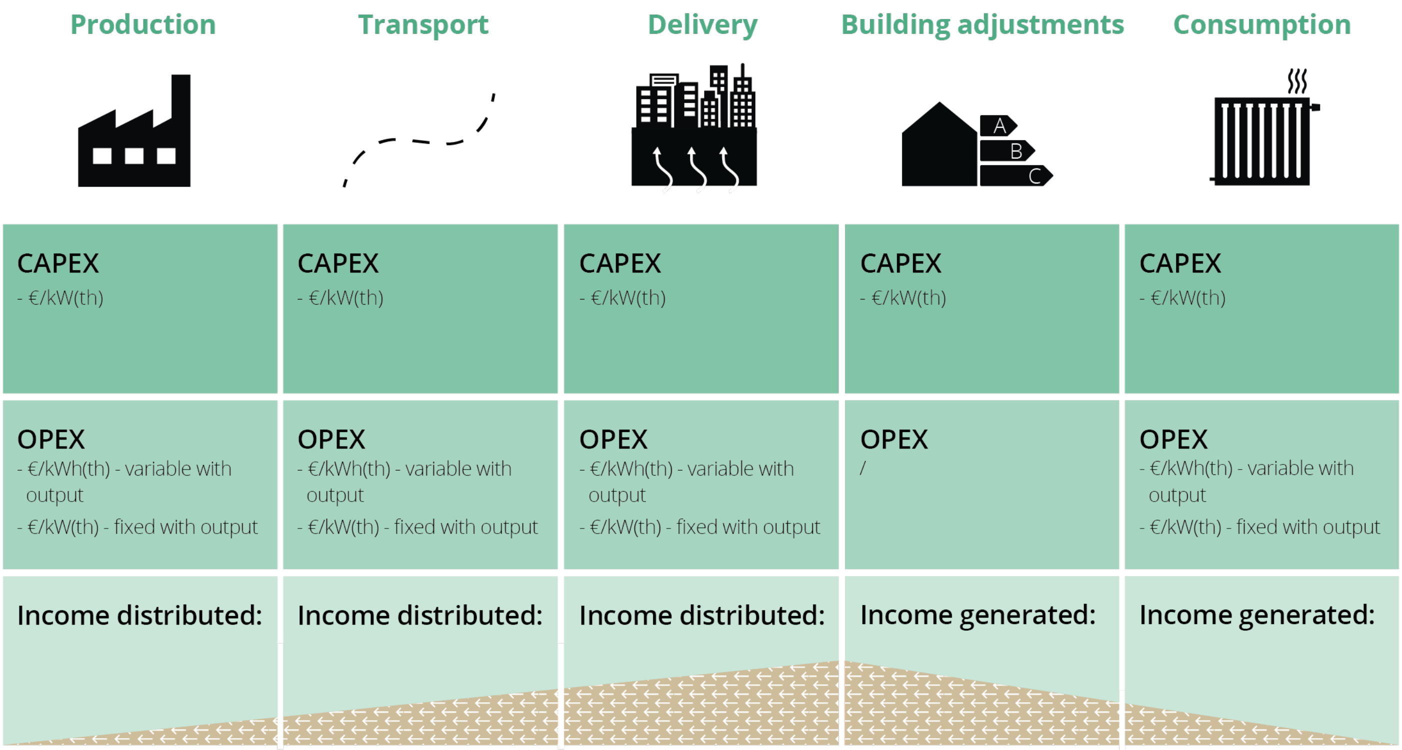


Figure 4.1 – Business case and monetary flow in DH systems, adapted from (Fakton-Energy, 2020)

pricing in (Li et al., 2015).

4.1.3 Step 3 - How to allocate costs for tariff setting?

In an ideal market, it would to possible to estimate and allocate the marginal costs of heating and cooling delivery for every point in time for every customer at every location. If this allocation would be applied in a tariff, pricing on cost reflectivity could be achieved when prioritized as an objective. In practice, this information is hard to estimate and not transparent. Different levels of differentiation under various criteria can be applied to counter this uncertainty in cost allocation. Some examples are listed below:

- Geography
- Time-of-use
- Contribution to critical (network) peak
- Fixed and variable elements
- Type of services
- Type of consumers

4.1.4 Step 4 - What is the tariff structure?

The tariff structure is determined by the number of different components that follow from the criteria chosen in the previous step and how these components are differentiated over the chosen criteria. A straightforward structure is using a flat volumetric rate, where customers are charged with a constant energy charge [€/kWh(th)] throughout the year. Differentiation creates more dynamic tariffs. An advantage is that incentives can be incorporated, but dynamic tariffs will be increasingly complex and will therefore be harder to understand.

Different labels can be found in literature, but dynamic tariffs can be roughly categorized in the following subgroups: Time-Of-Use pricing (TOU), Critical Consumption Pricing (CCP) Real-Time Pricing (RTP) and Consumption-based tariffs (S3C-Consortium, 2013). The dynamics of a dynamic tariff can be expressed by the number of time blocks per day in which the rate can vary, the price update frequency and the price spread, i.e. price differentials between time blocks. To illustrate Figure 4.2 demonstrates an example of a flat rate by combining generation by a base load source, shoulder load source and peak load source and the constant distribution cost components.

Time-of-Use (TOU)

A rather simple time differentiated tariff structure is created by adding a time of use component. There are several bases for applying TOU blocks, ranging from daily/weekly to seasonally. An example for a daily TOU can be seen in Figure 4.3.

Critical Consumption Pricing (CCP)

As the label suggests, it is aimed at the critical network peaks. Its goal is to either reduce critical peak demand through Critical Peak Pricing (CPP) or to increase demand in case of excess power though Critical Peak Rebates (CPR). Illustration of both strategies can be found in Figure 4.3. The price spread in CCP tariffs is larger compared to TOU structures, since critical peaks only occur a few times each year. In these

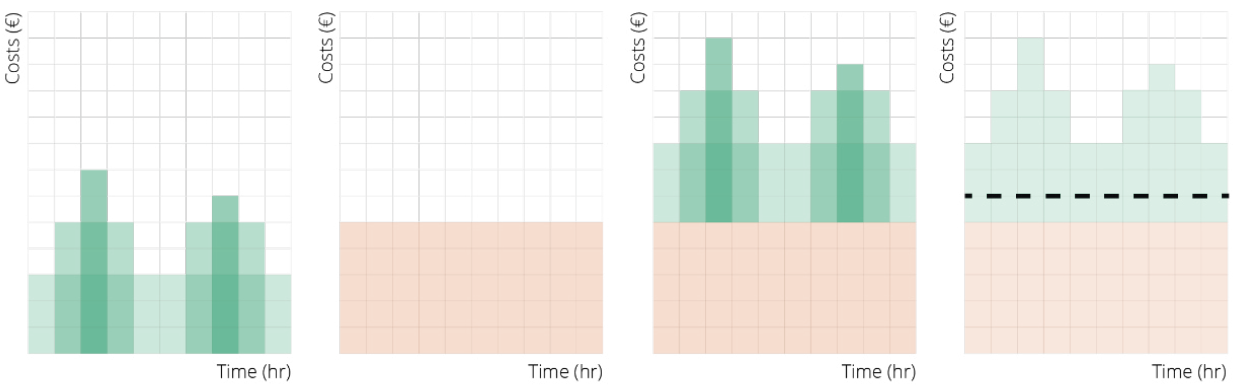


Figure 4.2 – Illustrative method for charging a flat rate for generation and distribution

rare occasions, the potential benefit should be made sufficiently high to increase participation.

Real-Time Pricing (RTP)

Its aim is to adapt consumption to external variables and preferences that can be driven by price levels and prognoses, excess power from TES and/or potential grid overload. This tariff structure requires a lot of data and transparency. The structure is depicted in Figure 4.3.

Consumption-based

Consumption based tariffs can be divided into energy charge or volumetric charge alternatively, and/or a power component called the demand charge. Consumption-based tariffs can be aimed at energy savings, reduction of demand levels or both. Within this differentiation, the structures above can be implemented. In the case of two charges – an energy charge and demand charge – complexity will increase and also the possible interference between incentives.

4.1.5 Step 5 - Who should pay?

Last step of the tariff design is to choose how the cost is distributed between users, producers and in this case prosumers. Future cost that are not (fully) recovered by the tariff structure have to be appointed to a one of the relevant actors or, alternatively, to society as a whole through taxes.

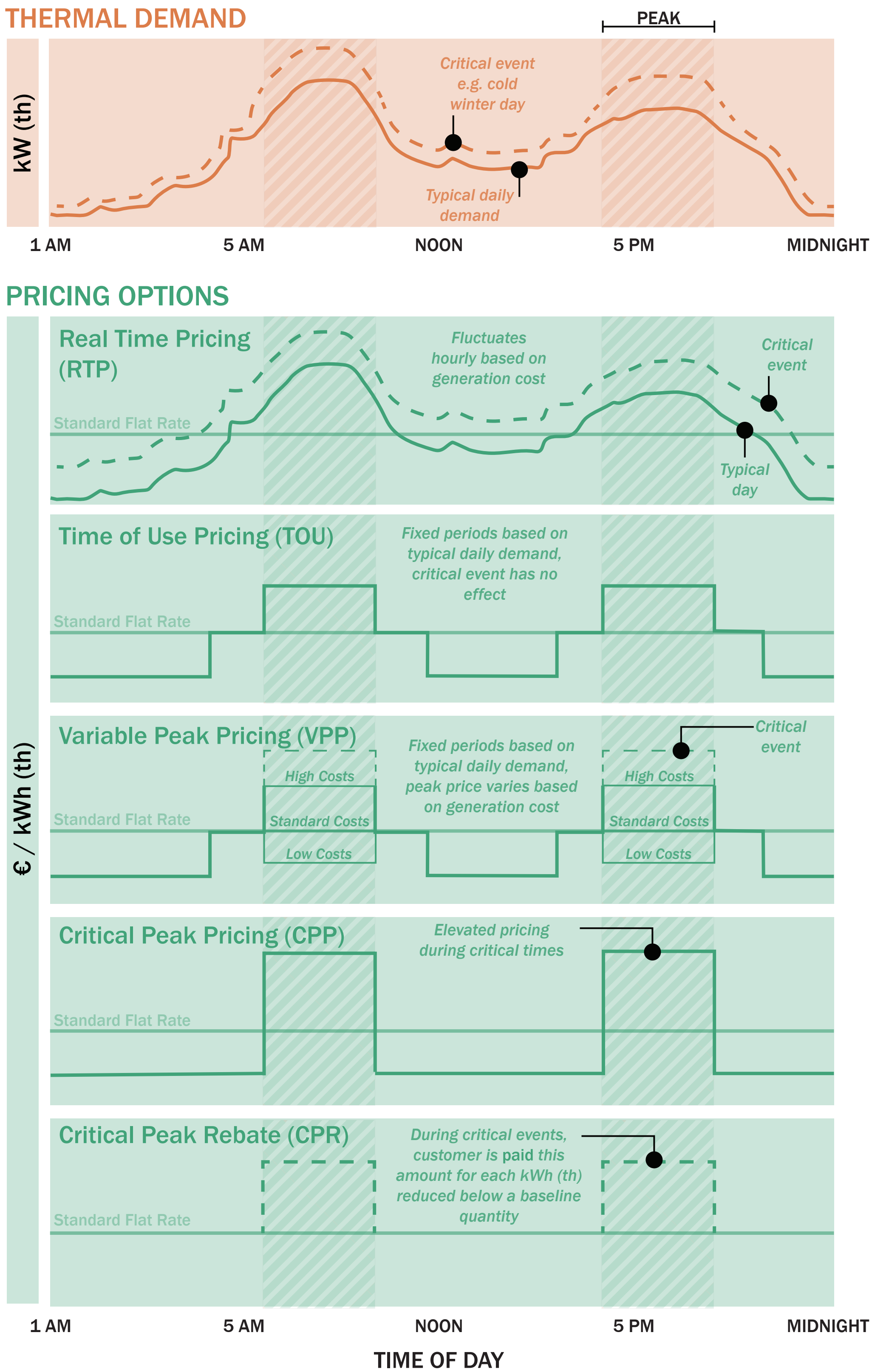


Figure 4.3 – Dynamic tariff structures for typical heat demand: Real-time pricing, Time-of-Use pricing, Variable Peak Pricing and Critical Peak Pricing and Critical Peak Rebates, adapted from (Matisoff et al., 2020)

4.2 Tariffs in the DHC sector

Network tariff design is shaped by the prioritisation of objectives and regulatory principles that support fulfilment of the values in Subsection 3.3.2. Frictions exist between the objectives and regulatory principles, which is why selection and prioritisation is required. Both regulated and deregulated markets can be seen for DHC. Cost-plus pricing is commonly applied in the first, while marginal cost pricing paradigms occur regularly in the latter.

Cost-plus pricing allows operators to charge costs with an additional permitted profit. Cost-plus pricing offers a number of advantages to sellers, buyers and regulators, such as simplicity, flexibility and ease of administration. However, a regulated market does not allow DH companies to compete with other heating solutions by adjusting DH prices, while the subsidisation of DH systems is often needed in order to make DHC as competitive as its alternatives. Moreover, as all costs are chargeable the regulator should implement incentives to promote efficiency, investments and innovation.

Under marginal cost pricing, the cost of one additional unit of production is the core of main cost driver. In an NCE presumed ideal market, marginal cost pricing promotes efficiency and sustainability as all externalities are fully internalized. This is typically not the case, so the DHC market often faces some type of regulation to protect its customers.

4.2.1 4Price components

The overall cost of DH generally depends on three main factors: (1) the connection costs for customers, (2) the costs of a distribution network, which depend on the size of the DH network and its thermal loads, and (3) the production costs of thermal energy (Li et al., 2017). Correspondingly, DHC tariffs often comprise of three price components: a connection fee, standing costs and unit cost. Other additional components can be incidentally found in DH systems in other countries (Li et al., 2015), but these three are considered mainstream price components for DH tariffs.

Connection fee

The connection fee refers to the price for connecting a dwelling to a DH network and is usually a one-off fee. It can be paid by the developer or the landlord, or by consumers who pay a connection fee included into the price of a dwelling. How, if at all, to charge the connection fee is debatable. To reduce demand risk, Kostama (2003) argued against a connection fee. It should not be charged to incentivize potential new customers to connect to the networks This way speed and quantity of roll-oud is increased, reducing demand risk. Delay or lack of connections could hit the network developer with unexpected cost. An alternative is to base the connection fee on the length and diameter of the connection pipeline creating a connection fee that is reflective of true cost for connection.

Standing cost

Basically, standing costs are fixed costs associated with the energy supply such as meter reading, maintenance, and keeping the connection to the network. Standing costs are paid to the companies that operate and maintain the DHC network and are usually charged on periodic basis e.g. €/yr.

Unit cost

Unit Cost is the price per unit of supplied heat or cooling that must cover the production of energy. Volumetric prices charging per unit of heat [€/kWh(th)] or [€/GJ] are common use in tariff DHC networks. An alternative terminology refers to the unit cost as the energy charge.

4.2.2 Heating and cooling tariffs in the Netherlands

Currently, the Dutch DHC tariffs for domestic users has indeed the aforementioned three main price components: (1) connection fee, (2) standing cost, (3) unit cost and (4) an efficiency cost component. The price level of the individual components is regulated by the Dutch Heat Act. A price-cap links the tariffs to those of natural gas. This principle ensures that, on average, a heat consumer does not pay more for heat from DH than one would for heating with natural gas. The Dutch regulator, ACM, sets fixed price-caps with annual updates.

To illustrate Dutch heating and cooling tariffs, customer charges in the Mijnwater project in Heerlen are used as an example. In The Netherlands, the Mijnwater project is considered a 5GDHC network. When zoomed in a on the tariffs for domestic users, the reoccurring charges are the standing cost and unit cost. The Dutch Heat Act sets price-caps and differentiates for different types of services: space heating, space cooling and DHW consumption. In the Mijnwater case, space heating and DHW are charged with a fixed and variable charge: standing cost and unit cost. Cooling is charged solely by standing cost("Duurzaam mijnwaterenergie in uw woning, Zo werkt het!," 2017). No feed-in charge nor rebate is included, as they are not included in the current Heat Act.

Tariff regulation under a new Dutch Heat Act

Tariff regulation under the current Heat Act, is aimed at consumer protection: price-caps and legislation regarding security of supply is meant to safeguard consumers in the natural monopoly of DHC systems. The current Heat Act is lacking incentives and regulatory tools to increase roll-out of DHC systems and to decarbonize the heating and cooling provision. The recently proposed new Heat Act is based on three main pillars: (1) a new market structure, (2) decarbonization and (3) a transparent tariff regulation(Rus-van der Velde & Den Boer, 2020a). These three are of course inter-reliant, but the latter will be the main focus to be elaborated in the next paragraph.

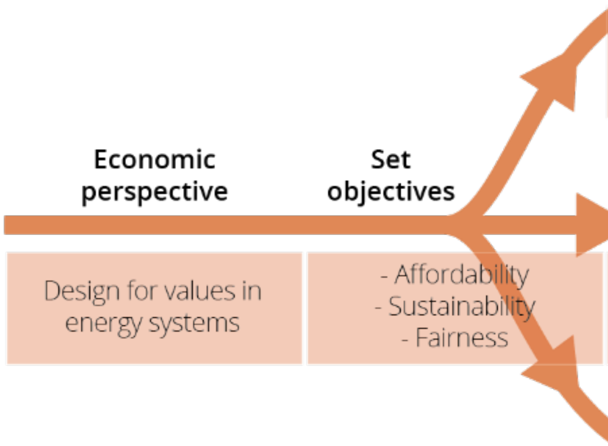
Tariff regulation under the new Heat Act does not enforce price levels that are associated those of natural gas. It was concluded that it did not reflect true costs and lacks transparency and it therefore ampers the roll-out of DHC systems. New tariff regulation is aimed at a cost-reflective tariff design. DHC operators are faced with efficiency incentives to ensure affordability, security of supply and sustainability. Tariff differentiation based on local conditions will be allowed. Tariff regulation will be based on a cost-plus principle, which allows an operator to recuperate its cost and earn a predetermined rate on investments. This newly proposed tariff regulation does not apply to small scale collective DHC systems (Rus-van der Velde & Den Boer, 2020b). In conclusion, under the proposed new Heat Act every DHC system will have its own system specific and cost-reflective tariff. This new legislation is not in place yet, its specifics are still being discussed in Dutch Parliament.

4.3 Objectives and regulatory principles for 5GDHC tariff design

Tariff objectives and regulatory principles shape the choices in the tariff design. The economics of tariffs follow two main objectives: first of all, they must generate the income required to cover all the costs of the supply chain. Secondly, tariffs should send the right economic signals to each customer to ensure that they use the service - socio-economically speaking - in the most efficient way (Reneses et al., 2011). The first is a clear and quantifiable requirement. The latter, however, is debatable. Based on the different economic perspectives and the role 5GDHC is attributed to play in the future different approaches can be taken to what is considered the best outcome from a socio-economical perspective. This section will create an overview of possible roles for 5GDHC and what values are prioritized as tariff objectives in this research.

4.3.1 The trajectory for 5GDHC tariff structure proposals

Tariff design is part of a broader multi-disciplinary trajectory in a technical and social-, economic and political environment where the role for heating and



cooling and, in this case 5GDHC is determined. The trajectory through which 5GDHC tariff structures are established depends on the selected societal preference for these systems. An illustration of three general defined trajectories is presented in Figure 4.4. The economic perspectives provide the theoretical framework, from which values and can be selected and prioritized.

The future role is decisive: depending on the guarantees and requirements future 5GDHC systems should be able to fulfil, the trajectory splits into roughly three different sub-paths:

1. **Tariffs based on a utility principle** where a cost-plus philosophy is adhered to supply heating and cooling for the 'common good' of their customers, while return on investments is guaranteed. A common issue is that such a setup lacks efficiency incentives for efficient and low-cost operation for operators. This can be solved by the regulator, which has roughly two options: tariffs based on efficient costs and temporally fixed tariffs based on cost-reflectiveness. In line with the drafts of the new heat and cooling legislation in the Netherlands, this approach with a cost-plus regulation will be the assumed for this study.

2. **Tariffs that stimulate 5GDHC so that companies are enabled to differentiate tariffs** to optimally align 5GDHC features with customers preferences. In other words, performing daily business operations go hand in hand with potential risks and profits. Companies are allowed to charge tariffs that are not cost-based but based on preferences of their customers. This allows companies to optimize operation based on their customer preferences. Efficiency is promoted because that would increase profits. Sustainability goals should be enforced by the regulator. The regulator should protect customers from high price levels and a minimum required level of heating and/or cooling where a corresponding refence price can be suggested.

3. **Free tariffs with limited restrictions that promote an all in all efficient system.** In this scenario, 5GDHC competes with other heating and cooling technologies. Customers can feel powerless and subject to high prices. Price dialogues combined with transparency and predictable tariff developments could increase social acceptance.

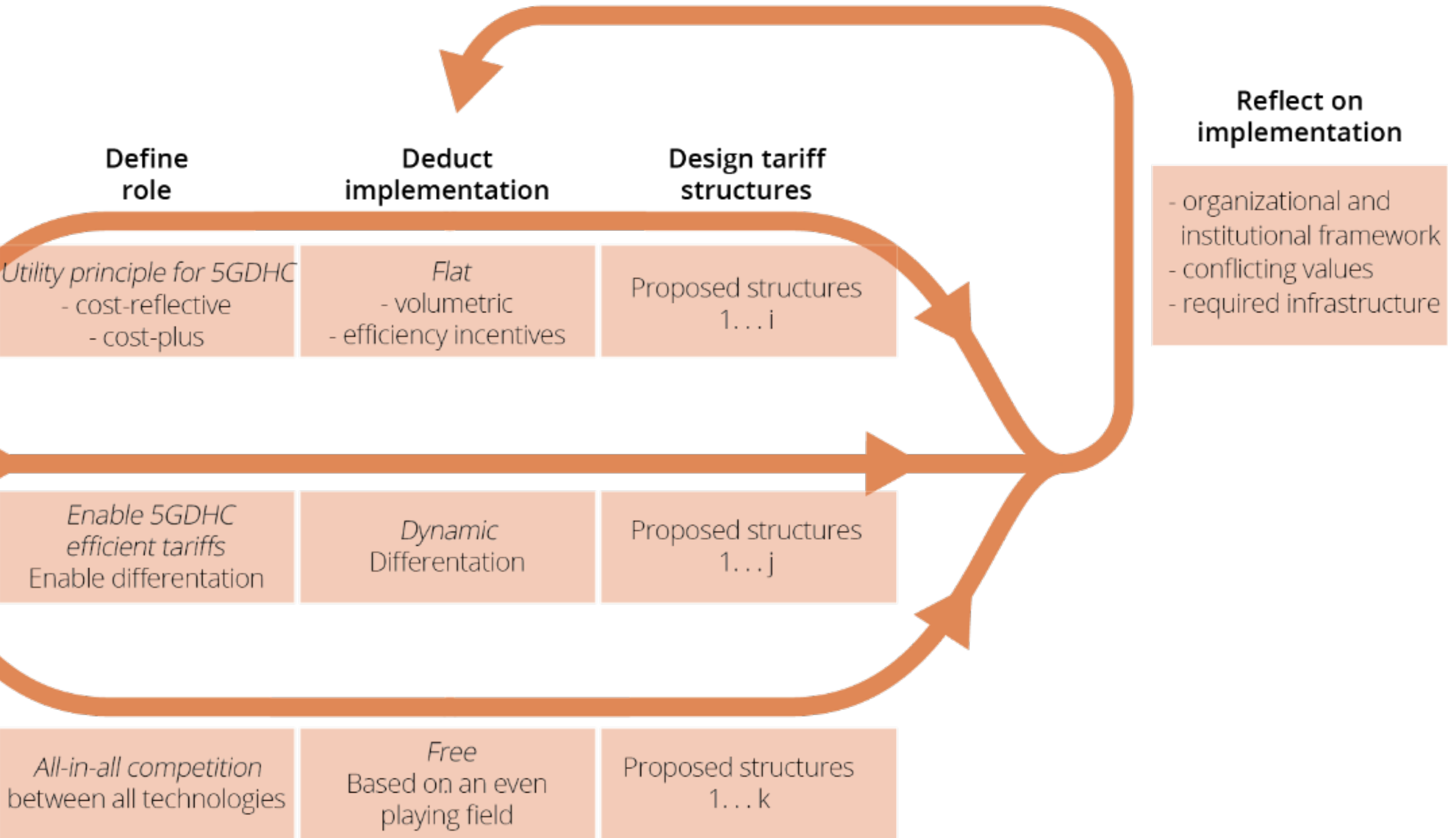


Figure 4.4 – Applied trajectory of tariff design (under construction for single page filled view)

Utility regulation

When cost-reflective tariffs are charged, the price level is determined on expected cost. For operators, this means they have to estimate cost ex ante. Over-estimation of the cost will lead to profits that could be corrected by the regulator, while an under-pricing leads to losses. A common solutions is to correct ex post for the initial estimation at the end of a billing period. Alternatively, correction can be used to adjust tariffs for the next billing period, when customers could readjust their consumption and/or subscription accordingly.

However, an issue arises: efficiency incentives are lacking when recuperation of cost is guaranteed. Potential solutions can be found in imposing efficiency goals, setting temporarily fixed tariffs or setting benchmarks. Transparency can be a first step towards introducing efficiency incentives. The regulator could require operators to report their performances and efficiency measures. Temporarily fixed tariffs or so-called price cap regulation, could motivate operators to improve efficiency to increase earnings. For a benchmark, groups of comparable of DHC system types can be reviewed for reference. As these systems are complex, the focus should be on criteria that can be quantified for reference. Consequently, a distribution function can be created where deviation of cost – either positive or negative – can be rewarded or penalized (Heida & de Haas, 2019). Utility regulation has undergone several developments. Additional perspectives and in-dept analyses can be found in publications like (Kahn, 1988) (Armstrong, Cowan, & Vickers, 1994) (Newbery, 2002) (Hertog, 2010).

4.4 Simplifications to explore 5GDHC tariff structures

4.4.1 Prioritisation of tariff objectives

In line with the proposed new legislation in the Netherlands, the cost-plus approach will be the main focus for this study. Of course, other paths would present different options and other simplifications would have been deemed necessary. Within the selected utility principle approach, the chosen objectives will focus on cost-reflectivity, efficiency and sustainability. Fulfilling the tariff objectives might not occur might not occur naturally through the market mechanisms at play and regulatory measures could be considered. Tariff regulation is amongst the potential measures, but governance structures and institutions can be regulated too.

Cost-reflectivity

The principle of cost-reflectiveness states that costs are allocated to those who impose costs on the network (CEER, 2017). Pricing based on cost-reflectivity sends out cost minimizing signals that could improve feasibility of the system as a whole.

Economic efficiency

Efficiency is a key value that has a major impact on the economic success of a technology. Efficiency means that it takes the least required amount of resources to achieve a desired purpose. By promoting efficiency through its tariffs, the 5GDHC system can become more feasible.

Sustainability

Sustainability in the sense that utilizing sustainable energy sources is promoted as well as energy saving. Promoting sustainability can thus be achieved by creating incentives to decrease energy demand or encourage to align the demand with the intermittent production of low-carbon or renewable energy sources.

4.4.2 Conflicting values

Conflicting values in smart grid environments have been introduced in section FXIME. Tariff objectives create a trade-off by definition, but additional conflicting values in SGs have not been considered in the exploration of tariff structures. This simplification allows 5GDHC tariff design to focus on the prioritised tariff objectives above. Afterwards, in the discussion there will be reflected upon confliction values related to data usage. This simplification means that the looming conflicting values in SG environments will not incorporated nor resolved in this 5GDHC tariff design.

4.4.3 Economic perspectives

The NIE and OIE perspectives are not used in 5GDHC tariff design in this study. Role distribution and different collaboration structures is not considered in tariff design. Different contracts and NIE efficiency lenses towards transaction cost will not be included. Moreover, the OIE perspective where (re)allocation of rights, i.e. property and decision rights, will not be considered to contribute to the objectives. This simplification means that the tariff structure is the main instrument for achieving the prioritised objectives.

4.5 Conclusion: The trade-off between tariff objectives determines the design choices in the tariff design trajectory

The previous chapter presented the different characteristics and criteria that are considered when tariff structures are designed. The aim of this chapter was to link the theoretical concepts presented in the literature review to the trajectory of a tariff design process while ansering researchquestion number two.

Q.2	***What criteria are considered in tariff design?***

The first characteristic is defining the tariff objective. **Tariff design is structured through its objectives, which originate from different potential scenarios for the future role of 5GDHC in society.** A first option is to shape tariffs from utility perspective, where cost-plus regulated tariffs are typically implemented. Allowing 5GDHC to differentiate based on customer-preferences is a basis for a second potential scenario. Tariff structures can differ significantly as well as price levels, which regulators will have to control. Price components are not necessarily align cost-reflective. A third potential scenario hardly enforces any restrictions: free tariffs to make 5GDHC compete with any other technology. In a true competitive market, 5GDHC and its corresponding tariffs have to outperform other systems for an uptake of implementation. For this study, the focus will be the cost-plus scenario as it aligns best with the pending new Dutch legislation, a new Heat Act, for DHC tariffs. In this research, tariff objectives are cost-reflectivity, economic efficiency and sustainability are prioritised. A compact reflection will discuss alternative tariff structures too.

The tariff structure can be equipped with incentives to promote several objectives like cost-reflectivity, economic efficiency and sustainability. Incentives can be created by dynamic tariffs that can be differentiated based on criteria such as time, type of service, fixed and variable elements. Theis more empirical tariff design process is executed as a part of a step-by-step framework answering five questions: (1) What should be priced? (2) What is the major pricing concept? (3) How to allocate costs for tariff setting? (4) What is the tariff structure? (5) Who should pay? The next task will be to align the incentives with the technological characteristics of 5GDHC. An additional characteristic for DHC systems is its monopolistic nature, which worries customers they might be charged with unreasonably high energy bills. This can partly be compensated by tariff regulation or by re-allocation of property and decision rights as discussed in Subsection 3.4.2.

However, **simplifications with regards to tariff objectives, conflicting values and economic perspectives were necessary in order to test the required parameters** without the complexity of the system causing a hindrance. In order to explore 5GDHC tariff structures, not all relevant factors are used and incorporated. For this study, it is deemed an acceptable compromise as its complexity is not ignored. It suits the exploratory nature of 5GDHC research and an additional reflection discusses these choices.

5. TARIFF DESIGN FOR 5GDHC

The previous chapter presented the different characteristics and criteria that are considered when tariff structures are designed. The objective of this chapter is to present potential tariff structures that follow from the trade-offs that are made between the previously discussed criteria, the alignment with the technological system and the characteristics of the different actors. This will result in potential 5GDHC tariff structures and thus answer the third sub-question.

Q.3	*What are potential 5GDHC tariff structures?*

The chapter is structured as follows. The 5GDHC system and the role of the building mix in tariff design is discussed in section 5.1. Section 5.2 discusses the alignment between the technical features of the system, both in design and in operation, with potential tariff structures. Next, potential tariff structures inspired by capacity subscriptions are presented and its design choices are evaluated. In section 5.3, an alternative approach is presented in section 5.4: tariffs that promote automated operation to allow optimisation of complex bi-directional thermal energy flows. Finally, section 5.5 discusses the characteristics of the involved actors in the 5GDHC network.

5.1 Introduction of the 5DHC system and building mix

As discussed before, there are many similar DHC networks that are labelled as 5GDHC. In this study, the definition of Buffa et al. (2019) is adhered as much as possible as discussed in Subsection 3.1.1. This means the selected 5GDHC system consists of a two-pipe network configuration with ULT network temperatures that are boosted at the individual building level by a reversible WSHP in combination with a DHW buffer. Individual households can locally produce thermal energy by installing PT or PVT on rooftops, effectively making them prosumers. Other possible 5GDHC network components are ULT thermal energy sources and TES facilities to compensate for the seasonal unbalances in the system. An illustration of such a 5GDHC system is shown in Figure 5.1.

The mix of connected buildings determines the coincident thermal demand of the network. The overlap of heating and cooling demands can be quantified by a demand overlap coefficient (DOC) (Wirtz, Kivilip, Remmen, & Müller, 2020b). This demand overlap coefficient (DOC) can take values between 0 and 1. Networks with high DOC contain thermal demand that overlap often. It quantifies the potential for bi-directional energy balancing within the network. A heterogeneous building mix with commercial and residential buildings often has a relatively high DOC as their heating and cooling demands are compatible. However, for most Dutch neighbourhoods a more homogenous building mix is more likely. Residential buildings have similar load profiles which means loads will often coincident: heating will be dominant in winter and cooling will be dominant in summer. The homogenous residential building mix will be the main focus in tariff design as this is likely to resemble most of the Dutch neighbourhoods.

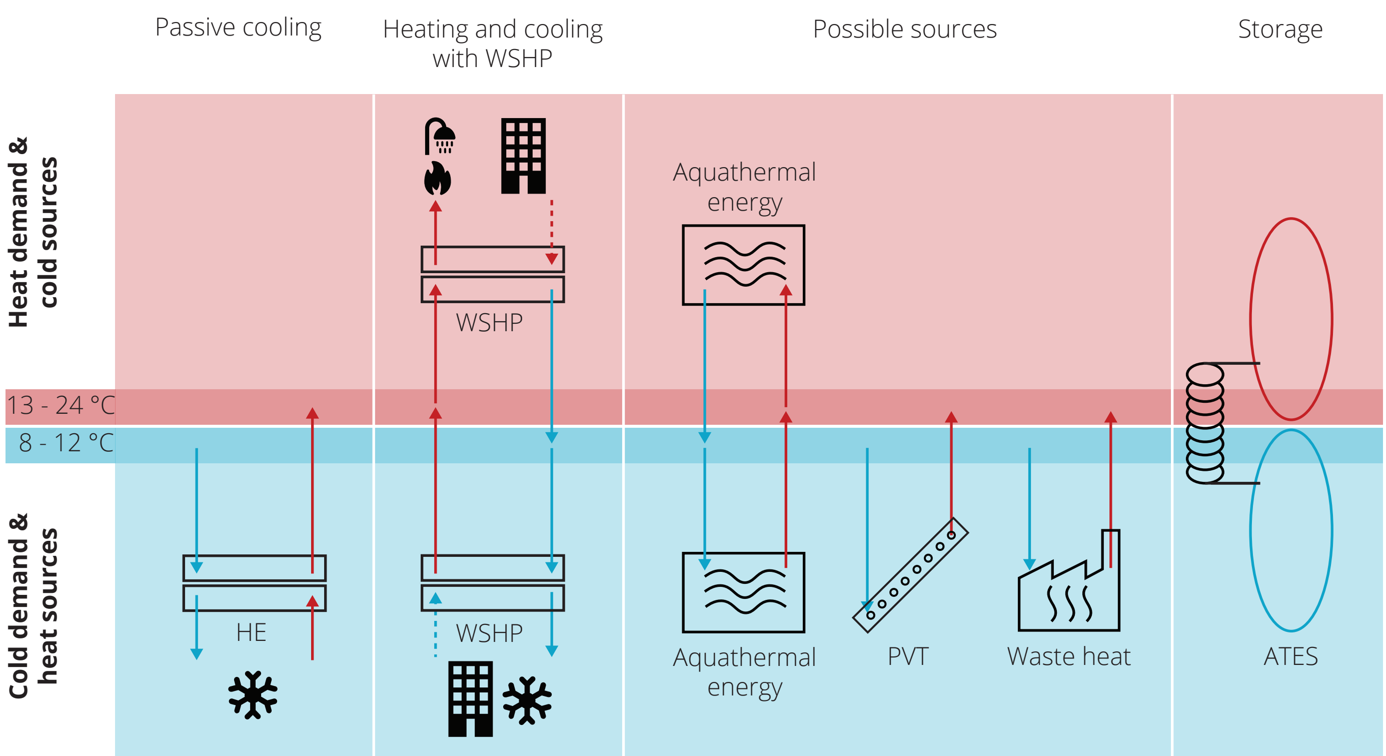


Figure 5.1 – A 5GDHC system configuration with typical operation and components as an example (Jansen & Verhoeven, 2020)

5.2 Aligning design and operations with tariff design

5.2.1 Reducing thermal peak load

5GDHC is aimed at optimal use of LT thermal energy sources and the interaction with low-energy buildings. The 5GDHC tariff objectives are aimed at cost-reflectiveness, economic efficiency and sustainability. In a homogenous residential area, a reduced thermal peak can serve all the objectives. This can be achieved during operation (DSM) or in the design phase (retrofitting). A reduced thermal peak impacts the design on an individual building level and a network level. Retrofitting and DSM strategies can be aimed at thermal peak reduction through load shifting, but alternative strategies are possible. Increasing loads during peaking renewable energy production could serve sustainability objectives better. But it would not be able to reduce the required capacity as much. Due to the shifted peaks, the more costly components at or close to the building level, the WSHP and connection pipe, cannot be designed for lower capacity levels. In short, sustainability will not be the main driver in this tariff design as the assumption is that incentives that promote cost-reflectiveness and economic efficiency are expected to serve sustainability indirectly. Potential cost reductions will boost 5GDHC implementation and result in decarbonized heating and cooling supply. Considering the aforementioned technological features of 5GDHC systems, reducing thermal peaks can reduce capital and operational cost through (Guelpa & Verda, 2021):

- Reduced required capacity of WSHPs
- Reduced connection pipeline dimensions
- Reduced distribution pipeline dimensions
- Enabling additional connections during operation without DH network extensions
- Reduced network pumping power
- The above can be achieved through retrofitting or DSM strategies.

Retrofitting

Retrofitting can be done during the design phase or later when maintenance or renovation is carried out. The buildings' heating and cooling demands are usually available in an early planning phase. Retrofitting could possibly be stimulated by tariffs if they transfer the benefits to those who participate while maintaining an acceptable level of service. Customers could then be persuaded to opt for lower capacity of their installation, which would result in a cost reduction at both the building level and network level. To keep their comfortable indoor temperatures, households will need to manually or automatically shift their thermal loads. The original peaks in their thermal load profiles cannot be fully capacitated after retrofitting measures. Alternatively, retrofitting can be done by customers by installing TES technologies to assist their thermal demand during anticipated peaks.

Demand Side Management

During operation, DSM strategies can be applied to reduce coincident thermal network peaks. This can be done by indirect or direct DSM. Indirect DSM is achieved by tariff structures equipped with incentives to motivate customers to change their routine and corresponding load profile. The outcome is uncertain as participation levels are hard to estimate beforehand. Direct DSM reduces manual operation and shifts the control and management towards the operator. The operator is allowed to modify some or all thermal loads in the network to optimize operation aimed on the effects that the operator wants to achieve. Uncertainty of the outcome is reduced compared to indirect DSM and 5GDHC features do allow for automated operation. However, households might be hesitant to hand over their manual operation and SG equipment and proper data management comes at a price too. The more complex operation will be, the higher cost it will incur.

5.2.2 Need for dynamic tariffs

Nowadays, the traditional volumetric tariffs are being reconsidered based on their cost-reflectivity and capability to price prosumers loads appropriately(Song et al., 2016)(Picciariello et al., 2015). 5GDHC networks could benefit from dynamic control strategies, where variable prices could be implemented (Cozzini et al., 2017). For DHC in general, dynamic pricing has been attracting attention especially following recent SG(th) developments. Capital investment to finance DHC network infrastructure is the main driver for adding a capacity charge. The demand charge should motivate consumers to reduce their peak consumption and charge customers accordingly. This should result in flatter thermal load profiles and therefor promote both cost-reflectivity and economic efficiency. Adding a demand charge is inherently more cost-reflective because consumers with higher peak consumption are charged more. Efficient use of the network is stimulated by rewarding peak load shifts to reduce load levels. Different demand levels can be designed to allow customers to reduce their demand charge.

The so-called capacity subscription tariffs have been gaining attention in the electricity sector ("Belemmeringen in nettarieven," 2018)(Bjelland Eriksen & Mook, 2020) and DHC sector (Song et al., 2016). Adding a form of a demand charge is proposed to increase cost-reflectivity in tariffs. However, a demand charge on its own does not motivate customers to reduce energy consumption (Li et al., 2017). To stimulate lower energy consumption, a volumetric energy charge can be maintained within the tariff structure.

By this rationale, A **5GDHC tariff structure for homogeneous residential networks should at least have:**

- A demand charge to promote cost-reflectivity and economic efficiency
- An energy charge to promote sustainabilitydistribution cost components.

5.3 5GDHC tariff design inspired by subscribed capacity

5.3.1 A three-tier structure

The proposed network structures are three-tier and existing of a demand charge, an energy charge and a fixed standing cost. The latter is charged for costs independent of consumption levels, such as maintenance and upholding the connection to the network.

Tariff structure based on subscribed capacity:

- A variable demand charge (€/kW(th)) with different subscription levels
- A flat volumetric energy charge (€/kWh(th))
- A fixed standing cost (€/yr.)

Tariff structure based on subscribed capacity with Time-of-Use:

- A variable demand charge (€/kW(th)) with different subscription levels
- A time-of-use volumetric energy charge (€/kWh(th)): a peak and off-peak price level
- A fixed standing cost (€/yr.)

These three price components and corresponding differentiations are a starting point, but decisions on design parameters are needed to complete the tariff structure. A visual representation of the tariff's demand and energy charge is depicted in Figure 5.2.

5.3.2 Design choices

The proposed three-tier tariff structure has three components. The price levels are cost-reflective except for the optional TOU structure in the energy charge. Other design choices for the dynamics of the tariff structure remain.

Variable demand charge

For the demand charge, the following design options should be considered:

1. ***Is exceeding the subscription level allowed?***

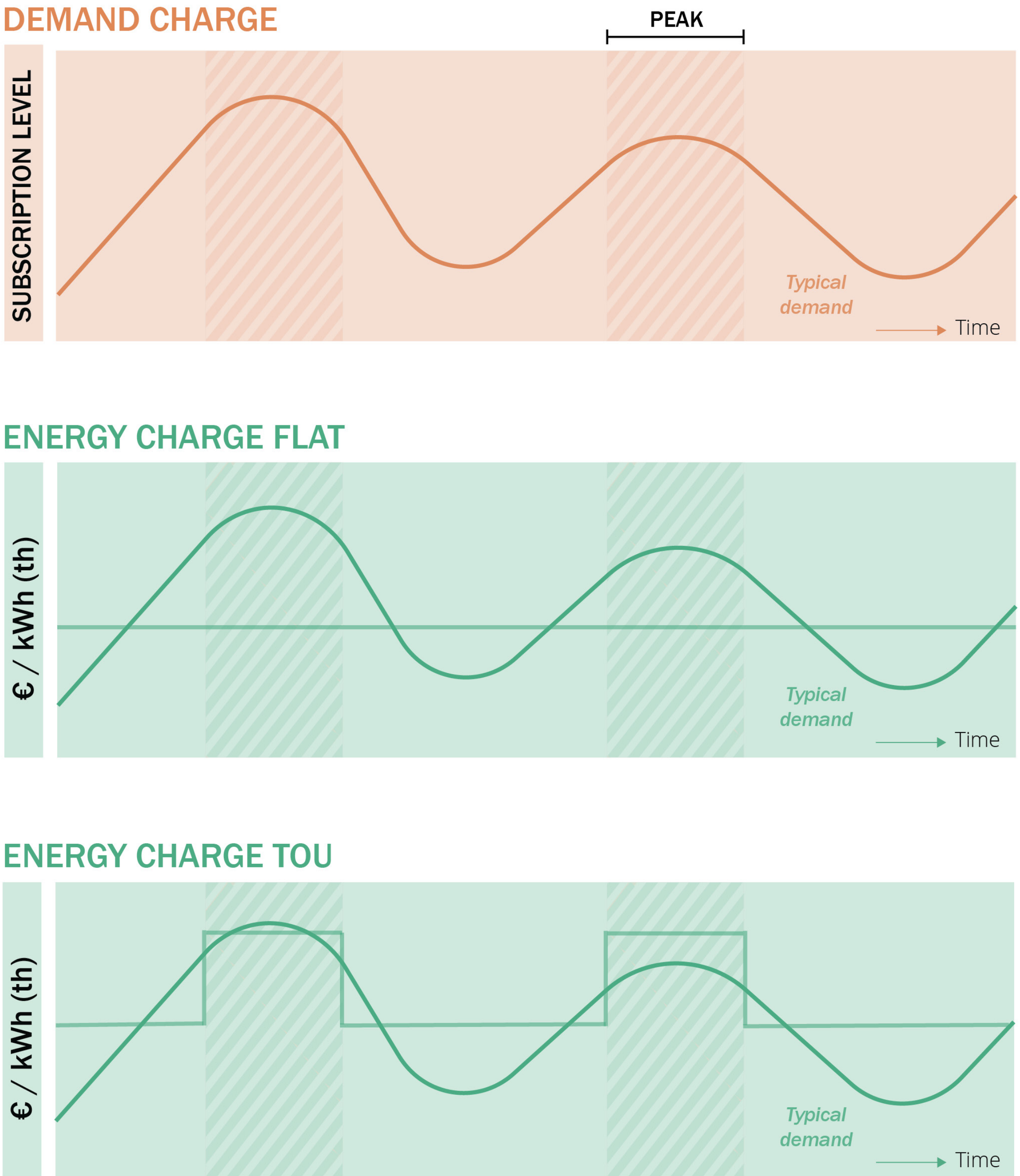


Figure 5.2 – Illustration of a variable demand charge and a flat or TOU energy charge

Exceeding your subscription level could induce higher cost and potential system failure. The latter is however definitely not often the case, as a coincident critical peak would need households to collectively exceed their subscription levels. This could happen during rare events of extreme cold or heat.

Preventing exceedance can be achieved either by design, e.g., reducing installed capacity, or by operational restrictions, e.g., programming the equipment. Allowing exceedance can be dealt with by charging penalties [€/kWh(th)] or by automatically bumping the user to a higher subscription level. System failure can be prevented by allowing the operator to restrict or curtail exceeding customers to their subscribed capacity level.

2. ***How many subscription levels are offered and what are their respective sizes?***

It is probably best to limit the amount of subscription levels to keep the tariff simple. As a reference, up to four subscription levels was advised by Dutch DSOs for capacity subscription tariffs for electricity distribution networks(Hennig et al., 2020).

Sizing of the subscription levels can be done be estimating a minimum and maximum subscription level. The maximum subscription level is based on the maximum unrestricted combined load of both space heating and cooling and domestic hot water on the coldest reference design day. The minimum subscription level can be determined by taking the average of that same day and create a completely flat load profile i.e. a completely peak shaved load profile. In this scenario, night-day time outdoor temperature fluctuations can impact indoor temperatures. However, due to thermal inertia and insulation, indoor temperature fluctuations of 8 °C is reduced to an indoor oscillation of 1.2 °C for typical dwelling ("Memo on impact of maximum peak shaving on indoor temperature variation", 2021). An exemplary calculation can be found in the memo in Appendix E.

3. ***For what period of time are the selected subscriptions fixed?***

Yearly price updates seem to be the best option in terms of cost-reflectivity, because the costs for network reinforcement are driven by the highest network peaks which follow an annual cycle.

Energy charge with or without TOU

The flat volumetric energy charge is straightforward. Its price level is cost-based. The TOU structure can be applied to promote economic and environmental efficiency and requires consideration of a number of design options:

1. ***What timescale is applied for the TOU blocks?***

A seasonal TOU structure aligns with the seasonal imbalances between thermal energy production and demand and would be reflecting the cost difference within the seasons. In the analysed 5GDHC system, this is less significant due to the seasonal TES facility. Thus, sending out daily signals to reduce peak demand is prioritized over seasonal TOU signals. Peak and off-peak blocks can be chosen considering peak hours for space heating: between 06:00 and 10:00 and 16:00 to 20:00 (Menkveld et al., 2021a).

2. ***What price spread should be applied?***

Typical TOU price spreads are between the ratio two to four, which means peak prices are up to four time the size of off-peak prices.

Other

Remaining design choices address general questions related to 5GDHC tariff design:

1. ***Is the same structure applied to both heating and cooling?***

Generally, the same principles apply to cooling. However, the load profile is slightly different from heating load profiles. Nowadays, Dutch cooling demand limits itself to a couple of summer weeks at most. Cooling demand is expected to rise in the future. Future Dutch residential cooling demand will probably rise in absolute numbers and in frequency. An in-dept analysis of the cooling component is outside the scope of this research.

2. ***Feed-in rebates and/or charges for prosumers***

Locally produced thermal energy that is fed into the 5GDHC network can be rebated by applying a rebate per kWh(th) or by rebating per square meter installed PT or PVT panel ("DeZONNET Eindrapport", 2020). Alternatively, a separate capacity subscription tariff can be designed to promote self-consumption or presumption. Thermal peaks of locally produced thermal energy impose cost on the 5GDHC system as much or potentially even more compared to the demand side. Further analysis in the upcoming chapter will be focused on the thermal demand.

5.4 An alternative approach: tariff modules to increase automation and customer preference alignment

End-users may respond to tariff structures manually or in an automated mode. Alternatively, tariffs can be used to promote automated operation by the operator: direct DSM. The tariff modules or subscriptions could include the following options for example preselected timing of heating or cooling, or allowed level of indoor temperature fluctuations. Adding flexibility modules or subscriptions that reward customers for the level of control they are prepared to wave could have advantages to both customers and operators.

5.4.1 Customer perspective

This is already applied for smart charging electric vehicles in the Netherlands(van Berkel & van Heesbeen, 2017). Customers can communicate their charging preferences to optimize the charging session in their preferred fashion. From the customer perspective, the loss of manual operation has to be rewarded to incentivize participation. A set of optional subscriptions are offered in return for comfort, costs reduction or sustainability. Customers can have different preferences. Monetary rewards can compensate for loss of control. Customers might have other priorities that could be originated from a sustainability point of view. Adding sustainable labels and options could be attractive. Some customers might value their manual operation to a point they are willing pay extra for keeping it. Depending on local sentiment, different customer groups could have different shared minds about what they would prefer. Tariff subscriptions could facilitate these preferences and cost-reflectivity could be trumped by other tariff objectives.

5.4.2 Operator perspective

Participation of automated heating and cooling demand allows the operator to optimize operation while staying within the flexibility bandwidths the subscriptions allow. It increases the predictability of the network and the certainty that critical coincident can be anticipated and avoided or dealt with within the network.

5.5 Actors in 5GDHC

The actors within the network are the parties that fulfil one or multiple roles within the 5GDHC network as discussed in Subsection 3.4. Multiple parties can take up a role, both private or public parties. Currently, energy companies fulfil most roles in the existing DHC Dutch networks. In the pending Dutch legislation for collective heating and cooling, private and public partnerships are possible as long as the actors are bonded as one legal entity. The underlying aim is to secure the reliability of the heating and cooling supply.

Whereas traditional DH networks are usually run by large energy companies, small-scale (U)LT DHC networks offer opportunities for a greater role for the end user. Households and residents' participation can increase public support if they feel included and heard. Participation ranges between an advisory role, being attributed with decision rights up to partial or full local ownership.

Participation could be facilitated in the form of price dialogues. Residents may have different heating and cooling preferences. Some might prefer low costs, others favour comfort and then another group might feel strongly about sustainability goals. In this scenario, tariff design could be impacted by participation of the community if the institutional embedding is designed to enable it.

5.6 Conclusion: 5GDHC three-tier tariffs with a variable demand charge can promote cost-reflectivity, efficiency and sustainability

The objective of this chapter was to identify potential tariff structures that align with the technical parameters of the 5GDHC system and the characteristics of the different actors. This resulted in potential 5GDHC tariff structures and thus answering the third sub-question.

Q.3	*What are potential 5GDHC tariff structures?*

The tariff design was focused on 5GDHC systems with a homogenous building mix of residential buildings. For these 5GDHC networks, **three-tier tariffs combining a subscribed capacity charge, an energy charge and a fixed standing cost have to potential to promote cost-reflectivity, economic efficiency and sustainability in 5GDHC networks dominated by residential connections.** The subscribed capacity charge is a variable demand charge. It sends out incentives to reduce thermal peak loads by rewarding load shifting at the final bill. The tariff structure promotes cost-reflectivity by increasingly charging higher capacity subscriptions and thus allowing higher peak consumption with higher charges. End-users can either install TES technologies, increase self-consumption and/or subscribing to a lower subscription level. Economic efficiency is promoted by incentivizing flatter load profiles allowing more efficient utilisation of the available network infrastructure. Sustainability is promoted through the variable demand charge and the energy charge.

Adding a daily time-of-use structure can promote shifting peak consumption from space heating and cooling to off-peak hours. Depending on participation levels, this could reduce coincident thermal peak loads.

Tariff structures facilitating other DSM strategies than load shifting can be applied, but load shifting is arguably the best fit for residential networks with low DOC. It aligns particularly good with the 5GDHC configuration at the individual household level. When load profiles are flattened, the individual WSHPs can be designed at a reduced capacity levels and operate more efficiently, while the connection pipe dimensions can be reduced. This reduces costs in both the design and operational phase, while the impact on the electricity grid is reduced.

Tariff modules containing rebates for automated operation can be an alternative ot complementary approach for 5GDHC tariff design. 5GDHC unlocks the potential for automation and optimisation of operation in DHC due to its SG features. In residential networks with a low DOC, automatization can be used allow the operator to optimize load shifting based on consumer preferences. Tariff modules can contain similar programs as rolled out in EV smart charging. Customers can select flexible and sustainable subscriptions that fit with their desired level of control, price, flexibility and sustainability. However, applicability is uncertain, as the regulatory and institutional context in the electricity sector differs from that of the current DHC sector.

A general reflection; i**f cost-reflectivity is demoted from the main tariff objectives, tariff design based on customer preferences would enable 5GDHC operators to increase efficient operation.** A range of tariff structures and subscriptions can be negotiated through price dialogues. The range of options could increase complexity in the tariffs, which can be countered by automated operation: direct DSM. To avoid exorbitant profits through steep charges, some form of regulation should be implemented to protect end-users.

6. MODELLING EXERCISE: TESTING 5GDHC TARIFF STRUCTURES

The previous chapter presented potential tariff structures. The aim of this chapter is to test and demonstrate the performance of the potential tariff structures in a model. The modelling exercise is carried out to test the proposed three-tier tariff structures.

First, the objective and approach are discussed in section 6.1. Section 6.2 the design of a test case is introduced. Section 6.3 presents the input parameters and section 6.4 states the model output.

6.1 Model objective & approach

6.1.1 Narrative and objective

A model is created to serve as a testing environment for the proposed 5GDHC tariff structures. The objective is to show how and to what extend the tariff structures succeed to promote cost-reflectivity, perform given different demand profiles, user load profiles and thermal energy sources. The aim is to gain insight into the outcome for different user cases and type of tariff structures.

The approach is to create a test case where two types of customers choose to either engage in load shifting and opt for a low subscription level, or to prefer a higher subscription level. The two proposed tariff structures are compared to a two-tier reference tariff structure without a demand charge: a flat volumetric energy charge with a fixed standing cost. This test case will model the load profiles and corresponding tariff structures for a single year. An overview is depicted in Figure 6.1 which will be further explained in the remainder of this chapter.

Overview the design phase

1. Select network configuration for the 5GDHC test bank
2. Determine the thermal load profiles on the demand side
3. Determine the thermal loads on the supply side
4. Sizing of the network

6.2 Designing a test case for potential 5GDHC tariff structures

6.2.1 The DeZONNET case-study

The 5GDHC test bank is strongly inspired on the DEZONNET 5GDH case study in The Netherlands (DeZONNET Eindrapport, 2020). This case-study was chosen because its data was easy to access and the choice of existing projects is limited. The DeZONNET research studies an existing neighbourhood where a 5GDH grid replaces the gas grid to heat around 1200 households.

To summarize the DeZONNET concept:

- An ULT grid is fed by PVT panels installed on the household rooftops.
- WSHPs are installed in each household to supply space heating and DHW at the appropriate temperature.
- The WSHP utilizes either the heat generated from the PVT panels or it extracts its heat from the ULT grid, depending on the heat demand and the PVT generated heat.
- Heat is fed back to the ULT grid when PVT generation exceeds the household demand.
- Thermal surplus in the summer is stored in a seasonal TES facility, an aquifer thermal energy storage (ATES) installation, which feeds it back into the ULT grid in winter time. The ATES is replenished through the PVT-ATES combination, which enables PVT heat surpluses

Thermal load profiles				Tested tariff structures and cases		
Energy label Household energy label A or B		Customer types Conventional (C) and/or Dynamic (D)		Two-tier tariff Incl. flat energy charge For reference	Three-tier tariff Incl. flat energy charge	Three-tier tariff Incl. TOU energy charge
	B	100% C		Aquathermal Waste heat	Aquathermal Waste heat	Aquathermal Waste heat
	B		100% D	Aquathermal Waste heat	Aquathermal Waste heat	Aquathermal Waste heat
A	B	50% C	50% D	Aquathermal Waste heat	Aquathermal Waste heat	Aquathermal Waste heat

Figure 6.1 - Scenario overview of the modelling exercise

to restore thermal balance in thesystem.

- Connected households need a base level of insulation and a number of additional building adjustments to become ULT ready.

This concept has three seasonal operational modes: winter mode, summer mode, and stand-alone mode. The latter refers to the operational mode where heat is directly used within the building without any interaction with the grid. This is most likely in timestamps between summer and winter.

- Winter mode - heat is transferred from the ATES through the ULT grid to the dwelling.
- Spring/autumn mode – Heat demand is covered directly through self-consumption of the PVT produced heat: prosumption. This stand-alone operation will mostly occur outside the summer and winter periods.
- Summer mode – PVT panels heats the water from the cold pipes and surpluses are fed back to the ATES where it stored to be used during winter mode.

System design

Dwellings are equipped with WSHP and a DHW buffer. A number of PVT panels are installed on the rough. How many is determined by the thermal demand within the network. The heat delivery system which is where energy flows are (re)directed. A system overview of the household design is shown in Figure 6.3.

Although cooling can be incorporated, this design is not yet equipped with the required equipment to supply cooling. Thus, the system cannot be labelled as 5GDHC. It could be adjusted to supply cooling by adding an additional heat exchanger. To test the proposed 5GDHC tariffs, this 5GDH case-study with corresponding heat demand profiles will suffice for an initial demonstration.

The network layout

The initial network design is based on a concept neighbourhood consisting of 1200 dwellings, which was split into four subsections with an ATES each. An aerial schematic representation is shown in Figure 6.4. Most dwellings are terraced houses with deep gardens of six meter on average. The corresponding pipeline dimensions can be found in Figure 6.4, where the inner diameter, the total length and the average length per connection is depicted. The length is for a single pipe only, so the warm and cold pipe together would have twice the dimensions of Figure 6.4.

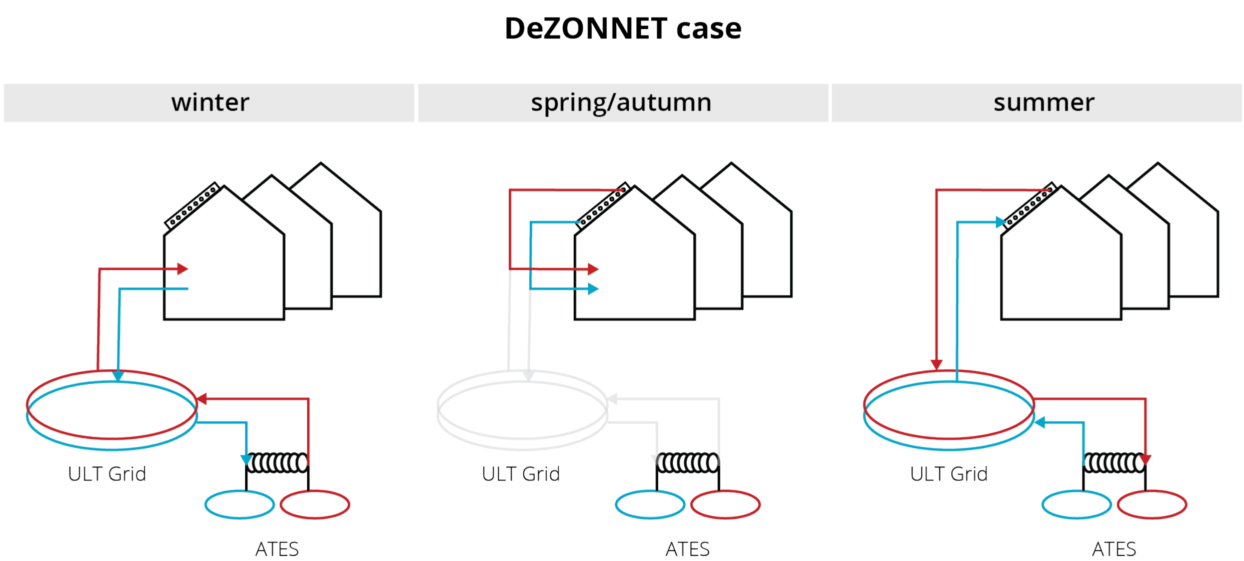


Figure 6.2 – Operational modes in the DeZONNET case, adopted from ("DeZONNET Eindrapport", 2020)

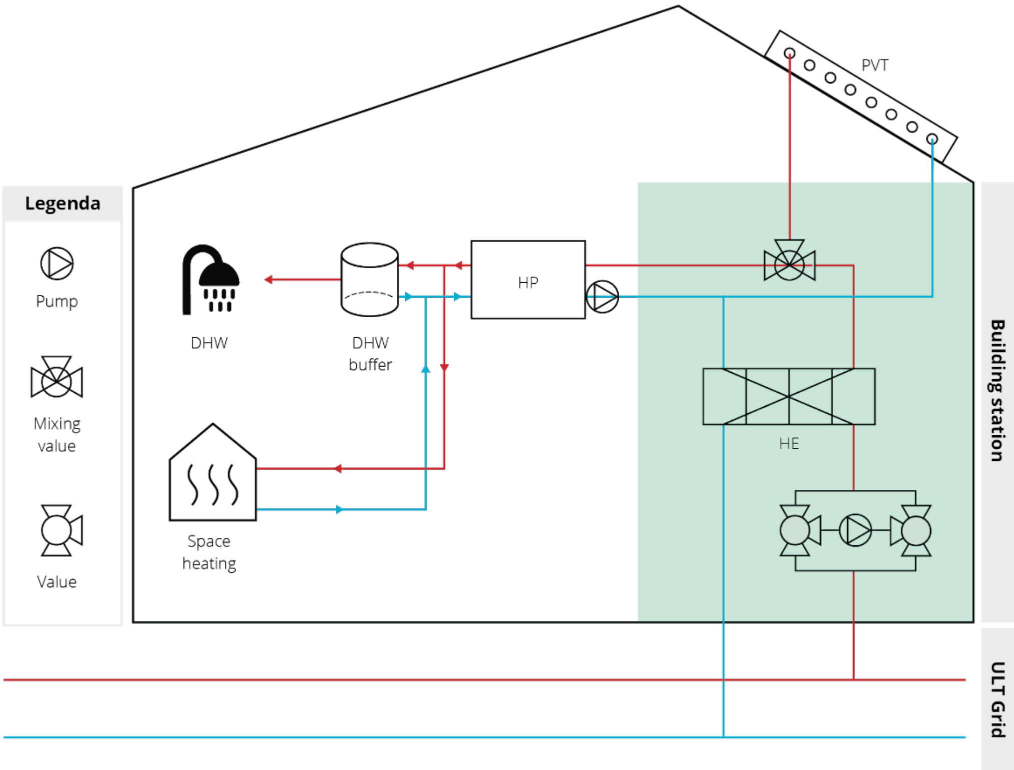


Figure. 6.3 – Building setup for the DeZONNET case, adopted from ("DeZONNET Eindrapport", 2020)

Various temperature levels and temperature differences have been studied in the DeZONNET research. For the creation of the test model, we will proceed with a temperature difference of seven degrees Celsius between the hot and cold pipeline. The pipeline diameters are designed based on a common design consideration that suggests that flow velocities should stay below 2 m/s. The mass flow rate is determined as follows:

$$\dot{m} = \frac{Q_{max} * 3600 \text{ sec}}{c_n * \Delta T}$$

Where:

- Q_{max} is the maximum design power in [W]
- C_n is the volumetric heat capacity of water (4200 kJ/m³/°C)
- ΔT is the temperature difference of 7 °C.

The network was designed for 7 kW per dwelling, caused by PVT generation rather than thermal demand. This is due to the assumed simultaneity factor (SF) for PVT generation. As the sun shines the simultaneously for all households, a SF of approximately 1 is assumed for PVT generated heat from the rooftops. A few adjustments were made from this initial DeZONNET concept to make it a useful test case for demonstrating the proposed 5GDHC tariff structures. Some adjustments and simplifications are required to make the DeZONNET case a suitable test case for the proposed 5GDHC tariff structures:

6.2.2 Creating a 5GDHC tariff test environment

Some adjustments and simplifications are required to make the DeZONNET case a suitable test case for the proposed 5GDHC tariff structures:

Adjustments and simplifications

1. ***50% less PVT panels on household rooftops to reduce thermal peaks from PVT production.***

The thermal peaks from thermal demand profiles in the original set-up are not determinative for the network capacity. It is actually the PVT generation on the sunniest day that is critical, because the simultaneity factor of the PVT panels is considered 1 and their collective thermal peak therefore exceeds the collective peak of the demand side.

The tariffs are designed for thermal demand and by reducing the amount of PVT, the thermal demand profiles become the main factor again. This is a realistic scenario as there are two factors limiting the rooftop area available for PVT panels. First of all, households are installing PV installations themselves and while this is normally a good thing, it means PVT and PV are competing for the same rooftop area. If the 5GDH system and its PVT panels lose the race for the rooftop area, it will have to make due with less. Secondly, not all rooftops are suitable for PVT panels. Some might be shaded or there is simply a lack of suitable surfaces

2. ***The remaining 50% of heat demand is supplied by a secondary thermal energy source***

To compensate for the loss of half the PVT generated heat, a secondary thermal energy sources will be connected to the network. The thermal energy source will be assumed to operate with as little difference to the original configuration as possible. The temperature differences of seven degrees Celsius within the network pipes is maintained. Two secondary ULT sources are considered: aquathermal energy and waste heat . The first is modelled as a seasonal load source, while the second is considered a base load source.

3. ***The impact of the secondary source on the ATES and pumping energy is not considered***

This simplification was also made in order to reduce the complexity of the modelling exercise. An in-dept analysis of effects a different energy mix has on network design and operation is not carried out. The ATES facilities are assumed to handle the secondary sources without adjustments.

4. ***Two types of customer types and corresponding thermal load profiles***

This simplification was also made in order to reduce the complexity of the modelling exercise. The building characteristics are the same for both customers. The same average energy label B dwelling of the DeZONNET research was applied for all households. This allows a clear comparison between two different customer types: Customer type C and Customer type D:

Nominal diameter [mm]	Total length [m]	Length per connection [m/con.]
25	16298	13.58
40	457	0.38
50	618	0.52
63	1039	0.87
75	681	0.57
90	823	0.69
110	1033	0.86
125	561	0.47
140	346	0.29
160	534	0.45
180	258	0.22
200	66	0.06
225	175	0.15
250	32	0.03

Figure 6.4 – The concept neighbourhood with network design and corresponding pipeline dimensions for a single line configuration of the test case with Aquathermal energy as a secondary source

Conventional customer type C

The customer does not participate in thermal load reduction through load shifting or otherwise. The dwelling is designed to supply based on initial demand estimations for the building setup.

Dynamic customer type D

The customer participates fully in load shifting on a daily basis. Its thermal load profile is reshaped into a flat and constant load level that varies with daily thermal demands of the households.

6.2.3 Two test cases: aquathermal energy or waste heat as a secondary source

Half of the heat production will be supplied by a secondary source. Two options results in the design of two test cases. The first option uses aquathermal energy i.e., thermal energy from surface water as a secondary source. The seasonal load profile of aquathermal energy is similar to that of the PVT panels. The configuration is depicted in Figure. 6.5. The second network configuration utilizes waste heat from a commercial building e.g., a data centre nearby. As a base load source, it has a flat production profile throughout the year.

6.3 Input parameters

6.3.1 Thermal load profiles

Building characteristics

The thermal load profile is related to building characteristics and operation. The thermal demand of the households is based on the average energy label B dwelling of the DeZONNET case. The annual heat demand for space heating is roughly 6606 kWh(th) and the heat for DHW supplied to the buffer is responsible for roughly 3000 kWh(th). The DHW is supplied from a DHW buffer. Hence the typically peaked DHW profile is converted to a flat load profile that does not impact thermal peak consumption of the consumer as significantly as before. The combined annual load profile is illustrated in Figure 6.7.

Additional tests with energy label A dwellings will be run to estimate the impact of energy saving measures. For these test, the space heating demand is altered due to these measures. The impact of energy saving measures was estimated after analysing the differences between the load profiles of label B and label A. For the input data of customer type C, the overall space heating demand is lowered by 53%, while the highest peak of an individual household is reduced by 37%.

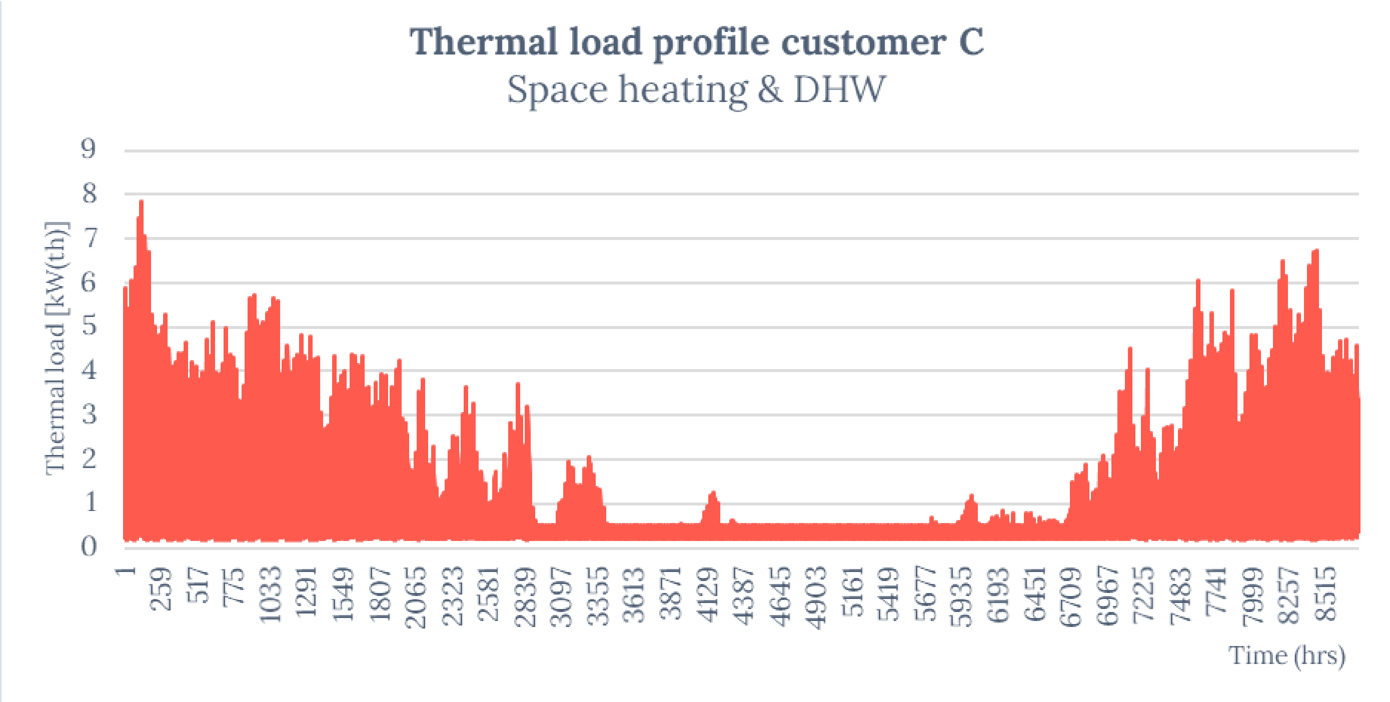


Figure 6.5 – One-year heat load profile for a single conventional customer type, adopted from received data DeZONNET Case (“DeZONNET Eindrapport”, Energy, 2020)

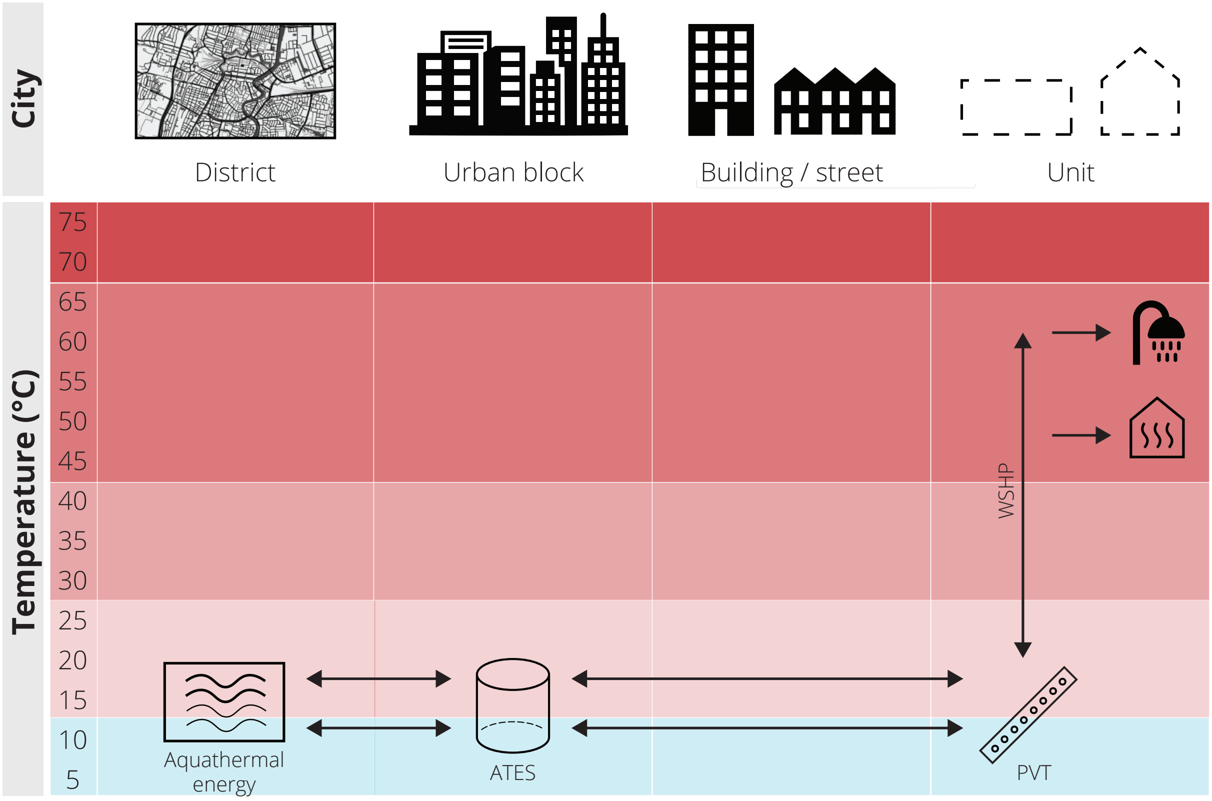


Figure 6.6 – The configuration of the test case with Aquathermal energy as secondary source

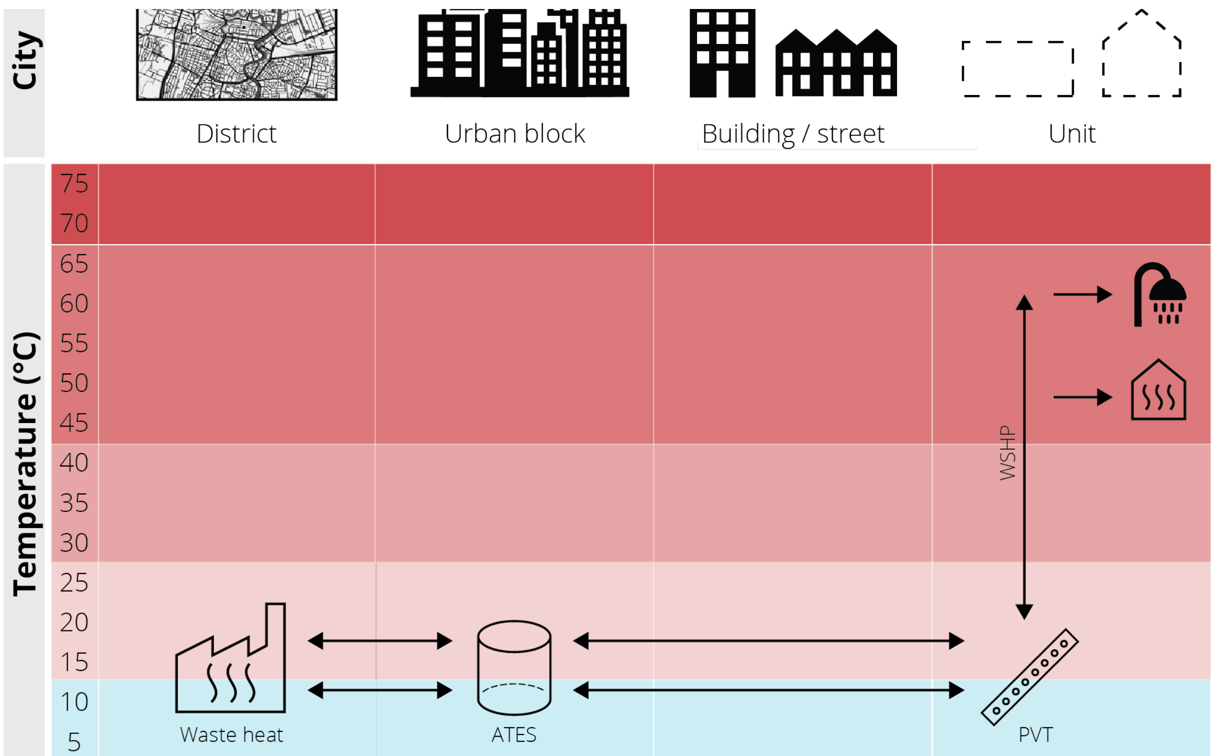


Figure 6.7 – The configuration of the test case with Waste heat as a secondary source

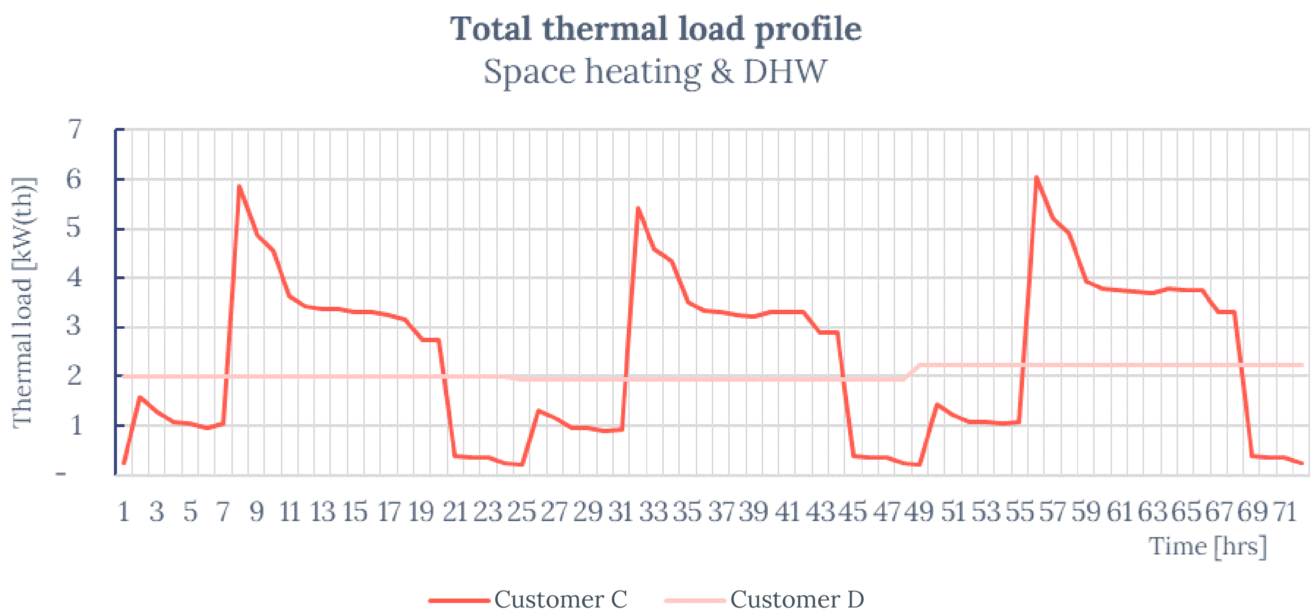


Figure 6.8 – Illustration of Customer C and D's daily load profiles for a three-day segment

Customer types and operation

The operation is different for customer types C and D. Customer C maintains conventional operation. Customer D, a participant of DSM strategies, has a fully peak shaved thermal load profile which is illustrated in Figure 6.8. Customer D will experience minor indoor temperature variations due to the thermal mass of the buildings. The conventional load profile of consumer C creates a night setback that results in a temperature drop during the night. This must be compensated during the morning peak where, as a consequence, thermal peaks occur. Hence, customer A will experience the larger indoor temperature fluctuations.

WSHP sizing

Sizing of the WSHP is done considering the individual thermal peak of consumer C and D and the SCOP of the WSHP. Estimation is based on an assumed SCOP of 5.8 and estimated maximum peak loads of 8.5 kW(th) and 4 kW(th), for consumer C and consumer D respectively. An installed capacity of 6 kW(th) and 4 kW(th) should suffice (TripleSolar, personal communication, 2021). The design criteria, input parameters and the estimation itself can be found in Appendix B.

Secondary source

Half of the heat demand will be covered by a secondary source. Sizing of the secondary sources is based on the seasonal COP (SCOP) of the WSHPs, an annual accumulated heat demand of 9606 kWh(th) per dwelling and 3500 and 8760 full load hours, for the aquathermal energy and waste heat scenario respectively. The required heat supply to the WSHPs is calculated with SCOP:

$$Q_{sec} = 1 - \frac{1}{SCOP} * Q_{secdem}$$

Where:

- Qsec is the annual heat production supplied by the secondary source
- SCOP is the seasonal coefficient of performance of the WSHP, assumed to be 5.8 (Boon & Loogman, 2020)
- Qsecdem is 50% of the cumulative annual demand of the households. The remainder is supplied by PVT.

The installed capacity was the determined by dividing the required Qsec is the annual heat production by its full load hours.

6.3.2 Network sizing

Peak load

The network was sized based on the coincident peaks of consumers. The coincident network was determined by the size of the loads and the simultaneity. The size i.e., load level is covered by the thermal load profiles. The simultaneity factor (SF) for both consumer types needs some revision.

Thermal peaks in space heating typically do not occur simultaneously. For networks exceeding 205 dwellings, a simultaneity factor of 0.55 is to be expected (ISSO, 2017). As DHW is supplied from the DHW buffer, its peaks are not impacting the load profiles in the context of peak consumption. Their Sf can therefore be neglected. The 0.55 SF for space heating is based on traditional operation. Customer B does not operate based on this consensus. The fully load shifted thermal profiles do not longer contain peaks and the SF becomes 1. As all customers of type B will heat their house with a constant level continuously, their operation will overlap a 100% of the time. Their thermal peak was estimated to be 4 kW(th), as can be found in Appendix B.

The distribution grid

The pipelines of the original DeZONNET concept were designed based on a 7 kW(th) peak from PVT generation. To redesign the network on a different network peak based on consumption rather than production is a complex design process. For simplicity reasons, another approach was adopted. Instead, the original network peak was compared to the network peak imposed by the different ratios of consumer groups A and B: 100% A, 100% B or an evenly split population. The new network peaks were divided by the original to create a network peak multiplier. The distribution network and its pipeline dimensions are adjusted accordingly. The newly determined pipeline dimensions are matched with the available pipeline diameters in the original DeZONNET case and reselected. This estimation can be found in Appendix C.

6.3.3 Network cost

The tariffs are cost-reflective. To determine the reference tariff and the two proposed three-tier tariff structures, the network cost need to be determined. Based on the structure of Subsection 4.1, the considered network cost can be divided into generation and distribution, where cost components are driven by CAPEX [€/kW(th)], fixed and variable OPEX [€/yr. and €/kWh(th) respectively].

Network Cost adapted from the original DeZONNET TCO model

The publicly accessible TCO model of DeZONNET was used to estimate CAPEX of OPEX components included in the original DeZONNET concept. Some input parameters are adjusted:

- The number of PV panels was set to three instead of six to halve the PVT production
- Participation rate was set to 100%
- Building measures are neglected
- The grid was dimensioned and calculated for a building mix of 50% user type C and 50% customer type D.

Redesign of the grid and the pipe dimension is based on the reduced coincident peak due to the different thermal loads compare to the original DeZONNET concept. The estimated costs can be found in Tables 6.1-6.3. The estimation is explained in Appendix A, B and C.

The fixed and variable OPEX are based on an annual space heating demand of 6606 kWh(th) and 3000 kWh(th) for DHW with three PVT panels (“DeZONNET Eindrapport”, 2020) per household.

Table 6.1 – the estimated average annual cost per household over 30 years from CAPEX of the network & equipment

Equipment			Cost excl. taxes	Reference
Building equipment	WSHP	Customer C (6 kW(th))	€ 6,840	TCO model (Boon & Loogman, 2020)
		Customer D (4 kW(th))	€ 5,248	Indication TripleSolar (personal communication)
	Indoor piping and meters		€ 2,280	TCO model (Boon & Loogman, 2020)
	PVT panels (three)		€ 2,715.	TCO model (Boon & Loogman, 2020)
	Inverters		€ 570	TCO model (Boon & Loogman, 2020)
	Thermal delivery system		€ 2,300	TCO model (Boon & Loogman, 2020)
ULT grid	Connection pipes	Customer C (8 kW(th))	€ 3,891	Appendix C (Boon & Loogman, 2020) (Fockert et al., n.d.)
		Customer D (4 kW(th))	€ 3,400	Appendix C (Boon & Loogman, 2020) (Fockert et al., n.d.)
	Distribution grid	Customer C (8 kW(th))	€ 2,020	Appendix C (Boon & Loogman, 2020) (Fockert et al., n.d.)
		Customer D (4 kW(th))	€ 1,896	Appendix C (Boon & Loogman, 2020) (Fockert et al., n.d.)
System equipment	ATES		€ 2,000	TCO model (Boon & Loogman, 2020)
	Centralized system facilities		€ 350	TCO model (Boon & Loogman, 2020)

Table 6.2 – Estimated average annual cost per household over 30 years from CAPEX of secondary sources

Secondary source	Q_{sec} [kWh(th)]	Q_{sec} [kW(th)]	Cost excl. taxes	Reference
Aquathermal energy	4769876	940	€ 224	(Groen, Smekens, Beurskens, & Lensink, 2021)
Waste heat	4769876	375	€ 165	(Muller et al., 2021)

Table 6.3 – Estimated average annual cost per household over 30 years from OPEX

Equipment			Cost excl. taxes	Reference
Building	O&M		€ 224	TCO model (Boon & Loogman, 2020)
	Electricity		€ 165	TCO model (Boon & Loogman, 2020)
Grid	O&M		€ 252	TCO model (Boon & Loogman, 2020)
	Electricity		€ 49	TCO model (Boon & Loogman, 2020)

6.3.4 Proposed three-tier tariff structures

Variable demand charge

Two subscription levels are created: a maximum level based on the thermal peak in the original load profile and a minimum level based on the 100% load shifted load profile. The two price levels are based on the fixed demand charge that was determined by the CAPEX. These are annual subscriptions.

Energy charge

The price level for the flat energy charge is cost-reflective of variable O&M cost driven by energy consumption. The ratio of the price spread between peak and off-peak is four. TOU peak hours are common space heating: between 06:00 and 10:00 and between 16:00 and 20:00 (Menkveld et al., 2021).

Standing cost

The standing cost are characterized by the sum of all fixed O&M components. This charge is the same for all tested tariffs, but different in each secondary source scenario: Aquathermal energy or waste heat.

Table 6.4 – The variable demand charge with estimated subscription levels for the proposed three-tier tariffs

Subscription levels [kW(th)]	Price Aquathermal energy scenario [€/kW(th)/yr.]	Price Waste heat scenario [€/kW(th)/yr.]
4	€ 577	€ 537
8	€ 1153	€ 1075
Fixed	€ 865	€ 806

Table 6.5– energy charge of the two proposed three-tier tariff structures

Energy charge	Price Aquathermal energy scenario [€/kWh(th)]	Price Waste heat scenario [€/kWh(th)]
Flat	€ 577	€ 0.0324
TOU - peak		€ 0.0647
TOU – off-peak	€ 865	€ 0.0167

Table 6.6 – Estimated standing cost for testing the proposed three-tier tariffs

Standing costs	Price Aquathermal energy scenario [€/kWh(th)]	Price Waste heat scenario [€/kWh(th)]
Standing cost	€ 566	€ 557

Table 6.7 – Reference tariff based on an estimated flat volumetric energy charge

Reference tariff	Aquathermal energy case [€/kWh(th)]	Waste heat case [€/kWh(th)]
Energy charge – price level	€ 0.114	€ 0.154

6.3.5 A volumetric reference tariff structure

Based on the exact same costs it however does not include a demand charge. Costs are incorporated into the volumetric energy charge. This two-tier structure has two components: a flat volumetric energy charge and fixed standing cost as defined in Table 6.7.

6.3.6 Performance indicators

Cost-reflectivity

Determining future cost to allocate cost-reflective tariffs complex and fundamentally problematic to calculate. Alternatively, an indicator can be created to assess the cost-reflectiveness and compare the annual tariff charges to evaluate so-called cross-subsidisation between the two customer groups: C and D. When D is charged for services C is utilizing, Consumer D is cross-subsidizing consumer D.

As the network design is driven by its coincidental network peak, a peak contribution indicator is determined based on the indicator adapted from (Teun, 2021). However, instead of choosing the single highest critical peak, an alternative approach was adopted. Probabilistic approaches are adopted more frequently for network design and operation nowadays. It considers the probability of loss of energy supply under demand forecast scenarios, which contain different levels of uncertainty.

$$\text{Consumer costs C} = \frac{\text{Total network costs} \times \text{average coicident top 1\% peak contribution share C}}{\text{number of network consumers C}}$$

$$\text{Consumer costs D} = \frac{\text{Total network costs} \times \text{average coicident top 1\% peak contribution share D}}{\text{number of network consumers D}}$$

$$\text{Indicator-ratio C} = \frac{\text{Annual charge Consumer C}}{\text{Consumer costs C}}$$

$$\text{Indicator-ratio D} = \frac{\text{Annual charge Consumer D}}{\text{Consumer costs D}}$$

$$\text{Indicator score} = \frac{\text{Indicator} - \text{ratio C}}{\text{Indicator} - \text{ratio D}}$$

An argument can be made that the network capacity and thus investment cost are not driven by the single highest peak. Instead, the size, frequency and probability of critical peak loads are more relevant parameters. There will be no ideal number of peaks against which to assess cost-reflectivity for all networks (Passey et al., 2017). An in-dept statistical analysis is not within this scope. Alternatively, the top 1% peak loads are set to be an appropriate choice.

The coincident thermal peak share is thus assessed at the top 1% of the hourly load profile over the course of the simulated year:

Economic efficiency

Economic efficiency in networks is often assessed by calculating the load factor. The load factor under the different tariff structures is found by dividing the average load by the maximum load capacity of the network. Higher load factors indicate more efficient operation and efficient investments. Thus, a high load factor promotes economic efficiency.

Sustainability

Sustainability is promoted by rewarding an increase of renewable energy sources usage in the final share of demand, or by decreasing consumption. There are many options to demonstrate the sustainability promoting features of a tariff. As the tariff structure charges energy consumption per kWh, price signals to reduce consumption are embedded within the proposed three-tier tariff and the two tier-tariff.

An performance indicator is not applied as such. Instead, a demonstration of the impact of energy saving is applied. As earlier discussed, energy label B houses and their corresponding thermal load profiles were used to design the original test cases. Households with an energy label A and their corresponding thermal load profiles are used to demonstrate the impact under the proposed three-tier tariffs compared to the reference tariff.

6.4 Model outputs

The model will provide five different outcomes. These outcomes consist of different number of results, based on the tested parameters. An overview of the expected outcomes and number of results is provided below:

1. Network costs, six results in total, based on:
   (a) two test cases
   (b) three different customer ratios

2. Annual charges, 12 results in total, based on:
   (a) two customer types: conventional customer C and active customer D
   (b) two different test cases
   (c) three different tariff structures

3. Cost-reflectivity scores, six results in total, based on:
   (a) one consumer ratio: 50% C and 50% D
   (b) two test cases
   (c) three different tariff structures

4. Load factors, three results in total: based on three consumer ratios

5. 5. Sustainability indication: six results in total, cost reduction due to energy saving measures
   (a) one consumer ratio: 50% C and 50% D
   (b) two test cases
   (c) three different tariff structures

6. Income generated for the DHC operator, six results in total
   (a) one consumer ratio: 50% C and 50% D
   (b) two test cases
   (c) three different tariff structures

7. TEST RESULTS

7.1 Network cost and annual charges

The network capacity is reduced by a lower network peak. Lowering the lowered level of required network capacity reduces capital investments for the network. The potential of potential cost reductions is depicted in Figure 7.1, where a network of single customer group, either C or D, is related to the test scenario of an evenly distributed mix of 50% Customer C and 50% Customer D.

The annual charges of both consumers groups in the two test cases, based on an even mix of customer types C and D, is depicted in Figure 7.2.

7.2 Performance on tariff objectives

The prioritized tariff objectives for the proposed tariff structures were: cost reflectivity, economic efficiency and sustainability. The performance with respect to the tariff objectives is scored based on two performance indicators. The sustainability objective is inherently a part of tariff structures with a volumetric energy charge.

7.2.1 Cost-reflectivity indicator

Based on the top 1% of the coincident network thermal peaks, which can be found in Table 7.1, the performance on the cost-reflectivity objective was estimated.

The score of this indicator can range between -100% (D is charged for all cost imposed by C) and +100% (C is charged for all cost imposed by D). The scores for each of the tariff structures in the two different test cases are shown in Figure 7.3.

7.2.2 Economic efficiency

The load factor of the network is determined by the thermal load profiles. These load profiles were fed to the model and predetermined. However, the load factor does show what the potential efficiency gain is for different ratios of the defined customer types. As shown in Figure 7.4, increased load factors are found when tariffs result in load shifting.

7.2.3 Sustainability

Sustainability is inherently a part of the tariff structures because an energy charge is incorporated in all tested tariffs. It can be noted that this component is significantly bigger in the reference tariff compared to the proposed three-tier tariffs, since energy consumption is its only charging criteria next to the standing cost.

In this scenario, energy saving measures result in an energy label A classification instead of an energy label B for all households. This yields altered thermal load profiles for both customer type C and D. Under the tested tariff structures and their corresponding price levels, this results in the following relative annual savings depicted in Figure 7.5. Savings are biggest in the reference tariff. However, customer type D saves realtively more than customer type C in the tested tariff proposals.

Table 7.1 – top 1% critical peak contribution customer type C versus customer type D

Top 1% Coincident network peak [kW]	Peak hour	Coincident contribution C		Coincident contribution D	
4144	128	2502	60.39%	1642	39.61%
3977	104	2381	59.86%	1596	40.14%
3781	152	2250	59.51%	1531	40.49%
3538	8432	2121	59.97%	1416	40.03%
On average			59.93%		40.07%

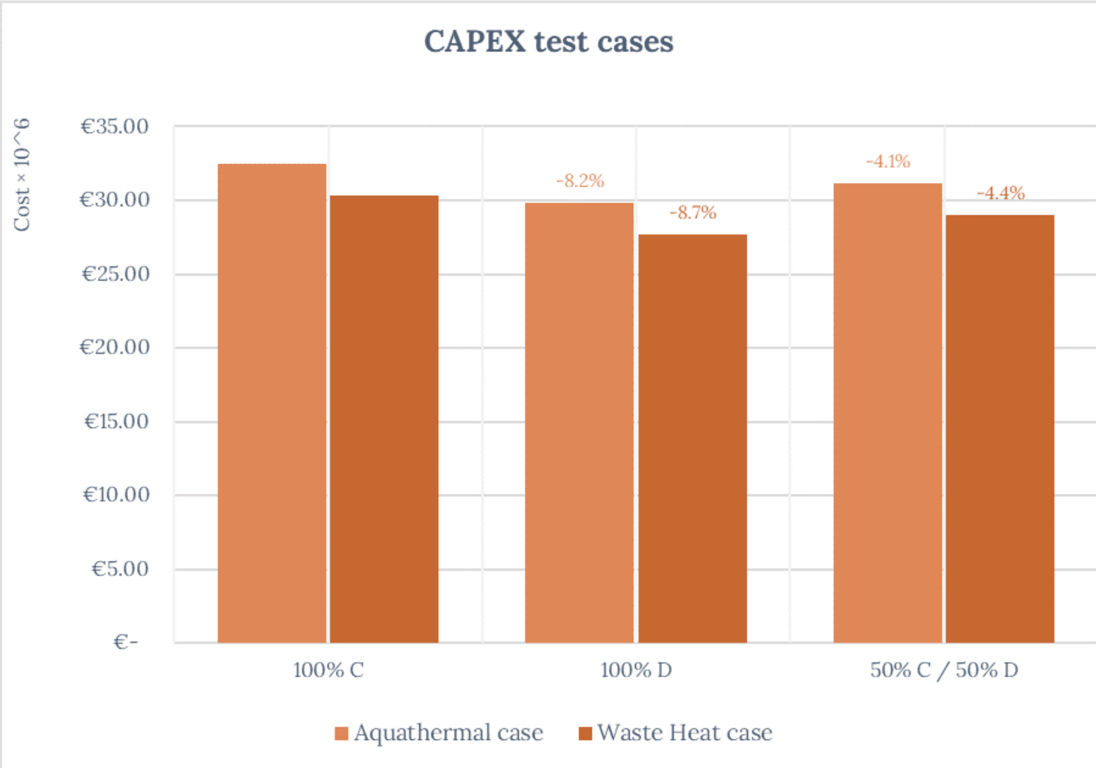


Figure 7.1 – The CAPEX results for the different customer ratios of conventional (C) and dynamic (D) customers

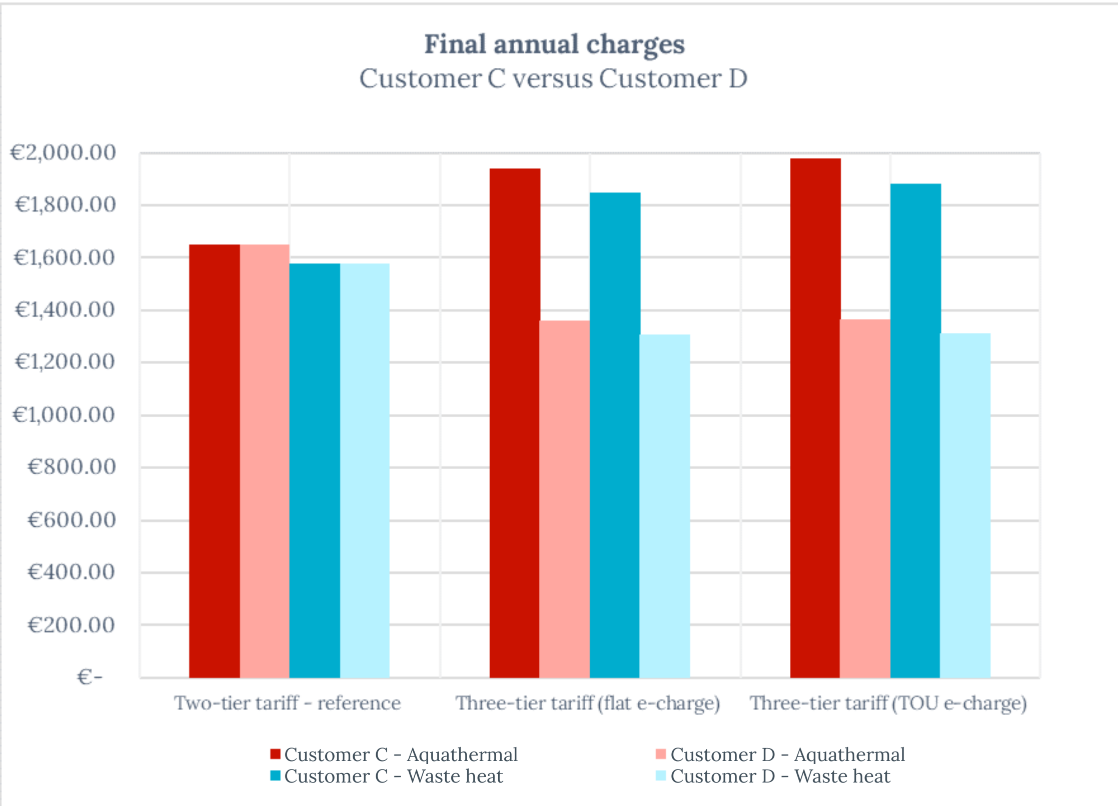


Figure 7.2 – Final annual charges of the consumer types C and D for test cases with aquathermal energy and industrial waste heat as a secondary source

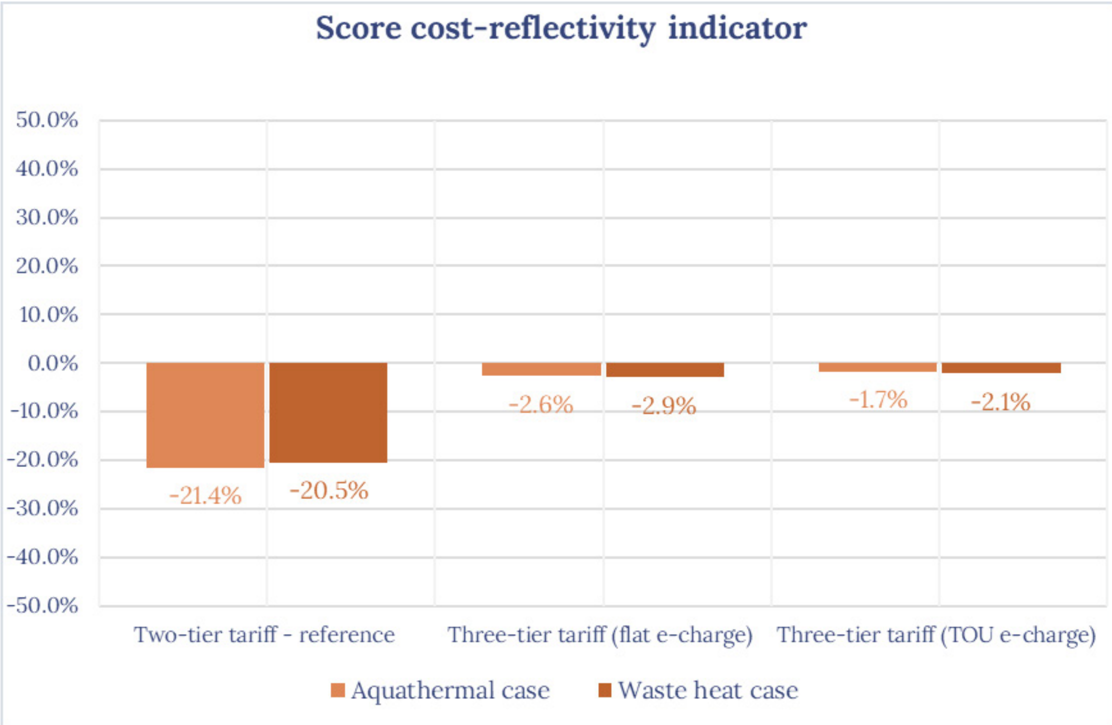


Figure 7.3 – Cost-reflectivity score between customer type C and D for test case Aquathermal energy and Waste heat

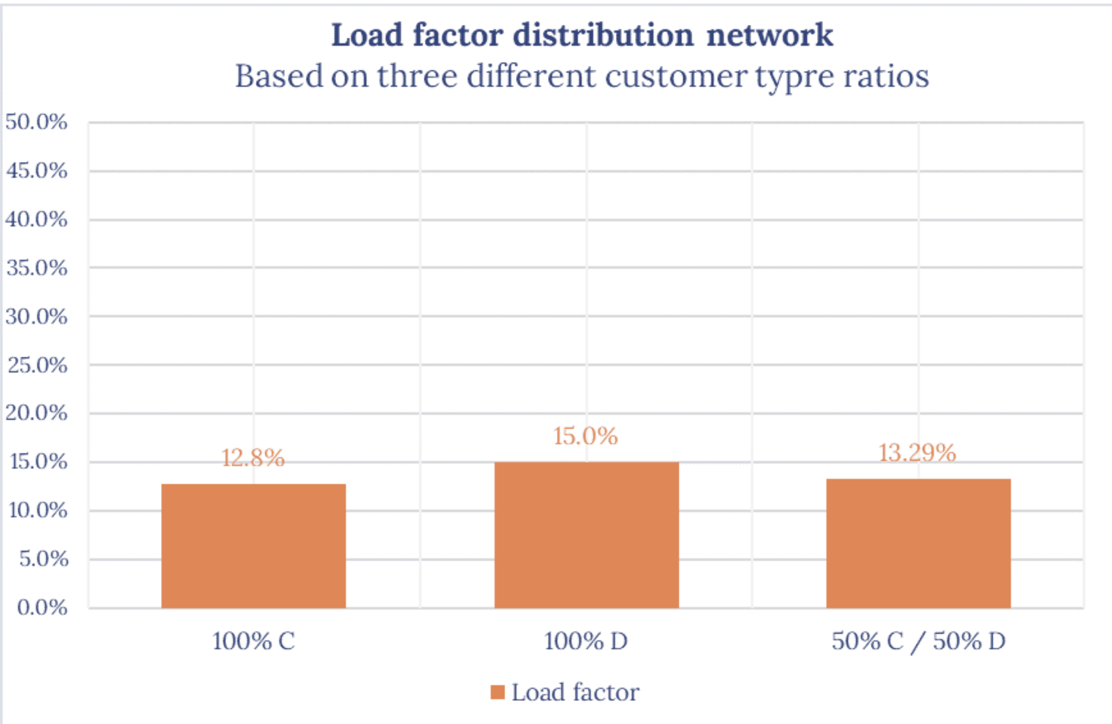
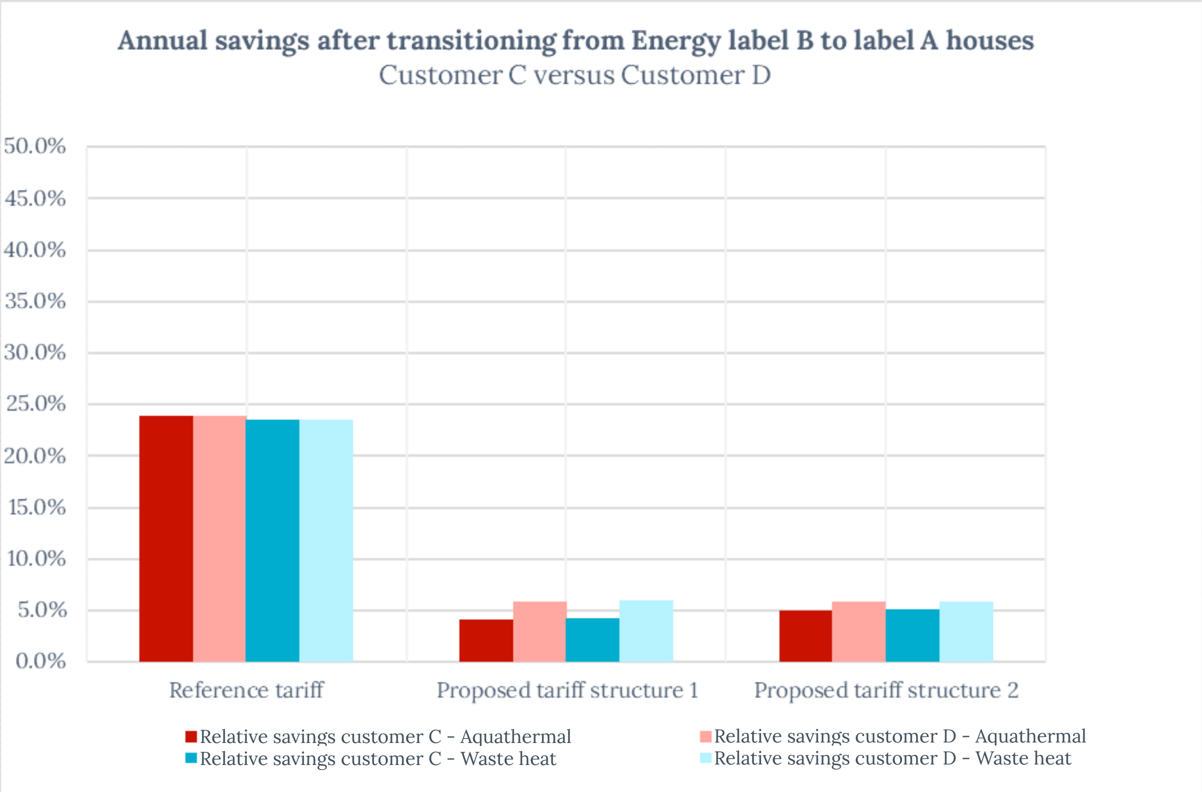


Figure 7.4 – Network load factors for three consumer type ratios: (i) 100% C, (ii) 100% D and (iii) 50% C and 50% D


Annual savings after transitioning from Energy label B to label A houses
Customer C versus Customer D
50.0%
45.0%
40.0%
35.0%
30.0%
25.0%
20.0%
15.0%
10.0%
5.0%
0.0%
Reference tariff
Proposed tariff structure 1
Proposed tariff structure 2
Relative savings customer C - Aquathermal
Relative savings customer D - Aquathermal
Relative savings customer C - Waste heat
Relative savings customer D - Waste heat

7.3 The operator's perspective: profit margins

7.3.1 The operator perspective: profits margins

As can be seen in Tables 7.2 and 7.3, the cost-reflective tariffs guarantee the recuperation of costs. Since no profit margin was allocated for these tests, there is a break-even. The added Time-Of-Use structure to the energy charge results in slightly higher returns which results in a small margin of profit.

Table 7.2 – Generated income for the operator and the corresponding profit margin for the Aquathermal case

	Two-tier tariff - reference	Three-tier tariff (flat e-charge)	Three-tier tariff (TOU e-charge)
Average annual cost	€ 1,980,929	€ 1,980,929	€ 1,980,929
Revenues	€ 1,980,929	€ 1,980,929	€ 2,005,262
Profit margin	**0.00%**	**0.00%**	**1.21%**

Table 7.3 – Generated income for the operator and the corresponding profit margin for the Waste heat case

	Two-tier tariff - reference	Three-tier tariff (flat e-charge)	Three-tier tariff (TOU e-charge)
Average annual cost	€ 1,892,840	€ 1,892,840	€ 1,892,840
Revenues	€ 1,892,840	€ 1,892,840	€ 2,005,262
Profit margin	**0.00%**	**0.00%**	**1.23%**

8. DISCUSSION

This chapter discusses and interprets the results from the modelling exercise. Furthermore it reflects on the limitations and the impact of the tariff structures and of its implementation. The aim is to discuss, interpret and reflect on this entire study. Within this chapter, an answer to the fifth research question is provided:

Q.4	***What is the impact of implementing potential 5GDHC tariff structures?***

It is structured as follows: section 8.1 evaluates the test results. Section 8.2 reflects on the implementation and implications of the proposed tariff structures. Section 8.3 reflects on the simplifications for this 5GDHC tariff design. Limitations of this thesis research are discussed in Section 8.4. finally, conclusions and an answer to the fourth research question are provided in Section 8.5

8.1 Evaluation of the test results

8.1.1 Performance indicators

For the aquathermal energy and waste heat test cases, the results for this single year were tested for the tariff objectives of cost-reflectivity, economic efficiency and sustainability. The results of this thesis show that the proposed three-tier tariff structures are more cost-reflective and efficient in comparison with the two-tier reference tariff, with a slight edge for the tariff with a TOU structure included in the energy charge.

However, when the test was performed for the sustainability indicator – after improving the household's energy label from B to A – the results showed that the reference tariff had significantly greater savings than the proposed three-tier tariffs. While other parameters remained the same, this altercations showed that annual charges are reduced the most within the reference tariff. The reference tariff outperformed the proposed three-tier tariff structures based on this indicator. This was to be expected, since the improved energy label results in a relative reduction of overall consumption which is bigger than that the reduction of the highest peak: 53% versus 37%. This estimation was made on the individual load profile for customer type C. This image was confirmed when considering the 1% highest network peaks after simulation. Peak reduction ranged between 34% and 38%, while overall network energy consumption was reduced by 53%. This raises the question about how sustainability in tariff design should be considered.

Although this sustainability indicator showed a seemingly unsatisfactory result, sustainability is still promoted in the proposed tariff structures albeit to a lesser extent. The argument can be made that this trade-off was made to advance roll-out of 5GDHC and increase utilisation of (U)LT renewable thermal energy sources. The biggest impact on sustainability most likely to be achieved through enabling 5GDHC systems. Indicating the performance of promoting sustainability is thus not as straightforward as cost-reflectivity and economic efficiency.

8.1.2 The operator perspective - profit margins

An important result from an operator perspective is the income that is generated. Based on the tests with energy label B households, all cost are recuperated. This was to be expected, since the tariffs were designed based on cost-reflectivity.

The added Time-Of-Use structure results in slightly higher returns that result in a small margin of profit. The proposed three-tier tariff structures encourage customers to actively contribute to load shifting. The tariffs are based on expected consumption, shifts in consumption patterns impact the result in either losses or profits. This is confirmed by the results of running energy label A households. Consumption is decreased and the customers save on their annual billings. This effectively means a reduction of revenues for the operator. Over-estimation of the cost will lead to profits that could be corrected by the regulator, while an under-pricing leads to losses. A common solutions is to correct ex post for the initial estimation at the end of a billing period as discussed in Subsection 4.3.1.

However, this situation deserves extra attention as promoting energy saving measures would be considered positive. Decreasing energy consumption adheres to the goal to reduce carbon emissions. Thus, the following situation holds true:

Dynamic customers that participate in load shifting reduce network peak, which could:

- Reduce the required network capacity and thus investment cost for future networks
- Free up space for extra network connections without grid reinforcements of existing networks

The operator should receive some kind of benefit in both scenarios to satisfy both customer and operator preferences. In turn, efficiency incentives should be enforced by the regulator to stimulate operators' efficient operation and investments. When cost-reflective tariffs are charged, the price level is determined on expected cost. For operators, this means they have to estimate cost ex ante. Alternatively, correction can be used to adjust tariffs for the next billing period, when customers could readjust their consumption and/or subscription level accordingly.

8.1.3 Network design implications

Moreover, the DeZONNET showed that locally produced thermal energy from the PVT panels can be responsible for the critical network design. If this is the case, the impact of consumption -based tariff structures are impacted and most likely reduced.

8.2 Implementation and implications of the proposed three-tier tariffs

8.2.1 Manual or automated implementation

Customers can respond to tariffs either manually or automatically. Automatic control tends to be a more efficient service with a higher level of comfort. The gain from load shifting is likely to be close to optimal as the operator has the control and operates within limited uncertainty of the thermal loads in the network. Manual control requires high shares of customer participation and changes of routines. Without active involvement, the impact of the shifted loads is dampened.

Moreover, the manual implementation could result in unpredictable or even unwanted outcomes, where customers (un)intentionally adjust their thermal loads to a disadvantageous system performance. However, the loss of manual control discourages customers to participate and social acceptance of the system is likely to be threatened. Providing customers with the final control on the load flexibility operations is strongly recommended, also in the automatic approach. (S3C project, n.d.). Since overwriting the automated operation is disadvantageous to system efficiency as a whole, a fee could be charged for this efficiency loss.

For both options, operation requires appropriate equipment and a lot of data. The smart energy system requires smart meters and detectors to measure thermal loads and enable real-time communication. For manual operation, tariffs need to be supported by commination services and facilities enabling consumers to access and understand all the relevant information and respond accordingly. For automatic control, communication does not necessarily have to be communicated on a real time basis. The challenge is more likely to engage customers in automation. The benefits during their daily routines should be clearly communicated with careful consideration of the impact: operation cannot be too intrusive.

8.2.2 Data and privacy implications

Consumer data is collected, stored, processed and managed to enable both manual or automated operation. As was discussed in section 3.3.2, a value conflict arises in smart grid environments, such as 5GDHC. IT applications enable smart grid operations, but the required data raises privacy concerns. Access to consumption data could reveal personal information about behavioural patterns of customers. Cybersecurity is another concern, where security of supply could be threatened by cyberattacks. A potential solution can be found within the organisational framework, through appointing or creating an authority within a company or market in charge of safeguarding privacy (De Wildt et al., 2019).

8.3 Reflection on simplifications 5GDHC tariff design

8.3.1 Recap 5GDHC complexity

Several factors contribute to the complexity of 5GDHC tariff design, as concluded in Subsection 3.5. As discussed in section, the exploratory nature of this study required a number of simplifications. A recap of the complexity of 5GDHC tariff design and the simplification is provided to create a fitting perspective in which the results should be regarded. The complexity of 5GDHC tariff design is retraced to:

- **The smart grid features of a 5GDHC: It is based on fundamentally different principles than traditional DHC.** It includes decentralized production by prosumers, bi-directional thermal energy exchange and potentially demands side management. Aside from the technological challenges in design and optimization of operation, these features affect tariff design. Smart grid features are not incorporated in existing DHC tariff design.

- **Economic perspectives: NCE, NIE and OIE provide different economic lenses which can be applied to equip tariffs with design for values and tariff objectives**. Finding and maintaining a trade-off that balances efficiency orientated values (NCE/NIE) and social vales (OIE) is a non-trivial assignment. It goes beyond how the tariffs are structured. It considers an institutional framework where different organisational structures can be considered and an suitable allocation of property and discussion rights should be reviewed. Moreover, a change of existing tariffs and paradigms results inevitably to winners and losers in the new situation.

- **Conflicting values in smart energy environments:** This factor is closely related to the first two. SGs, like 5GDHC, have several potential benefits, but looming value conflicts threaten their social acceptance. 5GDHC tariff design should factor in, try to solve or at least not exemplify these potential conflicts.
- **A multi-disciplinary field: Tariff design is a piece of a puzzle that integrates multiple fields.** It is embedded in a technological, economic and institutional environment. Finding and including all relevant (f)actors is a challenging assignment as is.

Defining its complexity has value to current and future 5GDHC research. Simplifications were necessary to explore potential 5GDHC tariff structures fitting with the exploratory stage of this technology. These simplifications were discussed in Subsection 4.4.

8.3.2 Implications for this research

This means the results could be different when the full complexity is considered. It raises the question: What would have been the implications for this research without these simplifications? To answer this question, the imagined implications, based on the knowledge gained in this research, are listed below.

Potential future roles for 5GDHC

First of all, the future role of 5GDHC systems determines along which path 5GDHC tariff design can evolve. For example, tariff structures and modules aligned with customer preferences can be explored much more without the cost-reflectivity requirement, such as: (1) differentiated 5GDHC tariffs that stimulate roll-out for DHC companies or (2) free tariffs with limited rules, to enable an all-in-all efficient system with perfect competition.

Alternative paths with less focus on cost-reflectivity could allow a wider variety of tariff structures. Subscriptions and corresponding tariffs that align with customer preferences and which allow the operator to optimally control and shift the thermal demand profiles of its customers. The number of required guarantees, i.e. a minimum level of heat, for thermal energy supply is an important driver that guides and limits tariff design.

Economic perspectives on the organisational and institutional embedding

If the NIE and OIE lenses were to be applied to this 5GDHC tariff design, a few factors would be considered. First of all, the role distribution and organisational structures. Market design variables like horizontal and network unbundling and integrated versus decentralized market determine which type of collaborations are allowed. The NIE perspective focusses on transaction costs for an efficient structure. A**dding this perspective to the 5GDHC tariff design could impact the tariff structure. The nature of the contracts and transactions is namely a main determent for the kind of actors that are enabled to fulfil one or multiple roles.** The OIE perspective provides additional parameters compared to that of NIE. The most efficient organisational structure might not be found satisfactory by the public. **Shifting property and decision rights might be necessary to raise social acceptance.** Local ownership could be an example, or another would be to organise price dialogues and award customers with decision rights. This would create a wider variety of potential 5GDHC tariff structures. Important to note is that an optimum is probably temporary as prioritized values tend to shift over time.

Secondly, conflicting values in smart grids have been introduced but only data usage has been reflected upon. For instance, an authority for safeguarding privacy of its customers has been suggested. Considering other looming value conflicts and potential solutions could impact 5GDHC tariffs as they might increase price levels or require a redistribution of cost components.

Transaction cost in smart grid environments

The promise of SGs like 5GDHC is founded on increased efficiency and sustainability. Data and active and participating actors are required to reach their full potential. The level of required interaction is an important factor to determine whether a SG solution is worth it considering the required flow of information in respect to the transaction cost. An highly inter-active system requires additional activities and infrastructure. High levels of interaction require complex optimization of control, extensive inter-active communication & information provision and increasingly complex billing procedures. From TCE point of view, the benefits have to outweigh the cost for the solution to be justified. In tariff design, this extra consideration could benefit simpler solutions over more complex structures. The benefits of the latter are then mitigated by the impact of implementation.

8.4 Limitations of the research

As for all research activities, limitations exist for this study too. They can be divided into three main categories: limitations of doing exploratory research, limitations related to availability of data and limitations of the results related to the assumptions and design choices in the modelling exercise. In short, the biggest limitation would be that 5GDHC systems barely exist yet.

8.4.1 Limitations of doing exploratory research

To do exploratory research means to investigate a problem which is not clearly defined yet. It is needed to create a better understanding of the existing problem, but will not provide conclusive results directly. This is a very real limitation of this research as a large portion of this research was of an exploratory nature since 5GDHC is a relatively recent innovation. Thus, the value of this research is mostly found in the contribution to how the problem of 5GDHC tariff design is defined, which questions should be asked and answered to ultimately result in well founded 5GDHC tariff structures.

Moreover, tariff design is a multi-disciplinary field where technological, institutional and organisational frameworks collide and impact one another. To conduct an inter-disciplinary study like this, a wide range of knowledge is required to capture the full complexity and deliver a substantial final contribution. Ideally, this type of research would probably require a multi-disciplinary team.

8.4.2 Limitations of the data

First of all, the available data was very limited. Data for 5GDHC specifically was not available, as the real projects are very rare still. The Mijnwater project did not match the exact network configuration that was studied for this research and so data from another study, the DeZONNET research, was used. However, this was a 5GDH study and cooling was not included. The received data contains space heating and DHW demand for a single year: an average year with weather conditions. This data does not include extreme events i.e. extremely cold or power or power outages. Furthermore, the data has a limited amount of customer types and demand profiles based on an average household. PVT thermal production profiles were not included.

8.4.3 Limitations of the results

One main limitation of the results is related to the proposed three-tier structure itself. Only two subscription levels were tested: 4kW and 8kW. Furthermore, a number of design choices remained unaddressed in the 5GDHC tariff design exploration. The two main variables are pricing or rebating cooling and feed-in thermal energy by prosumers and cooling. Without these components, the test provide a demonstration. A complete tariff structure, the tariffs can transition from exploration to formalisation.

Moreover, the subscriptions and corresponding price levels in the three-tier tariff structures remained the same as the input was changed from energy label B households to label A. As indicated, energy saving measures reduce thermal peaks and thus the required installed capacity. This allows for lower subscription levels than before. Households that are improved with energy saving measures should be able to select lower subscription levels to reduce their annual charges. This test was not carried out as such.

Furthermore, this modelling exercise was limited to a one year simulation. Thus, the results are based on a single year simulation of a network that will operate for multiple decades. With regards to the tariffs and utility regulation: how to correct ex-post for profits and losses was not included.

The other limitations are related to the modelling exercise. The model is a simplified network that neglects complex design issues within the 5GDHC system. A number of assumptions were made to create a testing environment suitable for assessing the tariff structures:

- **Limited number of tested customer type ratios:** A limited number of customer types were tested. The customer did either fully participate in load shifting (dynamic customer type D) or not at all (conventional customer type C). A 50% versus 50% scenario was tested, but other ratios can be thought of. Furthermore, partial participation in load shifting was not tested as an option.
- **A homogeneous residential building mix:** the same building type was used for all households

in the model. A wider variety could generate a more real image.

- E**ven distribution of installed PVT**: not all rooftops are suitable for PVT panels nor does every customer decide to install them. These potential differences could mean some individual connections are impacting network capacity more than others.
- **No orientation differences:** this affects the production profiles of PVT. They could become an extra limiting factor in design or, on the contrary, a less important parameter.

8.5 Conclusion: Impact of 5GDHC tariff structures

Firstly, this chapter reflected on the test results from the modelling exercise. Furthermore, it reflected on the limitations and the impact of the tariff structures and of its implementation. Within this chapter, an answer to the fifth research question was provided:

Q.4	***What is the impact of implementing potential 5GDHC tariff structures?***

To answer this question appropriately, this final section should be split in two: (1) the impact of the proposed three-tier tariff structures that contain a variable demand charge, an energy charge and a fixed standing cost and secondly (2) the impact of 5GDHC tariff design in general.

Impact of the proposed three-tier tariff structures

The impact of the proposed three-tier tariff structure is determined by the local production by prosumers. If production is the critical design criteria for 5GDHC networks, the impact of the proposed consumption-based structures is reduced. This can be countered by installing TES, which is constricted by spatial characteristics in and around the households

Furthermore, **a value conflict of SG(th) arises when a choice between manual of automated operation has to be made: efficiency versus security and autonomy.** A seemingly practical dilemma between manual and automated control but this dilemma raises value-conflicts commonly encountered in SG environments. Manual control requires a communicative on top of the smart metering infrastructure. It increases uncertainty of the outcome, since households can (un)intentionally adjust their thermal loads to a disadvantageous system impact. The data that has to be collected, stored, processed and managed - needed in both but arguably more in automated control – raises data security and privacy issues. An authority needs to be appointed to see to safeguarding data of customers.

Impact of 5GDHC tariff design

Another implication can be found in the TCE. **Transaction cost are expected to rise by all this**

required data and the level of required interaction between actors in the network. The benefits should outweigh the cost for it to make sense. These costs will impact price levels and the equired interaction within the tariff structures and billing procedures. The smartness within 5GDHC requires data gathering, storing, managing and securing which raises both transaction cost and privacy concerns. These concerns hence impact 5GDHC tariff design as it is an extra restraint for complex tariff structures

9. CONCLUSIONS

9.1 Answers to the research questions

The main research question of this thesis research was answered by systematically answering the research questions defined in Chapter 2. The answers to these research questions provide an answer to the main research question. A concise summary of the answers to these research questions is provided:

Q.1 *What makes tariff design for 5GDHC complex?*

5GDHC tariff design, like the technology itself, is new. **Guidelines, documentation and operational experience of 5GDHC systems is very limited. 5GDHC combines technological features – e.g., DG, DSM, prosumers - that are not commonly incorporated in DHC systems and its tariff design yet.** Changing existing tariff structures and the corresponding institutional framework will result on winners and losers of that change. Despite their potential, roll-out needs careful consideration its social implications. Tariffs can sooth or exemplify social acceptance issues of 5GDHC due to looming value conflicts in 5GDHC as they typically arise in electrical smart grids too.

Q.2 *What criteria are considered in tariff design?w*

Tariff design is structured through its objectives, which originate from different potential scenarios for the future role of 5GDHC in society. Considering different economic perspectives from NCE, NIE and OIE provides a value trade-off where objectives can be prioritized to structure tariff design and the corresponding regulatory and institutional framework. The tariff structure can be equipped with incentives to promote these objectives. Incentives can be created by dynamic tariffs that can be differentiated based on criteria such as time, type of service, fixed and variable elements. To align with the pending Dutch legislation, a utility principle is adhered, where cost-reflectivity is a prioritized objective. Economic efficiency and sustainability are additional tariff objectives for the 5GDHC tariff structures.

An alternative approach would be to devalue cost-reflectivity in favour of economic efficiency. It would enable 5GDHC companies to differentiate tariffs based on customer preferences, rather than the cost they impose.

Q.3 *What are potential 5GDHC tariff structures?*

Three-tier tariffs combining a variable demand charge (offering subscription levels), an energy charge and a fixed standing cost have to potential to promote cost-reflectivity, economic efficiency and sustainability in 5GDHC networks dominated by residential connections. Adding a daily time-of-use structure can be seen as an extended version of the proposed three-tier tariff structure. It could be added as an extra incentive to shift peak consumption from space heating and cooling to off-peak hours. Depending on participation levels, this could reduce coincident thermal peak loads.

Tariff modules containing rebates for automated operation can be an complementing option for 5GDHC tariff design. 5GDHC unlocks the potential for automation and optimisation of operation in DHC due to its SG features. Necessity for automated control is increased in networks where a high level heterogeneous thermal energy flows are present. A network containing commercial buildings, data centres and a variety of residential buildings. In short, operating a building mix of somewhat similar dwellings is less complex than 5GDHC operation in a highly diffused network with relatively high DOCs. Studying the design of corresponding models was not pursued in this research as the focus was on households in residential neighbourhoods.

Q.4 *What is the impact of implementing potential 5GDHC tariff structures?*

Firstly, the impact of the proposed three-tier tariff structure is determined by the local production by prosumers. If production is the critical design criteria for 5GDHC networks, the impact of the proposed consumption-based structures is reduced.

Furthermore, a value conflict of SG(th) arises when a choice between manual of automated operation has to be made: efficiency versus security and autonomy..

A trade-off between manual and automated control needs to be made. Manual control requires a communicative on top of the smart metering infrastructure. It increases uncertainty of the outcome, since households can (un)intentionally adjust their thermal loads to a disadvantageous system impact. The data that has to be collected, stored, processed and managed - needed in both but arguably more in automated control – raises data security and privacy issues. An authority needs to be appointed to see to safeguarding data of customers.

Another implication can be found in the TCE. **Transaction cost are expected to rise by all this required data and the level of required interaction between actors in the network. The benefits should outweigh the cost for it to make sense.** These costs will impact price levels and the allowed complexity within the tariff structures. The smartness within 5GDHC requires data gathering, storing, managing and securing which raises both transaction cost and privacy concerns. These concerns hence impact 5GDHC tariff design

9.2 Answer to main research question

The research questions provide the answer to the main research question which is restated below.

Main research question

What tariff structures can facilitate 5GDHC networks to stimulate efficient and sustainable heating and cooling for Dutch households?

The results of this thesis research show that a **three-tier tariff structure containing a variable demand charge, an either flat or a TOU structured energy charge, and fixed standing cost can promote cost-reflective, economic efficient and sustainable heating and cooling for Dutch households by 5GDHC.** Optionally, rebates to increase participation in automated operation can be included.

Two proposals were tested: one with a flat volumetric energy charge, the other with a TOU structure. For both proposals, a variable demand charge was designed by offering different subscription levels, enables incentives for a demand side management strategy called load shifting. As demonstrated in the modelling exercise, the three-tier tariffs outperformed the flat volumetric reference tariff reference on cost-reflectivity and efficiency promotion. The results showed that active and dynamic customers will pay less than passive conventional consumers for the proposed tariff structures. Energy saving measures were better rewarded in the reference tariff, but the outcome is acceptable since proposed three-tier tariffs enable increased roll-out of 5GDHC. The latter is expected to have the biggest impact. In relation to the future role of 5GDHC systems: if a utility principle with a cost-plus approach is selected, regulation should focus on sending out efficiency incentives.

The expected impact of the tariff structures is determined by technical parameters and implementation choices. For instance, **if local production from PVT or PT panels is responsible for network dimensions, the argument for demand charges is weakened.** This could be countered by installing TES solutions at the local building level. The implementation choices such as the required data to facilitate implementation could impact 5GDHC tariff design. **Data driven optimization offers benefits but also raises privacy concerns. Furthermore, a highly interactive system could drive up transaction cost to a point where it outweighs the potential benefits.**

9.3 Recommendations

The recommendations can be split into three categories. First, recommendations that are meant for follow-up action for the proposed three-tier tariff structures. These new tariffs structures are new to DHC systems and the recommendations are advice for further development and implementation. Secondly, recommendations for 5GDHC tariff design in general. Simplifications were used to carry out this research. However, tariff design for 5GDHC is complex, as was discussed in this report. Recommendations are made to the general process and as a result of reflection on the complexity. Thirdly, recommendations to urban energy planning are made after reflecting on design issues that were encountered during this study.

9.3.1 For the proposed three-tier tariff structures

Incorporate incentives for automated control

Automated control is more predictable and the impact of DSM strategies is expected to be stronger than manual control. It should however be implemented without disrupting customer autonomy too gravely. An important element in operation is to stop the night setback, which avoids a huge morning peak. This results in a pattern which approaches the dynamic customer (D) pattern already. If full automated control turns out to be a bridge to far, focus should thus be on mitigating the night setback.

Check compatibility with and impact on other existing and future DHC networks

The three-tier structures with a variable demand charge is not limited to 5GDHC. It could enable the roll-out of (U)LT DHC in general. However, it could also have an impact on existing networks as their business-case has been based on existing tariff structures.

Elaborate on the operator's perspective

The operator perspective requires further attention. If the three-tier structure is not accepted by operators, the tariff structure will not become common practise. The proposed three-tier tariff structures send out signals to decrease the necessary network capacity. Installing 5GDHC should become less expensive, which should making heating and cooling more affordable for their customers. However, this has not been examined. It is therefore recommended to elaborate on the operator's perspective.

Complete the tariff structure with cooling and feed-in structures

After completing the proposed three-tier tariffs, test them in more advanced models and pilot projects. However, the tariff structures themselves are not complete yet. Subscriptions for cooling should be included and feed-in components for heating and cooling should be added to the tariff structure too.

9.3.2 Recommendations for 5GDHC tariff design

More attention for the impact of data usage and required level of interaction

Whether SG technologies like 5GDHC can deliver on their promised potential is related to how well data usage and interaction is handled. Besides the privacy issues related to IT optimized systems, highly interactive systems require continuous flows of information. A complex tariff could send out optimal efficiency signals, but the increased transaction cost due to its implementation could still prevent it from being the optimal solution. When considering the additional privacy related challenges of gathering, storing, managing and securing all this information, the impact of data usage should not be underestimated.

Incorporate flexibility in tariff design

As 5GDHC is still a recent innovation and research is in an exploratory, flexibility for early adaptors is advised: adjust for lessons learned during operation and allow the possibility to annually correct for unexpected and unwanted outcomes.

This sparks another point: Pay more attention to so-called meta rules that determine how and by whom future tariff adjustments can be proposed, judged and regulated. This related to the institutional embedding of the system.

9.3.3 Recommendations for urban energy planning

Determine the future role for rooftop areas of energy prosumers

PV and PVT applications are essentially competing for the same surfaces. Individual benefits could clash with those of the general public. Recognizing this development and contributing research could lead to policies e.g. one that promote either PV, PVT or otherwise for specific types of households.

Consider long-term impact of cooling demand

Alternative cooling solutions, i.e. ACs, are more accessible than alternative solutions for heating. Thus price elasticity is higher than that of heating, which means pricing cooling based on cost-reflectivity might not be very tempting for households. However, the power grid will need to be reinforced if large amounts of ACs are being installed in the upcoming years. This would impose high cost on the society. Creating incentives to promote cooling through 5GDHC might be worth considering, especially with the expected rise of cooling demand.

9.4 Suggestions for future research

Explore other 5GHDC tariff design paths parallel to a utility-based ideology

The guarantees and requirements that future 5GDHC systems will have to fulfil with regards to heat and cooling delivery, determine the variety of options. Deviating from the utility principle enables more options to align with specific individual customer preferences. Other sectors e.g. telecom or airplane tickets can be observed for inspiration.

Use experience of SG(e) research and smart charging of electric vehicles as inspiration

Publication and experience have been gained on promoting flexibility and dealing with conflicting values in smart energy environments. Differences and similarities between SG(e) and SG(th) can be used for inspiration. For instance, the role of aggregators – who carry potential risks in return for control and optimization benefits - in the power grid might be worth considering for SG(th). Moreover, since the research objective was to increase 5GDHC roll-out, the social acceptance issues should be a vital factor for coming studies.

Study spill-over effects of sector coupling

As 5GDHC equips an ULT grid with WSHPs, it integrates heating, cooling and electricity in one network. The corresponding tariffs are each equipped with their own incentives. This can result in unexpected outcomes when these sectors are coupled.

Explore tariff design for non-residential 5GDHC users

The impact of large prosumers and thus the projected impact is different. Tariff structures that incorporate critical peak pricing or rebates might become more attractive, since the impact of this customers is much bigger. The reason is twofold: the amounts of thermal energy that circulates within their consumption patterns and, moreover, the amount of effort and information supply needed towards one huge customer. The first simply means their potential to smooth imbalances is bigger because of their size. The latter means transaction cost could be kept lower as it is expected to be less complex to coordinate one customer than several small residential customers.

BIBLIOGRAPHY

Armstrong, M., Cowan, S., & Vickers, J. (1994). *Regulatory Reform: Economic Analysis and British Experience.*

Belemmeringen in nettarieven. (2018). *Overlegtafel Energievoorziening.*

Bjelland Eriksen, A., & Mook, V. (2020). *Proposed changes to the design of network tariffs for low voltage grid users in Norway English summary.*

Boesten, S., Ivens, W., Dekker, S. C., & Eijdems, H. (2019). 5th Generation District Heating and Cooling Systems As a Solution for Renewable Urban Thermal Energy Supply. Advances in Geosciences, 49, 129–136. https://doi.org/10.5194/adgeo-49-129-2019

Bolsius, T. (2020). DSO cost allocation to households under new technology conditions.

Boon, J., & Loogman, J. (2020). *TCO model DeZONNET*. Retrieved from http://www.zonnewarmtenet.nl/

Bouwmeester, H. (2020). Regelgeving en aandachtspunten voor (bijna) energie-neutrale woningbouw. *Themagroep BENG En TO Juli*, (september).

Buffa, S., Cozzini, M., Antoni, M. D., Baratieri, M., & Fedrizzi, R. (2019). 5th generation district heating and cooling systems: A review of existing cases in Europe. *Renewable and Sustainable Energy Reviews*, 104(February), 504–522. https://doi.org/10.1016/j.rser.2018.12.059

Buffa, S., Cozzini, M., D'Antoni, M., Baratieri, M., & Fedrizzi, R. (2019). 5th generation district heating and cooling systems: A review of existing cases in Europe. *Renewable and Sustainable Energy Reviews*, 104(December 2018), 504–522. https://doi.org/10.1016/j.rser.2018.12.059

Carbon-Brief. (2013). Climate rhetoric: What's an energy trilemma? Retrieved May 13, 2020, from https://www.carbonbrief.org/climate-%0Arhetoric-whats-an-energy-trilemma

CEER. (2017). Electricity distribution network tariffs, guidelines of good practice.

Correljé, A., & Groenewegen, J. (2009). Public values in the energy sector: Economic perspectives. *International Journal of Public Policy*, 4(5), 395–413. https://doi.org/10.1504/IJPP.2009.025079

Correljé, A., Groenewegen, J., Künneke, R., & Scholten, D. (2014). Design for Values in Economics. (1988), 1–23. https://doi.org/10.1007/978-94-007-6994-6

Cozzini, M., D'antoni, M., Buffa, S., & Federizzi, R. (2017). Pricing strategies for neutral-temperature district heating and cooling networks based on heat pumps. BMC Public Health, 5(1), 1–8. Retrieved from https://ejournal.poltektegal.ac.id/index.php/siklus/article/view/298%257B%255C%2525%257D0Ahttp://repositorio.unan.edu.ni/2986/1/5624.pdf%257B%255C%2525%257D0Ahttp://dx.doi.org/10.1016/j.jana.2015.10.005%257B%255C%2525%257D0Ahttp://www.biomedcentral.com/14

Cozzini, M., D'Antoni, M., Buffa, S., & Fedrizzi, R. (2017). Pricing strategies for neutral-temperature district heating and cooling networks based on heat pumps. 12th IEA Heat Pump Conference 2017, (May), 1–11.

D2Grids. (2020). 5GDHC platform. Retrieved January 7, 2021, from https://5gdhc.eu/

De Jonge-Baas, M. (2020). Solar Magazine NL. Retrieved from https://solarmagazine.nl/nieuws-zonne-energie/i24409/ivo-pothof-pvt-warmtenetten-grote-kans-voor-gemeenten-in-transitievisie-warmte

De Wildt, T. E., Chappin, E. J. ., Van de Kaa, G., Herder, P. M., & Van de Poel, I. R. (2019). Conflicting values in the smart electricity grid a comprehensive overview. Renewable and Sustainable Energy Reviews, 111(March), 184–196. https://doi.org/10.1016/j.rser.2019.05.005

DeZONNET Eindrapport. (2020). Retrieved from http://www.zonnewarmtenet.nl/

Eccles, M. P., & Mittman, B. S. (2006). Welcome to Implementation Science. 3, 1–3. https://doi.org/10.1186/1748-5908-1-1

Eggertson, T. (1990). Economic behavior and institutions. *Cambridge University Press*.

Eid, C., Koliou, E., Valles, M., Reneses, J., & Hakvoort, R. (2016). Time-based pricing and electricity demand response : Existing barriers and next steps. Utilities Policy, 40, 15–25. https://doi.org/10.1016/j.jup.2016.04.001

El-hawary, M. E. (2014). Electric Power Components and Systems The Smart Grid — State-of-the-art and Future Trends. https://doi.org/10.1080/15325008.2013.868558

Energiecentrale met warmte- en koudeopslag. (2017). ISSO, (39).

Fakton-Energy. (2020). Expertsessie Aedes - Thuis raken in de businesscase warmte.

Fockert, A., Cardose, R., Molenaar, R., Van der Werff, B., De Vlieger, H., Godschalk, B., Moerman, A. (2021). Aquathermie configuraties - Overzicht TEO, TED en TEA door middel van factsheets, kostenkentallen en beslisbomen.

Groen, B. in 't, Smekens, K., Beurskens, L., & Lensink, S. (2021). Energie uit water, 1–17.

Groenewegen, J. P. M. (2004). Inzichten uit de institutionele economie. Maandblad Voor Accountancy En Bedrijfseconomie, 78(11), 515–523. https://doi.org/10.5117/mab.78.12783

Guelpa, E., & Marincioni, L. (2019). Demand side management in district heating systems by innovative control. Energy, 188, 116037. https://doi.org/10.1016/j.energy.2019.116037

Guelpa, E., & Verda, V. (2019). Thermal energy storage in district heating and cooling systems: A review. Applied Energy, Vol. 252. https://doi.org/10.1016/j.apenergy.2019.113474

Guelpa, E., & Verda, V. (2021). Demand response and other demand side management techniques for district heating : A review. Energy, 219, 119440. https://doi.org/10.1016/j.energy.2020.119440

Heida, J.-P., & de Haas, J. (2019). Tariefregulering warmtebedrijven voor kleinverbruikers. 111. Retrieved from https://www.sirm.nl/publicaties/tariefregulering-voor-kleinverbruikers-van-warmtenetten

Hennig, R., Jonker, M., Tindemans, S., & Vries, L. De. (2020). Capacity Subscription Tariffs for Electricity Distribution Networks : Design Choices and Congestion Management.

Hertog, J. den. (2010). Review of Economic Theories. Tjalling C. Koopmans Inst. Discuss. Pap. Ser., 10(18), 1–59. Retrieved from http://igitur-archive.library.uu.nl/CTK/2011-0110-200311/UUindex.html

Hoogervorst. (2017). Toekomstbeeld Klimaatneutrale warmtenetten in Nederland.

IEA. (2018). The Future of Cooling: Opportunities for energy-efficient air conditioning. The Future of Cooling: Opportunities for Energy-Efficient Air Conditioning, 92.

IPCC. (2021). Climate Change 2021 - The Physical Science Basis , Summary for Policymakers.

IRENA, IEA, & REN21. (2020). Renewable Energy Policies in a Time of Transition: Heating and Cooling.

ansen, S., Mohammadi, S., Elswijk, M., & Eijdems, H. (2019). 4GDH concepts, future DH production and systems. *5th International Conference on Smart Energy Systems*, (September-2019)

Jansen, S., & Verhoeven, R. (2020). Technisch Handboek Koele Warmtenetten, KOWANET.

Kahn, A. E. (1988). The Economics of Regulation: Principles and Institutions, Volume 1.

Klimaatakkoord. (2019). Afspraken in sectoren - De Gebouwde omgeving.

Kostama, J. (2003). European CHP Directive: Reference systems or the comparison of energy savings between separate and combined production of electricity and heat. Euroheat Power, 32(1–2), 26–27.

Li, H. (2020). A dynamic price model based on levelized cost for district heating. Energy, Ecology and Environment, 4(1), 15–25. https://doi.org/10.1007/s40974-019-00109-6

Li, H., Sun, Q., Zhang, Q., & Wallin, F. (2015). A review of the pricing mechanisms for district heating systems. Renewable and Sustainable Energy Reviews, 42, 56–65. https://doi.org/10.1016/j.rser.2014.10.003

Li, H., Wallin, F., & Song, J. (2017). A dynamic pricing mechanism for district heating. *Energiforsk* AB.

Lubbe, S. (2012). Using Matrix Analysis to Achieve Traction , Coherence , Progression and Closure in Problem-Solution Oriented Research.

Lund, H., Werner, S., Wiltshire, R., Svendsen, S., Thorsen, J. E., Hvelplund, F., & Mathiesen, B. V. (2014). 4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems. Energy, 68, 1–11. https://doi.org/10.1016/j.energy.2014.02.089

Matisoff, D. C., Beppler, R., Chan, G., & Carley, S. (2020). A review of barriers in implementing dynamic electricity pricing to achieve cost-causality

Memo on impact of maximum peak shaving on indoor temperature variation (2021), *personal communication I. Pothof*

Menkveld, M., Straver, K., Wijnant, S., & Schreuders, M. (2021). Vraagsturing in warmtenetten. *WarmingUP.*

Mijnwater-BV. (2017). Duurzaam mijnwaterenergie in uw woning, Zo werkt het!

Muller, M., Dam, D. Van, & Lensink, S. (2021). BENUTTING RESTWARMTE UIT. (april 2021), 1–18.

Müller, S., Elswijk, M., Roossien, B., & Jansen, S. (2020). Proces aanpak Van initiatie tot beheer & organisatievormen. KOWANET, 1–44.

Newbery, D. M. (2002). Rate-of-return Regulation Versus Price Regulation for Public Utilities. *The New Palgrave Dictionary of Economics and the Law*, (July), 1605–1610. https://doi.org/10.1007/978-1-349-74173-1_305

Passey, R., Haghdadi, N., Bruce, A., & Macgill, I. (2017). Designing more cost reflective electricity network tariffs with demand charges. 109(April), 642–649. https://doi.org/10.1016/j.enpol.2017.07.045

Petrov, K., & Keller, K. (2009). Network Pricing Models in Europe – From Normative Principles to Practical Issues.

Pfeiffer, E. (2017). Tariefregulering levering koude en lauw water in het kader van de Warm- tewet.

Picciariello, A., Vergara, C., Reneses, J., Frías, P., & Söder, L. (2015). Electricity distribution tariffs and distributed generation: Quantifying cross-subsidies from consumers to prosumers. *Utilities Policy*, 37, 23–33. https://doi.org/10.1016/j.jup.2015.09.007

Reneses, J., Gómez, T., Rivier, J., & Angarita, J. L. (2011). Electricity tariff design for transition economies Application to the Libyan power system. *Energy Economics*, 33(1), 33–43. https://doi.org/10.1016/j.eneco.2010.04.005

Respond-Project. (2021). Four Differences between Demand Side Management & Demand Response. Retrieved September 8, 2021, from Respond, Project website: http://project-respond.eu/4-differences-between-demand-side-management-demand-response/

Roossien, B. ., Barkmeijer, T. ., & Elswijk, M. . (2020). A technical design framework for cold heating and cooling D1.2 KOWANET.

Rus-van der Velde, M., & Den Boer, E. (2020a). De gemeentelijke taken en bevoegdheden onder de Warmtewet 2. 2(december).

Rus-van der Velde, M., & Den Boer, E. (2020b). Tariefregulering onder de Warmtewet 2. 2(december).

S3C-Consortium. (2013). Report on state -of-the-art and theoretical framework for end-user behaviour and market roles. 1(97), 1–97.

S3C project. (n.d.). Guideline: Using Flexibility Manually Or Automatically. 1–6.

Similä, L., Göran, K., & Veikko, K. (2011). Network tariff structures in Smart Grid environment.

Song, J., Wallin, F., Li, H., & Karlsson, B. (2016). Price models of district heating in Sweden. *Energy Procedia*, 88, 100–105. https://doi.org/10.1016/j.egypro.2016.06.031

Teun, S. (2021). Scriptie_Teun_Bolsius.pdf.

TKI-Urban-Energy. (2020). Marktmodellen DeZONNET. *TKI Project DeZONNET*, (Deliverable 5.2), 1–25.

van Berkel, T., & van Heesbeen, J. (2017). Smart charging with app solutions. *ATZelektronik Worldwide*, 12(6), 42–45. https://doi.org/10.1007/s38314-017-0078-2

Vasek, L., & Dolinay, V. (2017). Steps towards modern trends in district heating. MATEC Web of Conferences, 125, 1–6. https://doi.org/10.1051/matecconf/201712502026

von Rhein, J., Henze, G. P., Long, N., & Fu, Y. (2019). Development of a topology analysis tool for fifth-generation district heating and cooling networks. *Energy Conversion and Management*, 196(May), 705–716. https://doi.org/10.1016/j.enconman.2019.05.066

W/E-Adviseurs. (2018). Ontwikkeling van koudevraag van woningen.

Warmtecoalitie. (2020). Manifest – Naar een toekomstbestendige warmtewet.

Wiebes, E. Conceptversie - internetconsultatie Wet Ccollectieve Warmtevoorziening. , (2020).

Wiegerinck, S. V. H. J. . (2020). District heating systems for sustainable heating in metropolitan areas - how the planning & design of district heating systems in metropolitan areas can support stakeholders in their transition towards sustainable heating.

Wildt, T. E. De, Chappin, E. J. L., Kaa, G. Van De, Herder, P. M., & Poel, I. R. Van De. (2019). Conflicting values in the smart electricity grid a comprehensive overview. *Renewable and Sustainable Energy Reviews*, 111(March), 184–196. https://doi.org/10.1016/j.rser.2019.05.005

Williamson, O. E. (1998). Transaction costs economics: How it works, where is it headed. *De Economist*, 146(1), 23–58.

Wirtz, M., Kivilip, L., Remmen, P., & Müller, D. (2020a). Quantifying Demand Balancing in Bidirectional Low Temperature Networks. Energy and Buildings, 224, 110245. https://doi.org/10.1016/j.enbuild.2020.110245

Wirtz, M., Kivilip, L., Remmen, P., & Müller, D. (2020b). Quantifying Demand Balancing in Bidirectional Low Temperature Networks. *Energy and Buildings*. https://doi.org/10.1016/j.enbuild.2020.110245

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

APPENDIX

A. COST ESTIMATION OF DISTRIBUTION AND CONNECTION PIPES

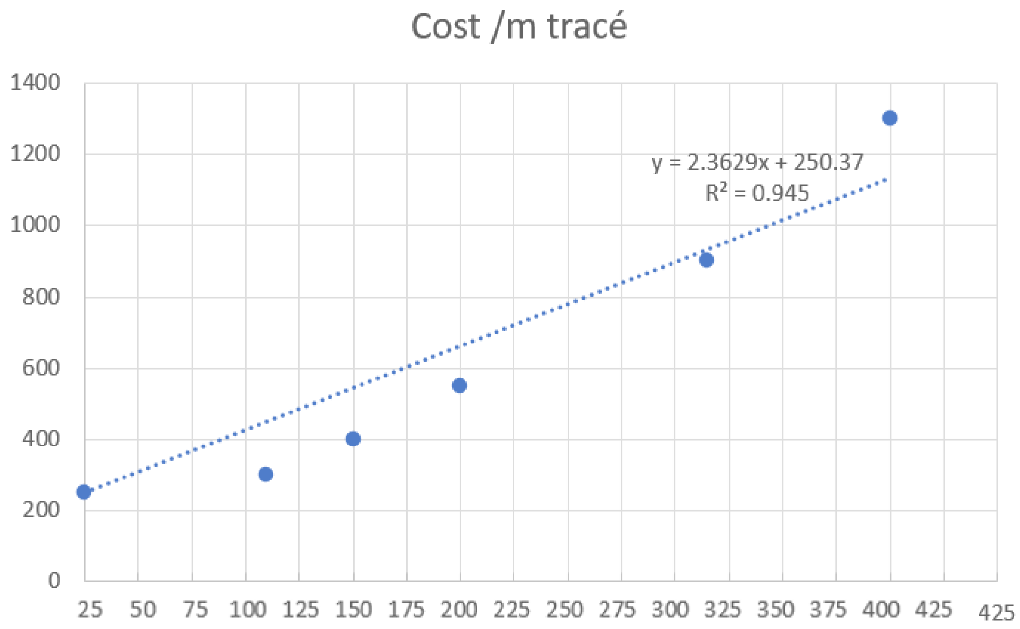


Figure A.1 - Cost estimation graph cost per pipe length

Diameter [mm]	Trend costs €/m	Datapoints costs €/m	Reference
25	€ 250	250	(Boon & Loogman, 2020)
40	€ 286		
50	€ 309		
63	€ 340		
75	€ 368		
90	€ 404		
110	€ 451	300	(Fockert et al., 2021)
125	€ 487		
140	€ 522		
150	€ 546	400	(Fockert et al., 2021)
160	€ 569		
180	€ 617		
200	€ 664	550	(Fockert et al., 2021)
225	€ 723		
250	€ 782		
315	€ 936	900	(Fockert et al., 2021)
400	€ 1,136	1300	(Fockert et al., 2021)

B. ESTIMATION INSTALLED CAPACITY CUSTOMER TYPE D

Input parameters				Reference
Design day reference				
Reference indoor temperature		18	°C	
Reference outdoor temperature		-10	°C	
Reference Heat Degree Days (HDD)		28	°C	
Heat Degree Days (HDD)				
	2010	3,373	HDD	
Selected	2017	2,685	HDD	
	2020	2,477	HDD	
Space heating demand				
Annual demand		6,606	kWh(th)/year	
	2010	54.8	kWh(th)/year	
Highest daily design demand	2017	68.9	kWh(th)/year	Selected moderate year
	2020	74.7	kWh(th)/year	
DHW demand				
Annual demand		3000.0	kWh(th)/year	
Daily demand		8.2	kWh(th)/day	
Buffer charging time		10.0	hrs	
Design peak capacity		0.8	kW(th)	
100% load shifting				
	2010	3.1		
Installed capacity	2017	3.7		
	2020	3.9		

Design capacity customer B		4	kW(th)	

Estimation		
Space heating		
Highest daily design demand	$= \frac{HDD_{ref} \times Annual\ demand}{HDD_{2017}}$ [kW(th)/day]	≈ 1% of annual demand
Design peak capacity	$= \frac{Highest\ daily\ design\ demand}{24hr}$ [kW(th)]	
DHW		
Design peak capacity	$= \frac{Daily\ demand}{Buffer\ charging\ time}$ [kW(th)]	
Combined design peak capacity		
Design capacity customer B (rounded to nearest floor integer)	= Design peak capacity space heating + Design peak capacity DHW [kW(th)]	

C. ESTIMATION PIPELINE DIMENSIONS

DeZonnet original				
	nominal diameter mm	total length m	length per connection m	Cost per unit length €/m1 trace
Connection pipe	25	16298	13.58	€ 250
Distribution pipes	40	457	0.38	€ 286
	50	618	0.52	€ 309
	63	1039	0.87	€ 340
	75	681	0.57	€ 369
	90	823	0.69	€ 404
	110	1033	0.86	€ 451
	125	561	0.47	€ 487
	140	346	0.29	€ 522
	160	534	0.45	€ 569
	180	258	0.22	€ 617
	200	66	0.06	€ 664
	225	175	0.15	€ 723
	250	32	0.03	€ 782
	315	0	0	€ 936
	400	0	0	€ 1,136

Peak factors for the scenarios				
PVT peak original			8400	kWh(th)
Peak multipliers	100% C		0.67	
	100% D		0.57	
	50%/50% MIX		0.62	

Example 50% A & 50% B MIX			
Nominal diameter	Selected diameter	Length per connection	Total cost
mm	mm	m	€
24.8	25	457	€ 114,404
31.0	40	618	€ 176,613
39.1	40	1039	€ 296,926
46.6	50	681	€ 210,708
55.9	63	823	€ 279,925
68.3	75	1033	€ 380,642
77.6	90	561	€ 226,602
86.9	90	346	€ 139,758
99.3	110	534	€ 240,932
111.7	125	258	€ 125,550
124.1	125	66	€ 32,117
139.7	140	175	€ 91,362
155.2	160	32	€ 18,219

D. SCHEMATIC OVERVIEW OF THE POTENTIAL EFFECTS OF DSM APPLICATIONS ON DHC SYSTEMS

Figure D.1 - Schematic overview of the potential effects of DSM applications on DHC systems (Guelpa & Verda, 2019)

E. ESTIMATION OF IMPACT MAXIMUM PEAK SHAVING ON INDOOR TEMPERATURE FLUCTUATIONS

demand. This results in a diurnal variation of the indoor temperature. The larger the thermal resistance of the building envelope (r) and thermal inertia (c), the smaller the indoor temperature variation.

The following is assumed:

- Outdoor temperature varies harmonically with amplitude A, typical value is 4 °C, leading to 8 °C between minimum and maximum temperature.
- Heat supply to the building is constant and sufficient to maintain a constant average indoor temperature.
- The thermal dynamics of the building is simplified to a 1R1C model

The indoor temperature is described by:

$$\frac{dT_i}{dt} = \frac{1}{RC}(T_e - T_i) + \frac{\bar{\varphi}}{C}$$

The indoor temperature oscillation, $\tau = T_i - \overline{T_i}$, is described by:

$$\frac{d\tau}{dt} = \frac{1}{RC} A \cdot sin(\alpha[t - t_0]) - \tau$$

Where $\alpha = 2 \cdot \pi/24$
Using partial integration, the homogeneous solution and a particular solution we can derive the general analytical solution for the indoor temperature oscillation t, Where phase shift $\vartheta = \arctan(RC\alpha)$

$$\tau(t) = \frac{A}{\sqrt{1 + [RC\alpha]^2}} sin(\alpha[t - t_0] - \vartheta)$$

A typical terraced dwelling has a R value of 5 K/kW and C-value of 5 kWh/K, yielding a thermal time constant of 25 hours as can be seen in the Figure below. This results in a damping of 0.15 only, which means that a typical outside temperature oscillation of 8 ºC (amplitude 4) is reduced to an indoor temperature oscillation of 1.2 ºC only (e.g. 19.4 – 20.6 ºC).

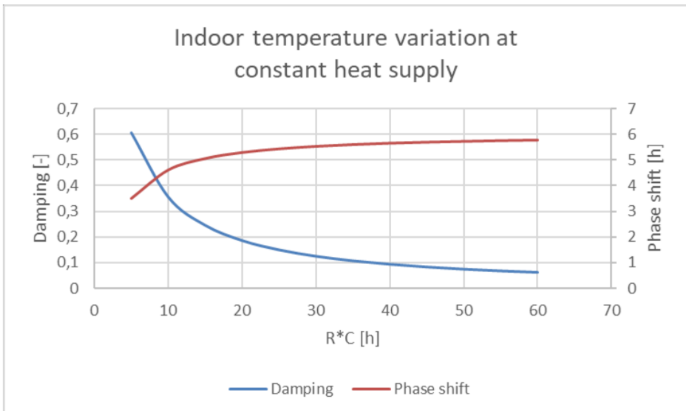


Figure E.1 – indoor variation at a fully load shifted thermal load profile (*Memo on impact of maximum peak shaving on indoor temperature variation*, n.d.)