What's cooler than being cool?

Overcoming barriers to district cooling implementations in Texas

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Thesis for the fulfilment of the
Master of Science in Environmental Management and Policy
Lund, Sweden, September 2019

iiiee THE INTERNATIONAL INSTITUTE FOR INDUSTRIAL ENVIRONMENTAL ECONOMICS

Published in 2015 by IIIEE, Lund University, P.O. Box 196, S-221 00 LUND, Sweden,
Tel: +46 – 46 222 02 00, Fax: +46 – 46 222 02 10, e-mail: iiiee@iiiee.lu.se.

ISSN 1401-9191

Acknowledgements

I feel extremely grateful to be writing these words as I finish the final requirement for the IIIEE EMP program. This effort could not have been possible without the support of friends, family, professors and classmates.

First, I want to thank my supervisors Daniela and Håkan for your support and guidance during this process. I want to thank Daniela for helping me shape this research and for providing insightful quick feedback. To Håkan, I want to thank for pushing me to leverage my technical skills and for getting excited about the topic with me. I would also like to thank Tareq and Marco at UNIDO for pointing me towards this interesting topic.

To all of my interviewees, I want to give a big thank you for taking the time out of your busy schedule to talk and share your knowledge with me. It has been a pleasure to learn from your experiences!

To all the people that hosted me during this nomadic thesis period: THANK YOU! Kimberly, Brittney, Marivi & Thomas, Madison, Monica & Basse, Rheanna, Natalie, Mel, Lisa & Adrian, and of course my parents. Thank you for opening the door to your homes and making me feel at home during my stay. I could not have done this without you.

To my peer reviewers Kelly, Alicia, and Jamie thank you for all your feedback and great notes! To all of B24, thank you for making this experience an unforgettable one. You are a source of inspiration and bring me hope for the future of our planet.

To the IIIEE Copenhagen half marathon runners, thank you for providing an escape that pushed me to keep my body moving and keep on runnin'!

Last but not least, I want to thank my parents and my sister for always supporting and encouraging me in all of my endeavours. Thank you for pushing me to follow my dreams and to always do my best. I would not be where I am without your love and support.

"What's the point of having the best technologies – and living in the world we are living in – if we are not joining forces to make this world better"

-Pierre Naterme

Abstract

The demand for space cooling is rising. The increase in cooling demand can put significant strain on the electric grid since approximately 99% of air-conditioning and refrigeration loads worldwide are met with electricity. Many hot weather cities could benefit from district cooling (DC) systems to meet their growing cooling demand in an effective sustainable manner. Since these systems require significant infrastructure investment and optimisation affecting multiple stakeholders, it is important to understand the role of local authorities or municipalities, energy companies, and end users in the planning for these implementations. This is due to the fact that the overall goals and objectives of these actors have a big influence on the success of these projects. A literature review was conducted to identify the role of DC systems in urban energy transitions and an exploratory, embedded multiple case study research method was used to identify the lessons learned from the DC system implementations in the downtown area of Houston and Austin. Even though the Austin system is owned and operated by the municipality and the Houston system is owned and operated by a private company, both systems had the same economic driver for implementation which was to capture load at the time of de-regulation of the electricity market in Texas. However, it was found that there were many benefits in the Austin system to be owned by the city. The information barrier was not prominent in Austin, but it was the main barrier mentioned in the Houston case. Since the system is owned by the city, it is part of the many utilities (water, electricity, etc.) that need to be considered during new developments and as a result there is more trust from end users. Private companies require more evidence if end users are not familiar with DE systems. Additionally, the environmental and social benefits of the DE system are not apparent when there is not a connection with the municipality. Although it is not a requirement for the municipality to be involved in implementing DC systems for it to be successful, it does have multiple social, economic, and environmental benefits that can drive municipalities to get involved.

Keywords: District Cooling, Space Cooling, Urban, Sustainable Energy, Demand Side Management

Executive Summary

Modern district energy (DE), which includes both heating (DH) and cooling (DC), has been identified by multiple organisations, like the United Nations Environment Programme (UNEP), as an effective and sustainable solution to meet increasing heating and cooling demands (Hinojosa, 2018; UNEP, 2015). DE enables districts to use multiple energy sources to meet the demand for heating and cooling of multiple consumers leveraging the economies of scale and facilitating the integration of local, renewable energy sources (IEA, 2009a). Countries like Denmark have used DE as a cornerstone to their transition to cleaner energy production, and DH systems are already widespread in Europe (UNEP, 2015).

District cooling (DC), a component of DE, uses a central chilling plant to generate and distribute chilled water through a network of pipes to end users in an efficient manner without the use of ozone depleting substances (ODS) (Cheshmehzangi and Butters, 2018; Palm and Gustafsson, 2018; UNEP, 2015). Furthermore, DC is one of the few cooling technologies that can help counteract the heat island effect in cities, a phenomenon experienced due to heat being trapped in dense areas (Cheshmehzangi and Butters, 2018).

DC systems have gotten increasing attention due to environmental, economic, efficiency and reliability benefits, and have been implemented in major cities around the world (Franchini et al., 2018). In Texas, both Houston and Austin have implemented DC systems in the downtown city centre to meet space cooling demands. Both cities have experienced large population growth between 2010 and 2018 with Austin having a 26.3% growth rate and Houston a 18. 2% growth rate (Valliani and Jankowiski, 2019). These cities experience hot and hot/humid summers and warm winters making them cooling demand dominated cities. Additionally, according to the C40, both cities rank as "serious" to the climate hazard of extreme hot days increasing the importance of space cooling (C40, n.d.).

Research Aim

Like Houston and Austin, many hot weather cities could benefit from DC systems to meet their growing cooling demand in an effective sustainable manner. DC has been explored to a good extent in terms of technical feasibility and optimisation, but only a few have studied how district cooling implementations have been connected to urban and energy planning. Since these systems require significant infrastructure investment and optimisation affecting multiple stakeholders, it is important to understand the role of local authorities or municipalities, energy companies, and end users in the planning for these implementations. This is due to the fact that the overall goals and objectives of these actors have a big influence on the success of these projects. Thus, the aim of this research is to identify best practices and key learnings to overcome the barriers to the implementation and expansion of DC systems in warm weather cities. The focus is on systems implemented in the downtown area of two major Texas cities (Houston and Austin).

Research Questions

To meet the aim of the research, the following research questions were considered:

- RQ1: What is the role of DC systems in urban energy transitions?
    - What are the fundamentals aspects of DC systems?
    - Who are the main stakeholders?
- RQ2: How is the downtown DC system integrated into the energy landscape in Austin and Houston?

- RQ3: What were/are the drivers and barriers to implementing and expanding the downtown DC systems in Austin and Houston?
- RQ4: What are the lessons learned from the DC system implementations in Austin and Houston?

Approach

A literature review was used to answer RQ1 and an embedded, multiple case study approach was used to answer RQ2, 3 and 4. A case study approach was chosen in order to understand the multiple aspects affecting the implementation in each case. For the case studies, data was collected from multiple sources which included archival records, open-ended interviews, and personal observations from site visits. The data was analysed using the learnings from the literature review on large technical system (LTS) barriers and local energy governance and organisation (LEGO).

Austin and Houston were chosen because both cities experience high temperatures throughout the year and space cooling demand is high. Additionally, these cities have been experiencing high urban development and population growth. Finally, each city represents a different role of local authorities in the energy system; in Austin, the utility is owned by the city while in Houston the utilities are privately owned.

Findings and Discussion

Role of DC Systems: There are multiple benefits to implementing district cooling systems in dense urban areas with high cooling demands. Four different stakeholder groups that benefit from DC systems were identified based on the analysis from the literature and the case studies: cities, end users, the electric grid, and the environment. These stakeholder groups gain value in different ways from having a city DC system.

Table 0-1: Summary of DC system benefits

Aspect	Cities	End Users	Electric Grid	Environment
Energy Efficiency		■		■
Peak Management			■	■
Renewables	■			■
Local Sources	■			■
Avoid ODS	■			■
Free-up Space		■		
Lower Building Costs		■		
Resiliency and Reliability	■	■	■	
Lower Operation and Maintenance Costs		■		

Source: Created by author based on literature review

The main benefits these stakeholders have include energy efficiency, peak management, use of renewable and local energy sources, increased resiliency and reliability, replacement of technologies that use ODS, free-up building space, lower initial building costs, and lower operation and maintenance costs. Table 0-1 summarises the benefits and indicates the main stakeholder group that benefits from each aspect.

Case Study Drivers for Implementation: The de-regulation of the electricity market in Texas played a major part in providing economic incentives to implement the downtown DC systems in Houston and Austin. For both cases, the de-regulation of the electricity market in Texas helped make the economic business case for the utilities in Houston and Austin to invest in DC system to capture load. For the Austin system, it also served as an economic incentive for the city to offer to new developments to densify the downtown area. These objectives match the drivers identified in section 2.3.1 of *Revenue Generation* and *Increase Local Economic Competitiveness*.

Role of Cost Saving Models: Cost saving models are important tools to promote DC systems. Both the Houston and Austin systems leveraged models to demonstrate the savings to potential customers. The Austin system used a lifecycle cost analysis tool that showed secondary and tertiary savings from space gained as well as lower maintenance and operation costs. Similarly, the Houston system used "Self-cooling" vs "Thermal System" models to compare the cost differences and show the efficiency gains from connecting to the DC system. Additionally, these tools provided predictable costs to end users.

Peak Management Benefit: DC systems with thermal storage are effective ways to manage peak demand. The Austin DC system evolved from an economic incentive tool to become part of Austin Energy's DSM tools. The system allows for the utility to shave the city's peak demand by using thermal storage (Interview 4). Since AE acts as a LSEs in the ERCOT wholesale market, the shaved peak load resulted in market savings from lower demand charges that benefited all electricity customers (Interview 4). AE set targets to shave 20 MW of peak demand by 2020 with the system, in 2018 the DC system shaved 19.2 MW of peak demand, and AE set a new target of shaving 30 MW by 2027 (Interview 4).

Role of Local Governments: Even though it is not necessary for municipalities to get involved in DC systems for the systems to be successful, having the support of the city is important to maximise benefits of the system. For the Austin case, it was beneficial to be connected with the city since all new developments must be approved by the city, and the DC system is considered part of the utilities needed (i.e. electricity, water, etc.). Additionally, having the support of the city helps build trust on the system, especially in areas where end users are not familiar with the technology. This can be concluded from the fact that in the Austin case, information imperfections were not identified as a barrier to expanding the system.

Role of Champions: Having champions of the technology is important for success. The origin of the DC system concept in the Houston case is not known. However, in the Austin case, the champions that pushed for the technology were important for success. Paul Robbins advocated for the city to implement this system, and later it was the leadership of the DC department which had ambitions to expand that increased the uptake of the system in Austin. On the other hand, without champions, the potential of these systems would not be fulfilled. For example, in San Antonio, another Texas city, the DC system is owned by the water utility thus the peak managing benefits from the system are not apparent and not leveraged (Interview 4).

Recommendations

This research contributes to the urban or district scale body of research for sustainable energy solutions. It highlights the importance of incorporating DE systems like DC in urban and energy planning. Additionally, it provides important lessons that can be leveraged in other DC system implementations. As the demand for cooling continues to grow, further research on how the generation part of DC systems can be opened for competition in practice would increase the attractiveness of these systems in warm weather cities. Moreover, further research on how to manage the demand for cooling to reduce fuel usage is important since DC systems provide some incentives to manage demand by end users, however they are only incentivised to stay within contract.

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Abbreviations

4CP – Four Coincidental Peaks

AC – Air Conditioning

AE – Austin Energy

AMI – Advance Metering Infrastructure

BAT – Best Available Technology

CCHP – Combined Cooling Heat and Power

CHP – Combined Heat and Power

DC – District Cooling

DE – District Energy

DH – District Heating

DOE – Department of Energy

DSM – Demand Side Management

ERCOT – Electric Reliability Council of Texas

GHG – Greenhouse Gas

GWP – Global Warming Potential

HIE – Heat Island Effect

HVAC – Heating, Ventilation and Air Conditioning

ISO – Independent System Operator

LEGO – Local Energy Governance and Organisation

LSEs – Load Serving Entities

LTS – Large Technical System

MDA – Master Development Agreement

ODS – Ozone Depleting Substances

PCM – Phase Change Material

PURA – Public Utility Regulatory Act

QSEs – Qualified Scheduling Entities

RPS – Renewables Portfolio Standards

SECO – State Energy Conservation Office

TES – Thermal Energy Storage

T&D – Transmission and Distribution

1 Introduction

The latest IPCC report warns the public on the consequences of going over the 1.5°C warming target set by the Paris Agreement (IPCC, 2018). Some countries are beginning to recognize the urgency of the situation and nations like the U.K. (Brown, 2019) and Ireland (France-Presse, 2019) have officially declared climate change a climate emergency. Nonetheless the impacts of global warming and climate change are already being observed (IPCC, 2018). Changes in climate are increasing temperatures worldwide and as a result increasing the need for space cooling in buildings (Eveloy and Ayou, 2019; IEA, 2009a; Palm and Gustafsson, 2018). This can be most observed in urban areas where there is a high concentration of activity, electrical equipment and resource use (IEA, 2009a; Palm and Gustafsson, 2018).

It is estimated that by 2050 around 6.5 billion people will live in urban areas increasing the demand for energy and the corresponding emissions (United Nations, 2014, Shidehpour et al., 2018). Cities represent 70 percent of the global energy demand with the one of largest sources of energy consumption coming from buildings, and space cooling and heating accounting for more than half of the energy consumption (Dominković and Krajačić, 2019; Eveloy and Ayou, 2019; UNEP, 2015). According to the International Energy Agency (IEA), cooling is the fastest growing energy demand in buildings having more than tripled since 1990 (Delmastro, 2019; Eveloy and Ayou, 2019; IEA, 2009b). The increase in cooling demand can put significant strain on the electric grid since approximately 99% of air-conditioning and refrigeration loads worldwide are met with electricity (Eveloy and Ayou, 2019). This is most prominent in cities that experience hot summers and warm winters as the typical cooling energy consumption in buildings in these urban areas is three times higher than in moderate climates (Eveloy and Ayou, 2019).

Modern district energy (DE), which includes both heating (DH) and cooling (DC), has been identified by organisations like the United Nations Environment Programme (UNEP), the United Nations Industrial Development Organisation (UNIDO), the Swiss State Secretariat for Economic Affairs (SECO), and the International Energy Agency (IEA) as an effective and sustainable solution to meet heating and cooling demand (Hinojosa, 2018; Rao et al., 2017; UNEP, 2015). DE enables districts to use multiple energy sources to meet the demand for heating and cooling of multiple consumers leveraging the economies of scale and facilitating the integration of local, renewable energy sources (IEA, 2009a). Countries like Denmark have used DE as a cornerstone to their transition to cleaner energy production, and DH systems are already widespread in Europe (UNEP, 2015).

District cooling (DC), a component of DE, uses a central chilling plant to generate and distribute chilled water to end users through a network of pipes to meet cooling demands in an efficient manner without the use of ozone depleting substances (ODS) (Cheshmehzangi and Butters, 2018; Palm and Gustafsson, 2018; UNEP, 2015). Furthermore, DC is one of the few cooling technologies that can help counteract the heat island effect in cities, a phenomenon experienced due to heat being trapped in dense areas (Cheshmehzangi and Butters, 2018). Figure 1-1 illustrates a typical DC system.

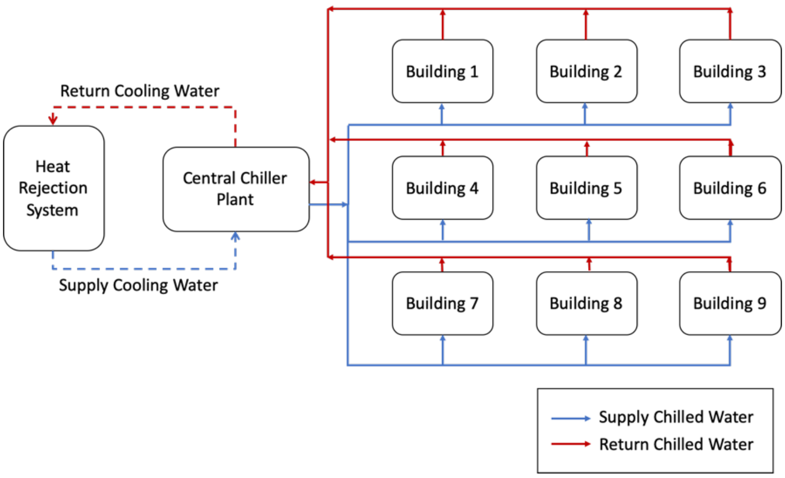

Figure 1-1: Diagram of a typical DC system

Source: Created by author; adapted from Eveloy and Ayou (2019) p. 64 and Gang et al. (2016) p. 255

The first known DC system was built in the United States to serve the Rockefeller Centre in New York and the U.S. capital buildings in Washington (Palm and Gustafsson, 2018; Werner, 2017). Not surprisingly, the largest district cooling capacity is in the United States at 16 gigawatts thermal (IFC and IDEA, 2018; UNEP, 2015), however DC holds only 2% of the market share for cooling buildings (IFC and IDEA, 2018) presenting an opportunity for growth. Growing cities in warm weather climates can benefit from DC systems to meet rising cooling needs. However, this technology requires significant capital and infrastructure investments with long payback periods as well as planning for optimisation to obtain high efficiency (Cheshmehzangi and Butters, 2018; Gang et al., 2016; Palm and Gustafsson, 2018). These factors often pose as barriers to implementation along with other factors that apply to the implementation of large technical systems (LTS) (Cheshmehzangi and Butters, 2018; Palm and Gustafsson, 2018).

Nevertheless, DC systems have gotten increasing attention due to environmental, economic, efficiency and reliability benefits, and have been implemented in major cities around the world (Franchini et al., 2018). In the United States, DC is projected to have an average growth of 1.2% due to the increased cooling demand from buildings (ICF and IDEA, 2018). In Texas, both Houston and Austin have implemented DC systems in the downtown city centre to meet space cooling demands. Both cities have experienced large population growth between 2010 and 2018 with Austin having a 26.3% growth rate and Houston a 18.2% growth rate (Valliani and Jankowiski, 2019). These cities experience hot and hot/humid summers and warm winters making them cooling demand dominated cities. Additionally, according to the C40, both cities rank as "serious" to the climate hazard of extreme hot days increasing the importance of space cooling (C40, n.d.).

1.1 Research Aim

Like Houston and Austin, many hot weather cities could benefit from DC systems to meet their growing cooling demand in an effective sustainable manner. DC has been explored to a good extent in terms of technical feasibility and optimisation, but only a few have studied how district cooling implementations have been connected in urban and energy planning. Since these systems require significant infrastructure investment and optimisation affecting multiple stakeholders, it is important to understand the role of local authorities or municipalities, energy companies, and end users in the planning for these implementations because the overall goals and objectives of these actors have a big influence on the success of these projects.

Furthermore, it is important to understand the different ownership models and business structures for the operation of the system to identify best practices and alternatives. Understanding these aspects can be used to facilitate future implementations of DC systems. This presents a good opportunity to utilise key lessons learned and best practices from cities that have implemented DC systems. This research adds knowledge at the urban dimension which is becoming more important as urban populations grow (Lehman, 2008)

Studying the important aspects and factors that pertain to the implementation of the DC systems in Austin and Houston can help stakeholders like municipalities, service providers, and third-party organisations learn from the experience and apply best practices to new implementations. Thus, the aim of this research is to identify best practices and key learnings to overcome the barriers to the implementation and expansion of DC systems in warm weather cities. The focus is on systems implemented in the downtown area of two major Texas cities (Houston and Austin).

1.2 Research Questions

To meet the aim of the research, the following research questions were considered:

- RQ1: What is the role of DC systems in urban energy transitions?
    - What are the fundamentals aspects of DC systems?
    - Who are the main stakeholders?
- RQ2: How is the downtown DC system integrated into the energy landscape in Austin and Houston?
- RQ3: What were/are the drivers and barriers to implementing and expanding the downtown DC systems in Austin and Houston?
- RQ4: What are the lessons learned from the DC system implementations in Austin and Houston?

A literature review was used to answer RQ1, and a case study approach was used to answer RQ2, 3 and 4. A case study approach was used to understand the multiple aspects affecting the implementation in each case. Austin and Houston were chosen because both cities experience high temperatures year-around and cooling demand is high. Additionally, these cities have been experiencing high population growth. Finally, each city represents the different role of local authority in the energy system; in Austin, the utility is owned by the city while in Houston the utilities are privately owned.

1.3 Limitations and Scope

The scope of this research is DC systems used for space cooling by buildings located in the city centre of Austin and Houston. Learnings from DC systems in university and medical centres in these cities will be considered but will not be the focus of study as the stakeholder interactions between the systems can vary significantly. This is due to the fact that university and medical centre buildings are often run by the same entity making the coordination among service provider and end user less complex.

Austin's DC system was chosen as a case study because it is run by the city owned electric utility and it is now in the process of building a two additional cooling plants in the downtown area. On the other hand, Houston's DC system is run by a private company separate from the electricity provider making it an interesting supporting case. When looking at the energy landscape for both cities, the focus this research is on electric and thermal energy since the majority of space cooling demand is met with electricity. Natural gas and other forms energy are out of the scope for this research.

One limitation of the study is that since the DC system in Houston is privately owned and operated, there is less documentation of the system that is publicly available. Additionally, the ownership of the system has changed multiple times since it was implemented, making it difficult to get multiple interviewees knowledgeable of the system.

As with all case studies, the generalization of the results is a limitation since the results are affected by the system they occurred in (Yin, 1994). However, these learnings can be applied to all Texas cities since they operate under the same de-regulated electricity market and state legislation. Additionally, the learnings from these cases can contribute to the breadth of knowledge that exists on DC systems since the structure of the systems are similar and the strategies and tools used by the energy companies can also be used elsewhere.

1.4 Ethical Considerations

This is an independent study conducted by the author with the supervision from the IIIEE. All documents analysed in this research are publicly available and non-confidential. All interviewees were identified and contacted by the author. Each interviewee was informed of the purpose of the study at the time of contact; Appendix I – Interview Requests contains an example of the emails sent to interviewees to request interviews. All interviewees were asked permission to be identified in citations. If an interview was recorded, consent was asked of the interviewee for recording.

Per request of one of the interviewees, the communications and public information representative for Austin Energy was contacted and informed of the study to identify potential conflicts. No sensitive information was collected for this research.

1.5 Audience

The learnings from this research can be used by municipalities, energy companies, and third-party organisations interested in either implementing or promoting DC system implementations. Municipalities can learn of the ways their jurisdiction can benefit from these systems and can build a case to why new policies promoting these systems can be beneficial. Additionally, it can provide incentives for municipalities to get more involved with the energy planning of their cities in order to lower the environmental impact of energy consumption and production. Similarly, energy companies can learn about the benefits of DC as well as strategies to turn them into a profitable revenue stream. Lastly, third-party organisations can learn of strategies and incentives to promote and support new DC implementations in warm weather cities.

1.6 Disposition

The content of this research is divided in the following chapters:

Chapter 1 serves as an introduction to the background and significance for addressing rising space cooling demand and the case for district cooling.

Chapter 2 presents a synthesis of the literature reviewed to inform the theoretical background and the current state of the research for urban energy transitions, district energy, district cooling, and demand side management.

Chapter 3 describes the methodology of how the research was conducted as well as the background for using an embedded multiple case study research method.

Chapter 4 presents the findings from the data collected for each of the case studies, as well as the context of the Texas electricity wholesale market.

Chapter 5 provides a discussion and analysis on the findings from this research along with lessons learned from the case studies and literature reviewed. Additionally, this chapter presents critical reflections on the research methods used.

Chapter 6 presents the conclusions to the study and the answers to the research questions stated in chapter 1. As well as closing thoughts with policy recommendations and suggestions for further research.

2 Literature Review

In order to understand how DC systems integrate into the energy system of a city, as well as what the drivers and barriers are for their implementation, academic and grey literature on urban energy transitions and governance, district level thinking, district energy and district cooling was reviewed and analysed. This section gives the policy background and context for urban energy transitions in the United States and the state of Texas where the scope of this research is based on.

This section also provides information on the increased demand for space cooling along with a review of demand side management strategies that are available to address the growing demand. Finally, this section introduces the reader to district level solutions and approaches and provides a review of the existing research on district cooling with a focus on warm weather cities.

2.1 Urban Energy Transitions and Governance

Energy consumption and the associated energy production are major emitters of GHGs which have negative impacts on the climate. Currently most cities are powered by fossil fuels which have the greatest share of carbon emissions at combustion and are growing by 1.8% yearly (IEA, 2009a). Climate change and energy security are major drivers to move away from fossil fuels to clean local energy creating a major transition in the energy sector (IEA, 2009a). Due to the complexity of energy systems and the multiple stakeholders involved, it is important to incorporate energy transitions into sustainability strategies to increase collaboration among stakeholders to obtain the most effective solutions. These are most apparent at the local or urban level since "linkages and synergies between climate policy and sustainable development become most obvious at local level" (Alber, 2008, p.2). At the smaller scale it is easier to identify the challenges and opportunities that are unique to the local context allowing for optimal solutions that can lower GHG emissions and address the risks due to climate change.

One of the factors that determine the response of local governments to participate in the governance of climate issues are national programmes that support local initiatives (Alber, 2008). Thus, many national governments have set out these policies along with tools to aid energy transitions. In the United States, the U.S. Department of Energy (DOE) has created the Energy Transitions Initiative (ETI) which provides long term energy visions to implement energy efficiency and renewable energy solutions, as well as tools for state and local government to implement these visions (U.S. DOE, n.d.-c). Additionally, the U.S. DOE has created the Better Buildings initiative to drive leadership in innovation from public and private leaders to increase energy efficiency in homes, commercial buildings and industry plans (U.S DOE, n.d.-b). Furthermore, the United States also has the U.S Renewable Portfolio Standards (RPS) which exist in 29 states as well as Washington D.C. and applies to 55% of the total U.S. retail electricity sales to promote the use of renewable energy (Barbose, 2018). RPS set requirements on retail electricity suppliers to supply a minimum percentage of electricity with eligible renewable sources. The standards vary from state to state, are typically backed with penalties, and are often accompanied with tradable renewable energy certificates to facilitate compliance (Barbose, 2018). Some of the most ambitious targets include Hawaii with a target of 100% renewables by 2045, California with a target of 60% by 2030, and Vermont with a target of 75% by 2032 (Barbose, 2018). The commitment for Texas, the state where this research was carried through, was of 5 880 MW of renewable energy by 2015 and 10 000 MW by 2025 which was surpassed significantly due to attractive wind energy economics in the state (Barbose, 2018). Currently Texas leads the nation in wind-powered generation producing a quarter of all of the United States wind electricity in 2017 (US EIA, n.d.).

In terms of energy management at the state level, Texas has set up the State Energy Conservation Office (SECO) which partners with local governments, county governments, public schools and universities and state agencies to provide funding, programs, energy codes and energy reporting to manage energy in the state. Compared to other states, Texas was ranked first in 2016 in total carbon emissions taking the spot as the largest energy-producing and energy-consuming state in the nation (EIA, 2016) presenting a good opportunity for improvement.

Both the national and state policies have a strong focus on enabling local governments to tackle energy transitions following the trends in energy policy which aim to improve energy efficiency and increase the use of renewable energy solutions (Alber, 2008). Alber (2008) identifies the following four modes of urban climate governance which can be used for energy, transport, waste, urban planning and land use:

- *Self-governing* – in terms of energy, this includes energy efficiency schemes and use of CHP within municipal buildings, procuring green energy for operations, as well as procuring energy efficient appliances.
- *Governing through enabling* -this includes promotion of renewable energy, campaigns and advice for energy efficiency.
- *Governing by provision* – this includes running energy service companies, providing grants and incentives for energy efficiency measures.
- *Governing by authority* – this includes strategic planning to enhance energy conservation, energy efficiency requirements in zoning ordinances.

These strategies can be used by local authorities to address the climate impact of their territory and take steps to sustainable practices.

2.2 Rising Space Cooling Demand

One of the sectors increasing energy demand in cities is the increased need for space cooling in buildings. There are many factors contributing to the increased demand for space cooling which include building architecture, rising internal heat loads, and the urban heat island effect (Eveloy and Ayou, 2019). Additionally, the rise of temperature due to climate change increases the frequency and intensity of extreme weather events like heat waves (IPCC, 2018). This expands the likelihood of heat related health risks making space cooling a necessity instead of a luxury.

The majority of space cooling loads around the world are met by individual air conditioning (AC) systems which include: window units used in single rooms, apartment units or small buildings; or central air-cooled chillers which tend to be located on the rooftop or basement of large buildings (Cheshmehzangi and Butters, 2018; Eveloy and Ayou, 2019). The efficiency of these systems varies with technology and operation, but it is typically half of the best available technology (BAT) which is defined by regulators to control pollution. Additionally, individual AC units eject waste heat into the environment "heating up its neighbours and increasing the energy load and heat island effect" (HIE) (Cheshmehzangi and Butters, 2018, p.7). This creates a positive feedback loop as it contributes to the increase of demand for space cooling.

One of the main challenges with addressing cooling needs is that unlike heating, the load profile for cooling is not constant, in most cases the demand for cooling is low in the mornings and peaks in the evening (Ondeck et al., 2015). This adds significant strain to the electric grid during times of peak demand. Peak demand or peak load is the highest level of electricity demand measured over a period of half an hour or an hour that occurs within a given time period, such as a day, season or year (IEA, 2018). Grid operators must ensure that the grid has the capacity to meet this peak demand to avoid blackouts or malfunctions of the grid. Managing this demand is important to maintain the reliability of the grid, as well as preventing the need for additional capacity to be built which can be costly. In the United States space cooling can represent 70% of the total peak demand on extremely hot days (IEA, 2018). For Texas, in the summer of 2010, the percentage of peak load from air conditioning increased from 20% in the spring to 48% in the summer (Rhodes et al., 2011).

The demand for cooling is often based on degree days which indicate how cold or warm an area is. A degree day compares the average outdoor temperature to a standard temperature indicating how extreme the outside temperature is (US EIA, 2018). The higher the number of degree days, the higher the demand of energy use for space cooling (US EIA, 2018). Furthermore, in North America, the unit of power used to measure the heat-extraction capacity of industrial AC units is a "ton of refrigeration" or "ton".

2.2.1 Demand Side Management

Demand Side Management (DSM) strategies aim to manage the overall consumption of commodities, such as electricity, by promoting higher efficiency, and/or by lowering the total load by shifting consumption or usage to non-peak periods (Boshell and Veloza, 2008). DSM is the concept of managing the demand of a commodity rather than the supply. Demand-side strategies have more co-benefits when compared to supply management options since they also increase the flexibility of systems and reduce risks of overload (Mundaca et al., 2019). Environmental issues like climate change have been identified as drivers for DSM diffusion (Strbac, 2008; Creutzig et al. 2016; Mundaca et al. 2019). Creutzig et al. (2016) describe DSM strategies as "a crucial class of mitigation options" for climate solutions (Creutzig et al., 2016, p. 173). Similarly, Mundaca et al. (2019) state that in order to have the possibility of reaching the 1.5 °C global warming target goal, "stringent demand-side policy portfolios are required to drive the pace and direction of deep decarbonization pathways" (Mundaca et al., 2019, p. 343).

DSM programs for energy management are based on three different concepts: Energy Efficiency, Energy Conservation, and Demand Response (Boshell and Veloza, 2008). Some of these programs have been enhanced with new technologies such as Smart Plugins and Smart Thermostats to facilitate management thus increasing the impact of the programs. These devices allow for individuals or grid managers to reschedule operations to manage loads and prevent the need for additional energy generation options (Strbac, 2008). As mentioned in previous sections, heating and cooling demand are some of the most energy intensive operations in the building sector, and many efforts in DSM focus on reducing the load from these areas.

Energy Efficiency and Energy Conservation

Energy efficiency and energy conservation are important measures to lower the impact of energy systems by lowering the use of fuel required to meet demand. Boshell and Veloza (2008) defined energy efficiency as "the permanent installation of energy efficient technologies or the elimination of energy losses in existing systems" (Boshell and Veloza, 2008, p. 1). Energy efficiency programs often include energy assessment tools to identify low hanging fruit for improved efficiency. In terms of energy efficiency measures for reducing cooling demand, there are two main ways to reduce the load which include: improved building design that includes passive cooling and the use of low embodied energy materials, as well as technological efficiency for lighting and air conditioners (Cheshmehzangi and Butters, 2018). Additionally, good urban planning can help provide passive cooling with the shading and cooling effect of trees. This highlights the need to create a link between engineering and architecture with landscape design, urban planning and energy planning to obtain the most effective and sustainable solutions (Cheshmehzangi and Butters, 2018).

Similarly to energy efficiency, Boshell and Veloza (2008) define energy conservation as the practice of "using less of a resource, usually by making a behavioural choice or change" (Boshell and Veloza, 2008, p.1). For this set of DSM measures it is important to engage consumers to address their energy usage behaviour and promote conservation measures.

Demand Response

The third category of DSM strategies is demand response. Boshell and Veloza (2008) define demand response as a set of measures that relate to the electricity market to manage load. The goal of demand response programs is for customers to curtail their load in response to a signal from the grid operator. According to Boshell and Veloza (2008), "these are different from conservation in that the activity (and energy consumption) is not necessarily reduced, but rather shifted to another time period" (Boshell and Veloza, 2008, p. 1). One common demand response program that is provided by electric utilities is AC cycling. This type of program allows for electric utilities to 'cycle' a customer's air conditioning unit to lower energy demand during peak load times removing the need for utilities to use other dispatchable energy sources that are often powered with fossil fuels. Another common type of DSM tool are peak management programs, these programs provide incentives to customers to lower their electricity during peak days by shifting the load from peak demand times to times of lower demand. Peak management programs require for customers to take actions to reduce their energy consumption (i.e.: lower thermostat, delay use of appliances like washing machines, etc.).

Furthermore, variable pricing programs provide a price signals for customers to shift their energy usage to times of low demand by giving the option for customers to pay the real time price of electricity. The spread of advanced metering infrastructure (AMI) has allowed for this program to be more robust by providing real time data to consumers. This type of program can be very useful to manage distributed energy resources (DER) and renewable energy resources. Variable pricing can be leveraged by sending price signals when renewable energy is plentiful (sunny and windy days) to give customers an incentive to consume during these times.

2.3 District Level Solutions

Most efforts discussed in the previous sections concentrate on gaining efficiency at the building level by encouraging more energy efficient appliances and retrofitting old homes. Even though building scale measures are important and necessary, there are opportunities for greater impact at the district or urban scale which are often overlooked (Hawkey, 2013; Ondeck et al., 2015). As mentioned in section 2.1, the synergies and impacts of climate change are most apparent at an urban scale which can be leveraged for more optimal solutions that are tailored to the specific area. Some of the first cities to engage in sustainability efforts at the district scale include Hammarby Sjöstad in Stockholm and Western Harbour in Malmö (EcoDistricts, 2018). District level solutions can leverage local interactions and economies of scale to optimise climate friendly technologies and practices.

2.3.1 Drivers for District Energy

District energy, which includes district cooling, has been identified as an effective and sustainable solution to address growing space cooling demands. These thermal grids are flexible and have the ability to leverage a variety of energy sources, as well as aggregate the load in a district. The main stakeholders that are involved in these systems include municipalities, service providers, and end users. Additionally, the electric grid and the environment are stakeholders that benefit from having a DE system installed. Some of the end users that can be connected to DE systems include residential customers, institutional customers such as hospitals and campuses, as well as commercial corporate customers (Rao et al., 2017). Rao et al. (2017) identified the main economic, social, and environmental drivers for implementing DE system which include the following; *Revenue generation* which enables utility companies or municipalities to establish a new source of revenue by implementing DE systems. These systems can be paid back overtime with the revenue from providing the service which creates a steady source of income and provide a reliable service. DE system can also *increase local economic competitiveness* by keeping the energy rates in the area low and stable making the territory attractive to new residents and new developments. Additionally, DE systems provide the scale for local resources to be used to meet thermal energy needs thus *boosting value of existing resources*. DE systems aggregate the thermal load of the district and enable strategies that would not be feasible at an individual building scale which as a result also stimulates the local economy.

In terms of environmental drivers, DE systems help municipalities *meet GHGs reduction goals* by reducing the overall use of energy for space heating and cooling as well as reducing and shifting the peak demand (Eveloy and Ayou, 2019; Gang et al., 2016; Rao et al., 2017). Additionally, DE systems help stimulate the *growth of renewable energy* since it can be incorporated and used to power these systems (IEA, 2009; Gang et al., 2016; Rao et al., 2017; Shandiz et al., 2019). Furthermore, by using TES, DE systems provide a form of energy storage which is crucial for intermittent renewable sources. Finally, DE systems for cooling replace technologies that use ODS, which contribute to ozone depletion and also have high global warming potentials (GWP) (Gang et al., 2016; Palm and Gustafsson, 2018; Werner, 2017).

Finally, DE systems also provide social benefits that support economic and physical resiliency as well as strengthen communities. Figure 2-1 provides a summary of the economic, environmental, and social drivers for implementing DE systems. These drivers do not need to all be present to make DE systems attractive in an urban area. Additionally, the drivers and objectives of the system may change over time as conditions change (Rao et al., 2017).

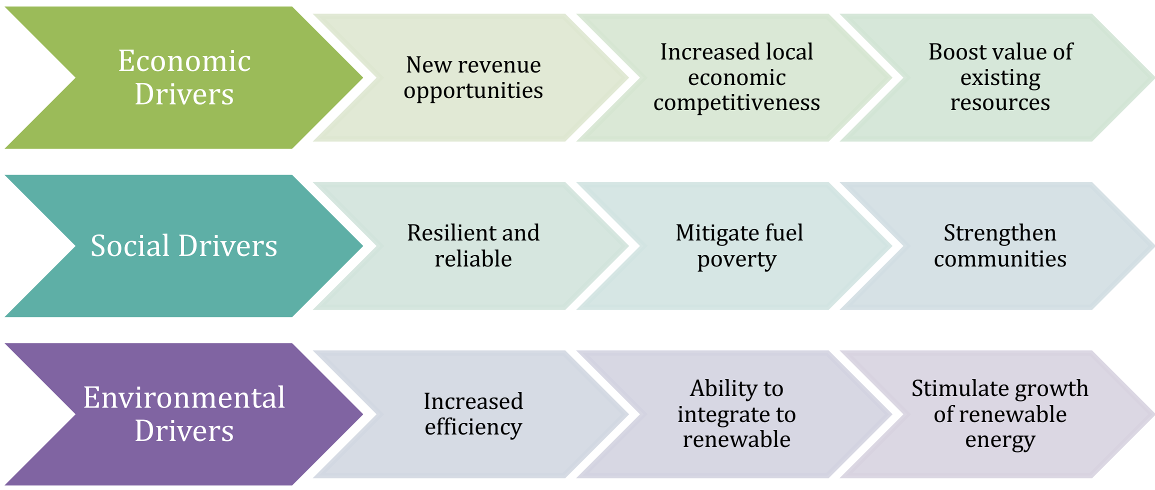

Figure 2-1: Summary of drivers to implement DE systems in cities

Source: Created by author from Rao et al. (2017)

2.4 District Cooling

As mentioned in previous sections, DC systems which are part of DE systems, have been identified by many organisations as an efficient and sustainable solution to meet space cooling demand in dense urban areas. This section will provide a review of the literature on DC systems, and will set out the background on the technical aspects, system lifecycle, finance and governance, as well as barriers of the systems.

2.4.1 Technical Aspects

As illustrated in Figure 1-1, DC systems provide chilled water to a "district" of buildings from a central chilling plant through a network of underground pipes. Water is chilled using cooling equipment such as electric chillers, adsorption chillers, or natural sources of cold energy. The most widely employed chillers are electrical centrifugal water-cooled due to their high performance (Eveloy and Ayou, 2019). Other basic equipment used in DC systems includes, but is not limited to, pumps to transfer chilled water and heat-rejection equipment for the return water.

Gang et al (2016) performed a review of the existing research and applications of DC systems in place focusing in Asia. The study concluded that DC systems are an effective way to incorporate local renewable energy and are highly efficient in areas with high density (IEA, 2009; Eveloy and Ayou, 2019; Gang et al., 2016; Rao et al., 2017). The study identified the multiple ways DC systems can be integrated with different technologies to optimise the system and meet local objectives. Figure 2-2 illustrates the four key integrations which include renewable energy, thermal storage, building mix, and combined cooling, heat and power (CCHP).

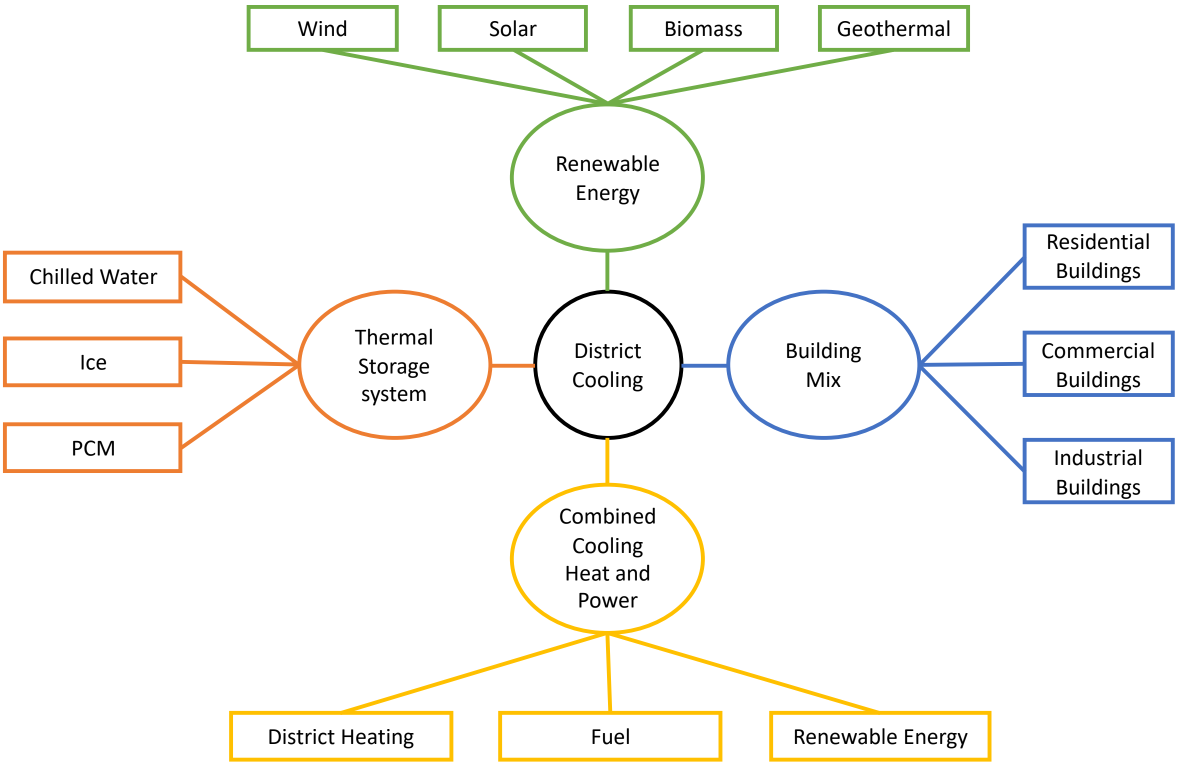

Figure 2-2: Integration of a DC system with different technologies and buildings

Source: Created by author; adapted from Gang et al. 2016, p. 255

Renewable Energy

DC systems enable districts to use renewable energy sources such as solar, wind, biomass, and geothermal and convert them into thermal energy to be used for space cooling. Additionally, cold energy from cold sources like surface water from the sea, rivers or lakes can also be leveraged and integrated into the DC system (Eveloy and Ayou, 2019; Gang et al., 2016; Werner, 2017). One of the largest DC systems is located in Stockholm and it uses cold sea water from the Baltic sea and sends it to heat pump units to provide cooling to end users (Gang et al., 2016).

Similarly, in Toronto, deep lake water is used to provide chilled water to downtown Toronto (Gang et al., 2016; Rao et al., 2017).

Moreover, renewable thermal energy (solar, geothermal, biomass waste) can be transformed into cooling energy using heat-driven chillers or into electrical/mechanical energy using thermal power plants to drive vapor compression chillers (Eveloy and Ayou, 2019). Geothermal energy which has energy from aquifers or underground water can have 90-95% energy that can be used for DC systems (Gang et al., 2016). Norway has one of the largest groundwater reservoirs which is used to serve the Gardermoen Airport as a complemental heat sink (Gang et al., 2016). Furthermore, solar energy collected by thermal collectors can be converted into hot water which then exchanges heat with circulating water from absorption chillers for cooling (Gang et al., 2016). As mentioned in section 2.3.1, DC provides the scale for these resources to be used that may not be feasible or cost effective at an individual building scale. By incorporating renewable energy sources in DC systems, the demand for energy from fossil fuels in lowered thus reducing the GHGs associated with the cooling system.

Thermal Storage

Thermal storage options like generating ice, chilled water, or using a phase change material (PCM) at times of low cooling and energy demand, or when extra renewable energy is available allows the system to shift the load from peak times to times of lower demand and respond to electricity market price signals (Gang et al., 2016; Rao et al., 2017). TES adds flexibility and reliability to the system since it creates back up capacity which can be deployed at times of emergency.

Water is usually used for thermal storage due to low cost and high thermal capacity (Gang et al., 2016). On the other hand, ice stores the energy in the form of latent heat and occupies less space compared to water storage. This is beneficial in tight downtown areas since it requires a smaller storage volume (Gang et al., 2016). Similar to ice, phase change material (PCM), also used latent heat to store cold energy. The most common PCMs used are inorganic salt hydrates (Gang et al., 2016).

Combined Cooling, Heat and Power

DC systems can be connected to CCHP to optimise resource use and address heat demand as well as generate power that can be fed to the electric grid or use in the plant's operations. Ondeck et al. (2015) determined that CHP combined with solar generation is a viable solution to provide district level cooling, heating and power to a residential district in a hot climate using data from residential customers in Austin, TX.

Building Mix

The building mix of the system determines the load density of the area. The combination of buildings in the system is important in order to optimise the DC system and have a constant even load. Having different types of buildings is beneficial to create a uniform load profile since each building type will have a different load profile that will vary based on the usage. For example, commercial buildings have high cooling loads for regular AC on weekdays but also to cool server rooms (Eveloy and Ayou, 2019). Cooling load is often considered the most critical input for the design, performance, and economic viability analysis of DC systems (Eveloy and Ayou, 2019). Similar to Eveloy and Ayou (2019), Gang et al (2016) agree that DC systems must be well planned, designed, and operated in order to be cost effective.

2.4.2 System Lifecycle

DE systems follow similar lifecycles which go from concept to feasibility, to design and build, to operations and maintenance. These stages are not linear, but rather flow according to objectives and the context of the system (Rao et al., 2017). Figure 2-3 shows the different lifecycle stages of a typical DE or DC system.

At the *concept* stage, the potential district is identified, and the concept is developed. Good candidates include new greenfield districts or rejuvenation of brownfield sites (Rao et al., 2017). Contemporary DC systems include universities, airports, healthcare campuses, and business districts (Eveloy and Ayou, 2019; IFC & IDEA, 2018). City scale DE systems were introduced in the 1930's and the use of DC systems expanded due to the ban of CFCs established to protect the ozone layer. DC systems were first implemented in the United States and Canada followed by Europe with France and Germany having the first implementations in Europe (Eveloy and Ayou 2019; Palm and Gustafsson, 2018; Werner, 2017). DC in Asia was introduced in Japan in 1970 "where it expanded rapidly under government intervention towards higher efficiency and reduced environmental emissions" (Eveloy and Ayou, 2019, p.3). Most recently, DC has experienced rapid growth globally due to significant deployments in the Middle East (Rao et al., 2017). Overall the "the advantages of DC systems are most pronounced in dense districts exposed to hot climate conditions throughout the year and characterised by rapid urbanisation and building development" (Eveloy and Ayou, 2019, p. 2).

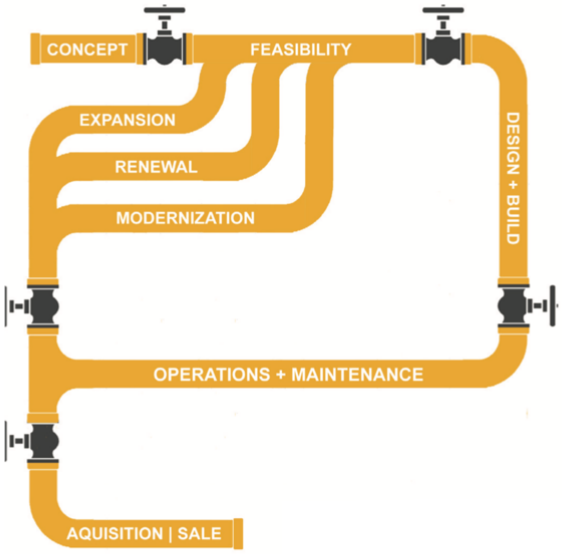

Figure 2-3: DE system/project lifecycle stages

Source: IDEA; Rao et al (2017) p. 43

After a potential district is identified, the next step in the lifecycle is to conduct a *feasibility* study to determine if DC is viable for the district. If the feasibility study is positive, the *design and build* stage comes next. At this stage, all of the technical aspects that were described in the previous section are analysed in-depth and the cooling load is determined. There are three different cooling load types that are typically measured or estimated for the design and analysis of DC systems. According to Eveloy and Ayou (2019), the cooling types are:

- peak cooling load data for system capacity sizing,
- annual average hourly cooling load data for economic (i.e., cost-benefit) analysis, and
- hourly daily cooling demand data for operational and control design/analysis (Eveloy and Ayou, 2019, p.26).

After design and build, the *operation and maintenance* stage occur throughout the lifespan of the system. This is a crucial stage since the optimal operation of the system is important in order to achieve the highest level of efficiency in operations (Gang et al., 2016). If these systems are not operated properly the economics of the system would not be favourable, and the efficiency gains would decline.

While the system is in the operation stage, it may also go through three different additional stages which include *expansion, renewal* and *modernisation*. As more end users connect to the system, the network and capacity of the system may need to be expanded to meet the additional load. For renewal, as DC systems age, they will require some additional capital to replace end of life equipment. As technology evolves, systems may require a modernisation stage to take advantage of new offerings to integrate more renewables and technologies like thermal storage (Rao et al., 2017). Finally, these systems can change ownership overtime requiring a *sale and acquisition* stage.

2.4.3 Governance and Finance

From the literature it is clear that DC systems are good solutions to meet growing cooling demand in dense urban areas. Furthermore, Rao et al. (2017) argues that although:

> Solid technical and engineering practices are essential to the success of a DE system, even more fundamental are viable economic and financial structures in conjunction with sustainable business models supported by appropriate governance models that will attract sufficient end-users and facilitate financing for new system deployment. (p.6)

Correspondingly, Hawkey et al. (2013) examined the organisation, governance, and financing of low carbon energy systems in the UK. The researchers focused on the meso-level of city- or urban-scale responses in relation to district heating (DH) and cooling (DC) and combined heat and power (CHP) in the UK, as well as the potential of city leadership in energy services. The research theorised – local energy governance and organisation (LEGO) and studied the range of *objectives*, *ownership* and *business structures* of three existing district energy systems in the UK. The researchers identified three methods local governments can create project pathways for DE which were:

- Stimulating business models, finance and non-local expertise,
- Configuring subscribers, and
- Engaging with energy markets and techno-economic expertise.

Hawkey et al. (2013) found that local authorities or municipalities could stimulate business modes by either having a direct investment on the DE system and/or by having long term contracts with the service provider to ensure significant loads and revenues. These strategies were found to vary based on local objectives. Similarly, Rao et al. (2017) indicates that identifying the objectives of a DE project is one of the crucial factors for selecting a business and ownership model. Additionally, Rao et al. (2017) identified the different types of ownership models for DE systems ranging from public to a public-private hybrid to fully private.

Public ownership models include:

- an *internal department* model which is developed within a department of the local government which owns and operates the system;
- a *social* model which is owned by the community and is not for profit. These models are most common in European countries like Denmark;
- and a *special purpose vehicle (SPV)* model which is a whole owned subsidiary independent from the local authority.

The public-private hybrid models include:

- a *concession* model where the public sector initiates the project, undertakes initial development, and continues to own the assets with a private operator;
- a *joint venture* model which is established as a company limited that is based on shares;
- and *SPV* where the ownership of shares is split between public and private entities.

Finally, the *private* models are fully owned and operated by the private sector which can also be joint ventures between two private companies. The steps to choosing business models include setting objectives, de-risking the project, and obtaining finance for the project. One of the major upfront capital investments necessary for DC systems is the network infrastructure which is typically 50 to 70% of the total initial investment (Eveloy and Ayou, 2019). Other costs include but are not limited to cooling equipment, pumps, heat-rejection equipment, and in some cases TES. As mentioned earlier, in some cases, high infrastructure costs were mitigated by municipal commitment depending on local objectives (Hawkey et al., 2013). Furthermore, Palm and Gustafsson (2018) recommends developing functional business models that could work as "market devices" in order to make DC attractive to both energy companies and end users which supports the findings by Hawkey et al. (2013). This would promote competition and cooperation between DC actors (Palm and Gustafsson, 2018).

2.4.4 Barriers to District Cooling

Palm and Gustafsson (2018) studied the barriers and enablers of DC expansion in Sweden. Even though cities in Sweden are not considered to have warm weather, the learnings from their DC systems are relevant to this study since the researchers conducted the study through the lens of large technical systems (LTS). They examined how energy companies, property owners, and tenants perceive the barriers and enablers of installing and using DC to meet space cooling demand. Large technical systems, like DC, "encompass a capital-intensive infrastructure, a broad range of technical components and technologies and a variety of actors

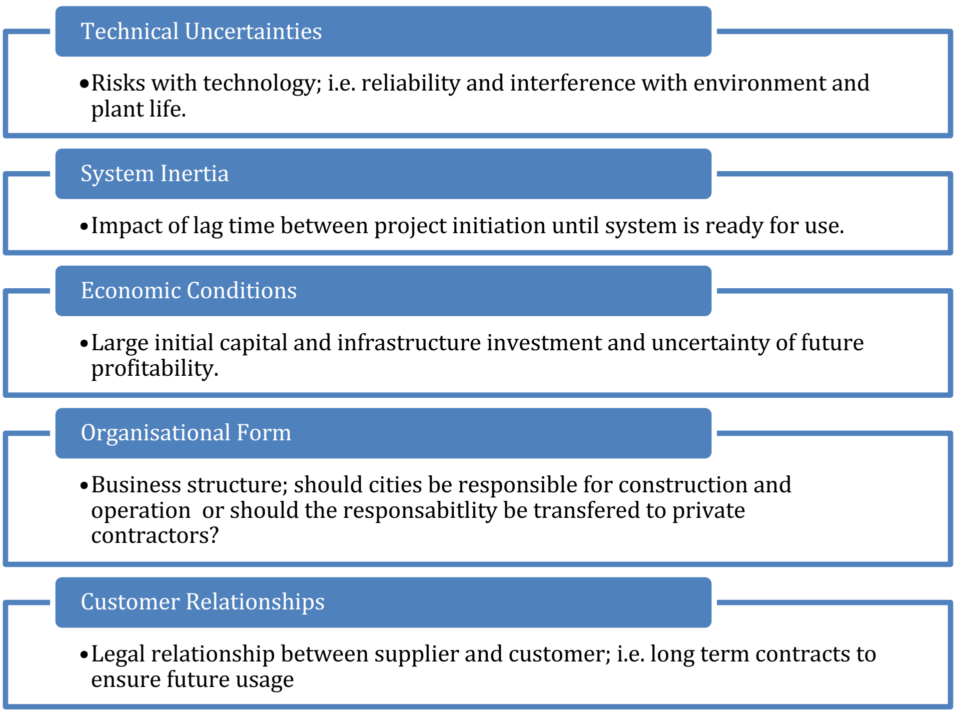

Figure 2-4: Key Issues with grid based LTS

Source: Created by author from Palm and Gustafsson, 2018, p. 40 and institutions" (Markard and Truffer, 2006, p.609). Due to their scale and complexity, there are five key issues to be solved when establishing new grid based LTS which include technical uncertainties, inertia in the system, economic conditions, organisational form, and customer relationship (Palm and Gustafsson, 2018). Figure 2-4 summarises the descriptions of the five issues associated with LTS.

Similar to Palm and Gustafsson (2018), Gang et al. (2016) agrees that technical uncertainties are one of the main challenges for future applications of DC systems. These uncertainties include uncertainties in districts (i.e. building type and number), and uncertainties in cooling load calculation which is dependent in outdoor weather conditions (i.e. outdoor air temperature, relative humidity, solar radiation, etc.), as well as the indoor environment (i.e. temperature set point, humidity, ventilation, occupants etc.). These criteria can vary significantly depending on building and the preferences of occupants.

When looking at the Swedish experience with DE, Palm and Gustafsson (2018) state that while DH is well established, widely distributed and regulated by law, DC is still in the expansion phase and it is relatively new introduced concept. For DH municipalities in collaboration with energy companies played a major role in the expansion of DH in Sweden, but the same has not been true for DC (Palm and Gustafsson, 2018; Werner, 2017).

The researchers found the main barriers to expansion of DC systems in Sweden are:

- Information imperfections where "customers are often poorly informed about market conditions, technology characteristics, and their own energy use" (Palm and Gustafsson, 2018, p.41)
- Split incentives where individual or entity that installs the energy efficiency technology is not the one that pays the bill.
- Hidden costs which are cost associated with contracts, meeting with sellers, seeking information, etc.
- Limited access to capital which is necessary for implementing DC system which require high capital costs.
- Risk which involve uncertainties about future energy prices and operating costs.
- Bounded rationality where individuals make decisions based on rules of thumb (Palm and Gustafsson, 2018).

Similar to Palm and Gustafsson (2018), Hawkey et al. (2013) also found that lack of familiarity with the technology, which fall under information imperfections, was a barrier to configure new customers to the district energy system in the UK. For these types of barriers, Rao et al. (2017) identified five key factors for successful DE implementations, which include DC, these factors include:

- *Risk* – Identifying allocating and managing risk
- *Information* – Gathering and disseminating information needed for decision making
- *Money* – Managing funds to align with the system lifecycle stage needs
- *People* - Including appropriate people and experts in decision-making
- *Tools* – Using available tools to improve decision-making.

Additionally, Palm and Gustafsson (2018) and Gang et al. (2016) recommend integrating DC system implementations and expansions into municipal planning. This allows for the system to be optimised for the highest efficiency. Additionally, DC system expansion could benefit from being incorporated into local climate and energy strategies to promote collaboration among actors (Palm and Gustafsson, 2018).

2.5 Summary

In many countries the fuel used to power cities comes from finite sources such as fossil fuels which emit GHG and other pollutants that are harmful to human health. As the realities of climate change become more prominent, the need for sustainable energy and urban energy transitions grows. Additionally, the demand for space cooling around the world is increasing significantly, the current technologies used for cooling are powered by electricity thus increasing the load on the electric grid at peak hours. Demand side management strategies, which include demand response, energy efficiency and energy conservation, are important to address the increasing demand.

District energy systems have been identified as an efficient and effective way to address the cooling demand. The academic and grey literature support the many benefits of using DC systems to meet cooling needs. In terms of environmental benefits, DC systems facilitate the use of local renewable energy sources that may not be cost effective or feasible at an individual building scale (IEA, 2009; Gang et al., 2016; Rao et al., 2017; Shandiz et al., 2019). This is also a social benefit since it stimulates the local economy for that energy source creating new jobs, and keeping revenues local (Rao et al., 2017). Another environmental benefit from using DC systems is that they replace technologies that use ozone depleting substances (ODS) for cooling (Gang et al., 2016; Palm and Gustafsson, 2018; Werner, 2017). Additionally, due to the efficiency gains from using high grade equipment at a greater scale the GHG emissions associated with cooling is lowered (Eveloy and Ayou, 2019). Furthermore, with the use of thermal storage, DC systems can shave the energy demand during peak periods (Eveloy and Ayou, 2019; Gang et al., 2016). These systems also have the potential to counter the heat island effect in cities since it is removing the need for each individual building to have cooling equipment that rejects heat into the environment (Cheshmehzangi and Butters, 2018).

Aside from environmental and social benefits of DC systems, the end users also have multiple benefits. Having a DC system frees up space in buildings where the chiller equipment would be (Eveloy and Ayou, 2019). It also lowers the cost of cooling due to higher efficiency and lower energy use, no maintenance and operations cost, as well as lower construction costs. Finally, DC systems offer a more reliable service since it uses high standard industrial equipment, it is an ongoing operation that is monitored, and it has a longer lifespan (Eveloy and Ayou, 2019)

However, this technology faces issues connected to grid based LTS and require high capital investments and interactions among multiple stakeholders. The main issues that are associated with grid based LTS include technical uncertainties, system inertia, economic conditions, organisational form, and customer relations. Furthermore, the main barriers found for DC system expansion in the Swedish context include information imperfections, split incentives, hidden costs, limited access to capital, risk, and bounded rationality (Palm and Gustafsson, 2018).

Five factors for the success of district energy project have been identified by Rao et al. (2017) which include the identification, allocation and management of risk, the collection and dissemination of information to facilitate decision making, the management of funds to align with the lifecycle of the system, the inclusion of the appropriate individuals and experts in decision making and the usage of available tools to improve decision making (Rao et al., 2017).

Additionally, three different project pathways for municipalities that want to promote the implementation of DC systems have been identified by Hawkeye et al (2013) including business models, finance and non-local expertise, the configuration of subscribers and the engagement with energy markets and techno-economic expertise.

District cooling has been explored to a good extent in terms of technical feasibility and optimisation, but only a few have studied how district cooling implementations have been connected to urban and energy planning in a district scale. This research will attempt to fill this gap and contribute to the existing knowledge synthesised in this section. There is a need to further understand the interactions between the actors that are involved in DC system implementations to gather best practices and lessons learned from their roles and interaction in the system in order to facilitate future projects.

3 Methodology

3.1 Research Design

A case study "investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident" (Yin, 1994, p. 13). This method was chosen since the context of DC implementations is important and will vary from case to case. Additionally, these cases involve multiple stakeholders for which drivers, and objectives will vary and have to converge for a successful implementation. Although each DC system has a different story, key lessons from each case can still be used to facilitate new implementations since the technological system differs only slightly (Rao et al., 2017). With a case study method unique new knowledge can be contributed to individual, organisational, social, and political phenomena (Yin, 1994). Case studies rely on multiple sources of evidence (Yin, 1994) which is important to understand the different angles and perspectives of a DC system implementation. Figure 3-1 illustrates the research framework used for this study.

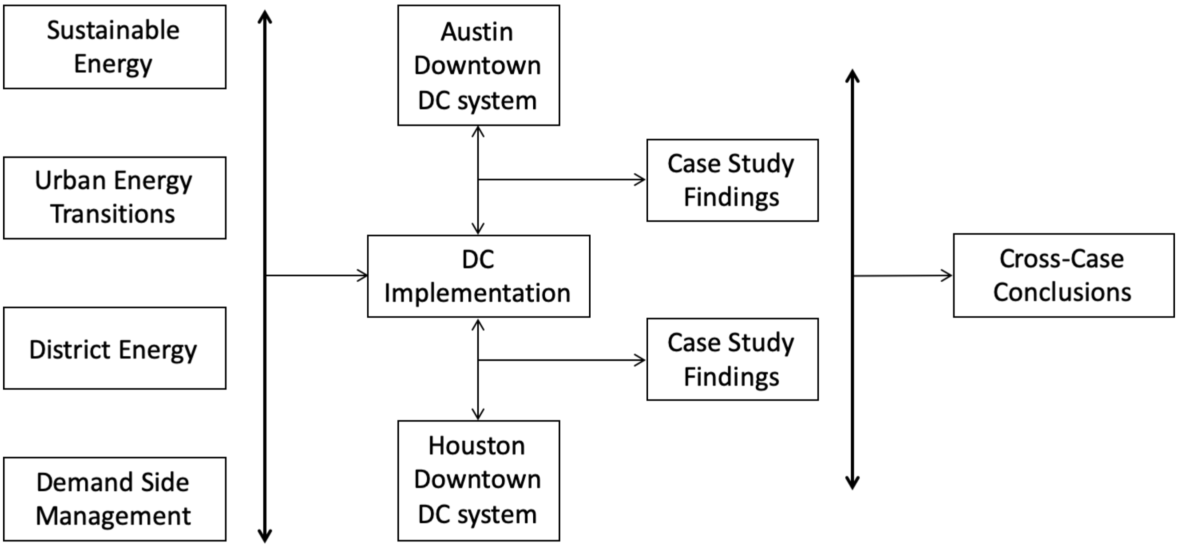

Figure 3-1: Research framework for DC implementations

Source: Created by author; adapted from Verschuren and Doorewaard, 2010, p.88

The research framework used to inform this research and answer RQ1 included literature on sustainable energy, urban energy transitions, district energy focusing on district cooling, and demand side management (DSM) strategies. The literature on sustainable energy and urban energy transitions helped set out the context in which district cooling falls into. Literature on demand side management provided information of how energy demand is currently being addressed and what the current status is on the matter. The literature on district energy presents the drivers and ownership models for DE systems. Lastly, the literature focusing on district cooling provided the current thinking and progress that has been made by researchers on the topic, as well as input into the analytical framework that was used to analyse the data collected.

In order to tackle the different angles that influence and impact DC implementations, an embedded multiple case study design was used. Embedded multiple case studies are useful in cases of urban planning where the units may be different interest groups affected by the project being studied (Scholz and Tietje, 2002).

For this research study, the units of analysis chosen are the Austin Downtown DC System and the Houston Downtown DC System, and the sub-units of analysis are the city, the service provider, and the end users for each case. Figure 3-2 illustrates the units and sub-units of analysis where Austin Energy and EnwaveUSA are the service providers for each case. A multiple case study approach was selected to study the experience of a public electric utility and a private service provider for DC. The Austin case represents the public utility while the Houston case represents the private service provider.

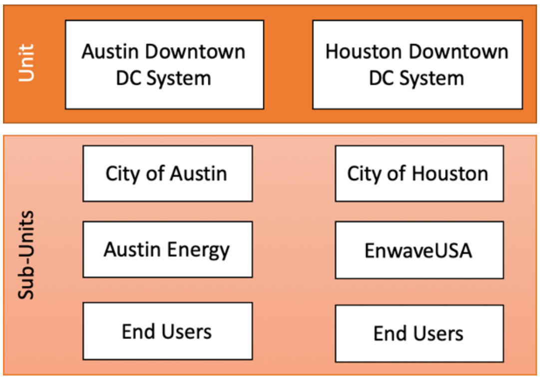

Figure 3-2: Units and sub-units for embeddea multiple case study

Source: Created by author

The research was exploratory in nature to identify key lessons and best practices for DC implementations in warm weather cities. This research explored the objectives, ownership models, business structures and barriers faced by the downtown DC systems in Austin and Houston based on the learnings on Local Energy Governance and Organisation (LEGO) from Hawkey et al. (2013), learnings on governance models from Rao et al. (2017), as well as the learnings on large technical system (LTS) implementation barriers from Palm and Gustafsson (2018). The goal of the study is to understand the role of DC systems in urban energy transitions as well as to get a clear picture of how service providers came to the decision to implement a DC system. Additionally, this study aims to understand the barriers that were faced at the time of implementation as well as expansion, and what strategies were used to overcome these barriers.

To answer RQ1: *What is the role of DC systems in urban energy transitions?* which was presented in section 1.2, a literature review was conducted to understand the fundamental aspects of DC systems, who are the main stakeholders, what are the benefits of installing such systems as well as the barriers faced for implementations.

To answer RQ2: *How is the downtown DC system integrated into the energy landscape in Austin and Houston?* - desktop research was conducted to understand the structure of the Texas electricity market as well as the arrangements of the Houston and Austin cases. Furthermore, data from interviews and archival records was analysed to understand how the DC systems in each city integrate in each case.

To answer RQ3: *What were/are the drivers and barriers to implementing and expanding the downtown DC systems in Austin and Houston?* - the five key issues to implementing new LTS, as well as the learnings from Hawkey et al. (2013) were used to guide the exploration. Individuals involved in the implementation of the DC systems were identified by searching for the history of the chiller plants in each city; the Paul Robbins District Cooling Plant in Austin and the Union Station Plant in Houston. After the individuals were identified, they were contacted by the author using LinkedIn, a professional networking website. Additionally, subject matter experts in district energy were contacted to participate in the research to learn how the cases fit at a larger scale.

Finally, to answer RQ4: *What are the lessons learned from the DC system implementations in Austin and Houston?* - the results from RQ1, 2 and 3 were used to find common themes and key aspects from each case.

3.2 Data Collection

One of the strengths of using case study research methods is the ability to use multiple sources of evidence (Yin, 1994). For this research, data was collected from three different data sources which include archival records, open-ended interviews, and direct observation. Figure 3-3 summarizes the data collection strategy.

Document Analysis

Publicly available documents from the city and service providers, as well as national or state documents that address renewable energy, sustainability targets, energy management and planning were analysed to understand the institutional and policy context of each project. Additionally, archival records that provided data on the journey that each system had were also analysed. These documents were found in government websites or were provided by interviewees.

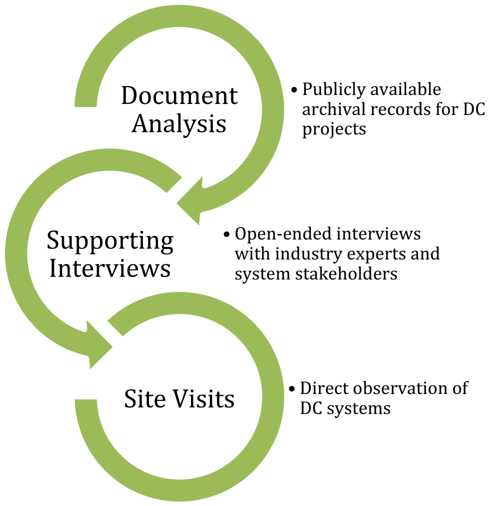

Figure 3-3: Case study data collection strategy

Source: Created by author

Supporting Interviews

The information from the documents analysed was then triangulated with open-ended interviews with individuals involved on the implementation of the DC system as well as individuals that work for the city and subject matter experts. Appendix I – Interview Requests, contains information on the message requests sent to interviewees and Appendix II – Interview Guide contains sample questions asked of the interviewees.

Site Visits

Lastly, when possible, data was collected from direct observation of the systems from site visits of the central chilling plants to understand how the system works in practice.

3.3 Data Analysis

The data collected for this study was analysed at the interests and systems level to identify key lessons and best practices between cases (Scholz and Tietje, 2002). The interview notes were organised and classified into objectives, ownership, and business structure. Additionally, the notes were used to identify the strategies used by each system to overcome the barriers associated with grid based LTS: technical uncertainties, system inertia, economic conditions, organisational form, and customer relationships. Furthermore, the data was analysed to detect if the five key factors for success presented by Rao et al. (2017) were present. From this analysis, key lessons learned from each system were identified and supported with data collected from subject matter experts.

4 Findings

The findings from the data collected for each case as well as an overview of the Texas electricity landscape are presented in this section. As mentioned in chapter 3, the data was gathered from archival records, open-ended interviews, and personal observations from site visits. The information collected from interviews is referenced by an interview number that matches the list found in Appendix III – Interview List. Due to the fact that the Austin DC system is owned and operated by the city and it has not changed ownership since it was built, there are more details to the feasibility study as well as system operations compared to the Houston system which is privately owned and has changed ownership multiple times over the years.

4.1 Background and Context

4.1.1 Local Climate Governance

Both Houston and Austin have engaged in local energy governance. The City of Austin adopted a Climate Protection Plan in 2007 where the city committed to make Austin a leader in climate protection. The city is prone to experience droughts which are exacerbated by climate change thus the city considers it one of the biggest threats to the economy and way of life (Athens et al., 2015). In the 2007 plan, the city set targets to reach carbon neutrality for municipal operations by 2020. In 2014, the city set new targets to reach net-zero community wide greenhouse gas emissions by 2050, and in 2015 the city adopted the Austin Community Climate Plan which declared the city's commitment to the Paris Agreement. According to a progress report from March 2018, the city has reduced its carbon footprint in operations by 75% from baseline levels calculated in 2007 (Athens and Baumer, 2018). However, the city will need to make carbon offset purchases to meet their 2020 goals (Athens and Baumer, 2018). Additionally, the city council set out an ordinance for all new developments to be solar ready (Interview 3 and 5). The city also runs Austin Energy, the electric utility that operates the grid and has targets to reduce carbon emissions.

Similarly the City of Houston, initiated the planning phase for the Houston Climate Action Plan which is scheduled to be completed by 2019 and implemented in the Spring of 2020 after experiencing three 500-year floods (1/500 chance of this type of flood happening) in the last 3 years with Hurricane Harvey the latest one and greatest rainfall (City of Houston, 2019). In the fall of 2018 the city, HARC, CenterPoint Energy, C40, and Jacob and Terese Hershey Foundation initiated the process to create a climate action plan. The plan has four focus areas which include transportation, energy transition, building optimisation, and materials management. The Houston plan is still in draft mode, but it currently includes targets to increase local solar generation and storage, renewable energy generated outside the city and invest in green infrastructure and carbon capture to offset emissions. Additionally, the city plans to work with other Texas cities to increase the Texas' RPS targets. Furthermore, the plan contains targets to be carbon neutral by 2050 starting with powering municipal operations with 100% renewable energy by 2025. Table 4-1 summarises how each city is engaging in the different modes of urban climate governance.

Table 4-1: Summary of modes of urban climate governance used by the City of Austin and City of Houston

MODE OF CLIMATE GOVERNANCE	CITY OF AUSTIN	CITY OF HOUSTON
Self-governing	• Carbon neutrality targets for municipal operations	• Carbon neutrality targets for municipal operations.
Governing through enabling	• Austin Energy promotes energy efficiency practices	• Work with other Texas cities to raise the RPS • Invest in new green infrastructure
Governing by provision	• Owns and operates Austin Energy	• N/A
Governing by authority	• Solar ready ordinance	• N/A

Source: Created by author based on Alber (2008)

4.1.2 Texas Energy Landscape

In order to answer RQ2 and RQ3 it is important to understand the Texas electricity landscape to appreciate the context for the energy landscape of Austin and Houston. In 1975, Texas cities were responsible for regulating the electric utility service rates for their region. Electric utilities had started to integrate themselves from generation to distribution to customer service, monopolizing the market of electricity despite the efforts of the Public Utility Regulatory Act (PURA) set out by the state to avoid this issue (Eisenbach Consulting, n.d.). In January 1st, 2002 the Texas legislature opened up the supply of energy for competition and private utilities were mandated to break up into three different types of entity based on the following functionalities (Eisenbach Consulting, n.d; ERCOT, 2005):

- *Retail Electric Providers* – which sell electric energy to customers in areas where electricity is open for competition.
- *Transmission and Distribution (T&D)* – which manage the distribution and transmission infrastructure and work with the independent system operator (ISO) to maintain the reliability of the grid and are charged with the management of metering services including meter reading activities.
- *Power Generation* – or resource entities that generate power to feed into the electric grid.

Utilities owned and operated by municipalities and co-operatives were exempt from the mandate and were allowed to remain vertically integrated across functionalities (Interview 9). The de-regulation bill mandated for the Electric Reliability Council of Texas (ERCOT), the independent system operator (ISO) who is responsible to manage the flow of electricity in the majority of Texas, to create competition and set up rules for the wholesale market of electricity.

ERCOT manages the electricity on the grid based on zones which "partitions the transmission grid and associated interconnected load and generation points into areas or zones" (ERCOT, 2005, p.6). The electricity retail market is then defined by the transmission and distribution (T&D) utilities which are either open for competition or "opt out" (ERCOT, 2005). Figure 4-1 illustrates the bilateral market where resource entities, electricity sellers, negotiate with load serving entities (LSEs), electricity buyers, to sell their energy and communicate their generation schedules (ERCOT, 2005). LSEs can represent competitive retailers or Non-Opt-in entities (NOIE) which are delivery points not open for competition like municipalities and co-operatives. LSEs forecast their customer load and negotiate privately with other market participants to meet their load. The loads and schedules are then balanced by a qualified scheduling entities (QSEs) which provide the necessary information to ERCOT. The schedules must be balanced between resources and obligation, anything that is not balanced gets rejected by ERCOT.

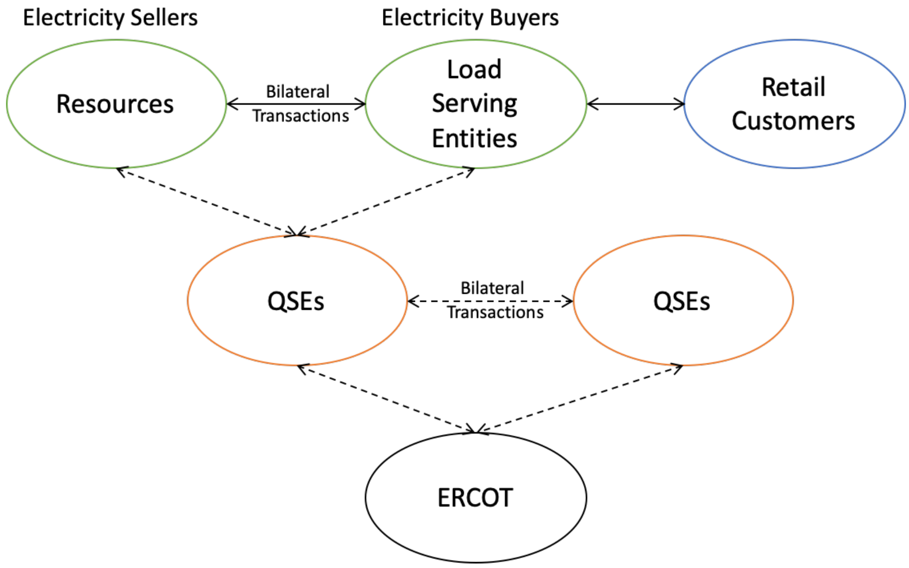

Figure 4-1: ERCOT bilateral market structure

Source: Created by author based on ERCOT (2005) p.9

For commercial customers and other LSEs, ERCOT has a market incentive to reduce consumption during peak times. The Four Coincident Peak (4CP) charge is 1 of 11 charges in the electric bill and it is calculated based on the system demands coinciding with the ERCOT system peak demand during June, July, August and September. These peaks are averaged during summer months and used for the next calendar year (Noria Corporation, n.d.). Reducing load during the 4CP measurement time of the day saves money on demand and regulatory charges for the following year.

4.2 Austin Case Study

4.2.1 Austin Energy Landscape

Austin Energy (AE) has been owned by the City of Austin for nearly 125 years (Austin Energy, 2019). The utility participates in the ERCOT wholesale electricity market as a NOIE, and it is vertically integrated across retail, T&D, and power generation. AE oversees a mix of more than 4 000 MW of total generation capacity and operates three natural gas-powered plants in the Austin area, as well as a coal and a nuclear plant outside of Austin (Austin Energy, 2013). AE also has purchase power agreements in place for other generation types including renewables.

The utility maintains almost 12 000 miles (around 19 312 km) of distribution and transmission lines that serve a 437 square mile area (around 1 132 sq. km) (Austin Energy, 2013). Austin Energy has been involved in renovating the grid and has a smart grid project to install advanced metering infrastructure (AMI). Austin Energy has a philosophy of distributed generation and is working to reduce carbon emissions by increasing the use of renewable energy sources and increase district energy (Interview 8).

4.2.2 Austin Downtown DC System

The Austin downtown DC system is owned and operated by Austin Energy. District cooling is part of Austin Energy's On-Site Energy Systems and Commercial Services. Along with the downtown system, the utility also provides chilled water service to two other areas of mixed use in Austin, the Domain and Mueller. Additionally, AE provides CHP for the Mueller research centre and the children's hospital (Austin Energy, 2013).

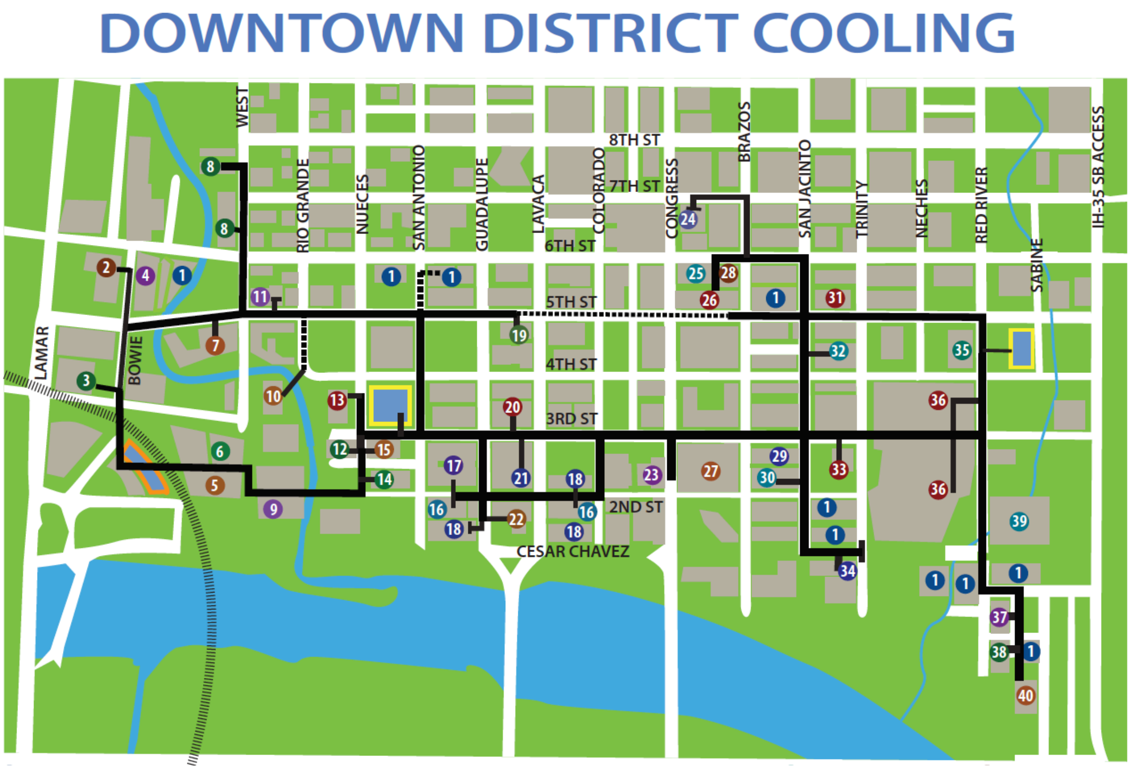

Figure 4-2: Austin Energy downtown district cooling system

Source: Austin Energy (Austin Energy, 2013)

The downtown district cooling system in Austin has two existing chiller plants (DCP-1 and DCP-2) pictured in Figure 4-3 and Figure 4-4 respectively. Currently AE is building a third (Figure 4-5) and fourth plant to increase the chilled water capacity of the system. Figure 4-2 illustrates the DC system with the planned piping expansion and plants. Not shown in the figure is the fourth plant that will be built on top of the Austin Convention centre marked with a number 36 on Figure 4-2. DCP-1 and DCP-2 are both equipped with thermal ice storage which uses cheap wind energy at night to generate ice that is later used during peak times (Athens, 2019). On a typical operation day, ice is made from 21:00 to 14:30 the next day and it is allowed to melt from 15:00-18:00 to provide chilled water with temperatures around 5-6°C to the system (Interview 1). During the time the ice is melted, all chillers are turned off and the electric demand from the plants goes down from around 16 MW to around 1 MW which is energy used to run the pumps transporting the chilled water (Interview 1). On days of high AC demand, some ice is used to meet the load on the off-peak hours, and one chiller is used to keep up with the

Figure 4-3: Paul Robbins District Cooling plant (DCP-1)

Source: Picture taken by author

Figure 4-4: Austin Energy DCP-2

Source: Picture taken by author

Figure 4-5: Austin Energy DCP-3

Source: Picture taken by author

demand during peak time (Interview 1). In this scenario, the demand from the plant goes down to 3 MW during the peak time.

Ice thermal storage was chosen for the TES in the Austin DC system because it takes less space. Since the plants are located in the city centre, saved space is an important factor (Interview 1). Comparatively, as mentioned in section 2.4.1, water thermal storage is typically less expensive and more efficient but takes up more space.

AE's 33 000-ton capable system runs 24/7 all year around and meets the cooling demand of a combination of commercial and residential buildings in the Austin downtown area. The buildings connected to the system include hotels, office buildings, retail buildings, condominiums, and apartments. The buildings are connected to the system through heat exchangers located inside each building and a network of pipes that run around 4.6 meters underground (Interview 1). Since the pipes are deep underground, they do not need to be insulated and do not interfere with other utility networks such as natural gas, potable water, storm drainage, etc. The Austin DC system is a near closed loop in terms of water usage. After the chilled water has passed through the buildings connected, it is returned to the DC plant where it is passed through a cooling tower where heat is rejected, the cooled water is later chilled again following the set up illustrated in Figure 1-1 in chapter 1.

In order for the DC system to be efficient and cost effective, optimal operation are crucial. Thus, the temperature differential and pressure of the system is monitored at all times. To ensure proper pressure is maintained in the system, the pressure is monitored at Whole Foods, marked by a number 2 in Figure 4-2, since it is the furthest customer from the DCP-2 on Sabine Street (Interview 1). This ensures that the pressure throughout the system is maintained for all connected customers. Figure 4-6 shows the operation control screen for DCP-1 and DCP-2 where the temperature differential, system load, and pressure are being monitored. While the system is in operation it uses electricity from the AE grid and acts as a customer of Austin Energy.

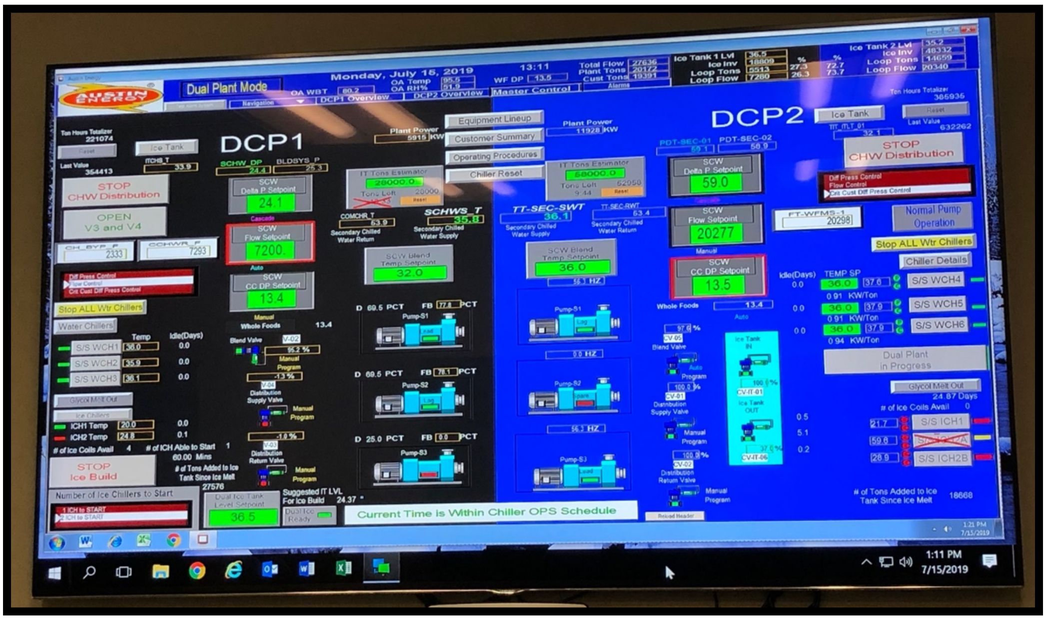

Figure 4-6: Austin Energy district cooling plant control screen

Source: Picture taken by author

4.2.3 Austin System Journey

DCP-1, the first district cooling plant in Austin, is named after Paul Robbins, an environmental activist from Austin that pushed for this system to be implemented in the city centre. Paul Robbins initially advocated for the city to build a CHP system with DC from waste heat when the Seaholm power plant was being decommissioned/rebuilt (Interview 8). Paul Robbins saw it as a good opportunity to create an incentive for businesses to relocate to the downtown area and develop the central city (Interview 8). Actors that were engaged at the time were City Council members and Austin Energy who were overall supportive of the technology (Interview 8).

On the Austin Energy side, Roger Duncan, a former City Council member, was leading the AE energy conservation program. Paul Robbins and Roger Duncan initiated the energy conservation movement in Austin and Roger Duncan was recognised as a leader in energy conservation activities. Additionally, being a former City Council member, he had the trust of the City Council to make decisions on energy conservation and efficiency matters (Interview 9). Eventually, as a result of pressure coming from Paul Robbins, Austin Energy on behalf of the City of Austin requested for a feasibility study to be conducted by a consulting firm to determine the role of a centralized community energy system within the Austin downtown area (Kattner/FVB, 1996). In the study a market, technology assessment as well as economic analysis and customer perspectives was conducted. For the study, the following criteria were analysed, which are necessary for any district energy system:

- The heating and cooling needs and systems within the potential service territory
- Market penetration estimates
- Heating and cooling load diversification factors
- Load density of the district heating and cooling service areas
- Heating and cooling degree days in the year
- Connected building load, and
- Yearly energy consumption

These criteria were used to estimate the production plant capacity, develop a load duration curve for the service area, estimate the equivalent full load duration hours, develop conceptual distribution piping network routes, as well as system development scenarios to ensure future development and expansion (Kattner/FVB, 1996). From the study it was concluded that a DH network was not attractive due to low energy use for heating, low heating degree days, and the lack of central heating systems in buildings in Austin. The study by Kattner/FVB also evaluated the feasibility of a CHP integration, which was the system being advocated by Paul Robbins, and it concluded that for the CHP system to be cost effective it would need to have sufficient tenants in the area to be connected to the system. Other factors against a CHP plant included the following reasons:

- Due to the plant being close to the city centre, a cogeneration plant would raise environmental and siting issues.
- Adding cogeneration would require higher capital cost, and higher operation costs for pumps and piping.
- DE with CHP requires both DH and DC to have high annual loads, which was not the case in Austin. In the Austin case, the equipment would be sized to meet peak cooling demand in summer but would run at a lower loads and lower efficiencies resulting in lower electrical production due to the lack of heating demand.
- At the time, the price of electricity in Austin was low making it difficult to justify the added expense for cogeneration.
- Lastly, phasing of cogeneration would be difficult to do, therefore requiring for the full capacity to be built at once representing higher initial capital costs.

On the other hand, a DC network warranted further investigation due to the high annual energy use for space cooling. In Austin, summer temperatures can reach above 37°C creating a high demand for cooling (Athens, 2019). Additionally, there was a large number of central AC systems in the city's buildings making the implementation of a DC system more feasible and cost effective (Kattner/FVB, 1996). When evaluated further, it was found that the cooling peak demand and annual energy requirements were substantial and viable for a DC system. The estimated market potential was found to be 45 592 tons peak demand with 113 980 000 ton-hours of energy per year within an area of 2.8 square miles which equates to 16 280 tons peak demand per square mile making it a very attractive "load density" (Kattner/FVB, 1996). The study also recommended the use of thermal energy storage (TES) to lower electrical demand and consumption charges by shifting to off-peak energy hours. Additionally, the system could offset installed plant capacity by replacing generation components with TES reducing plant production costs (smaller electrical service, chillers selected at more efficient operating conditions, pumps, piping, etc.) (Kattner/FVB, 1996). Finally, the study recommended for the system to be deployed in phases as additional customers are added to lower the initial capital investment.

With the results of the feasibility study and the good reputation that Roger Duncan had with the City Council, convincing the City Council of implementing a DC system was not an issue. However, an argument was needed to convince the electric utility to make the investment on a DC system (Interview 9). For this timing played a key role, as talks of the de-regulation of the electricity market in Texas mentioned in section 0, were happening at the same time. This key element was used to make the business case for the new DC system. With a DC system, a new revenue stream would be created for the utility by capturing load with a chilled water business that would make it harder for new retail utilities to undersell (Interview 9). This argument helped convince other stakeholders in AE that needed more economic incentives to make the investment.

In late 1998, a combined city hall and private office campus was announced for downtown Austin and Roger Duncan saw it as a good starting point to build the district cooling system (Interview 8). Additionally, the City of Austin used the system as an economic incentive to increase downtown development and densification by attracting companies to the area with cheap AC (Interview 4 and 8). The first private company that was lured downtown was Computer Science Corp which built two buildings on two blocks leased to by the city (Interview 8).

In order to finance the project, AE issued debt with the city to be paid back with the profits from the DC service without raising the bills of the utility's costumers (Interview 4 and 9). The City of Austin provided the funding since it had access to affordable capital (Interview 4 and 9). At first the utility's leadership had no clear intentions to grow the DC system, however the district cooling department leadership had ambitions to expand operations and they pursued new contracts with buildings close to the DC plant (Interview 4).

When the Austin Convention Centre (number 36 on Figure 4-2) was built, new piping was added from DCP-1 to serve the building with AC providing the main backbone for the expansion of the system (Interview 4). As more end users were connected to the DC system, Austin Energy appreciated the benefits of aggregating the load for space cooling in the downtown buildings, which provided a better curve of efficiency which is around 10- 15% more efficient than individual building chillers (Interview 4). Additionally, it allowed for the utility to shave the city's peak demand by using thermal storage (Interview 4). Since AE acts as a LSEs in the ERCOT wholesale market, the shaved peak load resulted in market savings from lower demand charges that benefited all electricity customers (Interview 4). The DC system then became part of the utility's DSM strategies and AE set targets to shave 20 MW of peak demand by 2020 with the system, in 2018 the DC system shaved 19.2 MW of peak demand, and AE set a new target of shaving 30 MW by 2027 (Interview 4).

When the system first started, service agreements were negotiated between AE and the end users, but eventually the cost of service for DC was determined by the district cooling department and a lifecycle cost analysis tool was created to present to new potential customers showing where the cost of service came from (Interview 4). The charges were made up of capital, capacity and variable charges which consist of the water, waste, electricity, and chemicals used in the process (Interview 4). The tool also showed secondary and tertiary savings that the end users would get from connecting to the service such as square feet of space gained, as well as operation, maintenance, and capital savings overtime (Interview 4). Initial capital cost saved by developers was one of the biggest incentives that attracted developers to connect to the system since they did not have to invest in AC equipment for the building. Hotels and condos are attracted to the value propositions (Interview 1). Issues would arise when the construction decisions were not locally made (Interview 9). Some apartment complexes that were developed by national companies already had blueprints for the building that were designed at the national office, as a result even if the value proposition to connect to the DC system was attractive, the building would not connect because they did not want to redesign (Interview 9). Similarly, apartments that were being built with the end goal of selling also would opt not to connect to the DC system, and instead would install a cheap chiller system (Interview 4).

Nevertheless, adding new end users to the Austin DC system has not been an issue (Interview 1, 4 and 9). Since the system is owned by the city, and all new developments need to get permits from the city, most new constructions come to the DC department to be connected and get the service. The department has actually had to turn down some new developments that are too far away from the system since it would require for additional piping to be installed. This would raise the cost of the service for all end users if other buildings in the area of the pipe do not connect to the system (Interview 9).

4.3 Houston Case Study

4.3.1 Houston Electricity Landscape

Houston's electric utility, Houston Light & Power, was privately owned and was affected by the mandate set out for de-regulation. The utility had to restructure into separate entities that fulfilled the functions set out by the mandate: Retail, Transmission & Distribution (T&D), and Power generation. The transmission & distribution entity became the company that is now known as CenterPoint Energy which owns and operates the T&D infrastructure in the Houston area. CenterPoint also operates a natural gas distribution system as well as other energy services (CenterPoint, n.d.). Currently there are 41 electricity retail companies available for the zip code where the Houston DC system is located. These companies act as LSEs in the wholesale market and many sell renewable energy percentages from 10% to 100% (PURA, n.d.).

4.3.2 Houston Downtown DC System

The Houston downtown DC system is owned by Brookfield Infrastructure and it operates under EnwaveUSA (Interview 10). The system has 5.45 miles (8.77 km) of chilled water piping throughout the Houston downtown area. The system serves 21 customers consisting of 24 buildings of mixed use. This represents 6.5 million sq. ft (about 604 000 sq. meters) of space in downtown Houston. End users are connected to the system through pipes and a close approach heat exchanger that is highly efficient (Interview 7). Figure 4-7 illustrates the distribution plan that is currently in place. Figure 4-8 illustrates the Union Station District cooling plant which has 8 electric chillers and two ice storage tanks. The plant occupies a block in the downtown area and is supplied with power from two separate 34.5 KV feeds from a substation located nearby that has automatic rollover from two separate transmission lines helping with the reliability of the system (EnwaveUSA, n.d.). The plant has a full capacity of 35 000 tons with a distribution system capacity of 80 000 ton and it is currently built at 29 290-ton capacity. The system is expanding its capacity and adding additional chilled water to meet growing loads and new construction (Interview 10). The Houston DC system acts as an electricity customer and is reactive to the ERCOT 4CP to lower the cost for electricity and pass it down to customers the following year.

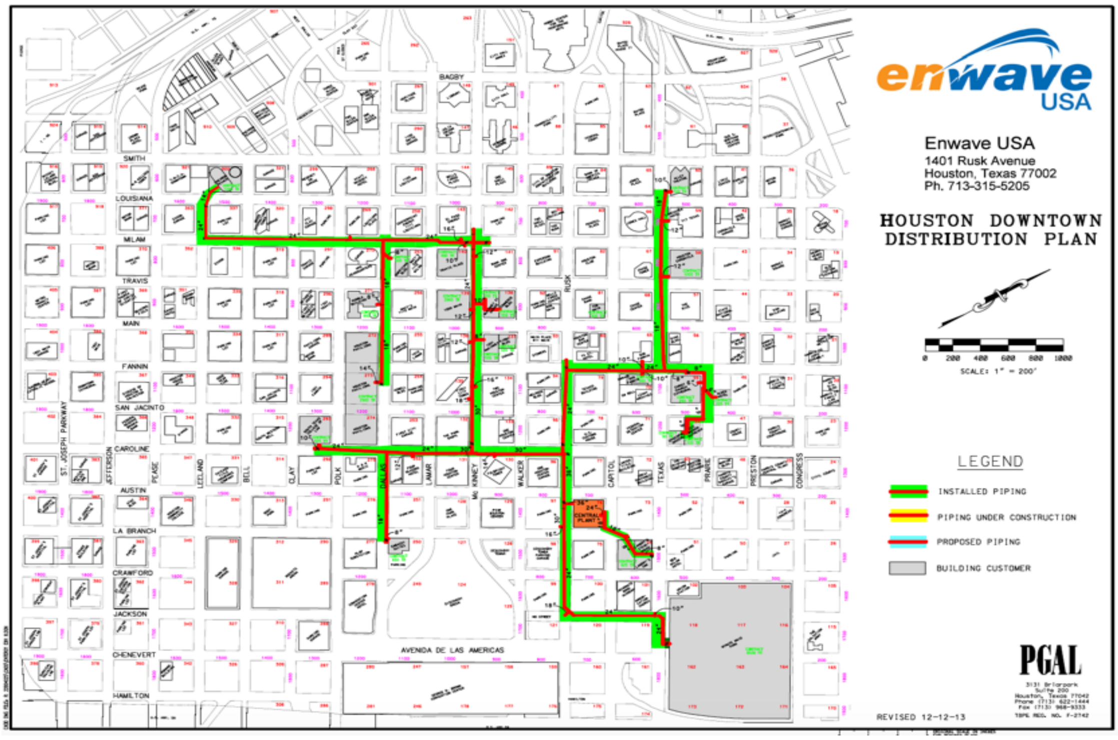

Figure 4-7: Houston District Cooling distribution map

Source: EnwaveUSA (2013)

4.3.3 Houston System Journey

The Houston DC system started as a joint venture or limited partnership between Houston Industries, the parent electric utility at the time, and Northwind from Chicago, also referred to as Exelon Thermal (Interview 10) and ComEd (Interview 7) by interviewees. Northwind Chicago had implemented a DE system in the city of Chicago and took a team of engineers from Houston to develop the Houston version of the DE system (Interview 7). The Union Station Plant that occupies a block in the city centre began construction in April 1998 and began providing chilled water to Minute Maid Park, a 28.9-acre baseball park, in April 1999 (EnwaveUSA, n.d.). After deregulation the plant was operated by Reliant Energy Thermal Systems, a separate entity from the utility which also provided other energy efficiency services to commercial customers (Interview 7). Eventually the Houston Entity bought out the Chicago entity to fully own the system (Interview 10).

The DC system in Houston has changed ownership multiple times going from Reliant Energy Thermal Systems to CenterPoint Energy Management Services (CEMS). CenterPoint Energy the T&D utility eventually sold CEMS to Entergy Solutions District Energy to focus on the core business of electric energy delivery (Houston Business Journal, 2003), and eventually the system was bought by Brookfield Infrastructure and is operated by the company under EnwaveUSA. Brookfield Infrastructure is one of the largest owners and operators of infrastructure that facilitate the movement and storage of energy, water, freight, passengers and data including renewable power platforms across North America, South America, Europe and Asia (Brookfield Infrastructure Partners, 2019).

Similar to the Austin case, one of the main drivers for implementing the DC system in Houston was to capture load (i.e. load retention) at the time of the de-regulation of the electricity market.

The utility understood that by implementing a DC system, it could capture the electric demand for HVAC (Heating, Ventilation, Air Conditioning), which tends to be higher in southern climates by providing alternative HVAC services (Interview 7). The company understood that at a time when the retail market for electricity was opened for competition, customers that would be connected to the DC system would be less likely to switch providers (Interview 7). Also, since the contracts were set between 10-30 years, the end users were legally obligated to continue the service for chilled water even if they switched electric providers. The implementation of a district cooling system was a strategic value proposition to diversify the utility services (Interview 7). At the time carbon footprint reduction and sustainability were distant drivers (Interview 7).

Figure 4-8: Houston Union Station District Cooling Plant

Source: Picture taken by author

In terms of financing, the utility won the bid to provide the air conditioning service to the Minute Maid park that was being built at the time. Having this "anchor customer" made the economics look good since the building would require 9 000 tones of cooling, approximately one third of the load that was being built (Interview 7). This kicked of the business and made a good business case to invest the front-end capital which has a long-term payback period. Additionally, the security of having long term contracts with end users helped the business case.

For the Houston system, the timing was also beneficial; the system was installed during a time of high development and renewals of historic buildings in the Houston area. This contributed to the business case for retrofitting old buildings and connecting them to the DC system. One of the historic buildings that was part of this renewal period was the Humble Oil Building, pictured in Figure 4-9, which was retrofitted to add AC since historic buildings were not built with central air conditioning systems (Cook, 1999). These buildings were retrofitted with financial help from the city which "essentially loan the [development] company funds to pay school taxes, and the debt [was to] be repaid from income on the property once the facility open[ed] for business" (Cook, 1999, p.1).

Figure 4-9: Humble Oil Building in Houston

Source: Picture taken by author

One of the big technical challenges for the implementation of the Houston DC system was that the infrastructure in Houston was not conducive to implement a system of underground piping (Interview 7). City streets in Houston were very congested with utility lines making it harder to set up piping. As a result, the pipes were tunnelled to go deep underground under all the other utilities. Additionally, district cooling in Houston is more difficult because the city is more spread out lowering the load density (Interview 2).

Aside from technical challenges, one of the main barriers to implementation and expansion identified by interviewees was lack of familiarity with DE systems. End users in Texas do not have experience with DE and they want to have control of the operation of their chillers (Interview 10). In other words, end users lack the familiarity and trust with the system and were unfamiliar with what their responsibilities would be after connecting to the DC system (Interview 2). Users also did not want to be dependent on the system to get AC (Interview 2). Culturally DE systems were seen as a "northern" practice and not something that would work in the south (Interview 7). Additionally, building owners believed that the price of the building would decrease if it did not have an individual chiller system for when they want to sell it in the future (Interview 10). Furthermore, architects and engineers were not familiar with how to incorporate the differences to the building designs and were more comfortable with traditional individual AC systems (Interview 2).

In order to overcome the barriers, "Self-cooling" vs "Thermal System" models were used to compare the cost differences and demonstrate the efficiency gains from connecting to the DC system (Interview 7). Other benefits that were promoted to end users included the capital costs saved from not having to install a chiller and other equipment making the rate of return (ROT) for the building more attractive (Interview 7). Additionally, at the time, new regulations to comply with the Montreal Protocol were coming into effect, adding a new level of complexity to AC systems (users had to make sure the technologies being used or installed did not contain any ODS) (Interview 7). By connecting to the DC system, these concerns would be removed (Interview 7). At the bottom line connecting to the DC system was a simple choice that works, and its reliable (Interview 7).

5 Discussion and Analysis

The following section will provide the analysis of the findings from the literature review and case studies based on the units of analysis which were set out in chapter 3. The main unit of analysis for each case study was the city's downtown DC system. Additionally, the sub-units for each case study were the city, the service provider and the end users of the systems as illustrated in Figure 3-2.

5.1 Urban Energy Transitions and District Cooling

From the literature review it was found that there are multiple benefits to implementing district cooling system in dense urban areas with high cooling demands. Table 5-1 provides a summary of the benefits of implementing DC systems in a city. Four different stakeholder groups were identified based on the analysis from the literature and the case studies: cities, end users, electric grid, and the environment. These were the stakeholder groups that are benefited from a DC system. In the table, it is indicated which stakeholder is profited by each benefit.

Table 5-1: Summary of benefits of DC systems

Aspect	Cities	End Users	Electric Grid	Environment
Energy Efficiency		■		■
Peak Management			■	■
Renewables	■			■
Local Sources	■			■
Avoid ODS	■			■
Free-up Space		■		
Lower Building Costs		■		
Resiliency and Reliability	■	■	■	
Lower Operation and Maintenance Costs		■		

Source: Created by author based on literature review

Energy Efficiency is one of the main benefits of installing a DC system to provide space cooling in a city. Since these systems use high grade equipment that is monitored and maintained at a large scale, the operations are more efficient compared to individual building AC systems. As mentioned in the literature review, "the aim of energy efficiency is to maintain a comparable level of service, but reduce energy usage" (Boshell and Veloza, 2008, p. 1). DC systems not only reduce the energy usage of providing AC to buildings, but also provide a comparable and often times better level of service to the end users. This benefits end users since it translates in lower lifecycle costs. Similarly, energy efficiency of the system benefits the environment since it requires less fuel to run which results in less air pollution and corresponding GHGs.

Peak Management is another key benefit of using a DC system to meet space cooling demands. DC systems allow for the cooling load to be aggregated resulting in lower peak demand. Additionally, by installing thermal energy storage in the systems the peak load can be shifted to times of lower demand. This translates to lower transmission and distribution costs because the capacity of the grid needs to meet a lower peak demand. This benefits the electric grid as there is less strain preventing blackouts and overload increasing reliability. It also benefits the environment since lowering the peak demand lowers the corresponding GHGs from dispatchable sources which are often fossil fuels.

Furthermore, DC systems provide the scale to integrate *renewable* energy sources which help lower the negative emissions from energy production which are associated to fossil fuels benefiting the environment. Additionally, cities and communities that have set targets to reduce carbon emissions, can leverage DC systems to lower their impact through incorporating renewable energy sources. Similarly to the use of renewables, *local energy sources* can be used in DC systems which may not have been feasible at an individual building scale. This helps communities keep energy money circulating in the local economy, as well as create new markets for local resources. Moreover, DC systems increase the *resiliency and reliability* of the energy system since it increases the flexibility and allows for distributed fuel sources. This is especially important in areas that are at risk of natural disaster, however reliability is hard to factor into economic analysis.

Another environmental benefit of DC system is the prevention of using ODS. One of the main uses of ozone depleting substances (ODS) is refrigeration, by implementing DC systems, the use of ODS in individual AC units is avoided since it is replaced with the central unit which benefits the environment and communities. Finally, by using DC systems end users do not need to install their own equipment which *frees- up space* in roofs or basements of buildings also translating to *lower building costs,* and *lower operation and maintenance costs.*

5.2 District Cooling in Austin and Houston

From the literature we knew that DC systems have multiple integrations to optimise operations. Figure 5-1 illustrates the integrations that are part of the Houston and Austin DC systems. Both systems have similar integrations, since the conditions (i.e. weather, city development, renewable energy sources) are similar. Both systems provide chilled water for space cooling to a mix of residential and commercial buildings located in the city centre. They both have an ice TES system that uses cheap electricity at night to generate ice. The ice is later melted the next day and used during the time of peak electricity demand. The use of ice TES shifts the electric load from times of high demand to times of low demand adding flexibility and reliability to the electric grid. As mentioned in the literature review, Texas has abundant wind energy which is fed to the ERCOT electric grid and is readily available at night. Even though the wind energy generation is not directly connected to the DC systems it is still illustrated as part of the integrations since the DC system enables the storage of this energy.

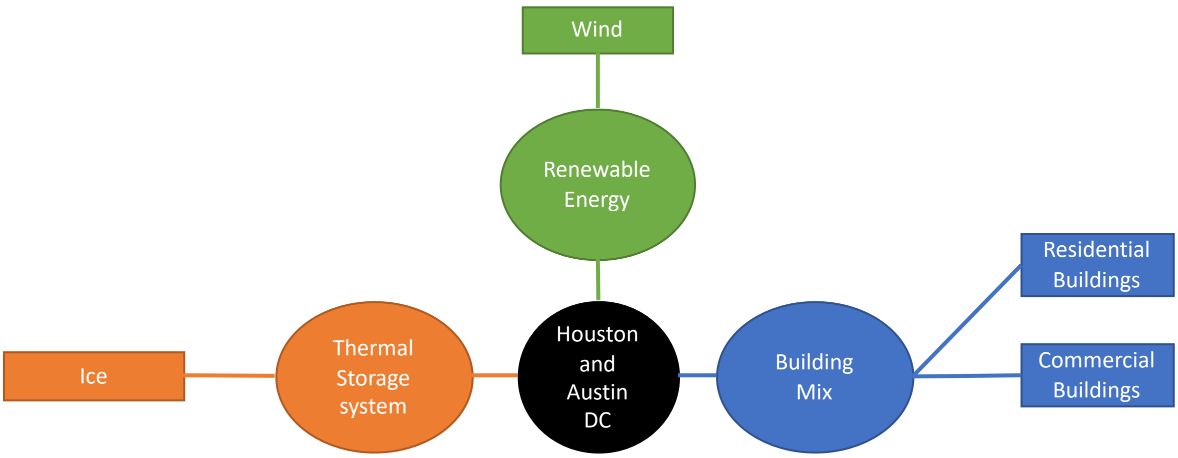

Figure 5-1: Integrations of the district cooling systems in Austin and Houston

Source: Created by author, adapted from Gang et al. (2016) p.255

The electricity landscape in Austin and Houston engage in different ways in the ERCOT electricity wholesale market. In Austin, the electricity market is not open for competition since the utility that services the Austin territory is vertically integrated, owned, and operated by the City of Austin. On the other hand, the electricity market in Houston is an open retail market and has multiple private retail companies competing to sell electricity to the end users in the city. Similarly to the electricity provision, the service providers for the DC service in each city follow the same pattern. In Houston, the downtown DC system is owned and operated by a private company. The Houston ownership structure has changed over time as it began as a joint venture between two private companies and it transitioned to a one company private model. On the other hand, the Austin DC system follows an internal department model where Austin Energy's On-Site Energy Services is a department within AE that is owned by the city.

Although the ownership models differ between case studies, the technical aspects of each system are similar. Table 5-2 provides an overview of the downtown DC systems in Houston and Austin. Both systems currently have similar installed capacities with Austin at 33 000 ton and Houston at 29 290 ton. Austin's DC plants are in different locations in the city centre while Houston houses all of its chillers at the same plant.

Table 5-2: Downtown DC system overview for Austin and Houston

ASPECT	AUSTIN DC SYSTEM	HOUSTON DC SYSTEM
Capacity	• 33 000 tons (116 MW)	• 29 290 tons (103 MW)
Buildings Served	• 40 mixed use	• 24 mixed use
Area Served	• 14 million sq. ft. (1.3 million sq. meters)	• 6.5 million sq. ft. (603 thousand sq. meters)
Equipment	• Water chillers • Ice chillers • Ice TES	• Water Chillers • Ice chillers • TES
Fuel	• Electricity	• Electricity
Use of thermal energy	• Space cooling	• Space cooling

Source: Created by author, based on Rao et al. (2017)

Even though both systems have similar capacities, the Austin system serves almost twice as many buildings and area compared to the Houston system. This is likely due to the buildings in Houston having a higher load density. The City of Austin has some of the most stringent building codes in the state of Texas (Interview 3 and 5) which can explain why the buildings in the area have a lower demand.

System Lifecycles

The Houston and Austin DC plants were installed within two years of each other. The Union Station Plant in Houston came live in 1999, and Austin's Paul Robbins DC plant in 2001. The DC systems have gone through the concept, feasibility, design and build stages of the system lifecycle described in section 2.4.2. With the difference that the Houston system has gone through sale and acquisition multiple times as it changed ownership over the years. The drivers for all of the ownership changes are unknown but are likely part strategic restructuring of the system. Figure 5-2 and Figure 5-3 illustrate the lifecycle stages for each system. Currently both systems are experiencing expansion to meet the growing demand in the downtown area of their respective city.

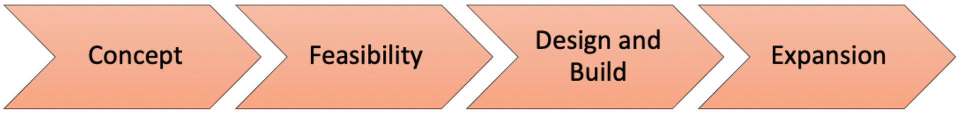

Figure 5-2: Austin DC system lifecycle

Source: Created by author based on Rao et al. (2017)

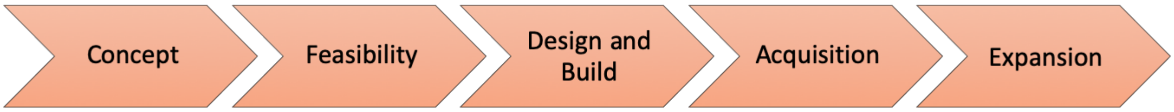

Figure 5-3: Houston DC system lifecycle

Source: Created by author based on Rao et al. (2017)

5.2.1 Drivers to DC Implementations

The drivers and objectives for implementing the Austin and Houston DC systems that were gathered from interviews were classified based on the sub-units of analysis for each case. Table 5-3 summarises the objectives for implementing the DC systems in the downtown area of each city. Identifying these drivers and objectives is important since "the most critical factor in choosing a business model [for DE systems] is identifying the objectives for the project" (Rao et al., 2017, p. 42).

Table 5-3: Summary of objectives for downtown district cooling systems in Houston and Austin

ACTOR	AUSTIN DC SYSTEM	HOUSTON DC SYSTEM
City	• Economic Incentive for densification of the downtown area	• N/A
Service Provider	• Energy Efficiency • New Revenue Stream/Capture Load	• Business strategy to capture Load
End User	• Lower upfront development cost • Lower maintenance cost • Gain space	• Better ROI for building

Source: Created by author

For both cases, the de-regulation of the electricity market in Texas contributed to the economic business case for the electric utilities in Houston and Austin to invest in a DC system to capture load. This created a strategic value proposition for the utilities to lower the risk of losing customers after the electricity market was open for competition. For the Austin system, the DC system also served as an economic incentive that was used by the city to promote development in the downtown area in order to densify the city. These objectives match the drivers identified by Rao et al. (2017) in section 2.3.1; capturing load was a mode of new *revenue generation* for the utilities, and the economic incentives allowed for the City of Austin to *increase local economic competitiveness*.

As the DC system in Austin grew, the objectives of the utility changed from a strategy to capture load to a demand side management strategy (DSM) to shave peak demand. Decreasing peak demand translates to savings for all of the electricity customers in the Austin area since it lowers the regulatory charges from ERCOT. On the other hand, the Houston DC system operator does not have the same incentive to shave the peak demand since the operation is not connected to the electric utility or T&D utility in the Houston area. However, the Houston system does react to ERCOT's 4CP to get lower demand and regulatory fees for DC customers by lowering the system's peak demand during the summer months. The Austin case provides an example of a system where the objectives evolve overtime as mentioned in section 2.3.1.

Furthermore, another factor of importance for both systems was that the city centre was experiencing new developments and renovations. If a building is being built or is being renovated it is easier to make the business case for the building to get connected to the DC system. By connecting to the DC systems, the developers get lower upfront cost resulting in a better ROI for the building. Additionally, the new buildings could be designed with the gained rooftop or basement space. Although the majority of the buildings that connected to the systems were new developments, there were a few that were retrofitted to connect to the system, In Houston, the city provided loans to developers to renew historic buildings in the city, and the incorporation of AC was facilitated by connecting to the DC system rather than having to install a chiller which occupies more space since only a heat exchanger was necessary for the building (Cook, 1999).

5.2.2 Barriers to DC Implementations

The barriers to implementations and expansion gathered from interviews were classified based on the barriers identified by Palm and Gustafson (2018) presented in section 2.4.5. Table 5-4 provides a list of the barriers identified by Palm and Gustafsson and indicates the barriers experienced by the Houston and Austin DC systems. Both systems identified *split incentives* as one of the barriers to expansion, apartment buildings that were being built with the intention of selling, were less motivated to connect to the system due to the short term thinking of developers. Similarly, both systems encountered cases of *bounded rationality* where the direction of the development, the engineers and architects were more comfortable designing buildings that had an individual central AC system in place.

Table 5-4: Summary of DC system barriers

	Austin DC System	Houston DC System
Information imperfections		■
Split incentives	■	■
Hidden costs		
Limited access to capital		
Risk	■	
Bounded rationality	■	■

Source: Created by author based on Palm and Gustafsson (2018)

Interviewees from the Houston case study identified *information imperfections* as one of the main barriers for implementation and expansion. End users in the area are not familiar with district energy systems and there is a lack of trust if the system would work in the area. It is interesting that interviewees from the Austin case did not identify this as one of the barriers for the Austin system even though both cities are in the same southern state where district energy systems are not well known. This is likely due to the fact that the service in Austin is provided by the utility owned by the city, and all new developments must get permits in the city. Having the city provide information for the system likely builds trust on the benefits and end users are more comfortable connecting. On the other hand, the interviewees from the Austin system identified *risk* as one of the barriers to expanding the system to buildings that requested the service and were further away from the chilling plant. Installing a pipe to deliver the service to these buildings would require an investment, but there is a risk that if the buildings on the way of the pipe do not connect, the payback period would be too long and the rates for all customers would need to be increased.

Other barriers that must be addressed in order to implement DC systems, are the issues that are associated with grid based LTS. Table 5-5 provides a summary of the methods the Houston and Austin systems addressed these issues.

Table 5-5: Summary of LTS issues for the Austin and Houston downtown DC system implementations

LTS ISSUE	AUSTIN DC SYSTEM	HOUSTON DC SYSTEM
Technical Uncertainties	Conducted a feasibility study with a consulting firm	Joint venture with a company with experience in district energy
System Inertia	Not mentioned as a big barrier for either system	
Economic Conditions	De-regulation played a big part for both systems – it was a strategy to capture load. Both had a large "anchor" end user that guaranteed a load.	
Organisational Form	Owned and operated by the city under Austin Energy	Joint venture between two private companies Currently owned and operated by Brookfield Infrastructure
Customer Relationships	15 to 20-year service agreement contracts	Shortest contract has been for 10 years, most are 20 can go up to 30 years

Source: Created by author, based on Palm and Gustafsson (2018)

To address *technical uncertainties* each system used a different strategy. The Austin system hired a consulting firm to conduct a feasibility study to identify the role of a DE system in downtown Austin. On the other hand, the Houston system chose to embark on a joint venture with a utility from Chicago that had experience with DE systems. The joint venture served as a way to mitigate risk and technical uncertainties of implementing a new DC system for the first time.

System inertia was not identified by any of the interviewees as an issue, even though both systems took about a year from the beginning of the project to when the system was live and providing service to their respective "anchor customers". These "anchor customer" were important to provide the *economic conditions* to initiate the systems and guarantee a significant load from the start. For the Houston system the "anchor customer" was the Minute Maid park and for Austin system it was the City Hall building. Later the "anchor customer" to expand the Austin system was the Austin Convention Centre.

In terms of *organisational form*, each system represents a different ownership model. The Austin DC system is a public internal department of Austin Energy. On the other hand, the Houston DC system is a private entity, and the City of Houston was and is not involved in the operations or decision making of the system. The *customer relationships* for both systems are similar since they both constitute of long-term contracts that range between 15 to 20 years for the Austin system, and 10-30 years for the Houston system. These long-term contracts provide economic security that the initial investment will be paid overtime.

5.3 Lessons Learned

There are many key lessons that can be learned from the findings of the downtown DC system case studies in Houston and Austin. These learnings can help overcome the barriers to the implementation and expansion of DC systems in other warm weather cities. This section will present the lessons learned from this research which contributes to the knowledge at the urban or district dimension.

Role of DC Systems: If managed properly, DC systems are profitable and crucial assets to the infrastructure of a city. From the case studies we can learn that even though DC systems require high investment costs to set up the network of the system, these systems become important assets to the infrastructure of the city. Both of the systems identified "anchor customers" that provided an initial significant load that helped the economics of the business case and secured revenue to pay back the investment.

In the Austin case, a publicly owned system, the infrastructure investments are being paid back with the revenue from the service. To ensure this, the cost of providing the service was calculated to maintain a healthy margin. Additionally, the expansion of the system is being controlled to ensure that the rates of all customers do not need to be raised.

In the Houston case, a privately-owned system, the system has been providing a reliable service to the buildings connected since 1999 with zero unplanned outages regardless of the ownership changes. Currently the system is expanding capacity to meet new and growing demand. It is hard to assess how or if the Houston DC system contributes to sustainability goals in Houston since it is not integrated to urban and energy planning, however it does demonstrate that DC systems can be profitable and economically sustainable.

Role of Cost Saving Models: Cost saving models are important tools to promote DC systems and configure subscribers. Both the Houston and Austin systems leveraged models to demonstrate the savings to potential customers. The Austin system used a lifecycle cost analysis tool that showed secondary and tertiary savings from space gained as well as lower maintenance and operation costs. Similarly, the Houston system used "Self-cooling" vs "Thermal System" models to compare the cost differences and show the efficiency gains from connecting to the system. Additionally, these tools provided predictable costs to end users.

Similarly, modelling tools can also be used to estimate the environmental and social benefits from having a DC system in a city. These benefits include emission reductions as well as impact and contributions to sustainable development (UNEP DTU, 2019). In order to achieve this, the UN Environment, encourages the use of processes to monitor, report, and verification (MRV) for district energy systems.

Role of Local Governments: Even though it is not necessary for municipalities to get involved in DC systems to be successful, having the support of the city is important to maximise benefits of the system. For the Austin case, it was beneficial to be connected with the city since all new developments must be approved by the city, and the DC system is considered as part of the utilities needed (i.e. electricity, water, etc.). Additionally, having the support of the city helps build trust in the system, especially in areas where end users are not familiar with district energy. This can be observed from the fact that in the Austin case, information imperfections were not identified as a barrier to expanding the system.

It is important for local governments to get involved with energy planning in order to facilitate the implementation of systems like district cooling. By engaging in energy planning cities will be able to facilitate carbon emission reductions in their territory. Many cities are involved in the planning and implementation of other utilities like water and are involved in road planning and public transit (Interview 6). The literature on DC recommends for these systems to be incorporated into municipal and urban planning to be successful. The findings of this research support this recommendation, since for both cases it was important that both cities were going through high development and/or renewal periods. This made the economic conditions cost effective. Additionally, it is easier to convince end users to connect when it is a new development since they can plan for the building with the gained space and can save initial capital cost from the AC equipment (chillers, etc.). If these systems are incorporated with the urban planning, synchronising the timing is facilitated and the potential for success is greater.

Third party organisations and service providers can educate municipalities and city council to understand the benefits of DC systems to provide incentives for developers to connect (Interview 4). In Houston, a new mix use development opted out because it they didn't know how long they would own the property (Interview 2). Conversely, in Austin, the mix use developments in the Domain and Mueller both opted to install DC systems to meet cooling demands.

Role of Champions: Having champions of the technology is important for success. The origin of the DC system concept in the Houston case is not known. However, in the Austin case, the champions that pushed for the technology were important for success. Paul Robbins advocated for the city to implement this system, and later it was the leadership of the DC department which had ambitions to expand that increased the uptake of the system in Austin. On the other hand, without champions, the potential of these systems would not be fulfilled. For example, in San Antonio, another Texas city, the DC system is owned by the water utility thus the peak managing benefits from the system are not apparent and not leveraged (Interview 4).

5.4 Critical Reflections

The findings from this research are specific to the experience of the individuals that were interviewed. The exploratory nature of the case study and open-ended interviews allowed for the interviewees to express what they believed was the most important aspects of each case. Having open ended interviews fit the research well since the recollection of the events and system journeys took the shape of a story. Both of the systems were implemented around twenty years ago, therefore the responses are hinged on the memory of the interviewees.

To further enrich this research, a quantitative method would have added valuable information to capture the end user side of the system. The end user perspective was captured through the interviews of the individuals involved in the implementation of the system. It would be an interesting input to gather data from end users connected to the systems, as well as buildings in the DC system territory that opted not to connect to the system.

5.4.1 Legitimacy

In terms of legitimacy, this research explores an important topic that is highly relevant at the moment. In the summer of 2019, many countries in Europe experienced the hottest summer temperatures that have been recorded. These heat waves caused multiple deaths and closed offices reducing productivity (UNEP, 2019). These temperatures increase the demand for air conditioning, making it a necessity in areas where it was previously considered a luxury. According to the UNEP, the emissions associated to air conditioning and refrigeration are estimated to rise by 90 percent by 2050 compared to 2017 levels. This 90 percent increase "would result in emission of 12 gigatons of carbon dioxide (GtCO2), equivalent to a third of our total emissions in 2017" (UNEP, 2019). Thus, promoting and overcoming barriers to solutions that address this growing demand in a sustainable manner is highly important.

This research identified important lessons from the implementation of DC systems in Houston and Austin and provided strategies that can be leveraged in other warm weather urban areas that are dense and have a high cooling load. Both of the systems are relatively young, and it is possible that they will eventually follow the path of DH systems in Sweden, where the monopoly aspect of the system can become an issue. In order to address this, further research on how DC systems can be opened for competition would be interesting. Many researchers suggest that the generation side of the DC system can be opened for competition, further research on how this can be achieved in practice would be interesting.

5.4.2 Generalisability

Although the results of this research are unique to the context and the timing of the system implementation, as well as the energy landscape of each of these cities, both systems follow typical DE system lifecycles. The learnings from this research can be applied to other dense Texas cities and warm weather cities. Additionally, this research provides examples of a public vs. private system and the factors that surround them. Furthermore, this research provides reasons for municipalities and grid operators to get involved in and implement DC systems.

6 Cross-Case Conclusions

The demand for space cooling is rising, current technologies that meet this demand are powered with electricity which adds strain to the electric grid and increases the peak demand. DE which includes DC, has been identified as an efficient and a sustainable solution to meet the growing cooling demand in dense urban areas. However, the implementation of DC systems requires cooperation among different stakeholders as well as significant upfront capital investments to set up the network. These factors often pose as barriers to the implementation of DC systems. In order to identify best practices to overcome such barriers, a literature review and two case studies were used to understand the different interactions among stakeholders involved in DC systems as well as the journeys they had to implementation and expansion. To guide this research, the following four questions were considered and answered:

- RQ1: What is the role of DC systems in urban energy transitions?
  - What are the fundamentals aspects of DC systems?
  - Who are the main stakeholders?
- RQ2: How is the downtown DC system integrated into the energy landscape in Austin and Houston?
- RQ3: What were/are the drivers and barriers to implementing and expanding the downtown DC systems in Austin and Houston?
- RQ4: What are the lessons learned from the DC system implementations in Austin and Houston?

The answers to each of the questions are summarised in this section followed by closing thoughts on the study.

RQ1: What is the role of DC systems in urban energy transitions?

DC systems have the potential to play a significant role in urban energy transitions. These systems can facilitate carbon reductions in dense urban areas where the demand for cooling is high and consistent. By aggregating the load from the buildings' air conditioning, DC systems lower the overall peak demand for the area providing higher efficiency and enabling the use of renewable and local resources for energy. Additionally, by incorporating thermal storage, DC systems allow for the peak load to be reduced and shifted to times when energy demand is low. These systems also increase the reliability of the service, and if combined with CCHP, they can also meet electricity demands in the area. This is common in medical centres where reliability is of most importance.

The benefits of DC systems are more prominent at the district level and impact multiple stakeholders. End users get an efficient, reliable service that provides even cooling with high grade industrial equipment. Additionally, end users save in maintenance and operation costs since the system is maintained and operated off-site. Building developers reduce initial capital costs from construction since they do not need to include their own chiller equipment which also translates to valuable space gained in their buildings that would have been occupied by HVAC equipment.

The electric grid and electric utilities benefit from the peak demand shaved which prevents from having to obtain additional energy sources to meet the peak demand and contributing to the reliability of the grid by preventing overloads during these times. Finally, municipalities can benefit from these systems by increasing local economic competitiveness. DC systems help keep energy rates low and stable in the area which is attractive for businesses and residents alike. Additionally, with the gained efficiency, DC systems help municipalities meet targets for GHGs reductions by increasing efficiency and incorporating renewable local energy sources.

RQ2: How is the downtown DC system integrated into the energy landscape in Austin and Houston?

Both DC systems use electricity to run the chillers and thus are customers of the electric grid. For the Austin case, the DC system is used as DSM strategy by AE, the electric utility, since the system is owned and operated by the utility. By incorporating ice thermal energy storage, the DC system has the ability to even out the demand on the electric grid during peak times. This results in savings to all AE customers from lower regulatory charges from ERCOT. AE has set targets to shave peak demand using the DC system, and the current target is to shave 30 MW by 2027.

For the Houston case, the system reacts to the 4CP set out by ERCOT and lowers their demand in order to reduce charges for the upcoming years. In Houston, the local T&D utility, CenterPoint Energy, is not involved in the system though it owned the system at some point in the past. Since Houston's electricity market is open for competition, the DC system is also competing for load with other retail electric suppliers.

RQ3: What were/are the drivers and barriers to implementing and expanding the downtown DC systems in Austin and Houston?

Both case studies shared similar drivers to implementing their respective DC systems. The de-regulation of the electricity market in Texas played a big role in proving an economic driver to implement the systems. Both Austin Energy and Houston Light and Power, which became Reliant Energy, used the DC system as a strategy to capture the load from HVAC at the time of de-regulation. In the Austin case, there were also energy efficiency and conservation drivers which put the system on the city's agenda. Eventually, the Austin DC system became part of the DSM strategies for Austin Energy to shave peak demand.

In terms of barriers, both systems identified split incentives and bounded rationality as barriers to the expansion of the system. Interestingly, the Houston system identified information imperfections as a barrier to implementing and expanding the system. On the other hand, in Austin information imperfetions was not mentioned as a barrier even though both cities did not have previous experience with DE. This is likely due to the fact that the Austin system is owned and operated by the city which likely instils more trust from end users. Conversely, the Austin system identified risk as one of the barriers for expansion since some of the buildings that requested the service would require additional long piping to provide chilled water. This would introduce a risk since the investment on the piping would only be cost effective if other buildings with a high load density connect to the system on the way. Thus, AE as had to turn away new customers to avoid raising rates for existing customers.

RQ4: What are the lessons learned from the DC system implementations in Austin and Houston?

The learnings from this research can be used by municipalities, energy companies, and third-party organisations interested in either implementing or promoting DC system. The key lessons learned from this research are as follows:

- **Role of DC Systems:** If managed properly, DC systems are profitable and are crucial assets to the infrastructure of a city. They can provide a mode of energy storage with TES and provide the scale to use local renewable energy sources boosting the local economy.
- **Role of Cost Saving Models:** Cost saving models are important tools to promote DC systems and configure subscribers. These models can be used as tools to show the

savings and benefits gained by the different stakeholders. Additionally, these models can be used to track and report the benefits of the system after implementation.

- **Role of Local Governments:** Even though it is not necessary for municipalities to get involved in DC systems to be successful, having the support of the city is important to maximise benefits of the system. The local government can choose to engage with the system in different ways to create project pathways and promote the technology.
- **Role of Champions:** Having champions of the technology is important for success. It is significant to identify a champion that believes in and knows the technology to manage the objectives, risks, and priorities of the system.

6.1 Closing Thoughts

This study contributes to the urban or district scale body of research for sustainable energy transitions. It presents the benefits and the potential of implementing DC systems in dense cities to meet space cooling demand. Additionally, it highlights the importance of incorporating DE systems, like DC, in urban and energy planning to obtain the most efficient solutions that are optimised to meet the specific objectives of the city.

DC systems are most effective in dense areas that are well planned. Thus, smart urban planning that is incorporated with energy planning can create more liveable spaces that use local energy sources and can reduce the demand for cooling and the heat island effect by increasing shading and ventilation. Moreover, good planning can encourage other practices that reduce the carbon footprint of the area by making walking and alternative modes of transportation more attractive.

Policy Recommendations

In order to increase the uptake of energy efficient systems and practices, policies for new developments are important since often developers will build up to the standards that are required in the area to maximise profit. There is always a split incentive with new constructions since the first entity to develop on a land has the opportunity to maximise their profit, and the construction costs are taken from their margin. Therefore developers do not have an incentive to invest in energy efficient materials, designs, or systems like DC that may have a higher upfront cost but pay back in the long term with energy efficiency gains and benefits to the community. Large development companies will often stick to what is required by law, highlighting the importance of buildings standards and certifications. Currently there are technologies to develop net-zero buildings and communities which reduce the impact of operations on the environment. However, these will only be implemented if the local policies exist that provide incentives, promote, or demand the use of energy efficient technologies. Similarly to new developments, aging built environments that are approaching a renewal stage are also good candidates to increase energy efficiency and implement practices like DC to increase efficiency and reduce energy demand.

Additionally, as cities in emerging economies grow and the demand for air conditioning continues to rise, it is important for municipalities and grid operators to get ahead of the peak demand issue. This is crucial in order to maintain a reliable and flexible grid and prevent the increase of GHGs emissions as well as the use of ODS. With DC systems, dense urban areas can meet thermal energy demands in an efficient and sustainable manner. Additionally, it is crucial for municipalities to encourage the use of energy efficient materials, and practices through building codes and smart urban planning.

Further Research Recommendations

As the demand for cooling continues to grow, further research on how the generation part of DC systems can be open for competition, in practice, would increase the attractiveness of these systems in warm weather cities. Moreover, further research on how to manage the demand for cooling to reduce fuel usage is important since DC systems provide some incentives to manage demand by end users, however, they are only incentivised to stay within contract. This could potentially have a negative lock in effect that eliminates incentives for additional efficiency measures on the demand side (i.e. efficient windows, curtains, etc) which are crucial for meeting carbon reduction goals and targets. Additionally, further research on accurate baseline methods to measure the benefits of implementing DC systems can help municipalities build the business case to implement these systems to meet GHGs reduction commitments.

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Appendix I – Interview Requests

Hi <interviewee name>,

My name is Silvia P. Guevara, I am an alumnus from the University of Texas – Austin and are currently a master's student in the Environmental Management and Policy (EMP) program at the International Institute for Industrial Environmental Economics (IIIEE) at Lund University in Sweden. I am working on my master thesis on district cooling implementations and would like to get your input for my research.

Modern district energy (DE), which includes both heating and cooling, has been identified by many organisations, like the United Nations Environment Programme (UNEP), as an effective and sustainable solution to meet heating and cooling demand. For my thesis, I am using the district cooling system in downtown Austin as a case study to learn how the different stakeholders (i.e.: city, service provider, customers) worked together to implement the system. The goal of my research is to gather key lessons learned to facilitate implementations and expansions in other cities.

Austin Contacts

I will be in Austin from July 8th to the 26th and would appreciate an in-person meeting. If an in-person meeting is not possible, I can also meet through skype or zoom.

Houston Contacts

I will be in Houston from July 29th to August 6th and would appreciate an in-person meeting. If an in-person meeting is not possible, I can also meet through skype or zoom.

Subject Matter Experts

I will be in Texas from July 8th to August 6th and would appreciate an in-person meeting. If an in-person meeting is not possible, I can also meet through skype or zoom.

If you would like to learn more about the IIIEE here is the institute's website for your reference: https://www.iiiee.lu.se/

Let me know if you have any questions regarding my project, I look forward to hearing from you.

All the best,

Silvia P. Guevara

https://www.linkedin.com/in/silvia-guevara-649b6157

Appendix II – Interview Guide

The interviews carried out were open and explorative in nature. For all interviews, the author gave an overview and the purpose of the project and used the following questions as a guide:

- In your opinion what are the main drivers to district energy in warm weather cities?
  - Follow up question - what actors benefit from these?
- In your opinion what are the main barriers to district energy in warm weather cities?
  - Follow up question - what actors are affected by these?
  - Do you have example of how these been addressed?
- What is the business structure of the system?
- What are the best practices to measure the benefits of a DE project? i.e. GHG reduced? Space saved? Efficiency gained? Reliability?
- Demand management appears to be important in order to make these systems economical and efficient, what are the best practices to address demand issues (Management? Measurement? Reduction?)

Appendix III – Interview List

1. Armando Armengol, *Austin Energy*, Plant Superintendent, July 15th, 2019
2. Gavin Dillingham, PhD, *Houston Advance Research Centre*, Director of Energy Policy, July 29th, 2019
3. Jan Adler, *City of Austin*, Plans Examiner Supervisor, July 23rd, 2019
4. Jim Collins, *Austin Energy*, Former Director of Energy District Cooling Program, July 17th, 2019
5. Kristin Simpson Carlton, *City of Austin*, Senior Environmental Revisions Specialist, July 23rd, 2019
6. Laxmi Rao, *International District Energy Association*, Senior Director, July 18th, 2019
7. Mark Widaski, *Enable Midstream Partners*, Vice President of Engineering and Construction, July 26th, 2019
8. Paul Robbins, *Austin Environmental Directory*, Editor, July 9th, 2019
9. Roger Duncan, *Austin Energy*, Former Vice President, July 18th, 2019
10. *Enwave Houston*, Vice President General Manager, August 4, 2019